Geoengineering technologies 2018/2019

– a critical analysis of solar radiation management and carbon capture and storage

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Contents

Solar radiation management

Discussion paper for AirClim

Fredrik Lundberg, March 2019

Summary: Solar radiation management is not needed. Actual greenhouse emissions cuts can achieve more; faster, surer, cheaper, cleaner and without the risk. SRM is dangerous, as there is no way to predict the consequences of intervening with a highly complex system.

Solar radiation management, SRM, is a group of proposed geoengineering technologies that aim to reduce the inflow of solar energy, rather than to reduce global warming by reducing greenhouse gases. It "aims to offset greenhouse warming by reducing the incidence and absorption of incoming solar (short-wave) radiation (often referred to as insolation). Solar radiation management (SRM) methods propose to do this by making the Earth more reflective, that is by increasing the planetary albedo, or by otherwise diverting incoming solar radiation. This provides a cooling effect to counteract the warming influence of increasing greenhouse gases."[1]

The physics of SRM is, in principle, rather straightforward. A doubling of CO_2 concentration compared to the pre-industrial level would cause a warming of about 4 watts per m^2. This is a small number in relation to the 107 watts that is reflected back to space, so if 111 watts were reflected instead of 107, there would be no global warming.

The case for SRM is simple: by shading a small proportion of the sunlight, global warming can be halted, even reversed, in some cases fast and in some cases possibly at low cost.

For obvious reasons global warming will hit hot regions disproportionately, which risks making SRM into a North-South issue. A group of scientists claiming to be neutral about SRM recently accused the ETC group (an NGO critical of SRM[2]) of "paternalism"[3] in an opinion article for Nature headlined "Developing countries must lead on solar geoengineering research".

A case could easily be made for the opposite view, that SRM is yet another way for the North to procrastinate and escape responsibility for emissions. As the Nature article points out, "most solar-geoengineering research is being done in the well-heeled universities of Europe and North America." It could also be added that substantial funding comes not only from the rich countries but also from rich northern philanthropists. The case has also been made that SRM research has been initiated and maintained by Big Oil as a strategic alternative to reduction of fossil fuel use and to some extent a conscious effort to divert attention from the dangers of climate change[4].

1 https://royalsociety.org/~/media/royal_society_content/policy/publications/2009/8693.pdf p23

2 ETC's views and briefings at www.geoengineeringmonitor.org, especially http://www.geoengineeringmonitor.org/technologies/#srm

3 A. Atiq Rahman, Paulo Artaxo, Asfawossen Asrat, Andy Parker and 8 co-signatories. https://www.nature.com/articles/d41586-018-03917-8 April 3, 2018

4 Fuel to the Fire: How Geoengineering Threatens to Entrench Fossil Fuels and Accelerate the Climate Crisis, Center for International Environmental Law (CIEL), Heinrich Böll Foundation, 2019 p34ff

The main danger of northern paternalism towards the global South may not necessarily come from small NGOs such as the ETC group.

Another line of argument for SRM, by Mike Muller at Witwatersrand University, South Africa, goes:
"Africa must look hard at uncomfortable options or face being left behind by other countries with fewer scruples."[5]

It is not clear whether Muller just means that the frontrunner of a technology will reap the fruits compared to later adopters, or if he means that someone else will actually steal the rain before it reaches Africa.

Proposed SRM technologies

What actually constitutes an SRM technology is neither theoretically nor empirically well defined, but the following are often mentioned:

Surface albedo methods include white roofs and brightening of human settlements, use of more reflective crop varieties by selection or genetic engineering, land use change (deserts and grasslands are more reflective than conifer forests), desert reflectors (mirrors) on an enormous scale, afforestation in deserts such as the Sahara to increase evapotranspiration, deforestation at high latitudes (where trees are much darker than snow cover), and spreading white sand on dark soil. Yet another method is making the oceans brighter with chemicals that create small bubbles in the water or, in a more limited way, just making the wakes of ships longer and brighter.

Cloud albedo enhancement means making the clouds whiter, by spraying salt water into them.

Injection of stratospheric sulphur or other particles makes the high atmosphere hazier, so more light is reflected back and less energy reaches the Earth surface. This takes place in nature after very large volcanic eruptions such as Pinatubu in 1991, which lowered the temperature for some 5 years by at most 0,5 degrees. The artificial injection method was proposed by Budyko[6] in 1974 and would mean injecting millions of tons of SO_2 into the stratosphere, each year.

Space-based methods aim at putting lenses, mirrors or dust in space so as to deflect or diffuse solar radiation before it reachess Earth.

More proposed methods[7] are microbubbles in the seas, to make the surface more reflective, and cirrus cloud thinning.

The Royal Society[8] proposed four criteria for assessment of each geoengineeering technology in 2009:

"1. Effectiveness: including confidence in the scientific and technological basis, technological feasibility, and the magnitude, spatial scale and uniformity of the effect achievable.

5 https://theconversation.com/a-sunshade-to-help-southern-africa-cope-with-climate-change-53452

6 Tellus 1977 https://onlinelibrary.wiley.com/doi/epdf/10.1111/j.2153-3490.1977.tb00725.x

7 http://www.geoengineeringmonitor.org/technologies/#srm

8 https://royalsociety.org/~/media/royal_society_content/policy/publications/2009/8693.pdf p. 1

2. Timeliness: including the state of readiness for implementation (and the extent to which any necessary experiments and/or modelling has been completed), and the speed with which the intended effect (on climate change) would occur.

3. Safety: including the predictability and verifiability of the intended effects, the absence of predictable or unintended adverse side-effects and environmental impacts (especially effects on inherently unpredictable biological systems), and low potential for things to go wrong on a large scale.

