Achieving the 1.5 Degree Rise Celsius Paris Agreement Target and Is it Realistically Feasible? Radical Futureproofing Answers to Climate Change and Investigating Terraforming, Geo-Engineering, Blue Carbon and Negative//Net Emission Solutions

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1: Introduction

How seriously are we as a planet, as the human species, business, society and policymakers committed to saving our planet? What extent are we prepared to change our behaviour, consumption, economy and existence to stabilise our climate and environment? Global, human accelerated climatic change represents along with overpopulation pressures, the greatest threat to our own survival, as scientifically validated by the Intergovernmental Panel on Climate Change, scientific research and ample evidence. In July 2015, 196 nations ambitiously committed to attaining no more than a 1.5 degree Celsius global average rise in temperatures. 2 degrees Celsius appeared more likely. Countries were free to determine how to attain that target with no penalties or incentives, via nationally determined contribution calculations and subsequent reduction methods. The UK and EU were subsequently joined by China, Japan and South Korea pledging to carbon neutrality as nations by 2050 along with 10 other nations as of August 2020. Bhutan and Suriname committed to being carbon negative.

The November Mock-COP26 event organised by climate change activists such as “Students for Sustainability: or the efforts and voices of those such as teenager Greta Thunberg has drawn attention of a resurgence in popular support for action in acting more decisively to implement real change. On 12th November China pledged to the world’s largest carbon emission trading scheme by 2025. The US President elect Joe Biden claimed in his electoral campaign that he wished to make the US carbon neutral by 2050. The emphasis is on carbon capture and storage technology. The United States offer a 45Q tax credit for local carbon sequestration. Other recent news includes pledges by aviation, steel producers and companies such as Microsoft committed to investing in reducing carbon and climate innovation. The financial sector including insurers and pension/sovereign wealth funds are divesting from climate change at a rapid rate.

Yet, we and our planet are rapidly running out of time for options… Global ecological restoration, rehabilitation and expansion, curbing population growth, developing a truly sustainable circular economy and being proactive against threats such as pollution, overfishing and poaching and others, needs rapid upscaling as many reminders echo. Yet how realistic and feasible can we as humans achieve the 1.5 degree Celsius scenario during and post-COVID19, blue economy minded world? When so many are committed to the emissions intensive, polluting current means of production, how can we rapidly make progress? This article targets how we can focus on radical futureproofing answers to climate change and achieving the 1.5 Degree Paris Agreement targets.

This includes options such as afforestation, blue carbon, solar mirrors and modification; enhanced weathering, ocean fertilisation, iron alkalinisation, biochar, bioenergy, direct air capture, carbon capture and storage, soil carbon sequestration and management. To answer if its realistically feasible, it seeks to overcome both our ignorance and our unwillingness to consider extreme climate geoengineering, net emissions technologies, natural and other solutions that focus more one merely mitigating and adapting to emissions. This remains insufficient, when we have to swiftly determine solutions and what are priorities are to resolving climate change, given scarce time, attention and other resources for many. Every delay causes more extinctions, more impact costs from gradual and extreme related events, and more consequences. It creates fewer chances for getting it right in the future…

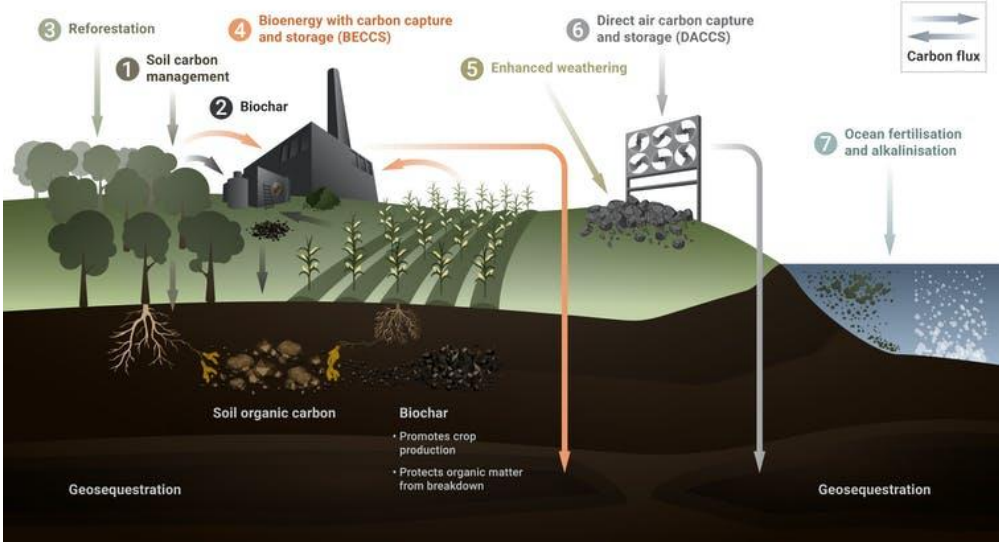
To attain a climate-resilient, business as usual and prosperous, aureal future, we need to accelerate immeasurable progress on really dealing with the extent of climate change to a not only carbon neutral and negative world, but towards all life-threatening greenhouse gas emissions. There is a need for net zero emissions. This includes not just mitigation but futureproofing, adaptation, contemplating if geoengineering and ecological restoration/blue carbon are essential to stabilising and protecting the planet against climate change and the environment including land, air, ocean and space. If possible, we need to reduce it to levels unprecedented since the pre-industrial era and allow our planet to recuperate, as the most historically effective mechanism. Therefore, this research will present an overview of recent trends, events and developments including stages of progress and funding for many of these technologies and radical solutions. It will aim to briefly clarify characteristics, the relative merits and risks of each, current uncertainties and information gaps; existing deployment and potential opportunities as core stakeholders and institutions. It will then consider current policies and how realistic these methods may be as possible responses to global climate change. By investigating terraforming, geo-engineering, blue carbon and negative//net emission solutions, this research is motivated to inspire future innovation, thought but more implementation action and understanding that significant climate change measures need to be considered by not just policymakers but all of us. Decisions that affect every lifeforce on this planet are too monumental and critical to rely on others. If we truly care about living or appreciating anything about our existence and legacy on Earth.

So, to achieve this target of a 1.5 degree future, just what volumes of emissions need to be initially targeted? Scientific estimates, as confirmed in a 11 November 2020 article by Lebling and Northrup project a minimum globally of 10-20 billion tons of CO_2 each year. Previous research of mine has highlighted the value and contributions/significance of marine renewable energy for the blue economy for carbon; blue carbon and attaining 30% of Earth as Marine Protected Areas for carbon/climate change mitigation. It also focused on the risks and implications of climate change for supply chains, individuals and communities; the need to consider airships and hydrogen as emissions neutral transport along with climate change data projections; psychology and finance as common barriers towards implementation, with the core priority of reducing these obstructions towards action. This research appears on my www.blueeconomyfuture.org.za website. This specific project differs in overcoming existing gaps towards innovative climate change resolutions, that with sufficient will, resources and effort permanently counteract many of these climate change issues, whilst providing myriad co-benefits/lower impact costs.

2: Overview of Net Emission Technologies and Solutions

Even if all emissions were to cease, the Intergovernmental Panel on Climate Change estimated the need to remove around 3 trillion of excess emissions. Without determining the combination of solutions to save our planet, favouring research and investment, our planet cannot attain a 1.5 degree or even 2 degree Celsius future, as envisioned in the Paris Agreement. Negative emission technologies and carbon neutral solutions can be divided into those natural (afforestation, biochar, soil carbon and enhanced weathering) and technological (Carbon Capture and Storage, Bioenergy Capture and Storage, Iron Fertilisation, ocean alkalinisation and solar radiation management) or others such as enhanced energy efficiency, renewable energy and the circular economy. Biological carbon capture processes focus on photosynthesis of marine organisms. Chemical processes include carbonate, silicate or other minerals including alkalinity, iron filings or other processes such as iron fertilisation, ocean alkalisation or enhanced weathering. More novel electrochemical techniques stimulate carbon absorption via electricity such as seawater electrolysis and hydrogen production. Several of these solutions are illuminated in Figure I.

Figure I: 7 Negative Emissions Technologies



Source: Claassens 2020.

2.1: Natural Solutions and Blue Carbon:

Natural solutions have historically proven to be the most cost effective, proven and simply replicable approaches. This includes blue carbon sequestration, directly relying on the oceans as greenhouse gas sinks via marine biological, nutrient and carbon cycles or blue carbon. This is processed by living marine organisms. Biological methods or blue carbon removal sources include whales, phytoplankton, seagrass, mangroves and salt marshes with other blue economy and ecosystem benefits as previously investigated. These also include ocean up-welling processes.

However, many of these core ecosystems would need to be extensively protected and extended to reduce emissions significantly beyond several hundred million tons per year, in alignment with the global interest in ensuring 30% of marine protected areas by 2030. For example, this includes the UK initiative to regrow its seagrass beds. Oceans 2050 in October aimed to survey and value the extent of global seaweed and its contribution to storing and reducing carbon emissions. It aims to market incentivise investors and producers based on blue ecosystem and environment benefits, then develop blue carbon credits against emissions. On 2nd November 2020 a major kelp farm was developed using up to $60,000,000 of climate finance over 5 years by Namibia's Eos Capital, Kelp Blue and Climate Fund Manager's Climate Investor Two Fund. Seaweed also has the benefits of ecological by-products such as species biodiversity, genetic benefit and reducing ocean acidification, producing revenue generation potential. It also offers potential for biotechnology, cosmetics, textiles, fisheries, biofuels, renewable energy and even fertiliser and construction material via seaweed processing and biochar.

Figure II: Seaweed Aquaculture Farm China

Figure III: Marine Ecosystems

Source: This Article.

Solutions may extend to artificial reefs, nutrient recycling and hydroponic systems and other methods as undertaken in the recent EU MARINER project. This also investigated Allam cycle electrical plants which could power these aquaculture farms with zero emissions via dry biomass. Estimates have calculated the potential to eradicate 28-38 billion tonnes of carbon each year at $25-$30 per ton, being more cost-effective than direct air capture (DAC) and carbon capture and storage (CCS). Although seaweed and other forms of aquaculture may reduce emissions indirectly, these benefits may be countered by other greenhouse gas contributions across the supply chain from greater industry exploitation. However recent research concluded that adding certain red seaweed species to the diets of cattle could reduce their released methane emissions by over 50%. It also reduces ocean acidification if fed to marine species. Yet too little red seaweed exists for 1.5 billion cattle, apart from other livestock, so it would necessitate rapid upscaling.

