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The role of Carbon Capture and Storage in the Mitigation of Climate Change

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Abstract: Scenario analysis clearly indicates that CCS is a critical technology in Paris consistent 'well below 2°C' scenarios. While the optimal deployment of CCS will be debated, the literature is clear that CCS is needed at a large-scale. Scenarios show CCS plays a key role in the power sector and industry, on fossil fuels and bioenergy, and in all world regions. The design of the Paris Agreement around five-yearly cycles to raise ambition is likely to lead to lower and uncertain carbon prices and thereby discourage the deployment of CCS. To ensure that CCS is deployed at the necessary scale, and to make a meaningful contribution to the Paris Agreement's 'well below 2°C' goal, it is likely innovative government support for CCS is necessary to operate in parallel to conventional climate policies.

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Executive Summary

Achieving the Paris Agreement's goal of limiting global warming to '*well below 2°C* above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels' requires rapid reductions in greenhouse gas emissions. There are now hundreds of emission scenarios showing different evolutions of the energy system that are consistent with the goals of the Paris Agreement. Carbon Capture and Storage (CCS) plays a crucial role in most of these emission scenarios in two fundamental ways: First, CCS is needed to reduce direct emissions from the use of fossil fuels in power generation and industry. Second, CCS is needed with bioenergy, direct air capture, or other technologies to remove CO_2 from the atmosphere at a scale that leads to net negative emissions. Without CCS used in both these ways, scenarios suggest it becomes nearly impossible to reduce CO_2 emissions sufficiently fast to keep global warming 'well below 2°C'.

There are three fundamental reasons why CCS may be a prerequisite to stay 'well below 2°C'. *First*, CO_2 emissions have a cumulative effect on the climate, requiring that CO_2 emissions must be net-zero to stop further increases in global temperature. It may be impossible to get emissions to net-zero fast enough without using CCS to eliminate direct emissions or in CO_2 removal. *Second*, competitively priced technologies do not exist, and may never exist, to reduce emissions to zero in some hard-to-mitigate sectors. It may be cheaper to reduce emissions in some hard-to-mitigate sectors with the direct application of CCS (like steel and cement) or with CCS used in CO_2 removal (like CCS used in CO_2 removal to offset emissions from long-distance shipping and aviation). *Third*, it may be cheaper to reduce emissions in some sectors with CCS or CO_2 removal, and the resources saved can be used for other societal priorities.

Cost optimising emission scenarios scale up CCS at a rate in excess of one new facility per day until 2050 (and beyond) to be consistent with the Paris Agreement's 'well below 2°C' goal. *Scenarios that restrict the use of CCS show higher mitigation costs, and an even faster growth in non-fossil energy sources to compensate for the lack of CCS.* Many models that exclude the use of CCS are not able to reduce emissions sufficiently fast to meet the 'well below 2°C' goal. CCS is deployed on both fossil and biomass sources, with the biomass sources leading to net CO_2 removal, and deployed in both power generation and industry. OECD and Asia generally have the highest level of CCS deployment, but Latin America and the Middle East and Africa have significant deployment in some models. Models suggest *Europe may have as many as 1,000 CCS facilities (~1GtCO_2/yr) by 2050.* The scenario literature is clear: meeting the Paris Agreement's 'well below 2°C' goal requires significant global deployment of CCS across regions and sectors.

Scenarios indicate that even in a high-fossil fuel world, aggressive mitigation can be done with appropriate levels of CCS alongside other measures. The deployment of large-scale CCS allows continued but declining use of fossil fuels, particularly coal and gas, and oil if it is offset by large-scale CO_2 removal. The deployment of CCS happens in parallel to a reduction in fossil fuel use, improvements in energy efficiency, and the rapid scale-up of other low-carbon technologies, such as solar, wind, and electric vehicles. *Scenarios that don't deploy CCS, or have lower levels of CCS, show steeper declines in fossil fuel use, more rapid growth in non-fossil energy sources (e.g., renewables and nuclear), and increased dependence on large-scale forestry activities for CO_2 removal.* It is important to note that CCS operates in parallel to other mitigation measures, and not as a substitute for other mitigation measures.

The five-yearly cycle to raise ambition in the Paris Agreement may lead to incrementalism and delay the scale up of CCS. Models mostly implement the Paris Agreement goals in a cost optimal way, which leads to high and uniform global carbon prices and encourages the early deployment of CCS. The five-yearly cycle to raise ambition in the Paris Agreement may lead to national policies with a gradual and uncertain rise in the carbon price that may be insufficient to encourage the development and deployment of CCS. *In this context, other policy mechanisms are needed to support and encourage the development and deployment of CCS in the absence of strong global carbon prices.*

Scenario analysis clearly indicates that CCS is a critical technology in Paris consistent 'well below 2°C' scenarios. While the optimal level of deployment of CCS can be debated, the literature is clear that CCS is needed at a large scale. Scenarios show CCS playing a leading role in the power sector and industry, on fossil fuels and bioenergy, and in all world regions. The design of the Paris Agreement around five-yearly cycles to raise ambition is likely to lead to lower and uncertain carbon prices and thereby discourage the deployment of CCS. To ensure that CCS is deployed at scale to make a meaningful contribution to the Paris Agreement's 'well below 2°C' goal, it is likely innovative government support is necessary to operate in parallel with conventional climate policies.

1 Introduction

Achieving the Paris Agreement goal of limiting global warming to well below 2°C requires rapid reductions in greenhouse gas (GHG) emissions. In almost all scenarios that are consistent with this goal, CO_2 emissions reach (net) zero in the second half of this century. The largest source of CO_2 emissions is from the burning of fossil fuels. Due to the unprecedented rate of CO_2 emissions reductions required to meet the Paris Agreement goal, Carbon Capture and Storage (CCS) plays a crucial role in two different ways: First, CCS is used to reduce direct emissions from the burning of fossil fuels. Second, CCS is used with bioenergy to remove CO_2 from the atmosphere at a scale that leads to net negative emissions (CO_2 emissions go below zero). Without CCS used in both these ways, it becomes considerably more difficult to reduce CO_2 emissions quickly enough and sufficiently to keep global warming to well below 2°C.

Carbon capture and storage (CCS) is a process that captures CO_2 from a point source and then stores it securely, usually in a geological formation. Since the location of capture and the location of storage are generally different, transport of CO_2 is also required. The capture of CO_2 can be from a power plant (coal, biomass, etc), industrial site (cement, steel, waste, etc), and in some definitions even Direct Air Capture (DAC) from the atmosphere. The CO_2 can be captured from a variety of processes (not discussed in this report), but capture generally requires energy and the capture efficiency is usually 80-90%. There are currently 19 operating CCS facilities around the world and four under construction[1], and these 23 facilities have a total capture capacity of about 40MtCO_2 per year. The amount of CO_2 stored annually is not reported. Most operating CCS facilities use industrial separation techniques, primarily in the gas industry[1]. There are two power plants with post-combustion CCS, both in North America[1]. In addition to the operating and under construction facilities, there are another 10 facilities in the advanced design phase, and another 18 in early development[1].

To complete the CCS process, once captured, the CO_2 must be transported and stored. Today, most CO_2 is transported by pipeline and used in Enhanced Oil Recovery (EOR) where it is stored. There is an increasing number of dedicated geological storage sites, but all storage occurs in or around oil & gas fields where the infrastructure and expertise exist. It is also possible to transport CO_2 by ship, and this may be increasingly important as the number of CCS facilities increase. The Norwegian Northern Lights Project will ship liquified CO_2 from different industrial capture sites to an onshore terminal, from where the CO_2 will be transported by pipeline to an offshore storage in the North Sea. This approach gives flexibility to take carbon from a range of different capture sites, spread over a large geographical area.