4. Cost: of both deployment and operation, for a given desired effect (ie for CDR methods, cost per GtC, and for SRM methods, cost per W/m^2) evaluated over century timescales (later also expressed as its inverse, ie affordability). In practice the information available on costs is extremely tentative and incomplete, and only order-of-magnitude estimates are possible."

These criteria are still useful, but should be compared to a default, such as coal power replaced by wind, solar or efficiency.

Fossils-to-RE is effective, can be done fast, has very few safety issues, and is cheap.

It should also be noted that SRM must beat fossils-to-RE on all the four criteria. It is not the question of weighted average. You cannot have it if it is cheap but dangerous, or if it is deemed to be effective, safe, and timely but costs much more than shutting down a coal power plant and build PV, per tonne of CO_2 avoided.

It is indeed hard to see how any proposed SRM technology could could pass through such a sieve. Most of the proposed SRM technologies are irresponsible and ill-founded, and not worthy of serious consideration.

However, highly respected scientists have argued for geoengineering either as a last resort or as a faster and more effective way to deal with warming than emission reductions.

Stephen Schneider[9] 1996:

"Supposing, a currently envisioned low probability but high consequence outcome really started to unfold in the decades ahead (for example, 5°C warming in this century) which I would characterize as having potential catastrophic implications for ecosystems... Under such a scenario, we would simply have to practice geo-engineering ..."

Paul Crutzen[10] 2006:

"Reductions in CO_2 and other greenhouse gas emissions are clearly the main priorities . However, this is a decades-long process and so far there is little reason to be optimistic."

Lord Rees of Ludlow, President of the Royal Society in the foreword to the Society's report on geoengineering in 2009:

"But if such reductions achieve too little, too late, there will surely be pressure to consider a 'plan B'—to seek ways to counteract the climatic effects of greenhouse gas emissions by 'geoengineering'."

The appendix gives a background to why the ideas of "last resort" and "Plan B" came up in the first place and why they are outdated.

9 Quoted after Crutzen https://link.springer.com/content/pdf/10.1007%2Fs10584-006-9101-y.pdf p214

10 https://link.springer.com/content/pdf/10.1007%2Fs10584-006-9101-y.pdf p. 217

There is now no strong industrial lobby behind SRM, but the idea keeps coming back. One reason why SRM is not yet completely discredited may be that the people who claim to be experts on SRM have a vested interest in keeping the research and debate alive. They claim that it is very complex and has to be investigated further. If SRM is given the short shrift it deserves, their expertise will no longer be needed.

Experiments underway

1. Stratospheric injection in Arizona

The Stratospheric Controlled Perturbation Experiment (SCoPEx) will spray small amounts of water, chalk powder and sulphate particles into the stratosphere from a balloon to investigate how much sunlight will be blocked, as measured from the same balloon.

According to the SCoPEx team:

The ETC group claims[11] that SCoPEx is against the 2010 moratorium on geoengineering activity under the Convention on Biological Diversity, and that experiments "would legitimize geoengineering and move us one step closer to a global sun-block". The SCoPEx team denies this.

The release of less than 1 kg of calcium cabonate into the air is indeed unlikely to have any actual effect on biodiversity. But it is not motivated by pure research:

"Why conduct the experiment?

This experiment will help us learn more about the efficacy and risks of solar geoengineering."[12]

Whether this experiment will infringe the Convention on Biological Diversity will not be looked into, as the United States, almost alone in the world, has not ratified the convention.

The funding of $20 million, comes from Harvard itself and from the privately funded Harvard's Solar Geoengineering Research Program[13] which gets money from Bill Gates and several other philanthropists.

Research started in 2017, field experiments were said to be due in 2018[14].

2. Marine Cloud Brightening Project, Moss Landing California

Aim: to test whether spraying a mist of sea water into clouds can make them whiter, eventually from ships. A previous larger scale effort involving ten ships and 10000 km^2 in 2010, bythe same people, was abandoned after media reports made funders such as Bill Gates withdraw their fsupport.

A land-based experiment is expected to go ahead in August 2018, but has been previously been delayed for years.[15] It is a test of the spray nozzle technology that "will gener-

11 http://www.geoengineeringmonitor.org/2017/11/scopex/

12 https://projects.iq.harvard.edu/keutschgroup/scopex

13 https://geoengineering.environment.harvard.edu/funding

14 As of March 2019 there are no news about actual experiments on the project's web.

15 As of March 2019 there are no news about actual experiments on the project's web.

ate controlled volumes and sizes of tiny sub-micrometer seawater particles in sufficient numbers to increase the local brightness of low clouds in a marine environment".[16]

The budget is said[17] to be $16,3 million but the project's web page has no information on funding.

"Senior scientists" for the project are Paul Crutzen, who won a Nobel prize for work on the ozone layer, and James Lovelock, the originator of the Gaia hypothesis. Two of the associated researchers are John Latham, the originator of geoengineering withmarine cloud brightening idea in 1990and Ken Caldeira, who was a lead author for the IPCC and a personal favourite of Bill Gates[18].

3. Ice 911 project: small glass bubbles of arctic ice

This project proposes to "preserve Arctic ice by spreading our eco-friendly sand...protecting the ice below"[19].

The project hopes to "deploy a medium-scale test area of our material solution on Arctic ice, where our material can have the greatest impact on saving ice and lowering the risks of climate change" by 2019, and make a large scale launch in the Fram Strait or Beaufort Gyre the next year. They have tested their sand on a modest scale (areas the size of a few football fields).[20]

Issues with Solar Radiation Management:

SRM addresses the wrong problem. The problem with climate change is not just that the average global temperature is rising. Redistribution of local and regional weather patterns can be disastrous for people and nature even if it does not influence the global average. More droughts and more deluges do not cancel each other out.

