Making an educated decision about Carbon Capture and Storage

The Bolin Centre Climate Arena aims to support cross-sector work aimed at "bending the curve" of climate change by:

- ✓ developing long lasting relations between academic, public, business and policy sectors,
- ✓ enhancing the impact and utilization of knowledge and research, and
- ✓ promoting climate education for the future.

The burning of fossil fuels and cement production release vast amounts of carbon dioxide to the atmosphere. Expressed simply, we are moving carbon dioxide from geological sources (coal, oil, natural gas and limestone) to the atmosphere. The rate at which this happens is far faster than the rates of geological processes that ultimately remove carbon dioxide from the atmosphere (the chemical weathering of rocks). Hence, because carbon dioxide is a greenhouse gas, we are thereby causing global warming.

This policy brief will cover the topic of carbon capture and storage, which is often abbreviated "CCS". The purpose is to provide you as a decision- or policymaker with the information needed to make decisions or policies concerning carbon capture and storage. Carbon capture and storage is a crucial component in global efforts to limit global warming to 1.5°C or at least well below 2°C following the recommendation of Paris-agreement 2015, and in accordance with the Intergovernmental Panel on Climate Change (IPCC) (2018). This policy brief consists of two parts; the first part aims to provide some necessary background knowledge about the carbon cycle and how it relates to climate. The second part assumes this knowledge and aims to provide motivated answers to specific questions about carbon capture and storage as a climate change solution.

Carbon dioxide can be captured by chemical reactions with volcanic rocks. Photo: Alasdair Skelton

Part 1: Understanding the carbon cycle

1 petagram (Pg) is equal to one billion tons. That is the approximate weight of 5 million jumbo jets or 600 million cars.

Figure 1 shows the carbon cycle before humans started affecting it. The units are **petagrams** (Pg) of carbon per year (yr). The carbon cycle has two parts; the first part (shaded green in the figures below) is a "fast cycle" whereby carbon circulates between the atmosphere, land, ocean, lakes and rivers. This cycle, which is governed by fast processes such as photosynthesis and exchange across water/air boundaries, operates on timescales ranging from seasons (or even shorter) to thousands of years. The second part (which is shaded in grey in the figures below) is a "slow cycle" whereby carbon circulates between the atmosphere and rocks. This cycle, which is governed by slow processes such as the weathering of rocks, operates on timescales ranging from hundreds of thousands to millions of years. Note that the amounts of carbon being added to and taken away from the atmosphere are the same. This is a system in balance.

Figure 2 shows how we have perturbed the carbon cycle. According to the IPCC (2013), we release 8.9 petagrams of carbon annually from fossil fuels, cement production and land use change. This carbon is taken up by the atmosphere, oceans and land surfaces. The carbon that is added to the atmosphere takes the form of carbon dioxide (CO_2)

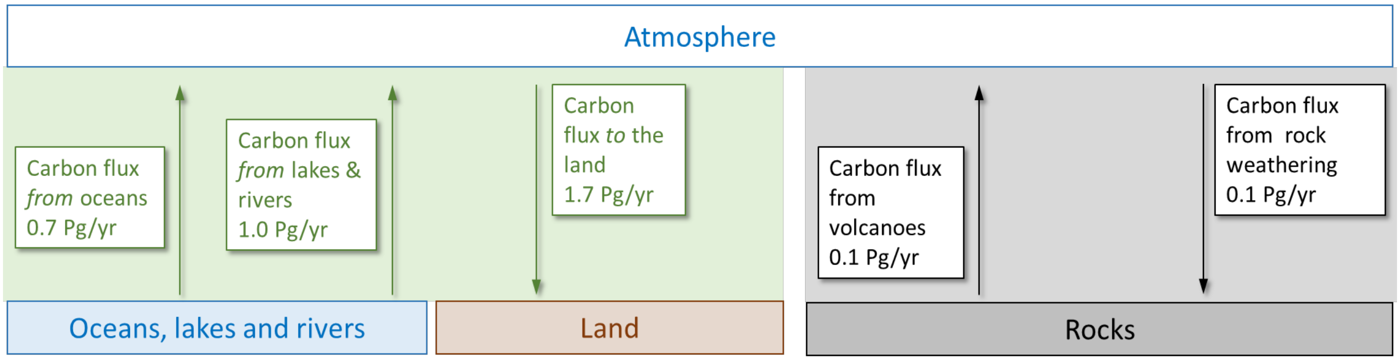

Figure 1. The pre-industrial carbon cycle (modified from the Fifth Assessment Report of the IPCC, 2013)