This report focuses on the role of CCS in scenarios consistent with the Paris Agreement's 'well below 2°C' temperature goal. Scenarios are plausible descriptions of how the future may develop based on assumptions about key driving forces (e.g., population, technology, policy). Thousands of scenarios have been developed in a climate context in the last decade, nearly all heavily dependent on CCS. The report first discusses some physical properties of the climate system which make CCS virtually unavoidable in scenarios consistent with climate stabilisation. The second section discusses key details of the Paris Agreement, as these may influence how much CCS is deployed in energy-system models and how much is deployed in real world conditions. The rest of the report discusses the role of CCS in Paris-compliant emission scenarios, and places some focus on the consequences if CCS is not deployed at scale. A final section has some concluding remarks in the Norwegian context.

2 Carbon Capture and Storage is Physically Needed

The physical characteristics of the climate problem make Carbon Capture and Storage (CCS) almost unavoidable. CO_2 emissions have a cumulative effect, and this means that CO_2 emissions must go to at least net-zero to stop further global warming. Since some sectors are hard-to-mitigate, either physically or financially, it is likely that some form of CO_2 removal is needed. Additionally, mitigation in some sectors might only be possible, or be significantly cheaper, by using CCS. Therefore, some level of CCS is probably essential, or at least, highly desirable. In this section, some of the physical reasons underlying the need for CCS are discussed.

2.1 Carbon dioxide emissions must go to (net-)zero!

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) published in 2013 and 2014 highlighted the strong relationship between global warming and cumulative carbon dioxide emissions, leading to the concept of the *carbon budget*. While the understanding of climate science was robust, and increasingly so through successive IPCC assessment reports, the cumulative emissions relationship had not received much attention until three high-profile papers were published in 2009[2-4]. The cumulative emissions concept is remarkably simple, and highlighted as a key message in IPCC AR5:

> *Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Most aspects of climate change will persist for many centuries even if emissions of CO_2 are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of CO_2. Cumulative total emissions of CO_2 and global mean surface temperature response are approximately linearly related.*

More concretely, the temperature increase above a given baseline period (e.g., average temperature in 1860-1880) was found to be roughly proportional to the total cumulative emissions of CO_2 from that time (Figure 1). This is a robust finding in both observations and model output. The relationship is affected by two key factors: non-CO_2 emissions and uncertainty. First, non-CO_2 emissions cause a temperature increase, which shifts the slope of the temperature increases upwards. This is seen in Figure 1, where the grey shaded region shows CO_2 warming only and the red shaded region shows total warming including from non-CO_2 emissions. Therefore, the more non-CO_2 that is emitted, the less CO_2 can be emitted. The relationship is still dominated by CO_2 emissions, but non-CO_2 emissions cannot be ignored. Second, models may have slightly different slopes and the relationship is closer to linear in some models than others. The slope of the relationship for the CO_2 induced warming has been estimated to have a likely range of 0.2°C to 0.7°C warming per 1000GtCO_2 emitted. This uncertainty changes how rapidly emission reductions are required and when net-zero CO_2 emissions must be reached, but it does not change the fundamental relationship.

A powerful conclusion of the cumulative emissions relationship is that emissions must go to zero to stop further global warming. This result is independent of the exact model and observational relationship, as the result is the same regardless of the proportionality constant between the temperature response and the cumulative emissions. When emissions reach zero, the temperature stops rising. This is what gives rise to the 'carbon budget' concept (Figure 1). While many definitions of the carbon budget exist, the cumulative emissions at the time of net-zero is one of the least ambiguous[5,6]. The exact size of the carbon budget depends on observations and model output, and is therefore inherently uncertain[5], but that uncertainty only affects *when* CO_2 emissions must reach zero, not *if* they need to reach zero. Non-CO_2 emissions are still important, and can cause the global temperature to decline if they are reduced sufficiently fast[7], but it is still necessary for CO_2 emissions to reach zero due to the long-lived nature of CO_2.

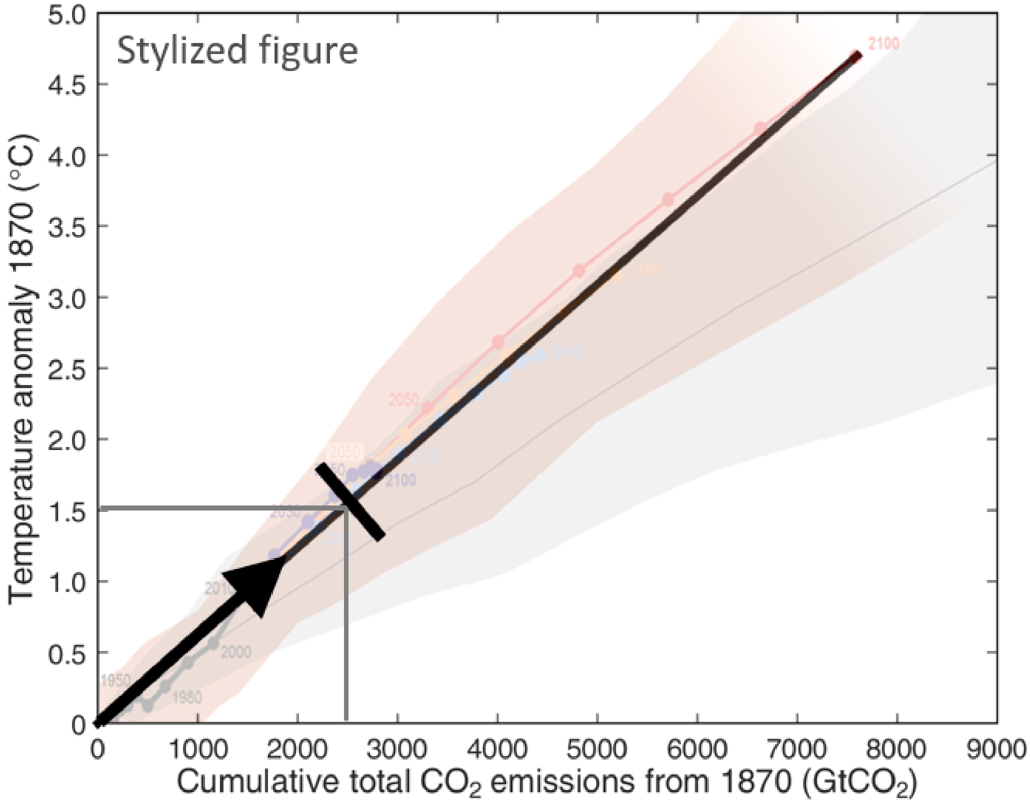

Figure 1: A stylised schematic of the temperature response versus cumulative total CO2 emissions superimposed on top of the IPCC AR5 Working Group I Summary for Policy Makers (SPM) Figure 10. While there are nuances related to non-CO_2 emissions (red versus grey in the background figure) and the uncertainties (spread in the background figure), the cumulative emission concept is a powerful and accurate way to communicate the effects of carbon dioxide emissions on temperature increase. The arrow indicates that further emissions of CO_2 increases the cumulative CO_2 emissions (arrow moves right and up), which leads to greater warming. When the cumulative CO_2 emissions stop rising, CO_2 emissions go to zero, and the temperature stops rising. At this point the 'carbon budget' can be defined, shown for 1.5°C in the figure.

2.2 Hard-to-mitigate sectors

After establishing that climate science requires CO_2 emissions to go to zero for the temperature increase to stop, the next question is how to make that happen. The atmosphere responds to the *net* CO_2 emissions entering the atmosphere, which are given by adding the *gross positive* and *gross negative* emissions (Figure 2). If gross positive emissions are greater than gross negative emissions then CO_2 enters the atmosphere, while CO_2 is removed from the atmosphere if gross negative emissions exceed the gross positive emissions.