SRM and other engineering is a Plan B, but a Plan B is not required if we focus on Plan A. There is now growing optimism that staying below 2 degrees and 1.5 degrees can be achieved this way. The IPCC 1.5 Special Report in 2018 showed several paths to achieve 1.5 degrees.

SRM leaves a number of important issues unattended. The problems caused by burning fossil fuel are not limited to CO_2 warming. They include ocean acidification, acid rain, black carbon emissions, N_2O, tropospheric ozone and methane emissions from the fossil fuels cycle, nitrogen eutrophication (terrestrial and aquatic), and health problems due to emissions of particles and mercury. Real CO_2 reduction reduces all such problems, but SRM does not. Some of those problems can be reduced with technical fixes (desulphurisation etc.) but SRM itself does not solve them. No fix exists for ocean acidification.

16 http://www.mcbproject.org/about.html

17 http://www.geoengineeringmonitor.org/2018/04/marine-cloud-brightening-project-geoengineering-experiment-briefing/

18 https://www.gatesnotes.com/About-Bill-Gates/Year-in-Review-2016

19 http://www.ice911.org/

20 http://www.ice911.org/arctic-testing. The website has no mentioned scientific publishing as of March 2019.

SRM expresses the notion that we have to find new solutions -- a kind of Manhattan Project or Apollo Project for the climate -- rather than using available technology, and policy measures, just more and faster.

The notion that brand new solutions are needed may be attractive to billionaires who want personal credit for saving the world, sometimes in tandem with media looking for individual heroes. But it is the less glamorous collective national and international effort that can do the job, as they represent far more knowledge, resources and tenacity.

SRM shifts attention from real GHG cuts, which represent a faster, surer, safer and more permanent way to mitigate climate change.

SRM creates false hope for the fossil fuel industry, and could delay its decline or transition.

The modelling of chaotic system will remain imperfect. Unforeseen consequences of human intervention in the climate and weather systems are to be expected.

SRM increases international tensions, because it changes precipitation patterns, which may mean that there are winners and certainly losers. More rain, and better harvests in one country may lead to droughts in another country.

SRM experiments and deployment could undermine the 1977 Environment Modification Convention.

Allegations of foul play are hard to confirm, or disprove. Accusations, justified or not, can cause diplomatic crises.

SRM could be “weaponized”, for example in an effort to change battlefield conditions or to starve an enemy population.

Some of the techniques discussed are not easily reversible, since a “termination shock”, a sudden redistribution of rain and wind patterns, may take place if the measure is discontinued for whatever reason (international conflict, economic crisis).

Physical implementation of SRM could be fast, but the political and legal process could go on fo a very long time or forever, making a long delay instead of a short cut.

Possible policy conclusions:

1. SRM is a diversion from greenhouse gas emission cuts. It represents a loss of focus and time, and should not be considered an option to limit climate change.
2. Renewables and efficient use of energy can cut most of the GHGs. Cutting emissions from production of steel and other metals, cement and lime production, refrigerants etc, and possibly reforestation can cut the rest, most of it by 2030-2040, and can be achieved whether nuclear power and CCS are parts of the mitigation or not.
3. Many SRM technologies are far-fetched, ineffective, costly and take longer time to implement than real GHG cuts.
4. Many SRM techologies are dangerous for the environment and/or for peace.

5. Global warming will hit already hot countries disproportionately, but throwing a second spanner into the gearbox of the climate system with SRM is no solution for any part of the globe.
6. Governments should be held responsible for SRM experiments on their territory, even if they are private initiatives. The climate system is not private property.
7. The Environment Modification Convention and the Convention on Biological Diversity can and should be used to stop development of SRM.
8. No special intergovernmental body is needed for governance of SRM or other geoengineering; existing conventions should be used.
9. Pressure to make The United States government join the Convention on Biological Diversity should be stepped up.
10. White roofs can be beneficial for indoor and local climate but should in no way be represented as a way to stop global warming, nor be eligible for CDMs.
11. Experiments for the express purpose of SRM should not be allowed
12. "Dual-use" experiments which can improve climate science, or other science, but also can be of use for SRM development should be kept under government control, and only be allowed if the scientific justification is adequate.
13. Most NGOs are completely against SRM, but some accept further research and want further debate. They effectively legitimize keeping the option open. If this is the result of decentralized decision-making, where the organisations' experts have had free rein, other NGOs could ask the leadership if they really embrace the view that SRM is an option.

Appendix: Solar radiation management and geoengineering: a background

The term geoengineering and the concept of solar radiation management go back to the early 1970's and to still earlier efforts at weather modification for military or other reasons.

This long history is important for two reasons. One predominant idea of the postwar decades was that scientists can predict and control anything, given enough resources. Another common belief was that economic growth inevitably leads to more CO_2 emissions.

Weather and climate modelling was first developed with the early computers in the 1940s and 1950s. The scientific community, having developed the atomic bomb and the hydrogen bomb, were clearly overconfident. John von Neumann, the computer pioneer who was dubbed "the smartest man on earth", worked on weather modelling. He believed that there were two kinds of weather, stable and unstable, and that all that was needed was bigger computers[21]:

21 As recalled by Freeman Dyson in his book Infinate in all directions.

"All processes that are stable we shall predict. All processes that are unstable we shall control. He imagined that we needed only to identify the points in space and time at which unstable processes originated, and then a few airplanes carrying smoke generators could fly to those points and introduce the appropriate small disturbances to make the unstable processes flip into the desired directions. A central committee of computer experts and meteorologists would tell the airplanes where to go in order to make sure that no rain would fall on the Fourth of July picnic."

In 1963, Edward Lorenz showed that predictability is very limited. If the input data is changed a tiny bit, the result (weather) can change completely.

Though weather and climate are not the same thing, they have similar flipping points. But Lorenz's article went unnoticed for more than a decade.