More efficient processes of blue carbon sequestration may need to be investigated to determine the most effective species, related management techniques and artificial restoration processes (Macreadie et al. 2019). The source calculates around $1000 per hectare in direct minimal blue carbon ecosystem benefits from tidal marsh, $2200 from coastal plankton, $3100 from deep sea sources, $13000 from seagrass but $91,000 from mangroves. It is also valuable to determine the extent of various blue carbon sinks and their resilience to climate change and how the absorption or filtering rates will be affected. How interference by natural or human processes will further influence the potency of this solution. Seaweed, seagrasses, tidal marshes, mangroves, whales, phytoplankton and algae sources could dramatically change in volume and surface area or migration patterns. Global seagrass could be rapidly expanded from 500,000-600,000 minimum km^2 to over 4,500,000. Various endeavours such as the Global Blue Carbon Initiative are working to link it to marine protected areas, carbon offset credit schemes, research and technical standards. There remains a need for greater connection to marine conservation, protected areas and climate/sustainable/blue economy finance initiatives.

2.2: Afforestation

Afforestation and reforestation is less controversial and effective as a nature based solution and refers to natural carbon removal processes via planting and protecting trees. This eliminates emissions as net carbon sinks. Aside from the ecosystem, food, habitat and other benefits it has widespread public acceptance, is cost-effective and simple to implement, proven to work since the inauguration of Earth. For afforestation China is rapidly upscaling its progress, with new forests planted in the past 3 decades equivalent to 35% of its carbon sink sources or billions of trees. Ethiopia is similarly committed with 350,000,000 trees planted. Armenia is reforesting to overcome previous damage to its environment after its war. The Armenia Tree Project committed to planting 6,000,000 trees at present in 1,200 communities. Armenia’s government in 50 years claimed the aim to double forest areas, although subsequently delayed. Despite chronic wildfires in Australia plus California and deliberate destruction of the Amazon; places such as these and Pakistan offer tangible expressions of confidence in this approach to mitigate against climate change. On 6th October 2020, Pakistan pledged to plant 500,000,000 trees, reaching 350,0000 hectares of land by the end of the year and 3 billion by 2023. This aims to reduce less than 3% of land currently forested, and produce indirectly up to 1,500,000 jobs, costing US $760,000,0000. It also pledged to act against illegal tree fellers more decisively. In Africa, 113,000,000 hectares is targeted under the African Forest Landscape Restoration Initiative.

Figure IV: Afforestation

Source: This Study

COVID implications favour afforestation for carbon offsetting schemes for travellers but people express concerns with wildfires and bushfire reputation. But that relies on neutrality not negative emissions and few endorse it for tourism. Over the past 3 decades Italy has committed to afforestation to reduce its emissions contributions under the Clean Development Mechanism/UNFCC Adaptation Fund initiative and carbon credits. (Corradini et al. 2020). The project planted 65,000 hectares and emission reductions of 556,000 tCO_2 each year. It argued the potential benefits of afforestation aside from timber and food exports, it promoted ecological biodiversity, species protection and conservation, renewable energy, education, women and youth empowerment along with jobs, pollution reduction and community benefit. Yet, there may be a trade-off opportunity cost between those that are valued commercially; those for biodiversity and indigenous and those capable of more efficient carbon sequestration. A series of afforestation projects in China from 2001 to 2010 affirmed its effectiveness as a solution (Lu et al. 2018). 6 projects were estimated to have stored an average of 74% of the regional total 132,000,000 kgs of carbon dioxide each year. China proposed an additional 4.5 billion cubic metres of forested would be planted between 2015 and 2030.

Whilst afforestation works effectively as a carbon sink, provider of food, materials, habitat and biodiversity; those opposed to it express concern over implications for water scarcity, impacts on grassland ecosystems and space limitations, with many often conflicting usages. Food security could be compromised if agricultural land was converted into forests. Afforestation also is a longer term project needing a minimum of 10-15 years for trees to reach maturity for certain species, even longer for many. Challenges with afforestation include each tree on average reduces up to 25-50 kg of carbon and being really cheap to plant trees costing below $50 per ton. As emphasised in California, Australia, South Africa and the 2019 European heatwaves, significant risks exist from higher temperatures under climate change and increased bushfires, presenting risks of increased emissions when burning. For example, Australia's devastating summer bushfires released around 830 million tonnes CO_2. Afforestation may also have albedo and evapotranspiration limits. Yet of many global nations, only South Africa frequently curbs forests and culls trees over cited claims of water security and chronic fears over invasive species as its contributions towards climate change and the environment.

2.3: Soil Carbon Storage and Sequestration

Soil carbon storage and sequestration operates via vegetation extracting carbon via photosynthesis, converting into soil organic carbon. Soil organic matter and carbon refines natural processes such as photosynthesis, soil erosion and decomposition over time to influence the rate at which this process occurs. Globally, soil carbon sinks are estimated to exceed just over 3,170 gigatons (GT), contrasting with the atmosphere of 800 GT and oceans of 38,400 GT. Certain estimates have indicated biotechnology, farming and other enterprises might be able to capture up to 25% of global carbon emissions each year whilst preserving up to 9 billion tons of soil loss. The extent to which this remains technically feasible, remains highly conditional upon various soil, climate, atmosphere, land use, erosion, climate change, pollution, water and soil quality and other factors. Soil carbon capture and storage remain constrained by available land, technology and skill limits. Improved management, technology and other techniques can increase the sequestration rate. Challenges remain as to monitoring the extended use of this negative emissions centred approach and the long-term implications for ecosystems and long-term cycles. Currently soil experiences many human and natural erosion based risks. It is also essential to consider mitigation, adaptation, resources for implementation and institutional capacity, local climate, ecosystem, incentives and psychology.

Figure V: Consequences of Poor Soil Carbon Management

Source: This Study.

Recently, soil organic carbon capture and storage has received greater attention as part of overall food security and more sustainable ecosystems/biodiversity under the European Green Deal and various agricultural policies. Soil carbon is claimed to be more natural, with proven technology, relatively cost-inexpensive for economies of scale and other benefits. A soil carbon sequestration experiment involving grasslands since 1994 (Yang et al. 2019) estimated a 70 to 200% increase in carbon storage rates. Australia's Soil Carbon Co for example, uses microbial bacteria and fungi to increase average soil carbon uptake by 7-17% and cost $25-$50 per ton in alignment with emissions market trading prices. They claim expansion would be able to reach 8 gigatons each year. Soil carbon capture and storage in 2020 became an Australian government priority as an officially recognised low emissions technological solution along with carbon capture and storage, reducing carbon intensive materials and production methods, promoting hydrogen, and energy storage. These also link to carbon market emission credits. In the USA they are considering financial incentives to encourage greater utilisation of this carbon emission reducing mechanism and to improve agricultural output/soil quality. Florida provide an SB286 tax credit for carbon farming. In 2020 Washington State proposed the equivalent Sustainable Farm and Fields Bill. US Congress proposed the Agriculture Resilience Act -soil sequestration and the S4875 carbon farming tax credit. However, international law and conventions have yet to consider soil carbon sequestration and capture as a mandatory/favoured recommended policy.

2.4: Direct Air Capture Technology

Direct Air Capture Technology (DAC) utilises membrane or gas/liquid, technology intensive and chemical processes to divert produced carbon emissions from the air into an alternative storage facility. Another method includes cryogenic freezing and removal via oxygen. This aims to provide a permanent resolving to prevent leakage into the atmosphere and contribute to global warming. It does not conflict with other land uses as much as certain other types in requiring less land and avoids the flammability risks of afforestation. It may only require as little as 25 l of water per ton of carbon extinguished versus 600 for BECCS. It also does not need legislative changes in many states, territories and internationally, in contrast to solar geoengineering, iron fertilisation or ocean alkalinisation. However, it is currently only operating in a few test and commercial plants, requiring significant time, investment of capital, skills and education upliftment and technology transfer in many global regions to replicate. For example, the Switzerland based Climeworks (Figure VI) can reduce up to 400 kg of CO_2 using 30 fans each day. It also enhances crop yields via adding soil organic carbon locally. DAC can also be significantly energy inefficient and cost intensive, dependent on a mechanism to power the capturing process.

Current costs per ton make it economically unfeasible on most emission trading schemes at present at $94-$232 per metric ton on average. It also incurs a reputational and marketing risk from those less familiar with the process and requires stable geological storage sites. It may incur high barriers to entry for many stakeholders. Uncertainty remains as to how long the process of effective capturing carbon will last. Only 15-20 global DAC facilities exist. Many are summarised in Table I below. Stored carbon needs to be secured and only utilised for non-emissions intensive processes. Developing this sector may support polluting hydrocarbons via enhanced oil recovery of processes or other applications as under Carbon Capture and Storage or utilisation. In 2019 the US Congress committed $35,000,000 to direct air capture out of a $60,000,000 budget for carbon technologies, a figure that may need to increase with the pledged commitment to the Paris Agreement by President elect Joe Biden. In 2020 Occidental Petroleum and Carbon Engineering in the USA proposed creating an oil recovery plant via Direct Air Capture Technology (DAC). Climeworks converted carbon to stone in their facilities. Future developments include direct capture from aircraft and marine vessels using scrubbers and other technology.

Figure VI: Climeworks DAC Facility, Switzerland and Iceland.

Source: Climeworks 2020

Another proposal for Direct Air Capture is to create artificial trees with greater absorption, filtering and storage capacity than many current species (Okesola et al 2018). Others include exploiting changes in humidity around 40 degrees Celsius and a polymer-based ion exchange resin system. Another advantage of DAC is not only the immediate environmental benefits over longer term methods but it may be less controversial and easier to persuade industry, including higher polluters to cooperate and fit existing polluting plants (Bipartisan Policy Centre 2020). To be even more effective however, it does require integration with utilisation and storage technologies. DAC can respond to the immediate high concentrations of atmospheric emissions presently contributing to global warming. It is also flexible and less dependent on environment and climates than biochar, enhanced weathering, BECCS and afforestation/blue carbon. However, on its own it needs to be discouraged as a panacea in discouraging the endorsement of effective human behaviour and process change as mitigation and adaptation solutions.