It is probably not possible to reduce all gross positive emissions to zero because there will remain some hard-to-mitigate sectors[8] and therefore 'residual emissions'[9] (Figure 2). These residual emissions need to be offset, leading to the need for CO_2 removal (gross negative emissions). Most scenarios include CO_2 removal beyond what is necessary to balance residual emissions to bring CO_2 emissions from net-zero to net-negative (below zero). The additional CO_2 removal is required because models cannot reduce emissions sufficiently fast, or it is too costly, to meet the climate target, which means they 'overshoot' the temperature target (or carbon budget) before returning to it. For example, most 1.5°C scenarios cross 1.5°C around 2030, reach a peak temperature of about 1.6°C or 1.7°C, and then use CO_2 removal to bring the temperature back down to 1.5°C or lower. The temperature overshoot is discussed further in the next section.

Because hard-to-mitigate sectors lead to residual emissions, it is likely that some level of CO_2 removal is needed in virtually all 1.5°C and 2°C (Paris compliant) scenarios. Models generally use two types of CO_2 removal, afforestation and Bioenergy with Carbon Capture and Storage (BECCS). While afforestation is generally seen to put less risk on adaptation, desertification, land degradation and food security[10], BECCS has much higher CO_2 uptake per unit land area[11,12] and many of the risks can be managed if BECCS is done sustainably[10]. There are many other types of CO_2 removal that are not well represented in models, including Direct Air Capture (DAC), soil management, enhanced weathering, and ocean fertilisation[12,13]. BECCS and DAC are the CO_2 removal options most likely to reach sufficient scale[14], and both require integrated CCS supply chains for the transport and storage of CO_2 at scale. DAC is only now being included in emission scenarios and complements BECCS when deployed together[15]. Despite perceived high cost, DAC has some advantages over BECCS[16] which may make it the preferred industrial scale type of CO_2 removal in the future.

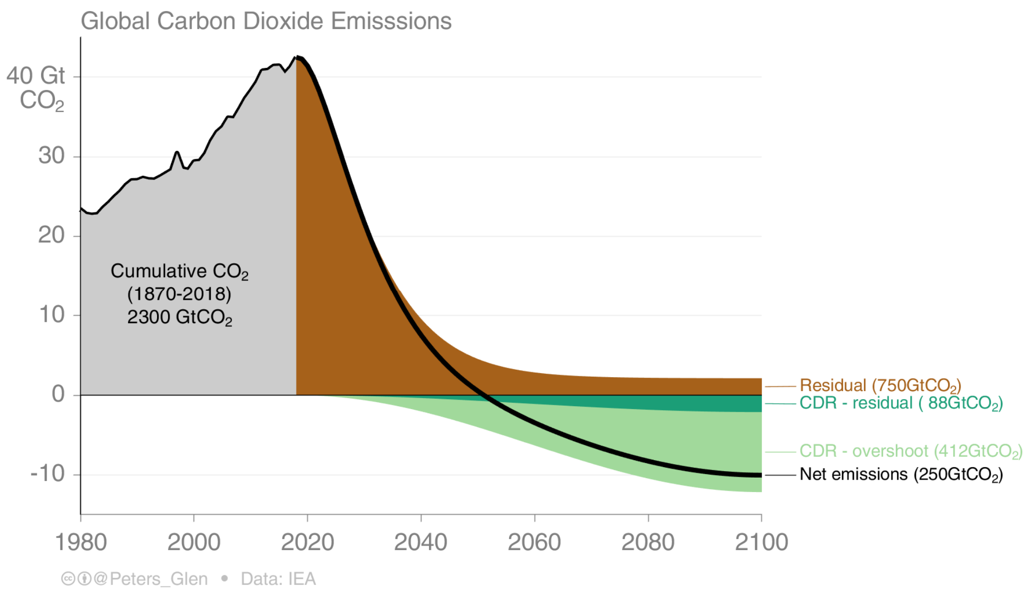

Figure 2: A stylised figure of an emissions pathway consistent with below 1.5°C in 2100, showing the gross positive or residual emissions (brown) and CO_2 removal or negative emissions (green) summing to give the net emissions (black line). The CO_2 removal has been split into a component that offsets the residual emissions in 2100 (dark green) and a component which reduces the temperature overshoot (light green). The relative level of residual emissions and the mix between CO_2 removal to offset the residual emissions and overshoot varies across individual scenarios and models.

In addition to the need for CO_2 removal to offset residual emissions, CCS may play an important role in hard-to-mitigate sectors[8]. To balance out intermittent electricity generation, it may be cost-effective to continue with some gas, or even coal, with CCS. If bioenergy is used in electricity generation (BECCS), then it may help support intermittent electricity generation in addition to CO_2 removal. Some industrial sectors have limited technological options to reduce CO_2 emissions, and the use of CCS may indeed be the cheapest form of mitigation in those sectors. Additionally, in a global climate regime with countries at different stages of development, some countries may be allowed to emit CO_2 a little longer requiring other countries to offset their emissions with CO_2 removal.

Thus, almost entirely on physical grounds, CCS or a technology with similar characteristics, is likely to be needed in order to meet the Paris Agreement's temperature goals. On top of this, some types of mitigation may be cheaper and preferable with CCS. On these grounds, it is hard to make a case not to invest in CCS innovation and deployment, whilst also pursuing other readily available mitigation options such as improved energy and material efficiency, a shift to non-fossil electricity generation, and alternative forms of transportation.

3 The Paris Agreement

The scale of CCS in the future depends on how the Paris Agreement is interpreted, and more specifically, implemented. A weak or strong interpretation of the Paris Agreement temperature goals could lead to different levels of CCS. The Paris Agreement's five-yearly process for raising the ambition of emission pledges could delay the development and deployment of CC, making it harder to reach the Paris goals. Further, the way the Paris Agreement is implemented in energy-system models could also impact the perceived level of CCS required. While the Paris Agreement has a well-known temperature goal, 'well below 2°C', the Paris Agreement is also structured around progressively raising ambition every five years until the emission pathway eventually aligns with the 'well below 2°C'. This could impact the deployment of CCS by inconsistent short- and long-term prices signals. This section gives an overview of key features of the Paris Agreement that are directly relevant to the deployment of CCS.

3.1 'Well Below 2°C'

The Paris Agreement has an explicit climate goal, specified in Article 2 (paragraph 1.a):

> *Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;*

It is ambiguous how to convert this temperature goal into a numerical statement that can be used in a coupled climate and energy-system model used to generate emissions scenarios. Most scenarios that are consistent with the Paris goal focus on an end-of-century (2100) radiative forcing target. There are several reasons behind this. First, it is complicated to integrate a simple climate model into an energy-system model and using radiative forcing instead of temperature is much less complicated. Due to the strong relationship between radiative forcing and temperature, this introduces only a modest uncertainty. Second, many models cannot meet aggressive climate targets without initially crossing the target and later returning to below the target (with CO_2 removal). This is often called an 'overshoot': a scenario may cross 1.5°C in 2030, reach 1.7°C in 2050, and return to below 1.5°C in 2100. To allow temperature overshoot, the target is set in 2100 and not over the entire 21st century (or all time). Third, an end-of-century target is easy to implement in many models, using an exponentially rising global carbon price in models with perfect foresight (known as Hotelling's Rule). While an end-of-century target is easy to implement, it leads to a carbon price development unlikely to be met in practice. These modelling choices are not without implications for how CCS is deployed in models, and therefore perceptions of how CCS needs to be deployed in reality.