Some people, especially those whose scientific roots stretch a long way back, still believe we can control the weather or the climate.

Another aspect of this long history is that by the 1970s, much of the scientific community actually did see global warming as a potential menace, though the general public was unaware of it. There was however not much sense of urgency, because the global warming theory was not corroborated by actual temperature data.

At that time economic growth was seen as inextricably linked to primary energy growth: transport growth, electricity demand growth, industrial output growth. Some if this growth was expected to be met by nuclear, including fast breeder reactors and fusion power.

Wind power did not exist, solar photovoltaic was extremely expensive, other renewable energy looked limited (hydro, biomass) or not very good (solar thermal, geothermal, electric cars). Very few people considered radical efficency improvement an option.

The conventional wisdom was that economic development would lead to very much increased CO_2 emissions for a very long time. An eventual threatening Peak Oil would be met with coal liquefaction and tar sands feed, with even higher CO_2 emissions than from conventional oil. This view was common for policymakers in the developed countries, in the third world and in the Soviet Bloc.

This mindset did not change fast.

Even though climate change entered the international political agenda in 1987, emissions largely kept climbing.

In 1997, the year of the Kyoto protocol, the renowned physicist Edward Teller[22] and the chief physicist at Lawrence Livermore national laboratory claimed that actually cutting emissions would cost more than $100bn/year, whereas for less than one per cent of that cost, warming could be "obviated" by sending millions of tons of sulphate or alumina aerosols into the stratosphere.

The decoupling between economic growth and emissions was not apparent by 2008-2009, when the Royal Society revived geoengineering first with a theme journal issue

22 https://www.osti.gov/accomplishments/documents/fullText/ACC0229.pdf

on the subject in 2008[23] and then with a report entitled **Geoengineering the climate: Science, governance and uncertainty**, in September 2009.

This in turn led in 2010 to the formation of the Solar Radiation Management Governance Initiative (SRMGI), "an international, NGO-driven project that seeks to expand the global conversation around the governance of SRM geoengineering research."

SRMGI does "not take a position on how SRM should be governed or whether it should ever be used", but it provides an important platform for those who want to keep SRM as an option.

Those who are opposed to geoengineering for whatever reason are not interested in expanding the global conversation about it.

The idea that geoengineering would be easier and cheaper than reducing emissions was questioned even by 2010, but the strongest evidence for the viability of GHG cuts is even more recent.

It is a different world now compared to 2007. It is not only conceivable that substantial GHG reductions can take place. It is a fact.

Table 1, CO_2 emissions, Mton

	2007	2017	change %
United States	5881	5088	-13
European Union	4144	3542	-15

Source: BP Statistical Review of World Energy 2018[24]

This was achieved during a period of economic growth, and without a very strong effort to cut emissions.

Even more noteworthy is that China, after a long period of dramatically growing CO_2 emissions more or less stabilised its emissions in 2013-2017, with growth of just 0.3 per cent over the four years.

This is not a question of low-hanging fruits, but of general, affordable methods with a very large remaining potential. For example, solar and wind are rolling out very fast, in richer and poorer countries:

Table 2 Wind power generation TWh

	2007	2017
United States	35	257
European Union	104	362
China	5	286
India	12	53

23 Philosophical Transactions A,13 November 2008 Theme Issue 'Geoscale engineering to avert dangerous climate change' compiled by Brian Launder and J. Michael T. Thompson

24 https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

Table 3 Solar power generation TWh

	2007	2017
United States	1	78
European Union	4	120
China	0,1	108
India	0,1	21

Energy efficiency is harder to measure than wind and solar as it includes a very large number of technologies and processes throughout the economy, from LED lamps to heat pumps. Electricity is ever more important, but we used less of it in 2017 than in 2007, both in the United States and in the European Union.

Further reading:

The Royal Society: Geoengineering and the climate. Science, governance and uncertainty. September 2009
https://royalsociety.org/~/media/royal_society_content/policy/publications/2009/8693.pdf

Policy Brief: Governance of Geoengineering German Federal Environment Agency, 2019
https://www.umweltbundesamt.de/sites/default/files/medien/2378/dokumente/policy_brief_governance_of_geoengineering_0.pdf

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The Big Bad Fix: The Case Against Geoengineering Biofuelwatch, Heinrich Böll Foundation, ETC Group, 2017
https://www.boell.de/en/2017/12/01/big-bad-fix-case-against-geoengineering

Riding the GeoStorm: A briefing from civil society on Geoengineering Governance Heinrich Böll Foundation, ETC Group, 2017 (currently being updated)
https://www.boell.de/en/2017/12/01/big-bad-fix-case-against-geoengineering

CCS 2001–2018: Expectations and results

As of May 2019, with some minor additions information by August 2020

The term "geoengineering" was coined in a paper by Cesare Marchetti at the IIASA in 1977. That paper also launched the idea of carbon capture and storage. Marchetti was well aware that increasing CO_2 levels would lead to disastrous climate change. His suggested solution was to pipeline all Europe's captured CO_2 to the Gibraltar Strait, where it would be dispersed evenly and carried by sea currents to the ocean floor[25].

Whether carbon capture and storage (CCS) now qualifies geoengineering is a moot point. Wikipedia defines geoengineering as "the deliberate and large-scale intervention in the Earth's climate system".

The scale is the key: planting a tree is not geoengineering, but planting trees on an India-sized area clearly is geoengineering. The IPCC 1.5 degrees report 2018 has four illustrative pathways which require an accumulated capture of up to 1218 gigatonnes of CO_2 until year 2100. Assuming a movement of 20 gigatonnes/year some years, CO_2 for CCS would be larger much commodity than oil and coal together now; in 2019, the world produced 4,5 gigatonnes of oil and 8,1 gigatonnes of coal. The infrastructure for transporting all this CO_2 in pipelines or ships would surpass all other goods transport. It would be a very big global machine for the sole purpose of regulating the concentration of CO_2 in the atmosphere.