Emissions reduction via renewable energy and other methods will be insufficient. DAC technology managed a 92% efficiency capture rate at a Texas enterprise Petra Nova but went bankrupt in entwining its commercial destiny with enhanced oil recovery and historically low oil barrel prices. In October 2020 Amazon, Microsoft and other companies concentrated on investing in the Canadian Carbon Cure Technologies enterprise to reduce emissions from existing concrete structures. This favours DAC and Carbon Capture, Storage and Utilisation (CCS based) enterprises. Other developments include the US allocation of $72,000,000 to 24 projects including a Permian basin major facility in the southeast US; Norway's Longship project and Microsoft/Amazon's partnership for radical climate change solutions. However, trade-offs exist between upgrading existing facilities or favouring the conversion to renewable energy and the green/circular economy, complicated by the long-term lifespan of many fossil fuel powered facilities and the conversion costs. From 2019-2020 the US private sector committed $180,000,000 although actual implementation of various projects increasingly remains conditional upon COVID-19 and related disruptions across supply chains. Although current costs make DAC often economically unappealing at $300-600 in pilot stage; then more mainstream projects at $100-$200 per ton, economies of scale have reduced this to between $23-80. Certain technologies could produce water and hydrogen as byproducts but DAC itself does not provide them without subsequent utilisation, storage and developing connected processes.

In June 2019, Climeworks became the first global company to launch a DAC linked, carbon emission removal subscription service of €7 per month. This funds around 85 kg of carbon per year transformed into stone. It targets the global aviation carbon offset sector. In contrast to the above facilities, Net Zero Teeside seeks to seize carbon from the ocean rather than the atmosphere/land or industrial processes in a September launched project in discarded oil and gas storage facilities under the North Sea. Other recent DAC trends include a new thermal energy powered, Climeworks facility planned for Iceland announced on October 2020. Carbon Engineering in Canada are also investigating using AI and the 4th Industrial Revolution to improve capturing rates for carbon emissions whilst combining recycling plastic polymers. In October, France announced a 4 year Demonstration and Innovative Applications of the DMX Process project for DAC, linked to industrial blast furnaces linked to IFPEN, Total Refining & Chemicals and ArcelorMittal France. In November 2020 at an IMO Marine Environment Protection Committee meeting, the shipping sector pledged an unprecedented $5 billion into decarbonising solutions. This follows an earlier October 2020 declaration by oil and gas corporations such as BP and Shell and shipping companies such as Stena and Maersk to investigate and finance mobile carbon capture technology from global shipping. Yet there have been protests by a number of concerned people and institutions claiming this will not deter the creation of emissions in the first place or progress far enough. There is a need to develop a lifecycle impact cost including ecological and storage and the effectiveness of reduced emissions before the capacity of DAC to reduce the planet's issues can be considered.

Table II: Global DAC Facilities November 2020

Company	Country	Sector	CO_2 storage or use	CO_2 capture capacity (tCO_2/year)	Start-up year
Climeworks	Switzerland	Greenhouse fertilisation	Use	900	2017
Climeworks	Switzerland	Beverage carbonation	Use	600	2018
Climeworks	Germany	Power-to-X	Use	3	2019
Climeworks	Netherlands	Power-to-X	Use	3	2019
Climeworks	Germany	Power-to-X	Use	3	2019
Climeworks	Switzerland	Power-to-X	Use	3	2018
Climeworks	Germany	Customer R&D	Use	1	2015
Climeworks	Switzerland	Power-to-X	Use	50	2016

Company	Country	Sector	CO_2 storage or use	CO_2 capture capacity (tCO_2/year)	Start-up year
Climeworks	Italy	Power-to-X	Use	150	2018
Climeworks	Germany	Power-to-X	Use	50	2020
Climeworks	Iceland	Mineralisation of CO_2	Storage	50	2017
Carbon Engineering	Canada	Power-to-X	-	365 (max)	2015
Global Thermostat	US	-	-	2500	2013
Global Thermostat	USA	-	-	500	2010
Global Thermostat	USA	-	-	4000	2019

Source: GCCSI 2019

DAC processes incur issues of releasing emissions as it lacks a completely 100% conversion and capture rate at present and involve the consumption of raw materials to construct, as with BECCS and CCUS facilities. (Sandalow et al. 2018). Entire lifecycle costs need to be considered. The effectiveness depends on the membrane or other process selected. Very few commercial companies such as Carbon Engineering exist, thus reducing available market competition. The California based business, Global Thermostat boast that with sufficient volumes of economies of scale, however, market prices could become even more competitive with 1000,000 tons captured for as little as $50 per ton. Arizona University's Centre for Negative Emissions has forecast costs could reach as low as $30 with sufficient support for its anionic exchange resin process. Infinitree are developing a method utilising ion exchange resin. Carbon Engineering favour a liquid alkali solution capable of extracting 1 ton of CO_2 per day versus Global Thermostat's ceramic attached amine method. DAC is simple to scale up and Earth has sufficient geological capacity to store carbon, however existing funding support has been limited (Gerrard 2020). Actual public support would remain highly influenced by marketing, the location and greater understanding as to the fate of the captured carbon with protected facilities.

2.5: Carbon Capture and Storage/Utilisation

Carbon Capture, utilisation and storage (CCUS) is similar to DAC in using technology not only to convey carbon emissions from the atmosphere or source, then transferring via vessel or pipeline to a secure storage facility or geological feature/cavern. CCUS can operate on chemical absorption, calcium looping, direct separation, oxy fuel, silica, organic or alternative forms of absorption and separation from the atmosphere or point of source. It can be stored in natural caverns, saline formations or existing oil//gas/other reservoirs. It can then be processed or utilised for alternative uses if not stored. A 2015 US Environmental Protection Agency investigation into CCUS technology divided existing types into steam forming boilers, combustion turbine/reciprocating internal combustion energy or integrated gasification, combined cycle processes. 29 US oil sites were identified as suitable by the US Department of Energy. A 2005 Intergovernmental Panel on Climate Change, special report identified separation could be pre-combustion, post-combustion, oxyfuel combustion or industrial separation via natural gas processing or ammonia production (Intergovernmental Panel on Climate Change 2005). The report estimated emissions reduction in 2005 could have reached 6,50 to 9,500 Mt CO_2 each year to 2010 and 13,200 to 18,500 by 2020. However, actual emissions reduction failed to receive the requisite level of support.

The technology remains in a prototype development phase as only around 21 global commercial CCS projects, exist as summarised in Table I. These plants sequester an average of 40 mega tons of CO2 each year. The technology has been proven and can profit profitable with emissions trading schemes/offset programmes or alternative usages of carbon such as conversion to hydrogen or concrete. The low hydrogen economy can empower vessels, airships, vehicles and other processes. It can directly remove present emissions and is starting to attract greater investment incentive interests. It has particular application benefits to reduce emissions intensive industrial processes. Currently the Global Carbon Capture Institute indicate sustainable financier sources are heavily interested in it with over 30 projects currently planned over the next 5 years and US $27,000,000,000. These may triple current global capacity of 130 MT per year. At least a present 40,000,000 tons of carbon dioxide emissions are being reduced each year. CCUS can prove to be economical reaching as low as $15 to $25 per ton to reduce.

In 2020, the US government committed over $4 billion in direct research and development incentives to develop CCUS technology. Norway are currently pursuing a dual hydrogen production facility and CCUS plant with conversion and storage capacity of emitted carbon. Additional incentives are existing under the EU Innovation Fund and Emissions Trading Scheme. Europe and Canada are looking at setting up regional distribution networks and storage hubs. In March 2020 UK CCUS infrastructure received a commitment by the government of 800,000,000 pounds and an additional 139,000,000 pounds in July. The US oil and gas sector pledged to investing in a prototype plant, as did Equinor, Shell and Total. However, unlike afforestation, DAC may not release the captured emissions into the atmosphere at the end of its lifespan (Gerrard 2020). It may be able to utilise many of the more redundant car manufacturing and industrial/mining sector workers, to reduce redundant displaced labour costs.

Existing oil, gas and other technology and experience could simplify the transition and related incurred opportunity costs. The Global Carbon Capture Institute, International Energy Agency and other sources have conducted a variety of research sources, estimating the potential to save up to 8000,000,000 tons of carbon emissions by 2050. Asia power plants and factories are even newer than many regions likely to pollute significantly and contribute to global climate change, unless the carbon is removed and more renewable energy mechanisms are generated. It also provides prospects for lucrative revenue from the stored carbon, enhancing its appeal over certain other methods. It can also produce methanol, low emissions intensive methods of chemicals, cement, iron, steel and other industrial processes. As with DAC it can work on producing hydrogen at rates ultimately as low as $1.2-3.3 per kg. These technology solutions are swifter to develop in not relying on the growth of lifeforms, biomass or significant volumes of land with competing uses, as for bioenergy, blue carbon and afforestation. It has also proven to be economical costing as little as US $15 per ton in certain types of industry, given sufficient economies of scale. Current pilot projects such as the CarbFix project in Iceland, the CIUDEN project in Spain, the Drax CCS pilot project in the United Kingdom the STEPWISE Project in Sweden and CCS in Croatia could be upscaled or used to ascertain the various risks, impact costs and benefits. There remains a need for more research and development.

Global CCUS sites include Europe's Gassanova, Equinor, Shell, Total, Norcem, Fortum Oslo Varne and Japan CCS -Tomakomai Project (Rasool et al 2020). In the US CCS projects previously received US $3.4 billion in total in 2019. At least 22 register US CCUS site operates exist. Canada offers 4 CCS facilities which commercially focus on oil recovery. Test facilities are present at Carbon Management Canada Research Institute, the Containment and Monitoring Institute and the Carbon Capture and the Carbon Capture and Conversion Institute. It offers 702 kilometres of devoted pipelines. A $41,000,000 test facility under the International Energy Authority or Greenhouse Gas Weyburn-Midale CO_2 monitoring and storage project provided background expertise between 2000 and 2012. Japan's government supported the Saga, Mikawa, Osaki Coolgen and Tomakomai demonstration CCUS plants. It also conducts related research under the Research Institute for Innovative Technology. Norway has the Sleipner and Snohvit projects, supported by a CO2 tax since 1991.It formed Gassanova in 2005 and the Technology Centre Mongstad. Australia has the Gorgon LNG project (AUD $60,000,000) and at least $460,000,000 on other projects. Pilot initiatives include the renowned Global CCS Institute, NGL Laboratory, Gipp Net and several power station experiment sites.