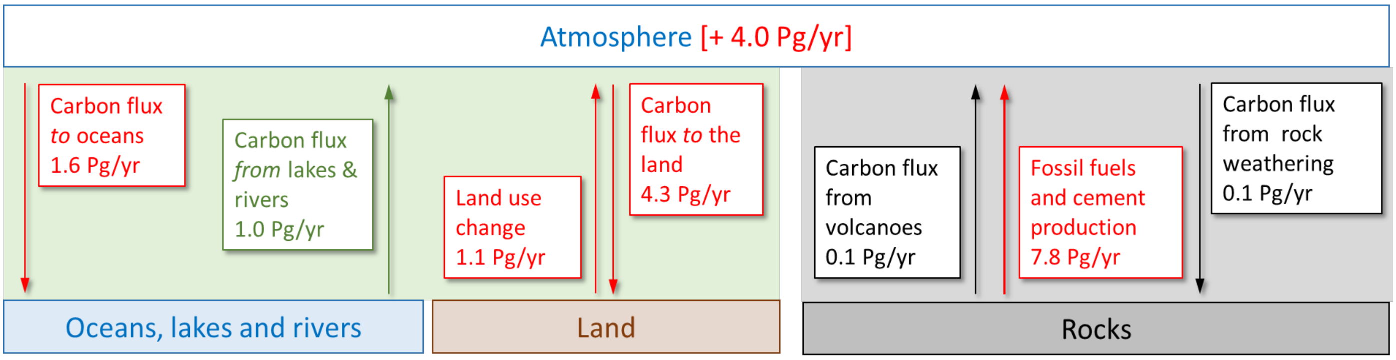

Figure 2. The carbon cycle from 2000–2009 (modified from the Fifth Assessment Report of the IPCC, 2013). In this figure, red arrows denote carbon fluxes which have changed due to human actions. One way of getting a better understanding of the numbers in this figure is to add the carbon fluxes ***to the atmosphere*** *from lakes and rivers (1.0 Pg/yr), from volcanoes (0.1 Pg/yr), from land use change (1.1 Pg/yr) and from fossil fuels and cement production (7.8 Pg/yr). This gives a total of 10 Pg/yr for carbon* ***entering the atmosphere****. Now subtract the carbon fluxes* ***from the atmosphere*** *to the oceans (1.6 g/yr), to the land (4.3 Pg/yr) and due to rock weathering (0.1 Pg/yr). This gives a total of 6 Pg/yr for carbon* ***exiting the atmosphere****. The remainder of 4 Pg/yr* ***stays in the atmosphere*** *and warms the planet.*

and methane (CH_4), causing global warming, and the carbon dioxide that is added to the ocean causes acidification.

Figure 3 shows the amounts of carbon stocked in each **reservoir**, and the red numbers illustrate the amount of carbon that has been changed due to our actions. By the end of 2019, we had released an estimated 427 Pg (calculated from the IPCC 2013 report) from rocks by burning fossil fuels and cement production. We had also caused a net loss of carbon from the land of approximately 18 petagrams. This carbon has been added to the atmosphere and oceans.

Evidently, the above figure shows a massive (46%) rise in the amount of carbon in the atmosphere. This causes global warming. The ultimate purpose of all climate change solutions, of which carbon capture and storage is one, is to make this number significantly smaller.

By **reservoir**, we mean the atmosphere, hydrosphere (oceans, lakes, and rivers), land and rocks.

Part 2: Carbon capture and storage (CCS)

Now that we have covered some necessary background information about the carbon cycle, we are ready to tackle specific questions about carbon capture and storage.

What is carbon capture and storage?

The term "carbon capture and storage" or the acronym "CCS" is used to describe a variety of approaches whereby carbon dioxide is captured, transported to and stored in one of the reservoirs shown in Figure 3, other than the atmosphere (where it causes global warming). Carbon capture and storage is a form of Carbon Dioxide Removal (CDR). This broader term encompasses not only CCS but also other artificial approaches for removing carbon dioxide from the atmosphere, such as afforestation (meaning planting trees where no trees were before).

Capture can be done at point sources, i.e., where carbon dioxide would otherwise have been released to the atmosphere. These point sources can be power plants or factories where fossil fuels or biofuels are burned. Carbon dioxide can also be captured directly from the air. Storage of carbon dioxide captured at a point source from biofuel burning is called Biomass Energy Carbon Capture and Storage (BECCS). Storage or carbon dioxide captured from the air is called Direct Air Carbon Capture and Storage (DACCS).

Transport of carbon dioxide is usually in liquid form by ship or in pipelines.