The use of an end-of-century target is an important consideration and has a historical context. Most models (around 2007) could not generate 2°C consistent emission scenarios[17] until they began to implement bioenergy with carbon capture and storage (BECCS), a CO_2 removal technology[18]. Many of these scenarios had to first 'overshoot' the target, before returning to it[17], and that required relaxing the constraint to avoid the target over the entire century. Now, nearly all models can produce 2°C consistent scenarios, and as models have improved, some can now also produce 1.5°C and 2°C consistent scenarios without BECCS or CCS at all (discussed later). With model improvements, and a new climate target, scenarios have now been developed in many models that are consistent with 1.5°C of global warming[19]. However, the end-of-century target was still necessary to meet these stringent targets. Given model improvements in the last 10 years, and the introduction of new CO_2 removal technologies in the models, it may now be possible to use a target over the entire 21st century and not just a target in 2100.

An additional complexity is the use of different terminology for Paris-compliant scenarios. Since models usually use a radiative forcing level, there needs to be a mapping from radiative forcing to temperature. Since IPCC AR5, a radiative forcing level of 2.6W/m^2 in 2100 has been used as consistent with a 66% chance to stay below 2°C global warming in 2100. The probability (66%) captures uncertainties in the climate response, such as the equilibrium climate sensitivity and similar parameters. A radiative forcing of 1.9W/m^2 is consistent with a 66% chance to stay below 1.5°C of global warming in 2100. Since these definitions apply the climate target in 2100, the radiative forcing and temperature may exceed the 2100 target between today and 2100. It only matters that the target is met in 2100.

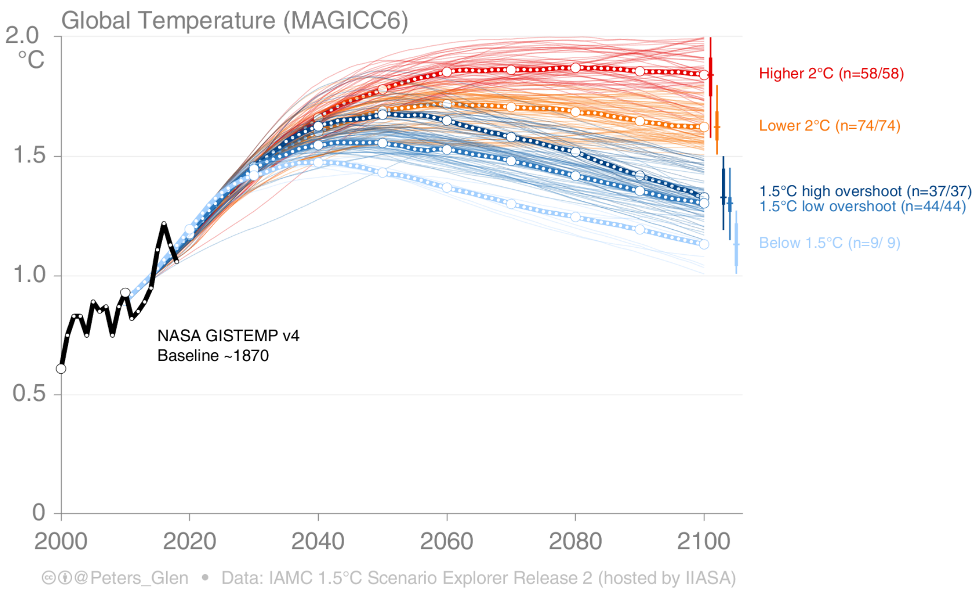

Figure 3: The temperature response to the labelled scenarios from the IPCC Special Report on Global Warming of 1.5°C scenario database[20,21].

Figure 3 shows the temperature response in 1.5°C and 2°C scenarios in the IPCC Special Report on Global Warming of 1.5°C (SR15). The temperature overshoot can clearly be seen (and is more pronounced in radiative forcing). Because of the different levels of overshoot IPCC SR15 used a variety of different classifications, indicated in the figure:

- Below 1.5°C: 50-66% chance below 1.5°C over the 21st century
- 1.5°C low overshoot: 50% chance below 1.5°C in 2100, peak generally below 1.6°C
- 1.5°C high overshoot: 50% chance below 1.5°C in 2100, peak generally over 1.6°C
- Lower 2°C: 66% chance below 2°C over the 21st century
- Higher 2°C: 50-66% chance below 2°C over the 21st century

The '1.5°C high overshoot' scenarios were removed from the analysis in the IPCC SR15 Summary for Policy Makers, as the consensus view was that the potential land impacts of those scenarios may make them an unattractive pathway for society to follow. In terms of CCS, the '1.5°C high overshoot' scenarios are not so different to the other scenarios and are therefore included in this report. The 'Lower 2°C' and 'Above 2°C' scenarios are selected on the basis of the temperature over the entire 21st century, but most of these scenarios were generated using an end-of-century target and can therefore exhibit high overshoot.

Linking to these definitions, Figure 3 shows the large variation between the different temperature definitions. The 'Below 1.5°C' scenarios always remain below 1.5°C, while the '1.5°C low overshoot' and '1.5°C high overshoot' scenarios temporary cross 1.5°C to varying degrees. All of the 1.5°C scenarios have declining temperatures after a peak temperature (which occurs around 2050), as the scenarios were generally implemented with a 2100 target. The 'Lower 2°C' (66%) and 'Higher 2°C' (50%) scenarios exhibit similar overshoot characteristics, but to a smaller degree. It becomes quite clear that both sets of the 2°C scenarios are well within the range of 1.5°C to 2°C set out by the Paris agreement, while the 1.5°C scenarios arguably sit at the more aggressive end of the Paris range.

The shape of the temperature profiles is important, as it effects the amount of CO_2 removal in each scenario and hence the deployment of CCS. And the shape of the temperature profile is a consequence of the way the Paris climate goals are implemented in cost-optimising models. Most alternative implementations of the Paris climate goals lead to greater short-term emission reductions and less CO_2 removal[22], but this may not overly effect the level of CCS. The Paris climate goals are ambitious, and a different implementation in a model may change how the goals are met, but not necessarily make it any easier to meet those goals. While these are largely technical points, they have important implications for the deployment of CCS in models and are an ongoing area of research.

3.2 The greenhouse gas balance

The Paris Agreement Article 4 also plots out what a scenario consistent with Article 2 looks like:

> *In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty.*

This 'balance' text can be interpreted in different ways[23], but assuming the terms are used consistently as elsewhere in climate negotiations, then Article 4 indicates that GHGs should become at least zero between 2050 and 2100. Not all scenarios that meet the 'well below 2°C' criteria (Article 2) meet the balance criteria (Article 4), as GHG emissions are still positive in 2100. Recent analysis suggests the balance criteria is unnecessary strong due to the behaviour of non-CO_2 emissions[7]. While CO_2 emissions are cumulative and must go to zero, non-CO_2 emissions are not cumulative and when they are reduced the induced warming is also reduced. Thus, it is possible to meet the 'well below 2°C' criteria with positive GHG emissions in 2100 if CO_2 emissions are zero and non-CO_2 emissions are declining sufficiently fast. Figure 4 shows that most scenarios consistent with 'well below 2°C' do reach net-zero CO_2 emissions by 2100 and this is consistent with the literature[7]. Most 'well below 2°C' scenarios reach the balance in GHG emissions about 10 to 20 years after they reach net-zero CO_2 emissions (not shown).