Table II: Large-scale 2020 Commercial CCUS Projects in Operation

Location	Facility Name	Year Operating	Type	EOR
United States (US)	Terrell natural gas plants (formerly Val Verde)	1972	Natural gas processing	0.5
United States (US)	Enid fertiliser	1982	Fertiliser production	0.7
United States (US)	Shute Creek gas processing facility	1986	Natural gas processing	7.0
Norway	Sleipner	1996	CO2 storage project	1
US/Canada	Great Plains Synfuels (Weyburn/Midale)	2000	Synthetic natural gas	3
Norway	Snohvit	2008	CO2 storage project	0.7
US	Century plant	2010	Natural gas processing	8.4
Spain	Elcogas Puertollano	2010	Hydrogen production	
US	US Air Products steam methane reformer	2013	Hydrogen production	1
US	Lost Cabin Gas Plant	2013	Natural gas processing	0.9
US	Coffeyville Gasification	2013	Fertiliser production	1
Brazil	Petrobras Santos Basin pre-salt oilfield CCS	2013	Natural gas processing	3
Canada	Boundary Dam CCS	2014	Power generation (coal)	1

Saudi Arabia	Uthmaniyah CO2-EOR demonstration	2015	Natural gas processing	0.8
Canada	Quest	2015	Hydrogen production	1
UAE	Abu Dhabi CCS	2016	iron and steel	0.8
US	Petra Nova	2017	Power generation (coal)	1.4
US	Illinois Industrial	2017	Ethanol production	1
China	Jilin oilfield CO2-EOR	2018	Natural gas processing	0.6
Australia	Gorgon Carbon Dioxide Injection	2019	Natural gas processing	3.4-4
Canada	Alberta Carbon Trunk Line (ACTL) with Agrium CO2 stream	2020	Fertiliser production	0.3-0.6
Canada	ACTL with North West Sturgeon Refinery CO2 stream	2020	Hydrogen production	1.2-1.4
China	Huaneng Green-Gen IGCC Project	2020	EOR	
UK	Summit Power Caledonia	2022		

Source: GCCSI 2019

The Global Carbon Capture Institute cite 4000 jobs could be produced from Norway's Longship project alone and 1,200 at the Teeside Net Zero project for the UK. This aligns to many emissions trading scheme prices as market competitive. As technology develops it is proving to be more cost-effective and feasible. Many of those nations who have pledged to carbon neutral targets have conceded the role of DAC and CCUS technology has instrumental in reducing their nationally determined contributions of greenhouse gases. Total global storage capacity has estimates ranging from 8000 to 55,000 GT but many of these locations would need to investigate research and devise suitable safeguards and regulations/monitoring and compliance and avoid risks to water, soil, species and ecosystems, if pursued.

One proposal for carbon capture and storage in California interviewed core stakeholders, conducted financial, ecological and geological modelling by Stanford University and the Energy Futures Initiative (Energy Futures Initiative and Stanford University 2020). It identified the high risks of relying on natural based processes, given extensive wildfires and higher surface temperatures projected under climate change. As the world's fifth largest economy, significant efforts were necessary to decarbonise its industry. It estimated potential reduction of 60 Mt of CO_2 by 2030 from CCUS compared to less than 3 at present, highlighting the lack of investment, technology, policy and other incentives to do so currently. It also identified 76 potential suitable facilities. California has stated a goal to be carbon neutral by 2045. Geologically it has potential to store 150-500 gigatons of CO_2. They identified uncertain ownership over pore space rights, unfavourable public perceptions, market demand and unknown cost estimates served as present deterrents. However, the US does offer the tax credit 45Q and a Low Carbon Fuel Standard as possible incentives to motivate initial efforts to research DAC and CCUS approaches. There is also potential for hydrogen production via electrolysis.

The technology incurs many similar cost, deployment and upscaling issues as DAC as a radical solution to climate change including refitting existing plants and creating new ones. If it is to be considered seriously, those investigating it are further required to consider geology for local storage of carbon; technological and skills requirements, possible implications for local ecosystems and climate or risks to human and other species' rights. Currently it would require greater publicity and marketing experts to change popular perceptions that it entails high risks or fails to address the actual problems of mitigation or adaptation. Significant regulations act as deterrent to potential investors such as 4 years in the US to get an initial carbon injection permit. Questions remain as to how to dispose of the carbon process and either stored or converted into alternative usages. The extent to which property rights apply to ownership of deep caverns and responsibilities over safe utilisation of carbon. Many investors currently remain unsure as to the projected rates of return on investment, extent of insurance and liability and policy or market uncertainty concerning the mechanism. Current investment in it is less than 0.5% of estimated clean energy finance from 2010 to 2020. Yet Carbon Cure, Solidia and Carbon 8 have managed to operate with profitable products.

Suitable uses of the carbon, incentives or fossil fuel deterrents or carbon trading markets have yet to appear in many emerging nations such as India, Brazil, South Africa, those of the Middle East and Southeast Asia. Some investments proved even less vulnerable from the low demand for oil recovery during the low oil price in April/May 2020 as with the problems of Petra Nova in the US, which ceased extracting carbon. The London Convention was amended to provisionally permit transboundary transport of carbon in October 2019, irrespective of the potential risks to the marine environment. Unlike afforestation and blue carbon, refitting or retiring the global supply of electricity plants whether by CCUS, DAC or renewable energy, will incur significant conversion issues, although absolutely imperative as they contribute 40% of current emissions precipitating climate change. Additionally, more investment in pipelines, transport and supporting infrastructure would be needed with adequate risk management, safety and security considerations. The existing fate of the carbon once captured needs to be considered.

Currently the US and Canada have an extensive network with 6 and 4 respectively. 2 pipeline networks exist in Europe (Norway and Netherlands) and 2 in the Middle East (UAE/Saudi Arabia). It would not be appropriate to highly ecologically sensitive areas and small island developing states/other geographically constrained locations. Other uncertain ecosystem risks exist. Stakeholders are still expressing concern about the lack of a commercial market for captured carbon or sufficient public support and endorsement for their product (Karayannis, Charalampides and Lakioti 2014). Technological innovation could lead to enhanced capture rates and become more lucrative with sufficient economies of scale. More specialists however would need to be trained. It may present opportunity costs to local communities if the extent of liability for captured and stored carbon is not confirmed. More successful business case studies and greater public awareness/demand would be instrumental if it were to be regarded seriously by the private sector rather than relying on government. Technology still needs to be improved to reduce the final 10% of emissions not captured, (International Energy Authority Clean Coal Centre 2020), by existing mainstream CCUS technology to be truly carbon neutral and attain zero carbon status.

As with other technologies, a lack of cooperation, coordination, policy certainty or incentives in many regions has helped to avert acceleration of carbon capture, storage and utilisation processes to reduce the pace of global climate change. The Global CCUS Institute estimate at least US$ 160,000,000,000 of investment is needed by 2030 to be on track to 1.5 degrees. The International

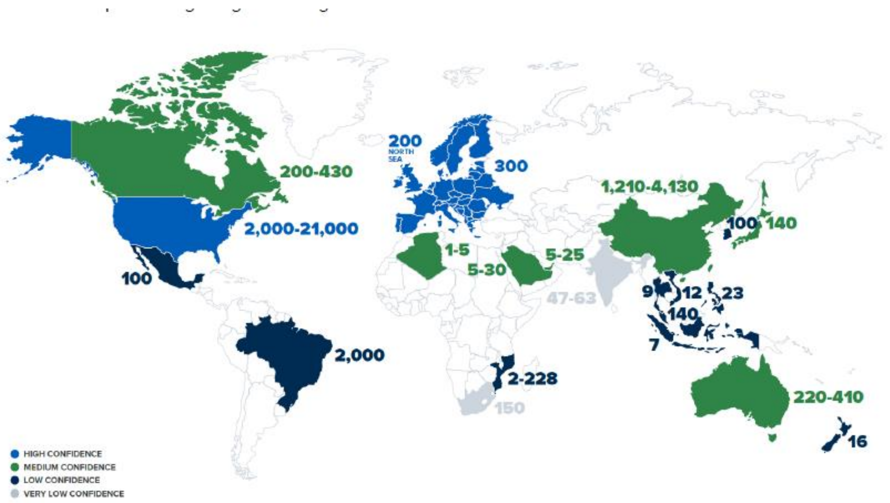
Energy Authority, Clean Coal Centre estimated 170 GW of coal powered plants would need to be fitted with CCUS to restrict emissions to a 2 Degree Climate Change scenario (International Energy Authority Clean Coal Centre 2020). It also calculated carbon emissions reduction could be even more profitable at $65 per ton. The US 45Q tax credit grants US $35 to 50 per ton as incentives by 2026. CCUS may present health and safety risks if insufficiently secured. Sufficient regulations and mass popular awareness, education, training and understanding may also be necessary to safeguard adequate, secure storage and utilisation.

Integrated carbon capture, storage and utilisation estimated 721,000 tons could be reduced via the technology for formic acid production (Mohsin et al. 2020). In 2019 42 gigatons of carbon dioxide required removing. One case study provides scenarios for a 500 MW NGCC power plant producing 4320 tons of Carbon each day; a carbon capture and sequestration plant or integrated CCUS facility or 864 tons a year. Existing gas revenue was $55 per MWh produced. These were proved to be economically viable under a modelling scenario. It is also essential to consider lifecycle costs and carbon footprints. There is a need to consider more research, development, governance and formulation of any related policies, implementation and extended deployment. One US study focused on complementary policy solutions such as emissions trading, increasing existing facility efficiency, technology and market based solutions (Morton 2020). It resonated emphasis on BECCS and DAC as most prevalent and effective climate change solutions. Alternatives such as fossil fuels should remain highly penalised.

A US investor guide to carbon capture and storage identifies possible risks of COVID19 delaying economic recovery and disrupting supply chains for the next several months to year (Loria 2020). It also identifies potential storage, transport, liability, counterparty and uncertain policy risks. It proposes supporting entrepreneurship, incubation and technological innovation, so the private sector supplements the over $100,000,000 each year currently spent by the Federal government. The source estimates a need to develop 30-60 global storage sites each year at a minimum until 2050 to capture and process all global emissions. As highlighted in Figure VII; the US could capture and store the most out of many global regions with 2000 to 21000 gigatons, versus 1210 to 4130 in China, 2000 in Brazil, 300 across Europe and 220 to 410 in Australia. At a minimum the sites need porous, permeable rock, stable geological risks away from ecosystems and seismic activity and 1000 metres or deeper below the surface. The process has proven to work with over 260,000,000 tons of carbon already stored.