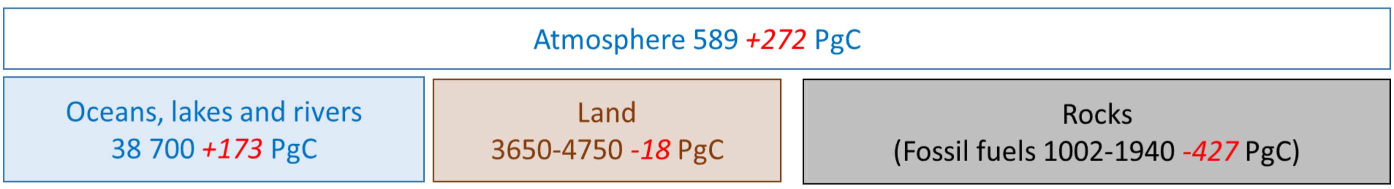

Figure 3. The numbers in this figure are calculated from IPCC's Fifth Assessment Report (2013). This illustrates estimated masses of carbon in the atmosphere, hydrosphere (oceans, lakes and rivers), land and fossil fuels. Note that these are ranges for land and rocks. These ranges express present uncertainties. The red numbers show carbon emissions from burning fossil fuels and cement production, a net loss of carbon from the land reservoirs (vegetation, soils and permafrost) and gains of carbon in the atmosphere and hydrosphere.

Storage of carbon dioxide can theoretically be done in any reservoir other than the atmosphere, as illustrated in Figure 4 below. However, storage of carbon dioxide in the oceans can be ruled out because it causes acidification which is hazardous for ocean life (IPCC, 2005). Carbon dioxide storage on land can be done by its conversion to biochar and subsequent storage in soils or by afforestation. Biochar can have positive effects for agriculture. The effectiveness of afforestation as well as risks for negative side effects such as biodiversity loss are hotly debated (Bastin et al., 2019; Veldman et al., 2019). The longevity of carbon storage in this manner remains uncertain with estimates ranging from decades (De la Rosa et al., 2017) to millennia (Kuzyakov et al., 2009). Alternatively, carbon dioxide can be stored in different types of rock formations. This can be as a **supercritical fluid** in porous sedimentary rock formations. These can be depleted oil reserves, coal beds or saline aquifers – in many cases the same places as the fossil fuel originated. Alternatively, carbon dioxide can be stored in some kinds of **porous** volcanic rocks. An important difference between sedimentary and volcanic rocks suitable for carbon dioxide storage is that whereas the sedimentary rocks are not very chemically reactive (inert), the volcanic rocks react readily with carbon dioxide.

Supercritical fluids combine properties of both gases and liquids. For example, if you would bring CO_2 beyond its critical point (that is if you apply high enough temperature and pressure) it no longer behaves like a gas or liquid, rather it behaves like something in between.

Porous describes rock formations that possess tiny spaces through which air or liquid can pass.

This is because the minerals which make up the volcanic rocks contain substantial amounts of calcium, magnesium and iron, which react with carbon dioxide to form solid carbonate minerals, such as calcite ($CaCO_3$). This type of mineralization is surprisingly fast. Preliminary results indicate that solid carbonate minerals can form in some volcanic rocks by reaction with injected carbon dioxide in only 100 days (Matter et al., 2016). An advantage of storing carbon dioxide as solid carbonate minerals is that leakage is less likely, and the storage longevity is millions of years.