Thinking big is nothing new for CCS proponents. Even larger annual CO_2 captures -- up to 37 gigatonnes by 2050 -- were suggested by the IPCC special CCS report in 2005.

In this perspective, two questions come to the fore:

Is very large scale CCS a good use of resources and time?

Is it really likely to happen? Or, if not, does it serve as a pretext for business-as-usual for the big CO_2 emitters?

Before 2008, there was a strong political thrust for CCS all over the world. It has not delivered. Results are miniscule, while there are faster, cleaner, surer, safer, more durable, more effective and cheaper ways to cut CO_2: renewables, efficiency measures and the development of carbon-free industrial processes, many of them demonstrated on a very large scale.

High hopes were pinned on CCS in the first decade of the 2000s. It gathered strong support from the US as part of the Bush administration agenda from 2001, and from the EU and the governments of the UK, Canada, Australia and Germany, especially after the IPCC special report in 2005. In 2008, the EU energy and climate package aimed to have 12 large demonstration plants in operation by 2015. The UN general secretary (and also German Chancellor Angela Merkel) appointed the CEO of Vattenfall, Lars G. Josefsson, a leading coal apologist and CCS champion, as climate advisor. The Norwegian prime minister, Jens Stoltenberg, declared in 2007 that CCS was "our moon landing".

The IPCC special report in 2005 claimed that "in most scenarios ... and in a least-

25 Marchetti, C. "On Geoengineering and the carbon dioxide problem", Climate Change 1 1977 https://link.springer.com/article/10.1007/BF00162777

cost portfolio of mitigation options, the economic potential of CCS would amount to 220–2,200 Gt CO_2 cumulatively, which would mean that CCS contributes 15–55% to the cumulative mitigation effort worldwide until 2100".

The report also said that "the projected potential of CO_2 capture associated with the above emission ranges has been estimated at an annual 2.6 to 4.9 $GtCO_2$ by 2020 and 4.7 to 37.5 $GtCO_2$ by 2050."

We now know that the figure for 2020 was about a hundred times too high: some 30-40 Mtons, some 90 percent of which was used for enhanced oil recovery.

This is much like getting 5 ml of lager when you have ordered a pint (or .5 ml with enhanced oil recovery deducted. Small beer, indeed.

But then, before the 2008 recession, almost every major power company believed coal was the future, and the only way to reconcile this with the belief that global warming was a serious threat was CCS. The European Commission summed up the mood in May 2008:

"Introducing CCS may delay the need to reduce levels of fossil fuel use by at least half a century."

The conventional wisdom was that

- renewables were too expensive to grow fast. CCS would be a bridge technology while alternatives to fossil fuels are further developed and deployed.
- there was a strong link between economic growth and energy growth, and especially electricity consumption, so the efficiency option was limited
- there was no realistic option to stop coal growth, so the fuel shift option (from coal to gas) was limited
- 550 ppm CO_2 and higher were considered as mitigations.

Some of these assumptions were reasonable at the time. Solar power was indeed very expensive, as was offshore wind. Energy and electricity demand grew with GDP. The coal lobby was a strong political force. The US had abandoned Kyoto, and an international climate policy which did not include the US did not seem realistic or relevant.

A new world from 2008

The Global Financial Crisis 2007-2008 changed everything.

President Obama was elected in 2008. This marginalized climate denial globally, though procrastination continues.

When the whole financial system was threatened in 2008, the response was collective and decisive. The collapse was averted, but the crisis was bad enough. And when it was over, by 2010-2011, the world moved in a different direction than it had before 2008.

Part of the recovery in the US and the EU was investments into infrastructure generally and all green things specifally. Germany was well prepared for this. China saw both needs for domestic growth, for its own environment, and for export opportunities.

The stage was set for a big effort on nuclear power, CCS and renewables.

But nuclear power ground to a halt with the Fukushima.

CCS got nowhere, as will be shown further down.

But climate policy began to show results, especially through growth of renewables.

Global CO_2 emissions only rose 0.5% per year in 2013–2017, compared to 2.5% in the previous 10 years. Electricity consumption fell in the US, the EU and Japan.

Coal use for power fell in the OECD from >4,000 TWh to <3000 in 2007–2019 (and <2,500 TWh in 2019).

New coal power became a no-no in an increasing number of countries, and a lot of capacity has been phased out.

Globally, wind power grew from 104 TWh in 2005, when the IPCC CCS report was published, to 1,123 TWh in 2017.

Hydro power grew from about 3000 TWh to 4000 TWh 2007-2017.

Solar photovoltaics from 4 TWh to 443 TWh, 2007-2017.

Solar heating[26] had a capacity of 472 GW (thermal) by end 2017, even more than photovoltaics (400 GW electric). It grew from about 126 GW in 2007[27].

Nuclear power decreased from 2608 to 2498 TWh 2007-2017.

Meagre results for CCS.

CCS was supposed to bridge the gap between a fossil-based world, especially for power, and a renewable world.

But renewables have stormed ahead while CCS got nowhere.

None of the 12 European CCS demo plants started. Several CCS projects were abandoned in the UK, the Netherlands, Germany, Denmark, Algeria and Norway.

CCS was in fact not a new technology when it was launched by the Bush administration 2001. It had been used for enhanced oil recovery (EOR) from1972, as CO_2 is inexpensive and much denser than air. EOR was not intended as climate mitigation, and is of course no credible climate mitigation technology. Most so-called CCS projects in the world are EOR.

The non-EOR a few and far between, as can be seen in Table 1. There are just four (fairly) big projects in the world, and just two started after 2007, through 2018. A fifth project may start injection in 2019. That included, their combined capacity is stated as 7.4 million tons per year.