Similar challenges exist for many developing nations and small island states facing labour, technology, skills, finance, time, information and other constraints to effective upscaling and deployment (Kulichenko and Ereira 2011). This extends to ensuring adequate transport, storage and monitoring/usage of products. There is also significant existing competition and regulatory barriers to DAC/CCUS, other technologies and renewable energy which threaten monopoly, inefficient state owned enterprises such as Eskom in South Africa. International conventions also preclude the favouring of CCSU and transportation under UNFCCC, the Kyoto Protocol, London Convention, Paris Agreement, UNCLOS, new 2020 High Seas Treaty, Basel Convention and others. UNCLOS Article 195 seeks states "*not to transfer, directly or indirectly, damage or hazards from one area to another*," whilst the Basel Convention curtails movement of hazardous waste.

Figure VII: Hypothetical Global Carbon Storage Sites



Source: Lori 2020.

Existing aid, climate/other sustainable finance and the green economy fail to consider resolving existing emissions, focusing more on mitigation and adaptation. The source highlighted highly unambitious targets for South Africa of only 2% from CCUS by 2030 or 275,000 tons per year gaining revenue of $40-50 per ton per year. It also estimates possibilities for 70% of the Balkans by 2030. Neither Africa nor the Balkans or many emerging nations have a policy or design and technical standards towards CCUS processes or effective pilot projects yet operational in 2020. The source estimated $4-5 billion per year would be needed for developing countries in investment by 2020, reaching $40 to $50 billion by 2030. However, many nations could investigate storing CO_2 into deep mineshafts or old oil and gas wells. Issues of possible liability, design and compensation for leakages is highly advised to be determined and incorporated into any issue. Monitoring and risk management plans and evaluation processes also need to be considered.

2.6: Bioenergy with Carbon Capture and Storage

Global bioenergy utilises natural trees, vegetation and other biomass via capturing, transport and conversion/storage processes or BECCS. BECCS became initially popular around 2001 but has become more popular as global emissions expand. It appears to be more cost-effective and realistic than solar radiation management and certain technology solutions such as Direct Air Capture. Mass investment in biomass would yield other direct and indirect ecosystem benefits until sequestered. In recent developments, on 22nd October the UK committed to a new 2022 biomass strategy, targeting bioenergy and other methods as a contribution towards its goals of climate neutrality by 2050. By 2030 bioenergy may satisfy up to 16% of total UK energy requirements demanded. On 2nd November 2020 the Japanese companies Toshiba and Chiyoda claimed to scale up carbon capture at a global prototype basis of a carbon capture bioenergy plant, powered by palm kernel shells and biomass. It aims to target 500 tons of CO_2 each day of 50% of that emitted by the plant via fuel gas desulphurisation. The company IFPEN are similarly experimenting as is Sweden's Aker. Figure VII illustrates the largest global BECCS commercial enterprise or Archer Daniels Midlands facility in Decatur, Illinois USA. Global BECCS prospects could exceed 11,000,000,000 tons each year of carbon. Current successful BECCS projects are summarised in Table III. The Illinois Industrial CCS Project, with a capture capacity of 1 MtCO2/year, is the most significant.

Figure VII: Archer Daniels Midlands BECCS Facility

The world's only large-scale BECCS facility is the Archer Daniel Midland's plant in the US city of Decatur in Illinois (Image: Google Earth)

Source: Google Earth 2020.

Table III: Current Global BECCS Projects.

Plant	*Country*	*Sector*	*CO_2 storage or use*	*CO_2 capture capacity (kt/year)*	*Start-up year*
Stockholm Exergi AB	*Sweden*	*Combined heat and power*	*-*	*Pilot*	*2019*
Arkalon CO_2 Compression Facility	*United States*	*Ethanol production*	*Storage (EOR)*	*290*	*2009*
OCAP	*Netherland*	*Ethanol production*	*Use*	*<400**	*2011*
Bonanza Bio-Energy CCUS EOR	United States	Ethanol production	Storage (EOR)	100	2012
Husky Energy CO_2 Injection	Canada	Ethanol production	Storage (EOR)	90	2012
Calgren Renewable Fuels CO_2 recovery plant	United States	Ethanol production	Use	150	2015
Lantmännen Agroetanol	Sweden	Ethanol production	Use	200	2015

Plant	*Country*	*Sector*	*CO_2 storage or use*	*CO_2 capture capacity (kt/year)*	*Start-up year*
Alco Biofuel bio-refinery CO_2 recovery plant	Belgium	Ethanol production	Use	100	2016
Cargill wheat processing CO_2 purification plant	United Kingdom	Ethanol production	Use	100	2016
Illinois Industrial Carbon Capture and Storage	United States	Ethanol production	Dedicated storage	1000	2017
Drax BECCS plant**	United Kingdom	Power generation	-	Pilot	2019
Mikawa post combustion capture plant	Japan	Power generation	-	180	2020
Saga City waste incineration plant	Japan	Waste-to-energy	Use	3	2016

Source: GCCUSI 2020.

The technology has yet to establish itself as viable on a significant scale with few commercial enterprises installed and high market entry costs or possible legal liability and storage risks. Biomass needs replenishment and has biological, climate and environment limits (Figure VIII). The International Renewable Energy Agency IRENA estimated 700,000,000 hectares of land would be necessary for a 2 degree Celsius limit, if the Earth was 100% reliant on the technology and even more than 50% of Earth's arable land surface would be necessary for a 1.5 degree Celsius scenario. One average this equates to between 1 000 and 17 000 km_2 per Mt of CO_2 removed Aside from food security, exports, trade and the economy, it presents possible deforestation risks if employed as the sole/major source of carbon capture and storage. More long-term monitoring systems would need to be deployed to assess its effectiveness and states/the private sector would have to invest in biomass conversion facilities. BECCS still needs to become cheaper to become even more competitive with alternative carbon reduction methods, ranging from US $60-80 on average per ton sequestered. However, it is more economical than mainstream DAC and CCUS technology for many facilities.

Figure VIII: Examples of Biomass from One's Home Country Estate/Farm

Source: This Study.

One UK study on bioenergy and carbon capture confirmed the government perspective as a recognised strategy for establishing carbon neutrality by 2050 (Ricardo Energy and Environment 2020). This included over 826,000,000 pounds in devoted infrastructure, funding and other support. It is further recognised in being able to contribute to hydrogen production and the green economy. It recognises constraints of fertiliser, water, land and potential for biomass growth as well as the need to consider hydrogen reduced. It identifies that 1,300 tons of CO_2 each year could be avoided via a 50 kW biochar pyrolysis facility. UK biomass energy increased from 3.9 TWh in 2000 to 35.9 in 2018 and could reach to 147 by 2030. Biomass offers similar recognition issues in society, legally and attracting financial investment support as other technologies that could really pulverise carbon and other greenhouse gases. The biomass conversion process needs to have additional plants and support. It needs to gain sufficient economies of scale if it is to prove itself effective. It estimates the technology could support 80 jobs by 2030 and 1250-1750 jobs direct by 2050; storing 14-19 billion pounds value of carbon by 2050 and air emissions damage, impact costs exceeding 106,000,000 pounds each year.

However, another more sceptical source indicates that for many locations BCCS may jeopardise the integrity of natural habitats and biomes (Farjardy et al 2019). Creating biofuel and bioenergy presents risks to those unfamiliar and inexperience. It estimated the need for at least 400,000,000 to 1,200,000,000 hectares of arable land. However, BCCS could remove up to 25% of current annual emissions produced. Biomass may be more complicated to calculate in terms of lifecycle emissions costs averted. Stakeholders have also expressed concerns for various locations as being climate, soil and environmental dependent, along with nutrients, land, water and phosphorous/fertile soil. One source estimated increasing biomass to non-biodegradable char in the cotton industry over a year could extract and suppress up to 7.62 tons of CO_2 per hectare (Proll 2019). It can also yield heat, biofuel and electricity byproducts. Biochar is more inexpensive than BECCS without needing logistics and storage capacity.

2.7: Biochar:

Biochar is similar to bioenergy-based solutions but utilises pyrolysis, microbes and soil clusters to convert organic material and biomass via carbon. The process can involve exothermic reactions via in situ methods via inserting carbon or ex situ approaches such as mining methods. Soil becomes a net carbon sink for biochar or greatly refined charcoal (Sudar Carbon Sciences, 2015) 50% of the biomass becomes char, 40% becomes byproducts such as biogas and bio oil for electricity but 10% is released as carbon emissions. However, it has extensive research pointing to the benefits including improving soil quality, reducing nutrient losses and overall agricultural output capable of improving average crop yields up to 16%. It can improve habitats, biodiversity and other aesthetic/health and welfare/community income benefits as with afforestation and blue carbon. It offers potential to remove 4,600,000,000 tons of emissions each year or 500 kg per acre. It can also reduce agricultural waste, add carbon as nutrients to soil however and lacks the technology intensive methods of DAC and CCUS.

This technology does not interfere with existing agricultural land use provided it is constrained to it, although DAC necessitates less land in total for the same emissions reduction output. Biochar uses less water than immediate afforestation and CCUS technologies. 2015 estimates indicated that a present 0.7 gigatons of carbon could be engulfed from the atmosphere for both biochar and soil organic carbon separately (Smith 2015). Improved soil fertility would increase the extinguishing capacity. It avoids direct interference with the albedo effect and atmosphere such as for solar geoengineering and radiation management and minor energy costs. Sudar Carbon Sciences in 2015 estimated South Africa could sequester 186,000 tons of CO_2 at a minimum total revenue of 930,000,000 euros for 5000,000 hectares after 5 years. Or after a year South Africa could commit 1000,000 hectares reducing 37,200,000 tons yielding 186,000,000 euros.

Similar implementation costs and challenges to other net emission solutions exist for those inexperienced. Certain challenges to biochar given very few pilot projects exist and it has legal uncertainty over applicable regulations. It also remains subject to biophysical, climate and environmental consequences. Other technologies may yield greater emissions reductions but at greater costs. One source estimated BECCS might remove 3.3 gigatons per year(Smith 2015) but would need an additional 380,000 to 700,000 hectares of land and 720 km^3 of water each year. Biochar could remove 0.7 to 1.3 but need only 40-260,000 hectares and no additional water at a similar cost. A 2013 research paper cautioned the finite biological and ecological limits of biochar and BCCS (Smith and Torn 2013) It estimated removing1 Pg of carbon per year via increasing tropical afforestation could need another 70,000,000 hectares of land, 0.2 TG of phosphorous and 0.09 of nitrogen. Switchgrass BCCS would require even more land at 200,000,000 hectares, 4000,000,000 kilolitres of water and 20% of current world nitrogen production. Certain crops are more efficient at yielding bioenergy.