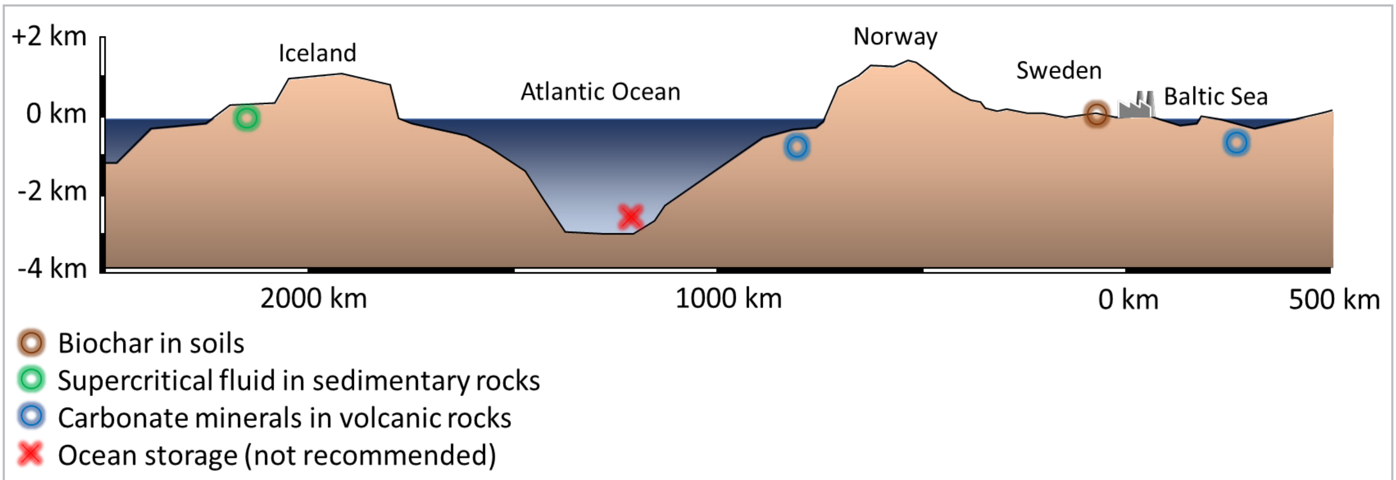

Figure 4. Storage options for carbon dioxide emitted from a point source in eastern Sweden.

Is CCS necessary?

The short answer to this question is yes. The climate is changing very rapidly. Presently, Earth is getting warmer at an unprecedented 0.2°C every 10 years. At this rate global warming will exceed 1.5°C within 2 decades. Limiting global warming and reversing this trend requires a combination of emissions reductions, natural climate solutions (i.e., reforestation, sustainable agriculture and preservation of wetlands [Griscom et al., 2017]), and carbon capture and storage (CCS). This was illustrated by the Intergovernmental Panel on Climate Change (IPCC) in their 2018 special report titled "Global Warming of 1.5°C". In this report, the IPCC presented illustrative pathways which, if followed, could limit global warming to 1.5°C. These pathways are shown in Figure 5. They rely not only on emissions reductions and natural climate solutions, but also on CCS.

Indeed, CCS will be necessary at a scale which so far remains unproven. In their 2018 report, the Global CCS Institute calculates that in order to keep global warming well below 2°C in accordance with the Paris Agreement, we would need to have roughly 2,500 large-scale (storage capacity greater than 1 megaton/year) CCS facilities in operation by 2040. In 2018, there were only 18 large-scale CCS facilities in operation. We should be constructing more than 100 large-scale CCS facilities every year until 2040; yet we are not doing so.

Is CCS a viable alternative to emissions reductions?

The short answer to this question is *no*. Figure 5 shows that limiting global warming below dangerous levels requires fast implementation of *all* available climate change solutions, not just some of them. Emissions reductions are by far the most effective climate change solution. Unfortunately, because we have delayed reducing our emissions, we are now reliant on not only emissions reductions but also on a range of natural climate solutions and CCS. In this respect it is important to note that according to the IPCC (2018): "CDR deployed at scale is unproven, and reliance on such technology is a major risk in the ability to limit warming to 1.5°C".