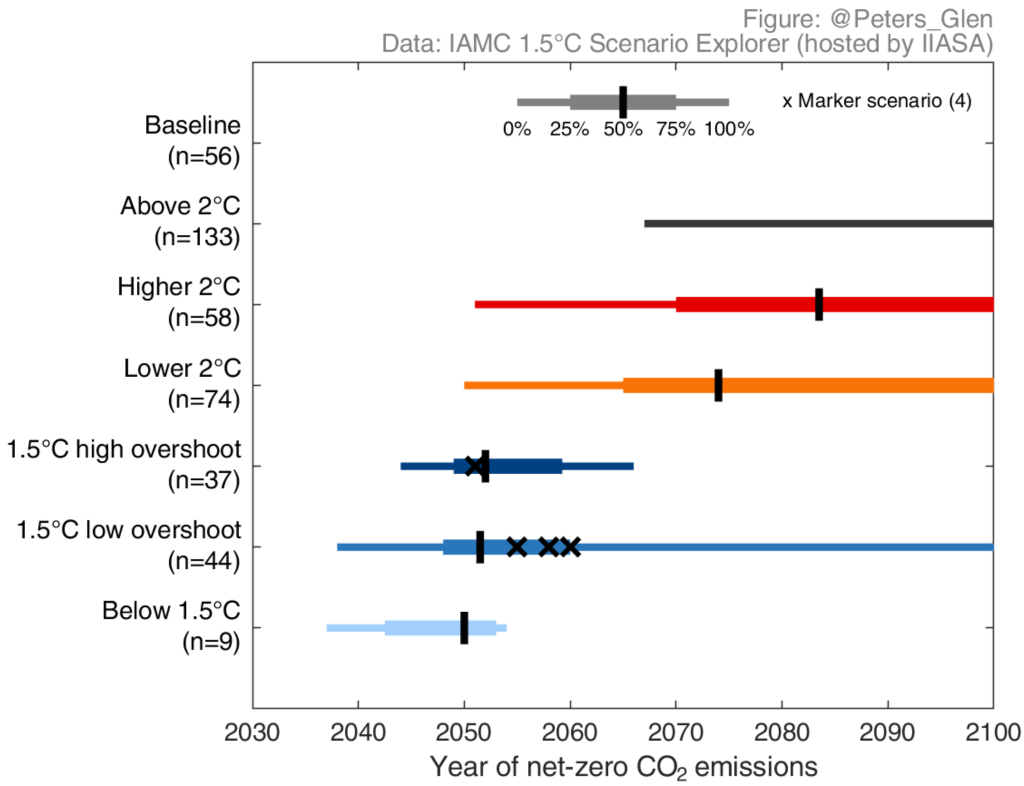

Figure 4: A histogram showing when different scenarios reach net-zero CO_2 emissions, indicating that most 1.5°C and almost all 2°C scenarios require net-zero CO_2 emissions. The same does not hold for GHG emissions (figure not shown) and these scenarios reach net-zero GHG emissions about 10-20 years later.

3.3 Raising ambition

Another important aspect of the Paris Agreement, colloquially known as the ‘ratchet mechanism’, is the process by which countries raise their ambition over time to eventually have policies collectively with other countries to be in line with ‘well below 2°C’. Essentially, the Paris Agreement acknowledges that the level of ambition will not immediately be consistent with ‘well below 2°C’. To address this, countries must submit new emission pledges every five years (starting in 2020), and the pledges are required to represent a progression over the last pledge. Every five years, starting in 2023, there is a ‘Global Stocktake’ to assess collective progress on mitigation, adaptation, and finance. The Global Stocktake should then inform the next round of emission pledges, until they are eventually consistent with ‘well below 2°C’.

The process to raise ambition is likely to have consequences for CCS deployment. A long-term mitigation scenario using a cost-optimising model will determine the optimal technology mix to meet the ‘well below 2°C’ criteria, and that leads to deployment of CCS. A consequence of the model implementation is a sufficiently high carbon price, often globally harmonised across sectors and regions, that would lead to the necessary CCS deployment. In contrast, if countries do not have enough mitigation ambition on the five-yearly cycle, the carbon price might remain too low to stimulate the necessary CCS deployment. Thus, the practical implementation of the Paris Agreement might act as a disincentive for CCS deployment. Because of this, it is likely that alternative policy instruments would be required to stimulate the uptake of CCS, as with other new or emerging technologies.

4 Carbon Capture and Storage in Paris Compliant Scenarios

There are a range of organisations that develop Paris compliant scenarios – the research community that contributes to IPCC assessments, intergovernmental agencies like the IEA, and energy companies like Equinor, Shell, and Statkraft – and many of these scenarios are developed with different purposes in mind. The research community has done a more systematic analysis of Paris compliant scenarios, and therefore have generated the most scenarios and explored various uncertainties and sensitivities. In this section, the implications for CCS are discussed for scenarios developed primarily by the research community, though connections are made to other scenarios where necessary. CCS is deployed at scale across a wide range of scenarios using different models with different socioeconomic and technology assumptions. Scenarios that do not include CCS have higher costs and more challenges for the same climate target. Overall, the scenario literature makes a strong case for supporting the development and deployment of CCS.

4.1 CCS in different scenarios

The research community have been developing long-term emission scenarios to study climate mitigation for decades[24,25]. These scenarios are periodically assessed by the IPCC, and these scenarios are often housed in a database hosted by the research organisation IIASA. The IPCC AR5 assessed about 1200 scenarios. Since then, the research community has developed a set of harmonised scenarios called the Shared Socioeconomic Pathways (SSPs). Those and additional scenarios were assessed in IPCC SR15. These scenario databases have also included scenarios from the IEA and some energy companies like Shell. However, there has not been a systematic assessment of scenarios developed outside of the research community, such as those by energy companies.

4.1.1 Shared Socioeconomic Pathways (SSPs)

The Shared Socioeconomic Pathways (SSPs) are a set of scenarios that start with qualitative narratives[26] and continue to quantification[27]. These will form the foundation for the next round of climate modelling[28]. The SSP narratives represent five hypothetical worlds characterized by different challenges to mitigation and adaptation, labelled as:

- SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)
- SSP2 Middle of the Road (Medium challenges to mitigation and adaptation)
- SSP3 Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)
- SSP4 Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)
- SSP5 Fossil-fuelled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

The SSPs are quantified using six different Integrated Assessment Models (IAMs). The SSPs are implemented in different models to harmonise key socioeconomic assumptions. Each model is then run for each SSPs in a baseline configuration (without climate policy), and then run again with different levels of carbon pricing (climate policy) to reach different radiative forcing (temperature) levels in 2100 producing what is known as the SSP/RCP matrix (Figure 5). The quantified SSPs[27] supplemented with 1.5°C scenarios[19] span scenarios with warming ranging from 1.5°C to 5°C in 2100, and offer a powerful way to show the key links between socioeconomics and climate, albeit only with a limited set of six models. The SSP/RCP matrix (Figure 5) shows that not all socioeconomics and models can reach the highest forcing levels (8.5W/m^2), and some socioeconomics and models cannot reach low forcing levels consistent with 'well below 2°C' (1.9-2.6W/m^2).

While the SSPs are a complex framework to understand, only a few key messages are relevant for this report. First, the SSPs are a way to ensure models have a consistent set of socioeconomic assumptions. Second, each model is only run at most once for each SSP/RCP combination (though not all models tried all combinations) and this greatly reduces model sample bias. Third, each model is run in its default configuration for each SSPs, without constraints on available technologies. This overall greatly increases comparability. The remainder of this subsection will detail some of the key results of the SSPs specifically in relation to CCS, and only draw on the complexity and richness of the SSP framework when necessary.