2.8: Enhanced Weathering

Enhanced weathering or carbon mineralisation refers to using natural rock storing processes, via destroyed smashed silicate rocks or other minerals, converting to a solid or exposing it to air and natural processes. It may only have pilot stage projects at research stages rather than commercial enterprises but is far less technically skilled and more inexpensive than DAC, BECCS and CCUS technologies. It can also draw upon millennia of mining, construction and related industrial tasks. It is energy intensive during the mining process, compared to natural afforestation, biochar and blue carbon methods. An alternative method incorporates including further alkaline based solutions, as dissolving mineral compounds but this demonstrates core risks to marine pelagic fishery species and related biogeochemical fluxes (Bach et al. 2019).

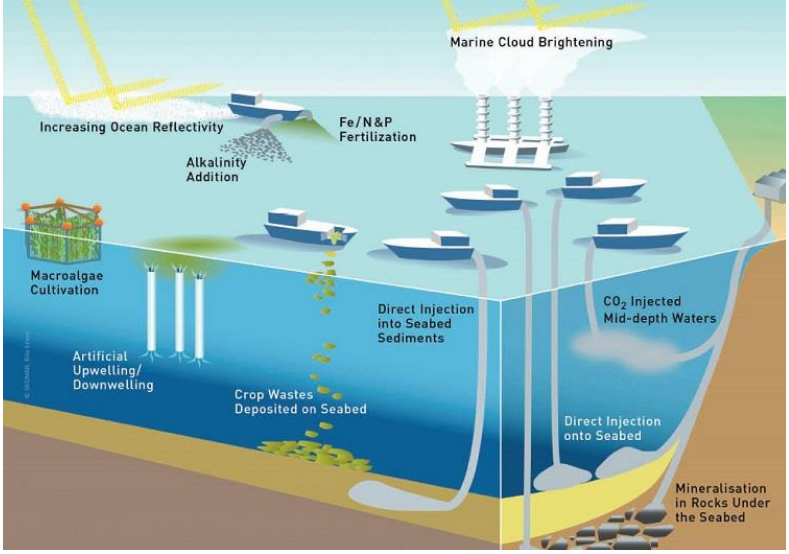
However, it is subject to natural limitations occurring over decades or years, unless with an artificial intervention such as crushing, erosion, enzymes, natural elements or similar methods. More surveys would be needed to locate the reactive rocks needed such as basalt. Seismic and geological risks may exist over long term stability to ecosystems and land use if insufficient monitoring and precautionary measures are taken including reducing resulting waste. Few long term experiments have been funded in contrast to other reviewed net zero emission approaches. Without more examples it is challenging to determine how effective enhanced weathering may be and the extent to which long term adverse externality cost consequences jeopardise other activities. A 2020 study estimated combining enhanced weathering with croplands could remove 0.5 to 2 gigatons of carbon dioxide at a rate of $80 to 180 per ton (Beerling et al, 2020) globally by 2040. It favoured prospects in Brazil, China, India and the USA. It identified possible limits to soil weathering rates, the possible risks of increasing mining activities and involving marine weathering conditions with ecological uncertainty. There is also a risk of increased atmospheric dust and health implications.

2.9: Ocean Iron Fertilisation

Ocean Iron Fertilization adds iron/other minerals to the ocean to accelerate photosynthesis and the ocean biological/carbon cycle to create carbon engulfment via algal blooms or additional phytoplankton. One method is to use long pipes via artificial upwelling or direct depositing. An alternative extreme method proposed is to use volcanic ash directly inserted into the oceans, which would reduce carbon via phytoplankton blooms, incidentally providing more food for whales as blue carbon sources. Examples include volcanos from Vanuatu, the Pacific Ring of Fire, Canaries and other islands. These methods, as with others, place an overemphasis on carbon capture rather than sulphur/nitrogen etc… They are presumed to be economical, not interfere with other land-based activities, proving effective for marine life in the Aleutians and other islands. Algae and phytoplankton can improve sinking rates. Globally, 13 main ocean fertilisation experiments have sought to verify this process from 1993 to 2009. 7 in the Southern Ocean. This entailed dumping several hundred kilograms of iron and with chemical tracers attached. Another project LHOFEX involved 6 kg of iron over 300 km^2 of ocean. Yet few such as EIFEX in the South Atlantic proved convincing evidence of success. Silicic acid was diminished along with changes in nutrient cycles and essential gases such as oxygen. Others included the CYCLOPS project over 16 km^2 and Fee-P over 2 areas of 25 km^2 each. A recent scientific expedition including the University of Southampton estimated 2750 CO_2 tons could be removed from dumping 50,000 tonnes of tephra off the Peruvian coast causing uncertain harm to ecosystems. To be efficient, it needs to remove carbon, without disturbing other ecological balances.

Existing ocean capacity of over 9,000,000,000 tons of carbon dioxide removal is projected to dramatically increase and be among the most simplistic and cost-effective solutions. It may also stimulate fisheries from additional phytoplankton and algal blooms. However, it does present uncertain ecological consequences to the ocean and climate cycles. It has not yet received favourable popular perceptions or a reputation. International conventions such as the London Convention, MARPOL, UNCLOS and the recent UN High Seas Treaty for areas beyond national jurisdiction specifically prohibit commercial exploitation of the oceans via dumping or deliberate dumping and interference to marine environments. Only legitimate scientific research enjoys and exemption. The “Assessment Framework for Scientific Research Involving Ocean Fertilization” (Resolution LC-LP.2(2010) has appropriate international guidelines to plan research, consider impact costs, responses and overcome gaps. Many local nations have similar restrictions against pollution. Algal blooms could reduce oxygen, chemicals, nutrients, communication and other natural processes for species, depending on local area characteristics.

Figure IX: Ocean Iron Fertilisation, Marine Cloud Brightening, Mineralisation and Other Climate Change Solutions



Source: International Maritime Organisation 2020

Another paper argued that whilst commercial iron fertilisation in the Southern Oceans should not be permitted due to high legal uncertainty and possible impact costs for marine ecosystems; permitting more scientific research trials could substantiate risks and benefits via empirical evidence (Rohr 2019). Certainly, here is far less regulatory and monitoring oversight than other areas such as fisheries, shipping, renewable energy and seabed mining/offshore oil and gas. Long term monitoring, research and evaluation has yet to prove convincing evidence of the effectiveness of ocean iron fertilisation, with minimal or non-existent environmental consequences. Other risks include safety, anoxia, hypoxia and eutrophication from the algal blooms. Additional ocean acidification and coral bleaching is possible. The proposal for rapid commercialisation is likely to not only cause issues with legislation involved in protecting the marine environment such as the London Convention and MARPOL but encounter significant issues of marine spatial planning conflicting with existing uses. These conventions and treaties such as UNCLOS would be challenging to amend as well as monitoring, enforcement and capacity to provide independent oversight (Mossop 2018). It will also encounter vociferous opposition from many concerned blue economy/coastal sector stakeholders, requiring extensive consultation.

Over the past 3 decades ocean fertilisation has encountered critique and scepticism from many ocean scientists given the complexities of marine systems (Chisholm, Falkowski and Cullen 2001). Minor scale scientific experiments have indicated a correlation between ocean iron fertilisation and a swift growth in phytoplankton, more rapid to absorb carbon than other methods, than time-consuming substitutes. However, it may be less influential by human means due to tides, waves, currents and other ocean/climate forces. An earlier 2010 investigation by the Secretariat of the Convention on Biological Diversity further expressed concern from artificial insemination of iron, nitrogen and phosphorous or wave powered pumps (Secretariat of the Convention on Biological Diversity 2010). It resulted in cautionary guidance arguing only for permitting ocean fertilisation under stringent scientific conditions rather than commercial, larger scale uses. The experiments only operate under limited timeframes and locations and depends on ecosystem resilience and vulnerability (UNESCO-IOC 2011). They further present risks of toxic algal blooms. The long-term implications for the generated phytoplankton and other marine communities would need to be considered, although favourable growth was identified for 5 out of the 13 experiments It estimated that 40-70% absorption rates could be managed in low oxygen zones but around 10-15% in higher oxygen zones. Atmospheric uptake efficiency only reached 20% compared to other methods. There remains a need to protect and restore if possible or interruptions to natural ocean, biological, solubility, chemical, nutrient cycles and carbon absorption processes where possible.

2.10: Ocean Alkalinisation

Artificial ocean alkalisation aims to counteract ocean acidification to balance the further acidity via adding basalt, olivine, lime, lye, calcium hydroxide or other material to the oceans. This subsequently seeks to sequester and remove blue carbon via seabed, beach or ocean/waterway as a sink at comparatively low cost as the oceans process more material from the atmosphere. An alternative approach utilises electrochemical/electrolysis processes i.e. currents and dissolved bicarbonate, with potential hydrogen as a by-product. Effective long-term observation, monitoring and evaluation, marine spatial planning, ocean governance and stakeholder consultation and engagement might complicate any extension of this more controversial solution. It offers potential to remove billions of tons of carbon dioxide at $70 to $160, as more expensive than many other technologies but eventually could be really cheap at $3-$5 per ton and with produced hydrogen. In Australia, they are reversing on climate change policy to focus on negative emissions technology, research, development and financial incentives under Prime Minister Scott Morrison, including ocean alkalinisation.

However, as with iron fertilisation it creates similar uncertain patterns to ecosystems, geological and other processes. It has yet to be accepted both commercially and under international maritime law, except for research and experimental purposes. Controversies exist as to whether humans should favour geoengineering, even where they can; given scientific ocean uncertainty and our previous track record. There remains a need for caution following the internationally advised Precautionary Principle. There are also issues of international legal processes -many prohibit damage to the marine environment or commercial exploitation/dumping in contrast to land. This frequently entails depending on individual nations for implementation/regulation within 12 nautical miles of territorial waters and limited capacity over the 200 mile Exclusive Economic Zone under UNCLOS. Ocean Alkalisation lacks the same guidelines as iron fertilisation but is anticipated to have similar effects, conditional upon ecosystem resilience, vulnerability, protection, the extent and type of the experiment, climate, ocean, environment and other conditions. Transport costs would nee to be factored in and there would be no direct immediately useful byproducts as with other radical climate change approaches considered. The Intergovernmental Panel on Climate Change among other scientists have raised ethical, technological, ecological, legal, deployment and other concerns over solar radiation methods (Light 2016).