26 http://www.iea-shc.org/solar-heat-worldwide

27 https://en.wikipedia.org/wiki/Solar_water_heating

Table 1. All large scale[28] CCS projects excluding EOR in the world 2019.

Project name		start		capacity Mton/yr
Sleipner	Norway	1996	Natural Gas Processing	1.0
Snøhvit	Norway	2008	Natural Gas Processing	0.7
Quest	Canada	2015	Hydrogen Production	1.0
Illinois Industrial	United States	2017	Ethanol Production	1.0
Gorgon	Australia	2019	Natural Gas Processing	3,4-4*

* Not yet producing at capacity[29] by August 2020

None of the five projects take CO_2 from the big streams such as fossil power and heat, production of steel or cement, and transport. Three of the five projects are for gas processing. Since CO_2 is not wanted in natural gas, it has to be removed, and this happens to take place within reasonable distance from a good storage site. This for-free CO2 is atypical. Gas processing is a minor diversion of carbon from the extraction of fossil gas, as most of the carbon goes with the product, natural gas.

3 out of 5 projects take CO_2 from gas processing. The Norwegian projects are a (minor) CO_2 abatement compared to just releasing the CO_2 into the air, if fossil natural gas has to be produced. But it does not show that CCS is a viable general method for mitigating CO_2 emissions. And if CCS is seen as a justification for fossil extraction industry, it does more harm than good.

The "fig-leaf" notion is not far-fetched, as demonstrated by the Australian Gorgon.

This is one of the biggest natural gas project in the world, according to owner Chevron. Gas production started in 2016 but carbon capture did not start until 2019. The total investment is $88 bn, of which CCS accounts for 2.5 bn. CCS was a political necessity and a prerequisite for government approval in 2009 for a project that will emit more than a gigaton of CO_2 when the gas is burned.

Quest takes CO_2 from for hydrogen production. The hydrogen is produced from fossil fuels and is used for oil production from oil sand/tar sand in Alberta, to make the tar more fluid, to gasoline or similar products. The tar sand operations by Shell Canada are among the dirtiest and most controversial of all fossils. It is also a dirty way to produce hydrogen; green hydrogen is produced by electrolysis of water with renewable electricity.

As for the Illinois industrial CCS, the documentation is not readily available. It is operated by the agri-giant Archer Daniels Midland Company (ADM). The mitigation effect, and cost effectiveness, of US corn ethanol is disputed among government agencies[30] and NGOs[31]. It is not clear that ethanol, produced as in the US, is a large scale alternative to gasoline, and that ethanol CCS represents a major general mitigation option.

Greater fuel efficiency, electric and hydrogen vehicles, shift from road and air transport to railway and sea transport are less controversial.

28 Source: CCS Institute which defines large scale as at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO_2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation).

29 www.swissre.com/australia_newzealand/insights/carbon-capture-and-storage.html

30 https://www.usda.gov/oce/climate_change/mitigation_technologies/Ethanol_Report_Factsheet_Final.pdf

31 https://www.sierraclub.org/press-releases/2017/11/epa-turns-blind-eye-ethanol-s-environmental-impacts

Real CO_2 emission cuts: from renewables

Globally, wind power produced 1,123 TWh in 2017. Assuming 0.5 kg of CO_2 emissions per kWh, wind power avoided 561 million tons of CO_2. All non-hydro renewable electricity avoided, by the same account, more than 1,000 Mtons of CO_2 in 2017.

Efficiency measures, such as LED lighting and heat pumps, avoid similar amounts of CO_2.

CCS avoided, at most, 3.7 million tons of CO_2 in 2017 (or 2018, when renewables got still higher.)

Renewables and efficiency achieved more than 500 more mitigation than CCS. They can do a lot more, and fast. Globally photovoltaics grew a phenomenal 35 per cent 2006-16, but did not flatten 2017: it grow another 50 per cent.

There are faster, cleaner, surer, safer, more durable, more effective and cheaper ways to cut CO_2: renewables, efficiency measures and the development of carbon-free industrial processes.

Keeping the CCS option open will only divert attention and resources.

CCS is not fast. It would take decades for it to make a significant contribution to mitigation.

It is not reliable. Even with a huge effort, there is no way to know that it will deliver.

It is not safe. CO_2 may escape over various timescales, carrying immediate risks to health, for inducing earthquakes and for renewed warming.

It is not clean. CCS uses about 25 per cent more fuel, which means more fossil extraction with several associated problems. A BECCS plant means more use of biofuel, which is a limited resource.

It is not durable. Fossil fuels are finite, and it is unsustainable to keep extracting them in enormous amounts in one place and burying the CO_2, which has three times as much mass, somewhere else.

It is not effective. The process captures much of the CO_2 but still emits 10 per cent or more directly into the atmosphere. The life cycle emissions from a CCS power plant are much higher than from a renewable plant.

It is not economic. A dollar spent on CCS mitigates less than a dollar spent on renewables etc. for the next year, the next decade or the next century. A recent article[32] in Nature Energy concluded that then energy return on energy invested is far lower for CCS than for wind and solar even accounting for storage, and with very favorable assumptions for CCS. This is not an economical comparison per se, but unfavorable physics can hardly be translated to sound economics.

Wind power onshore, solar photovoltaics, windpower offshore, solar heat, several biomass technologies have taken off on a large scale and are not dependent on subsidies for further development.

32 https://www.nature.com/articles/s41560-019-0365-7

CCS issues: 1 Storage

If CCS is to play a significant role as a mitigation option, it must store several billion tons (Gtons) of CO_2 per year. To store several Gtons, an enormous infrastructure will be needed, in the form of pipelines and/or CO_2 tankers. Even if there were political unanimity, and unlimited finance, such an infrastructure has a long lead time. It must also be coordinated with the capture of CO_2. That is hardly going to take place.