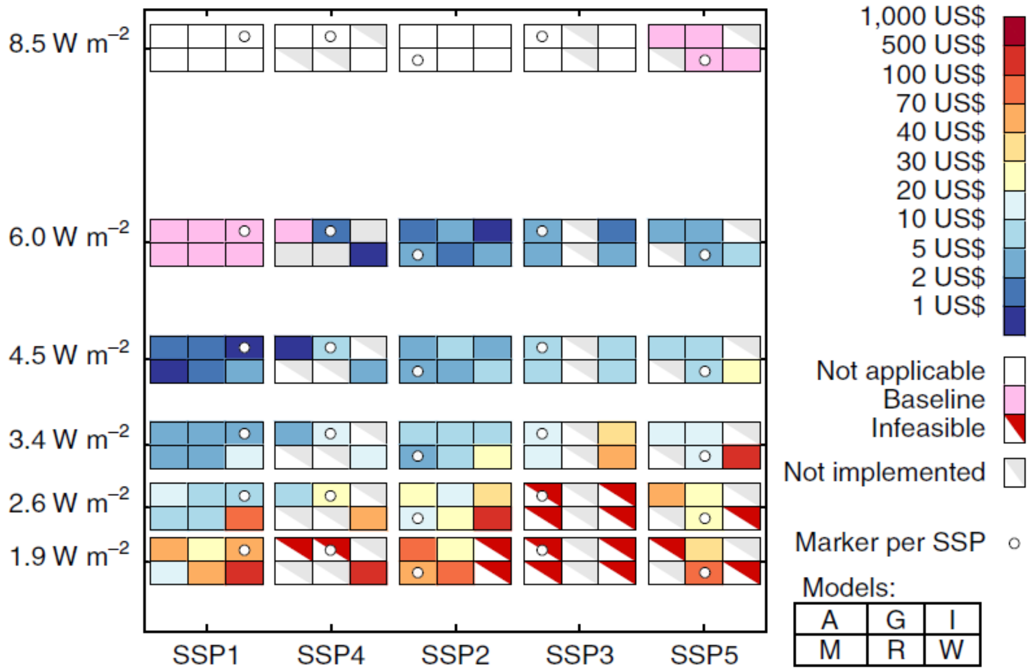

Figure 5: The five SSPs (columns) are linked to radiative forcing levels known as Representative Concentration Pathways (RCPs, rows) to make the SSP/RCP matrix. A set of six models explored this SSP/RCP matrix, to show that only particular SSP/RCP combinations can be solved with different models (boxes) and different combinations leads to different carbon prices (colours). For example, only SSP5 reach the highest radiative forcing level (RCP8.5), while only some models and SSPs are consistent with RCP1.9 and RCP2.6 (1.5°C and 2°C). Figure from Rogelj, et al. [29].

4.1.1.1 CCS at the global level

Figure 6 shows the deployment of CCS in the SSPs for different forcing levels. The colours represent different forcing levels, while the highlighted scenarios are known as 'markers' to represent the general characteristics of each scenario and to be used in more detailed analysis with climate models[28]. It is necessary to highlight two points:

1. The scale of CCS is significant
2. CCS is used at scale for almost all forcing (temperature) levels

The scale of CCS is significant. The quantified SSPs deploy up to 40GtCO_2/yr in 2100, which is comparable to the total emissions of CO_2 into the atmosphere today from all sources (~43GtCO_2/yr). It is necessary to put the scale of the CCS into perspective. The storage facility at Sleipner in Norway stores around 1MtCO_2/yr, and this also represents a decent average size of a capture facility[1] (a coal power plant may be 3MtCO_2/yr, while an industrial site may be 500ktCO_2/yr). If a 1MtCO_2/yr CCS facility is built every week, until 2050, then CCS in 2050 would be around 1GtCO_2/yr (1,000 facilities). If a 1MtCO_2/yr CCS facility is built every day, until 2050, then CCS in 2050 would be around 7GtCO_2/yr (7,000 facilities). Figure 6 shows that some scenarios are using up to 30GtCO_2/yr in 2050, with the median around 4GtCO_2/yr across all scenarios including those that exceed 2°C of warming in 2100. The median in 2050 for forcing levels of 1.9W/m^2 and 2.6W/m^2 (1.5°C and 2°C) is around 10GtCO_2/yr, or 10,000 1MtCO_2/yr built at a rate of 10 CCS facilities per week.

Almost all temperature levels use CCS at scale. Some of the scenarios with the highest CCS levels are not aggressive mitigation scenarios. For example, scenarios with forcing levels of 4.5W/m^2 (about 2.5°C in 2100) have a median CCS of 4GtCO_2/yr in 2050, requiring a build rate of about one new CCS facility every other day until 2050. The only scenarios without CCS are baseline scenarios that consider no climate policy. Essentially, as soon as a carbon price is applied to the model, CCS is deployed. This relates to relative costs, discount rates, and experimental design[30]. A cost optimisation model to 2100, with a discount rate of 5% per year, would find the cost of CCS negligible. Another factor, explored below, is that the deployment of CCS is somewhat dependent on the need for CO_2 removal, with a large share coming from BECCS.

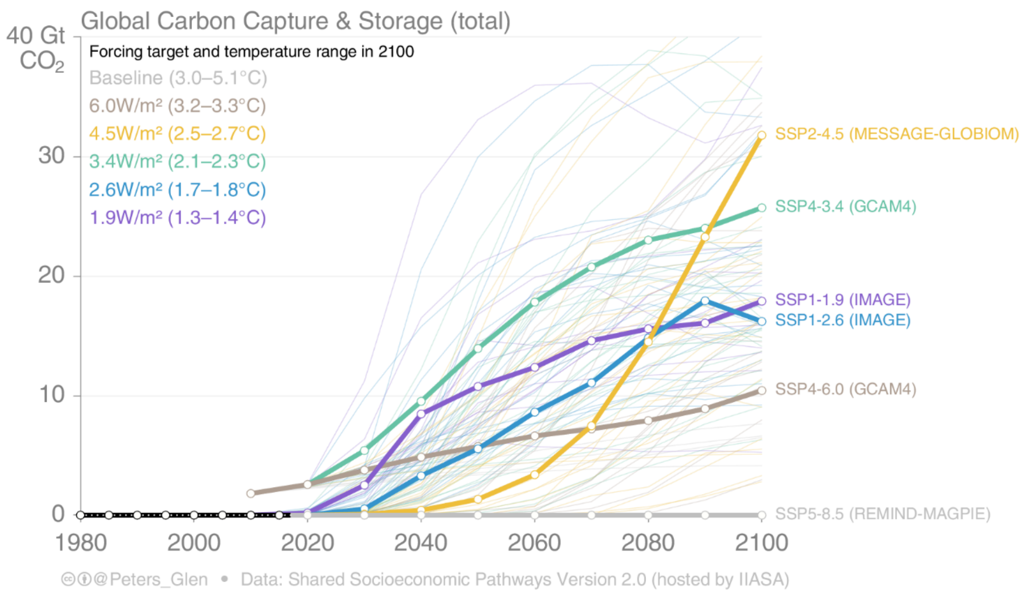

Figure 6: Carbon Capture and Storage in the quantified SSPs for different temperature levels (colours), with the "marker" scenarios shown in bold.

It is also worth noting, though with less prominence, that the level of CCS varies depending on the SSP (socioeconomics) and model. The model variations will be touched on below. The SSP variation stems from the fact that some SSPs depend more on fossil fuels (e.g., SSP5), requiring CCS in mitigation, while others have socioeconomics favouring sustainability and less fossil fuel usage (e.g., SSP1). While it is of academic interest to pursue the variation of CCS deployment across models and SSPs, and other factors affecting deployment, earlier work suggest this would require rerunning the models in a way that facilitates comparison[30].

4.1.1.2 CCS on fossil fuels and bioenergy

Figure 7 shows the CCS deployment in 1.5°C scenarios (RCP1.9) for a selection of SSPs and models. This figure serves several purposes. First, the figure shows clearly that the level of CCS varies by model and SSP. SSP1 (left side) generally has lower CCS as it is a sustainable development scenario, while SSP5 (right side) generally has higher CCS as it is a fossil fuel intensive scenario requiring more CCS for mitigation. The scenarios also show that even in a high-fossil fuel world, aggressive mitigation targets can be reached with appropriate levels of CCS. Second, the level of CCS varies by model. The figure shows four models, two for SSP1 (left side) and two for SSP5 (right side). The different models use different levels of CCS, even for the same socioeconomics (SSP1 or SSP5). And third, different models and SSPs use a different mix of CCS on fossil fuels and bioenergy.