Ocean Fertilisation and alkalinisation under the London Convention was also considered by the International Maritime Organisation in 2019. Several have indicated the need to research it prior to evaluating whether these approaches should be amended for ocean fertilisation and alkalinisation. These implications could be investigated as to whether they can resolve climate change impacts on oceans. The Haida Salmon Restoration Corporation's, 2012 ocean fertilization experiment in Korea or KIFES project confirmed how uncertain public perceptions of geoengineering and these experiments were. It presents uncertainty over who would be responsible for direct legal oversight, especially in the high seas, between the UN, IMO, International Seabed Authority or other entity. Who would enforce the “Polluter Pay’s Principle or extent of incurred liability? Additionally, trace metals and minerals could contaminate human and other species health via ingestion or other insertions into the food chain. It may also involve energy intensive and mining processes, depending on the technique used such as ocean enhanced weathering or mineralisation.

A study on marine monitoring of carbon capture and storage cautioned against potential risks of excess inorganic carbon (Omar 2018). Leakage risks need to be contained and monitored. There is a need for more effective solutions harnessing the ocean’s potential, whilst protecting ecosystems and the blue economy (Gattuso et al 2018) extending beyond ocean alkalinisation and fertilisation to consider extending existing blue carbon sources including seagrass, mangroves, phytoplankton, coral, whales, coral reefs and other habitats/species. These also need to factor in risks such as biotechnology, illegal and unregulated fishing, overpopulation and resource pressure growth, climate change risks including sea level rise and extreme events and ocean acidification/algal blooms. As stated, these methods include artificial reef restoration, species relocation, marine protected areas and assisted evolution for certain species, whilst removing threats and risks. Marine renewable energy can mitigate against total existing emissions. Others include restoring hydrology/reducing water and species’ pressures.

2.11: Other Radical Climate Change Solutions such as Solar Radiation Management/Geo-Engineering

Even more speculative solutions include solar radiation management/geoengineering only at the speculative/research stages rather than seriously include various solar radiation management/geoengineering such as albedo modification via marine cloud brightening via seawater spray and vessels, giant reflective mirrors in space or foams on the ocean surface. An alternative is stratospheric aerosol injection via aircraft, spacecraft, airships or balloons. Marine cloud brightening could enhance condensation and water vapour, filtering and purifying carbon via reflective surfaces but would require more experiments and research. Clouds are not always simple to forecast or remain sufficiently stable for long enough to ensure extensive carbon reductions necessarily.

One geoengineering study for Australia's Great Barrier Reef (McDonald et al. 2018), affirmed the need for stakeholder engagement, continued research including monitoring and an effective governance framework. It especially highlighted the risks of greater marine temperatures, heatwaves, ocean acidification and other risks. It proposed marine cloud brightening and a floating sunscreen as in Figure X. The sunscreen would serve as radiative cooling to form a radiative, biodegradable screen polymer Yet Australian domestic and international law currently prohibit any interference with the Reef, except for strictly controlled and monitored scientific experiments. It could also significantly affect local oceans, climates and fisheries.

Figure X: Australia Great Barrier Reef Solar Geoengineering Solutions

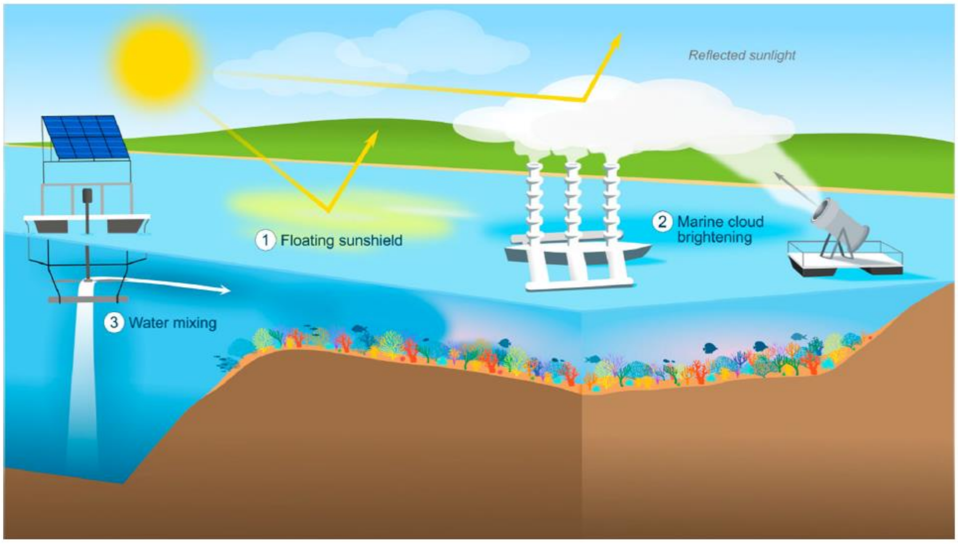


Figure 1. Funding has been awarded for feasibility studies of three geoengineering technologies to protect the reef: (1) a 'floating sunshield' of reflective surface film made of calcium carbonate to reflect sunlight and lower water temperatures; (2) marine cloud brightening; and (3) water mixing.

Source: McDonald et al. 2018

On 8th October, UCLA researchers launching a company Sky Cool; created a film material to export radiation away from the Earth into space without electrical energy or fuel as substitute air conditioners. This operates utilising the process of radiative cooling. The International Energy Agency estimated air conditions contribute 7% to the global target. Cloud thinning would require artificial cloud thinning via cirrus clouds. Orbiting space mirrors could further deflect emissions away. If more structures were to become reflective, this could reduce heat energy and related emissions. Many of these solutions present advantages of working even as climate change, overpopulation growth and resource pressure reduces the potency of natural afforestation, biochar, blue carbon, BECCS and others.

Yet these present significant risks to the environment, ocean acidification and high input, labour or resource intensive methods and lack investor incentives or certain governance and policy guidelines and would require far more detailed possible solutions if they are to be taken seriously. Uncertain consequences exist for the Earth's atmosphere, ozone layer and surface, air processes and water, carbon/biological cycles. Effective measures of deployment on a sufficient scale to make an impact would require modifying existing aircraft and processes and may violate certain provisions of domestic and international law if not investigated. High costs may exist in establishing the process and monitoring and evaluation. Other options include "assisted evolution" via artificial reefs/species regeneration, countering pollution and resource pressures and accelerating marine conservation and reserves such as extending seagrass and others. Moving onto insects, aquaculture, vegetarian and other diets might reduce methane, carbon and other livestock emissions further. As more people adapt to COVID19 remote working and virtual communications, this may reduce transport and office emission contributions to climate change but increase residential/IT based emissions.

Conclusion

In conclusion, this review provided an overview of radical net zero emission solutions to climate change, both natural and technological that have been proposed. Greater investigation of blue carbon, afforestation, organic soil carbon, Direct Air Capture, Carbon Capture, Utilisation and Storage, Bioenergy Capture and Storage, Biochar, enhanced weathering, ocean alkalinisation, ocean iron fertilisation and solar radiation management) or others such as enhanced energy efficiency, renewable energy and the circular economy have been presented with their characteristics, risks, scale of possible deployment and opportunities or benefits. It is possible to achieve the 1.5 degree Celsius rise of the Paris Agreement, or the 2 degree scenario if we rapidly contemplate a combination of the less riskier methods, combined with decarbonising our economy and converting to renewable energy, hydrogen and extended biomass or marine and land protected areas. Natural solutions such as blue carbon, afforestation and biochar have proven to be the most effective, given other direct and indirect consequences to ecology, expansion of scarce resources, biodiversity and the economy. However, DAC and BECCS/enhanced weathering may be indispensable to address existing atmospheric and soil concentrations in such high volumes. Currently, ocean iron fertilisation, alkalinisation and solar radiation management provide too limited and unconvincingly sincere empirical evidence in their favour; although greater scientific research may be needed to confirm these hypotheses on a greater scale. As humans, we need to not just investigate terraform, geo-engineering, natural and technological solutions but actually act upon them.

Aside from ecological, human, climate and other resource constraints such as land; to accelerate employment of net emissions technology, it remains also essential to consider interlinkages of these technologies and net zero emission solutions into existing and future industrial projects or electrical energy systems (Creutzig et al. 2019). The source estimates that even if emissions were ambitiously reduced by 80%, net emission technologies would still need to exceed 10 gigatons each year. Any emitted technology also needs to integrate into principles of renewable energy and the circular economy or reduce produced pollution. For example, hydrogen produced steel could curtail emissions by up to 80% compared to existing based methods. There is also the need to ensure the emissions continue to be removed and are not released later, so that full clear transparency and accountability are prevalent. Methods not only have to be upscaled, cost-effective and technically feasible with a market for commercial products to offset costs but securely stored and reliable, even under conditions of climate change. Over 67% of global energy is based upon fossil fuels, despite several nations pledging to climate neutral. Nations such as South Africa are still heavily investing in coal powered plants and oil/gas.

The European Academies Science Advisory Council conjecture less than 40-200 gigatons of carbon and 230 gigatons remained in 2018 to be produced to manage targets of 1.5 and 2 degrees Celsius successively in the Paris Agreement (European Academies Science Advisory Council 2018). It determined afforestation could absorb 1.1-3.3 gigatons per year. Soil carbon management could swallow annually 2-3 gigatons and bioenergy up to 3.3 gigatons. Enhanced weathering and ocean iron fertilisation could absorb 1 and 3.7 gigaton each year, which predominantly leaves ocean/blue carbon, DAC and CCUS or possible solar geoengineering to absorb the vast majority of emissions. Whilst natural sources are simpler, publicly accepted and cheaper, they are less effective at directly filtering out carbon in such intensive volumes and are considered less commercially appealing for certain investors. They may be more reversable or vulnerable to climate change. More research and incentives would need to be determined. All projections ignore human, environmental, extreme event, climate change, pollution, deforestation and other risks however. A decarbonised economy could swiftly pay for itself, providing over $26 trillion of additional benefits by 2050 if emissions were to have from transport, food sources and industry (Falk et al. 2019).

185 nations ratified the Paris Agreement but in 2019 only 8 had established the necessary legislation. There is still a need to remove 400 to 1000 billion tons of carbon to stabilise the planet by 2050 but 1 trillion to truly ensure our future at pre-industrial levels. It is also imperative to manage the subsequent exchange of technology, training, research and political diplomacy required (Farjardy et al. 2019; Finstad 2019; Friedmann 2019). Significant stakeholder awareness, communication and engagement is necessary. Psychologically changing human consumption and production behaviour, will and supporting more finance and innovation; may become equally paramount and challenging. Greater procrastinating and evading of our ecological responsibilities towards saving our planet and stabilising, even reversing our climate change related impacts; may result in even more desperate solar geoengineering solutions, migration crises and other extreme events. The International Renewable Energy Agency affirm the immediate need to act to restrict our future to 1.5 degrees and to also upscale renewable energy from 15% of Earth's total to 70+% (International Renewable Energy Agency 2018). Improved health, pollution and environment benefits would exceed $6 trillion by 2050. It estimates 19,000,000 jobs created could surpass the 7,400,000,000 lost in fossil fuels. This excludes employment, technology and other benefits from net emission technologies and capture.