Storage represents a cost for investment, injection and monitoring, but no benefit other than the CO_2 price. Carbon trading and carbon taxes have so far produced a weak and inconsistent incentive.

Carbon storage in geological formations has been tested since 1996 on the scale of up to a few million tons per year. On that scale, it does not matter very much if the storage sites leak. But why develop the whole scientific, engineering, political and legal machinery for just a few megatons?

Storage on a meaningful scale must be very resistant to leaks.

Perhaps it is possible to store CO_2 for billions of years, but we cannot know for sure.

The carbon storage problem has parallels with the nuclear waste storage problem, which has not really been solved anywhere, after many decades of research. CO_2 storage is in some respects even more difficult. Nuclear waste is solid and easier to keep in place than a gas or a liquid such as CO_2. Nuclear waste becomes less dangerous over time, but CO2 maintains its global warming ability forever. Also, nuclear leaks can be measured in minute quantities, so monitoring is much easier than for CO_2.

"The fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years," according to the IPCC CCS report.

"Very likely" means a probability of 90–99%, which would mean a 1–10 percent probability of faster or bigger leaks. "Likely" is a probability between 66 and 90%, meaning approximately "perhaps". Both assessments are qualified, and apply to appropriately selected and managed sites.

If this assessment stands, it means there is a probability of 10–34 percent that more than 1 percent will leak.

If, as a theoretical example, the leak rate is 0.1 percent per year, after 1,000 years 73 percent will have returned to the atmosphere, to which should be added some 10 percent losses at capture. After 10,000 years 99.995 percent would have leaked.

Small leak rates matter, as the one stable natural sink for CO_2 is silicate weathering, which operates on very long timescales.

The question of what happens at badly managed sites is very relevant in a perspective of several thousand years. We have no experience of international institutions with such longevity.

Anything from bankruptcy and associated failure of monitoring equipment to war, earthquakes or tsunamis could increase the risk, as could careless mining or drilling.

Large or small leaks over a long period of time pose other hazards than to the climate.

In high concentrations, CO_2 is lethal and kills without warning, as the 1986 Lake Nyos disaster demonstrated. The disaster was unrelated to CCS, but if a storage or pipeline breaks in populated areas, the gas is just as deadly under some circumstances. CO_2 is heavier than air so it is most dangerous in a valley, with low wind. A leak could also pollute groundwater.

CO_2 under pressure is an extremely efficient lubricant and may trigger earthquakes. "Large-scale CCS may have the potential for causing significant induced seismicity," according to the US National Academy of Sciences.

Irrespective of the actual risk, carbon storage has to take public opinion into consideration. Storage projects have been scrapped in Germany, the Netherlands and Denmark, as fossil companies have not been able persuade people that the benefits outweigh the risks.

CCS issues: 2: Capture

Carbon capture from fossil fuel combustion is technically proven on an industrial scale, but it is very expensive.

Capture adds cost and complexity to unabated fossil fuel combustion. The capture plant is the same size or bigger than the power plant itself, so both capital and operational costs are greatly increased.

Carbon capture also consumes energy, so to produce power or some other useful service, around 25 percent more fuel is needed than if emissions were not captured.

Capture is not 100 percent efficient. Some CO_2 escapes, on the order of 10 percent in theory, but often much more in real projects.

Because CCS only captures around 90 percent of CO_2, the carbon footprint of fossil power CCS is greater than that of renewables and efficiency measures.

There are three ways to dispose of the captured carbon: geological storage (above), enhanced oil recovery (EOR) and CCU.

EOR is clearly not a way to cut CO_2 emissions. 17 of the 21 operating CCS projects in the world 2018 are EOR[33].

CCU (carbon capture and utilisation) in which carbon is used as a feedstock, is not a serious climate mitigation option. If CO_2 is used to fertilise algae or greenhouses, the harvested plants will have to be stored forever. If they are combusted, all the CO_2 will be emitted.

The same problem occurs if the CO_2 is combined with hydrogen to produce methanol, for example.

Direct air carbon capture takes CO_2 from the air, of which it makes up 0.04%. This is technically possible, but economically absurd, estimated by the American Physical Society at \$600/tCO_2. This does not include transport and storage of CO_2.

33 See database at www.globalccsinstitute.com/projects/large-scale-ccs-projects

CCS issues 3: CCS in the energy system

Power stations. The most obvious candidate for CCS would be coal power. That is where there are very large amounts of CO_2, and in high concentration. Some power stations emit 10 Mt of CO_2, or more, per year, creating an economy of scale for capture, transport and storage. What works well in one coal power station can largely be replicated at another coal power station.

The second biggest stream of CO_2 is natural gas power. It is still worse than coal power, as gas power plants produce less CO_2 per kWh, tend to be smaller, and operate for fewer hours per year.

The economic reality is that fossil power CCS costs much more than renewable power. No such plant exists. No power producer would consider building a new coal or gas power plant with CCS, or retrofit an existing power plant for CCS, unless somebody else pays.

The economic case for power CCS used was originally based on a higher carbon price. But even a much higher carbon price will not necessarily help. Coal and gas are cheap to extract, but wind, solar and efficiency measures have no fuel costs at all. Fossil fuel costs are unpredictable and may increase. It is expensive and time-consuming to open a new coal mine, so the investor faces a lot of economic and political uncertainty.

Fossil power CCS is almost dead before it was born. Most of the opportunities for CCS have now gone, leaving only niche applications, which will then have to carry the full cost of research, development and infrastructure.