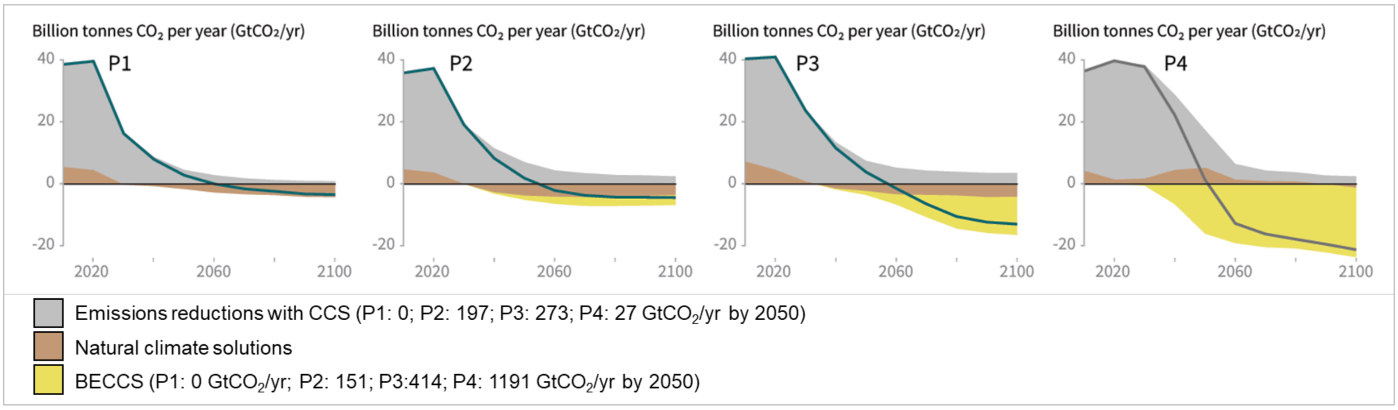

Figure 5. Illustrative pathways that limit global warming to 1.5°C, based on four different future scenarios, from the IPCC special report: Global Warming of 1.5°C (2018). The scenarios are: business and technological innovation result in low energy demand by 2050 (P1), a broad focus is on sustainability (P2), society as well as technological development follow historical patterns (P3) and economic growth and globalization lead to widespread adoption of greenhouse gas intensive lifestyles (P4). Note that moving from P1 to P4 we see an increasing reliance of BECCS. This is worrying because deployment of BECCS at scale is unproven and because biomass burning is seldom carbon neutral.

Does CCS generate negative emissions?

To answer this question, we must consider the source of the carbon dioxide that is being captured and how energy used for capture, transport and storage was generated:

If carbon dioxide released by burning fossil fuels to make energy is captured and stored, we are not adding carbon dioxide to the atmosphere. However, we are not removing carbon dioxide from the atmosphere either, so we are not generating negative emissions. Indeed, because energy is needed to capture, transport and store carbon dioxide, we are probably still generating emissions.

The case of BECCS is more complicated. If it were fair to state that biomass burning is carbon neutral, one could also argue that BECCS generates negative emissions. However, biomass burning is not necessarily carbon neutral. This depends on the type of biomass. Burning of household waste and certain industrial by-products can be carbon neutral, whereas wood harvesting for the sole purpose of supplying biomass is unlikely to be carbon neutral. This is for the following reasons:

- Energy plantations are not necessarily as good as the natural ecosystems they replace at storing carbon (Harper et al., 2018). Thus any "negative emissions" are countered by the loss of an ecosystem that would otherwise have removed carbon dioxide from the atmosphere.
- There can be a time lag after removal of biomass for burning and before it is replaced by new biomass during which less carbon dioxide is removed from the atmosphere by photosynthesis. This time lag comes with an emissions penalty which must be weighed against any "negative emissions".

Only storage of carbon captured from the air (DACCS) generates unequivocal negative emissions, and only if 1) carbon dioxide used to fulfill its energy requirements does not exceed the amount which is captured and stored and 2) carbon dioxide, once captured, is actually stored and not used for commercial purposes (e.g., making carbonated water).

Recommendation for Sweden

There are a number of point sources at which carbon dioxide could be captured in Sweden. These are various factories and energy plants. Storage options are as biochar in soils, as a supercritical fluid in sedimentary rocks or as carbonate minerals in volcanic rocks. There are advantages and disadvantages with each of these options. These concern transport costs and storage longevity and are summarized in Table 1. Production of biochar can be done locally which reduces or eliminates transport costs. However, the longevity of carbon storage in this manner is less certain, meaning that permanency cannot be guaranteed. In contrast, storage of carbon dioxide as a supercritical fluid in sedimentary formations can be viewed as permanent but only if leakage can be definitively avoided. Regarding permanency, storage of carbon dioxide as solid carbonate minerals is probably the best option because the risk for leakage is largely eliminated. However, suitable porous volcanic formations are not found close to Sweden (Iceland is the closest suitable location, See Figure 4).

Mode of carbon storage	Transport costs	Storage longevity
• Biochar in soils • Supercritical fluid in sedimentary rocks • Carbonate minerals in volcanic rocks	• Low • High • Very high	• Uncertain • Permanent if no leakage • Permanent

Table 1. Advantages and disadvantage of carbon storage options in Sweden.

In contrast, sedimentary rock formations which are suitable (or potentially suitable) for storage of carbon dioxide as a supercritical fluid are found closer to Sweden. These sites are offshore of Norway and beneath the Baltic Sea seafloor (Mortensen et al., 2017), meaning that transport distances and associated costs are nevertheless substantial.

From a climate perspective, permanency weighs more heavily than transport costs, so provided that emissions associated with transportation are low compared with the amount of carbon dioxide being captured, storage in rocks is recommended, at least until we know more about the longevity of storing biochar in soils.

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This policy brief is an expert statement by Alasdair Skelton and Kevin Noone, and it was peer-reviewed by Nina Kirchner and Paul Glantz who are scientists at the Bolin Centre for Climate Research. It is not necessarily a collective standpoint shared by all members of the Bolin Centre for Climate Research.

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