The United Nations Environmental Programme estimated the need to consider more technology and immediate action (United Nations Environmental Programme 2017). Yearly global CO2 emissions hover around 40 gigatons, the minimum for any new technological future. The source estimates South Africa, the US, Mexico, Canada and the USA are far behind the commitments of the other G20 nations in attaining their pledged reduction contributions, whilst Argentina, Saudi Arabia and Turkey have yet to act. More stakeholders need to facilitate international cooperation and support or disincentives and penalties such as sanctions or diplomatic censure for those failing to accept their individual responsibilities in addressing a global problem. Migration, resource pressures, changing species and species extinctions, overpopulation along with enhanced frequency, duration and intensity of climate related, extreme events will directly or indirectly influence us all.

For example, the UK could store up to 70 gigatons of carbon dioxide, provided it can ensure geological stability, protect land, water and soil use or composition (UK Houses of Parliament, Parliamentary Office of Science and Technology 2013). Biomass would need to be transparently and responsibly sourced so as to preserve historic/more eco-sensitive systems. In California it has also been proven as possible to convert Earth's fifth largest economy to carbon negative territory by 2045, although the actual recovery may depend on COVID19 pandemic (Baker et al 2020). This would entail using several NET methods to eliminate/store up to 125,000,000 tons each year. This included converting 56,000,000 bone dry tons of waste into fuel and carbon storage and 11,400,000 tons from afforestation, tidal marsh restoration, wetland, grassland, forestry management and soils. Soil and biochar could remove another 3,900,000 tons. It could be really economical at only 0.34% of California's GDP or \$8,000,000,000 each year or \$65 per CO_2 ton, which also provides other economy, employment, innovation, health and spill-over benefits. These technological and natural solutions would either have to link to carbon offsetting markets or bonds or alternatively produce certain byproducts or other incentives to appeal to investors. There is also a need for more favourable financial and other incentives and a demand for more sustainable/ low carbon industry solutions for climate change as research recognises such as improved battery performance, flywheels and thermal cycles (Napp et al. 2017).

A similar review into negative emission technologies for Ireland emphasised the need for speed and accelerated upscaling (Price et al. 2018). It assessed each solution in terms of its potential for removing carbon (DAC highest), readiness (soil carbon and biochar highest), cost and biodiversity risk (afforestation), vulnerability to future climate change and land pressure (DAC and CCUS). DAC and enhanced weathering require the greatest energy use compared to soil, blue carbon and afforestation. The Ireland study advise a local nation specific benefit-cost analysis, cost-effectiveness analysis, life cycle assessment and energy system model. It concluded to utilise natural processes as a priority up to their biological limits, estimated around 2035 but higher risk to depend on the technology of DAC and BCCS as more costly and time consuming to upscale, and develop a related infrastructure especially when factoring in public ignorance. Enhanced weathering presents greater risks of mining damage, pollution and other costs until more sustainable mechanisms can be determined for many locations.

All of the above solutions have shown theoretical and practical potential, yet remain completely under-prioritised and supported. Several such as enhanced weathering are ignored from current international agreements to reduce emissions. Each nation, related investors, individuals and the community is urged to focus on how all emissions can be reduced and the resources/implementation process to initiate (Royal Society 2018). The Royal Society estimated various techniques could prove profitable for these technologies such as ranging from $230 profit to $330 loss for biochar. Monitoring and evaluation processes, associated incentives and penalties could reinforce this. Substituting fossil fuel subsidies into net emission technologies and renewable energy may expand this further. Focusing on ecological restoration and natural carbon offset methods as an initial priority can avert further species extinction, whilst providing other co-benefits from mechanisms verified to have worked since the dawn of our planet. Emission efforts cannot however merely link to carbon alone without considering other gases such as sulphur, methane, nitrogen dioxide and other chronic risks.

Other unusual solutions yet to be fully investigated include enhanced down or ocean welling, biomass burial, DACCS by freezing Antarctic air and electrochemical liming. Ocean liming would involve calcination of crushed limestone and post-capture, combustion carbon scrubbers. Similar techniques would apply with a causticizer and calcination via scrubbing using an aqueous sodium hydroxide solution for a soda/lime process on land. There remain unknown implications of foams which float on the surface of the sea to reflect sunlight back into the atmosphere, marine cloud brightening and ocean reflectivity or albedo effect or injecting carbon into sabed sediments. For the moment, many favour the Precautionary Principle. The UN the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), echoes various scientists in their scepticism towards these radical approaches to climate change via marine, space, air and terrestrial engineering, citing more scientific evidence is necessary.

These, albedo modification, and solar geoengineering may be too costly and risky with existing technology but ought to be studied -or ruled out, with innovations encouraged as concepts. Again, many international regulations and policies might need to be investigated such as the Convention on Biological Diversity, MARPOL, OSPAR, High Seas treaty, UN DOALOS and others (Secretariat of the Convention on Biological Diversity 2016). Those advocating methods argue it is necessary to at least consider these and experimenting to determine the future. Reflecting sunlight away from the Earth or solar geoengineering/radiation management group of proposed technologies would, in theory, reflect sunlight away from the Earth’s surface before it has a chance to warm the atmosphere. Significant risks exist towards relying on these extreme methods including testing and the complexities of ecosystems, although resources are needed for emissions. The risks of solar radiation management/geoengineering may prove to be too much of a gamble however, disturbing ocean, climate and other natural processes but not being easily reversible if committed to. The various climate change COP events have also ruled out these methods. Caution was advertised in a cautionary note by the Secretariat in the “*absence of science based, global, transparent and effective control and regulatory mechanism following the Precautionary Principle*.”

The challenges remain in determining how potent these are at counteracting climate change, how safe it remains and how various risks and commercial opportunities can be managed. There remains the problem of time running out. Whatever solutions we make may require of many of us commitment, effort, will and a sacrifice. It may present an opportunity cost given resources required, level of consensus and effort attained -need to be sure it is the right option. It is therefore recommended to prioritise investigating all radical climate change solutions to determine the most feasible pathways, technologies and innovations forward; so that each of us can support more certain answers to save the planet. It has been confirmed by various scientific entities and policymakers that one or more of these methods will be needed, aside from a decarbonised economy and society, reduced population and greater efforts at conserving/restoring and extending existing natural sinks against climate change. Any existing political, financial, social, research, training, legal, technological and other barriers have to be overturned swiftly (US Academies of Science, Engineering and Medicine 2018). The swifter we act, the less we will have to commit and ultimately sacrifice to actually prosper and survive, on a timespan reaching centuries not causing our extinction or a severely compromised existence by 2100 as at present.

In conclusion, the resources are present, now more than ever to save our planet. For example, a recent database on carbon dioxide removal laws, polices and sequestration research was launched by Columbia University and its Sabin Centre for Climate Change Law. It provides online resources relating to many of the net emission solutions outlined in this research. Now more than ever, the prospects of innovation exist if we wholeheartedly support all pursuing those, along with the investors prepared to speculate such as the International Investors Group on Climate Change, the policymakers prepared to listen, those who have to conduct it and the activists such as Mock-COP20, Extinction Rebellion and others, committed to waking up the indifferent and the masses. Various other solutions to net zero emissions, and a climate change neutral existence, range from improved energy/fuel efficiency and reduced consumption, multiplied circular economy activity, decarbonised transport, marine and terrestrial renewable energy, hydrogen and other developments, In October 2020 these included the empowering of a green hydrogen project by Earth's most extensive floating wind farm. Changed agriculture and conversion from fisheries to aquaculture and moving towards more marine protected areas can exponentially develop carbon sink reserves with sufficient support. Improved techniques result in less emissions intensive methods. For example, an electrochemical CO2 capture system can rely on a thermal or voltage cycle system to improve the efficiency of existing industrial processes in reducing output emissions. On 4th August 2016, scientists created aluminium based electrochemical cells capable of carbon sequestration via oxygen. The National University of Singapore in pilot projects managed to convert minor volumes of CO_2 to more useful ethanol.

The US are currently involved in incentivising carbon dioxide removal via research, development, tax and investment incentives. The Energy Futures Initiative pressed for a $10.7 billion Federal commitment over the next decade, requiring cooperation across multiple departments and international partnerships pledging COP commitments (Sandalow et al. 2018; Energy Futures Initiative 2019). It specifically recognised Direct Air Capture, carbon mineralisation (enhanced weathering), coastal and ocean; terrestrial and biological along with geological, CO2 utilisation and intersectoral projects. It identifies the need to monitor mitigation and capture progress via transparent, accountable mechanisms with frequent monitoring and evaluation. Many solutions are land based and ignore the oceans. There is a need to incorporate the oceans as well as the land. There is a need with solutions to be flexible, maximising scope for being reversable if proving to be a mistake. There remains an imperative mandate to protect the carbon sinks, ocean carbon and biological/other cycles and processes…. I.e. not to worsen the problems any further. Whilst developing solutions, there is a need to counteract problems of climate change such as coral bleaching from ocean acidification simultaneously. Other issues to overcome include scaling up, deployment, technology transfer, psychology, policy and the law remain, ensuring adequate scholarship and funding based on ethics towards all species, stakeholder engagement, transparency and sound governance. More pilot projects and marine/land protected areas are critical as well as effective deterrents to poaching. Illegal deforestation and other ecocide crimes have to face harsh penalties and prosecutions/convictions as deterrents.

However, I affirm direct capture and storage of carbon and other greenhouse gases alone are insufficient without mitigating and reducing actual emissions in the process; establishing more energy efficient, less polluting and recycling ways, linked to the circular economy, whilst protecting and extending protected areas. Human psychology and interest need to intensify so we see more protests such as COP26, more reflective behaviour changes, more innovations, technology, funding, support for offset schemes, research, policies and actions from the public, rather than just too few…. Although more investors and even youth are favouring decarbonisation, there is a need to reduce emissions so that these solutions have even greater chances to help save humanity and our planet from its human engineered fate of climate change devastation. This research concedes the need for more convincing, less controvertible empirical data to convince people along with greater mass public awareness of these proposed solutions and the extent to which these should be funded and supported or not.

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