CCS for industrial processes is still under discussion. The iron and steel industry uses coal and coke to reduce iron ore (oxide) to metal. Similar processes are used for other metals, such as aluminium and copper. The cement industry uses fossil fuels to heat limestone, which then emits CO_2. District heating and some other industries (e.g. paper and pulp) emit CO_2 from fossil fuels or biofuels or a mix (e.g. household waste incineration). Other potential big point sources are oil or biofuel refineries.

The rationale for industrial CCS is that there is no alternative. There are however good arguments to the contrary, at least in a 2030–2040 perspective.

Iron ore mining should be reduced, through better recycling. Ore can be reduced by using hydrogen from the electrolysis of water, as renewable electricity can deliver vast amounts of cheap electricity. This is the strategic choice of Europe's biggest iron miner, LKAB and the Swedish steel company SSAB.

Aluminium can be produced either with hydrogen, or with inert electrodes instead of graphite electrodes.

CO_2-emitting Portland cement is one way of bonding rocks and sand together to make concrete. There are other binders: geopolymers (clays), pozzolans (volcanic ash, ash from coal combustion), slag, and magnesium-based cements.

Incineration of household and other waste with a large fraction of plastics is unsustainable. Waste prevention should first reduce, then reuse, then recycle the plastic in society.

District heating or industrial heat are far from ideal sources of CO_2 for CCS, because they are typically much smaller than power plants, as they are typically not operated anyway near base-load, so CCS will add greatly to the cost. If district heating costs are excessive, customers will defect and use other heating sources.

If it is recognised that fossil power CCS is too expensive, then more decentralised collection of CO_2 from district heating plants, steel mills, paper mills etc. must be much more expensive. A typical industrial or district CHP/heating plant is 1–100 megawatts. Each plant needs its own tailored engineering design, environmental impact assessment and associated political process. If a single 2 GW coal power plant, capturing 10 Mt CO_2/year does not make sense, 100 smaller plants, 10–100 kilometres apart, make even less sense.

CCS issues 4; Bioenergy CCS, BECCS and the notion of overshoot

If biomass is combusted in a power plant and then the CO2 is captured and stored, we would have a plant with negative emissions.

In theory, that is. The only practical example in the world of large scale bioenergy CCS, or BECCS, is the Illinois Industrial project at the agri-giant ADM in Decatur, Illinois. The plant produces ethanol from corn and captures some of the CO2 from it. The climate footprint of ethanol-from-corn is a hotly contested issue34. Some models even suggest that the US ethanol is worse than gasoline, some that it is much better. It is clearly not zero, which makes it more difficult to get to negative numbers even if most of the CO_2 is stored. The trickiest part of the calculation concerns land use; if you use an acre for corn ethanol, will this lead to another acre for food somewhere else on the planet?

This is an issue for BECCS not limited to corn and ethanol. The concept of sustainable development, launched by the UN report Only one Earth in 1987 originated in the forestry industry. It means that the felling rate is less than the growth rate measured as cubic meters of wood biomass. While it is obviously not sustainable to fell more than the growth rate, this misses a large part of the story with regard to carbon. Much of the forest carbon is in the soil, and the soil carbon continues to grow also in a mature forest. If the forest is cleared, the carbon growth stops or reverses over a number of years. The "negative emissions" do not start at zero here either.

And carbon balance is not everything. With other greenhouse gases, especially nitrogen oxides, taken into account, it is still more difficult to get into the negative numbers. The need to keep temperature increase down cannot be allowed to come at the cost of accelerating loss of biodiversity from increased use of pesticides, fertilizers and monocultures.

Biomass is a limited, though large, resource. The least controversial biomass is waste: biogenic household waste, waste streams from food industries (slaughtery waste, olive stones, rice husks), agriculture (e.g. straw, chaffe), wood and paperindustry (lignin, sawdust, bark). Everything that competes with food production and biodiversity for land is problematic at least on a large scale.

On a large scale, BECCS is kind of geoengineering. It implies the transformation of very large areas of land for drawdown of CO_2.

34 See for example https://www.vox.com/2016/2/22/11075200/ethanol-carbon-footprint

Much of the biomass is local and small scale, and often best suited for small scale combustion for local heating or biogas production. BECCS requires that the biomass is used in large combustion plants, transported in big pipelines, stored in big storages and compressed with big compressors. It is not practical to collect small streams of CO_2 from a detached house or a small factory.

BECCS plants will suffer the same parasitic loss as fossil CCS, so 20 or 25 percent of the biomass feedstock will be needed for energy for CCS – unless the energy requirements for capture and compression are supplied by other renewable energy. That renewable energy would be better used directly to replace coal power for many years to come.

Market forces and climate considerations will arrive at the same conclusion every time: wind, solar and efficiency measures will always be the preferred alternative to bio-CCS.

The rationale for bio-CCS or other negative emissions comes when the whole power sector, and some other minor large point sources, are decarbonised. Then, bio-CCS could draw down CO_2 from the atmosphere.

It is however very difficult to believe that one distinct moment will come when mankind suddenly sees that all options to cut emissions are exhausted and that we must switch to draw-down mode. The decarbonisation process is not synchronised between countries and sectors. Some can, and probably will, achieve near-zero carbon in 10 or 20 years' time, while big emitters will still be operating elsewhere. It is not clear who should shoulder the responsibility of building extremely expensive BECCS plants, and when.

Without a clear picture of how this would happen in the future, we cannot consider it an option. It is morally indefensible to presuppose that people will be different, and better, in the future, and that they will do what we are not doing. BECCS may not be an option in the future, so to bank on it in mitigation scenarios is tantamount to promising lifeboats now and letting the passengers find out later that they are not there.

The strategy of overshoot – first use a lot of fossils, then draw down the CO_2 later – suits the fossil industry, and unsustainable forestry and farming.

BECCS shifts the focus away from what we know can and must be done.