The scenarios clearly demonstrate that CCS is relevant for both fossil fuels and bioenergy, but with different drivers. On the fossil fuels (green), most scenarios show an initial deployment of CCS and later decline. Essentially, in the early years, new power plants will include CCS or old ones will be retrofitted, but in the longer term, there is a shift away from fossil fuels to non-fossil energy sources and therefore the need for CCS on fossil fuels declines. In contrast, the scenarios show a growing importance of CCS on bioenergy (BECCS). Since the bioenergy is assumed to be carbon neutral, or associated emission reported elsewhere, CCS applied to bioenergy removes CO_2 from the atmosphere. The use of BECCS for CO_2 removal is a key driver for CCS in scenarios.

BECCS plays an interesting role in scenarios, and may be both needed[9] and a distraction[31]. As shown in Figure 2, scenarios depend on CO_2 removal to offset residual positive emissions and to lower temperatures after initially overshooting. As discussed earlier, this is partly a scenario design question[22], but also depends on the discount rate[32]. A cost optimising model with a positive discount rate will find that the cost of BECCS is close to zero in the future, but the rising carbon price to reach the aggressive climate target leads to a large ‘profit’ for CO_2 removal which essentially collects the revenue from the carbon price[33]. In short, towards the end of the century, a model objective function will see BECCS as having near zero cost but generate large income from carbon price revenue. Models also use afforestation, but BECCS is generally more effective at removing CO_2 per unit area[11].

While the deployment of large-scale CCS and BECCS in scenarios may be debated from many different angles[31], its deployment does give several important indications. Less CO_2 removal or CCS translates into greater short-term mitigation. A lower discount rate clearly shows this, as it pushes mitigation to earlier time periods and higher carbon prices[32]. Models that don’t use CCS have higher costs (to be discussed later), if they can even reach a climate target without CCS[34]. Overall, very few scenarios can reach 1.5°C or 2°C in the absence of CCS. One interpretation of the deployment of CCS and BECCS in most scenarios is that it indicates how immense the mitigation challenge is and shows that CCS fills a niche that no other technology can cost-effectively replace.

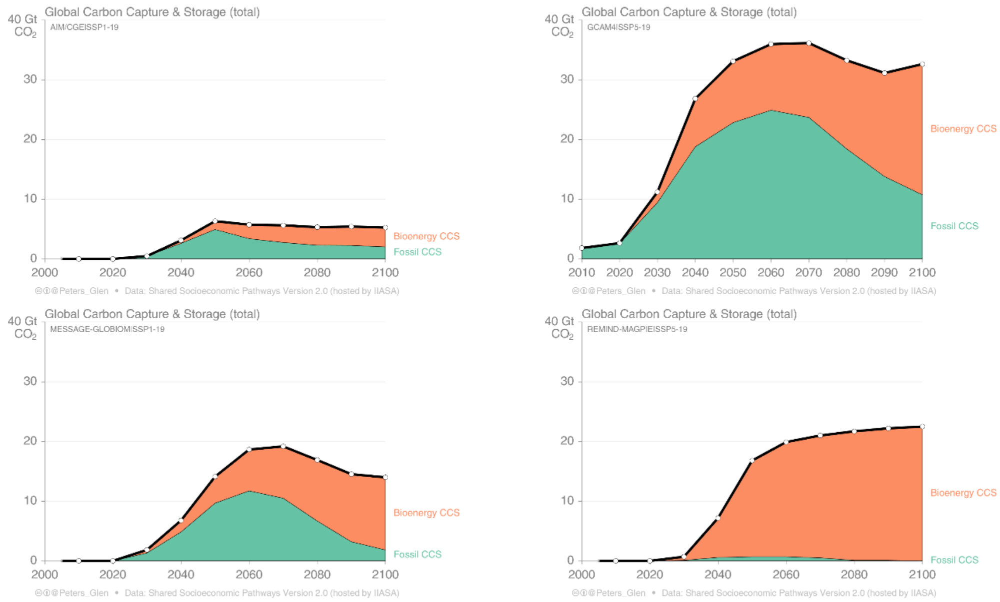

Figure 7: The variation of deployment of CCS on bioenergy and fossil fuels in selected 1.5°C scenarios, showing variation across SSP and model, and with all figures with the same vertical axis to highlight the variations

4.1.1.3 Regional variations

Figure 8 shows the regional variation across selected SSPs and models, indicating how the relative role of CCS may change between regions. Overall, in most cases, OECD and Asia dominate the deployment of CCS, though the relative share and deployment profile can vary. The high share in OECD and Asia reflects the large share of emissions. However, CCS deployment can be significant in other regions, depending on the model and socioeconomics. The WITCH model has a much larger deployment of CCS in Latin America, similar in size to Asia and larger than OECD, while REMIND has a large deployment in the Middle East and Africa. Both are likely related to the use of BECCS.

In the quantified SSPs, the deployment of CCS in the OECD has a median of 3.5GtCO_2/yr in 2050 for 1.5°C scenarios and 2.5GtCO_2/yr in 2050 for 2°C scenarios. While these models do not separate out Europe individually, a realistic expectation could be that a cost-effective Paris compliant scenarios would use around 1GtCO_2/yr CCS in 2050, consistent with an earlier study[35]. This could represent around 1,000 CCS facilities across Europe, with a build rate of around one per week. The cumulative storage potential in Europe to meet this deployment of CCS would be 7.5GtCO_2 by 2050 and 50GtCO_2 by 2100[35].

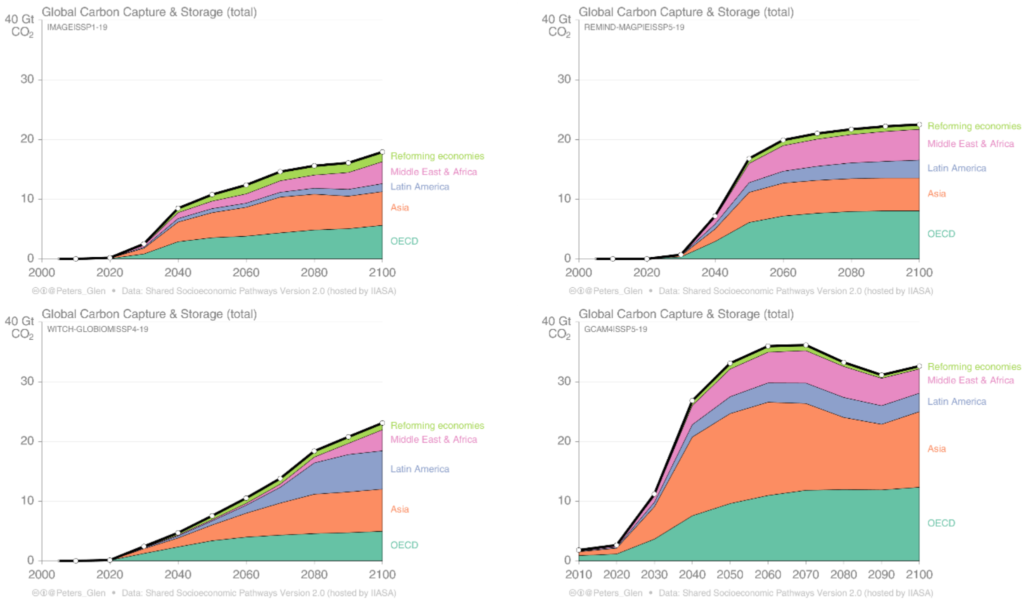

Figure 8: The regional variation in CCS deployment across different SSPs and different models, all figures with the same vertical axis to highlight the variations.

4.1.2 The IPCC Special Report on Global Warming of 1.5°C (SR15) scenarios

The IPCC SR15 is the most recent assessment of scenarios consistent with 1.5°C and 2°C of global warming. The SR15 scenario database[20] includes the SSPs from the previous section and additional scenarios from the same and other modelling groups. One disadvantage of the SR15 scenarios, in comparison to the SSPs, is that the number of scenarios submitted from different modelling groups was not controlled. The model groups using REMIND and AIM submitted around 90 scenarios each, of the 600 in total, while the IEA submitted only two. Thus, when presenting scenario ensembles, the scenario sample is biased by the frequency of different modelling frameworks, and care needs to be taken when interpreting the ensemble. A key advantage of the SR15 scenario database is that many modelling groups ran sensitivity analyses. The reason REMIND and AIM are overrepresented, is that those modelling groups performed various sensitivity studies. There are also scenarios with no CCS, to be discussed later.

4.1.2.1 CCS at the global level

Figure 9 shows the deployment of CCS in the 1.5°C and 2°C scenarios in the IPCC SR15 database. Additional scenarios cover the range above 2°C, including baseline scenarios, but these are not shown. The results are similar to the quantified SSPs (Figure 6): CCS is used at scale and needed at all temperature levels. The deployment of CCS does not vary significantly between different temperature outcomes. Table 1 shows the deployment of CCS in 2050 across the different climate categories shown in Figure 9. Here it can be clearly seen that different climate categories have different numbers of scenarios, so care needs to be taken in comparing the statistics across categories, but there is very little difference between CCS in different categories. A part of the reason for this is that in 2°C scenarios, models are already deploying as much CCS as feasible, so there is little additional CCS available for deployment when the temperature limit is lowered to 1.5°C.

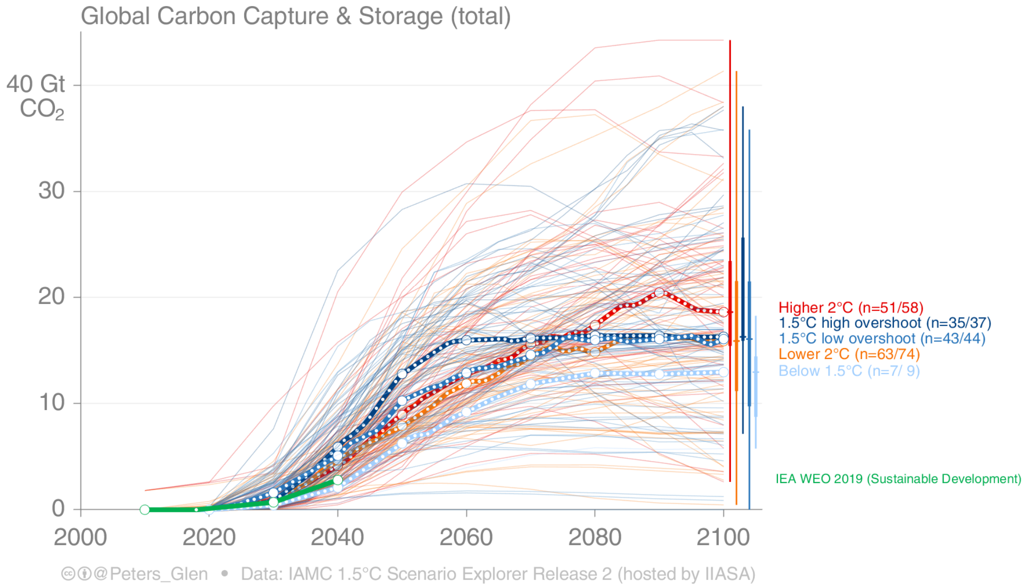

Figure 9: The deployment of CCS in scenarios consistent with 1.5°C and 2°C global warming assessed in the IPCC SR15 assessment. The figure includes the IEA World Energy Outlook (2019) Sustainable Development Scenario (SDS), which is not in the IPCC SR15 assessment but is an important reference point.

Table 2 gives an alternative view of the statistical distribution, showing how CCS varies across models. In comparison with Table 1, there is a lot more variation across models than across temperature outcomes. Some models have many more scenarios and thus appear more frequently in the statistical distribution (e.g., REMIND), which will tend to downplay the scenarios that appear less frequently (e.g., IEA). There is only one model that does not include CCS as a technology option (C-ROADS). These results show that modelling assumptions and modelling frameworks are perhaps more important for the deployment of CCS, then the temperature targets.

Table 1: The statistics of CCS deployment (in $GtCO_2$) in Paris-compliant scenarios in 2050, showing the percentiles across scenario categories. The 50-percentile is the same as the median.

		Percentiles				
	Scenario count	0	25	50	75	100
Higher 2°C	58	0	5	8	11	30
Lower 2°C	74	0	6	8	12	25
1.5°C high overshoot	37	0	10	13	15	28
1.5°C low overshoot	44	0	7	10	15	19
Below 1.5°C	9	0	2	6	7	12

It is worth picking out a few different scenarios from non-research organisations. The Shell Sky scenario is consistent with about 2°C of warming in 2100. The IPCC SR15 scenario database does not report the CCS from the Shell Sky scenario, but in 2050 Shell Sky has about $5GtCO_2$/yr CCS, which is high but on the low side of most other scenarios assessed in IPCC SR15. The IEA submitted two scenarios to the IPCC SR15 scenario database: the 'Below 2°C Scenario' (B2DS) from the Energy Technology Perspective (2017) and the 'Faster Transition Scenario' (FTS) from the World Energy Outlook (2017). The B2DS did not submit sufficient data for a climate assessment, while the FTS is consistent with 'Higher 2°C' (50% chance below 2°C). The scenarios deploy 8$GtCO_2$/yr and 5$GtCO_2$/yr respectively in 2050. The latest IEA World Energy Outlook[36] (2019) is not in the IPCC SR15 scenario database but is likely consistent with 'Lower 2°C' and has 2.8$GtCO_2$/yr CCS in 2040, the last year the scenario data is reported. This is at the low end of the scenarios. In general, scenarios produced from industry and the IEA are far more conservative in the deployment of CCS than research organisations.

Table 2: The statistics of CCS deployment (in $GtCO_2$) in Paris-compliant scenarios in 2050, showing the percentiles across models. The 50-percentile is the same as the median.

		Percentiles				
	Scenarios count	0	25	50	75	100
AIM/CGE	41	0	0	7	13	18
C-ROADS	5	0	0	0	0	0
GCAM	7	5	8	17	26	30
IEA	1			5		
IMAGE	26	4	8	10	13	19
MERGE	2	9	9	10	10	10
MESSAGE	36	0	11	14	16	25
POLES	28	1	4	6	10	19
REMIND	62	2	7	8	10	17
WITCH	14	6	7	7	8	10

A handful of scenarios, however, include no CCS at all. These will be discussed in a separate section.

4.1.2.2 CCS applied to the industry sector

A particularly relevant question is the level of CCS applied to the industrial sector. Unfortunately, many scenarios do not report this separately, and this is not reported at all in the SSP database. Figure 10 shows the scenarios applying CCS to the industrial sector in the IPCC SR15 scenario database, with only 12 of the 222 scenarios reporting industrial CCS separately, from three different models. While the CCS deployment seems relatively low, up to 3$GtCO_2$/yr, in comparison to the total CCS deployed (Figure 9), the level would still require 1-2 industrial CCS facilities to be built a week of the 1$MtCO_2$/yr size. Given industrial CCS facilities are likely to be smaller, this small sample of scenarios indicate a high level of CCS in the industrial sector. The IEA World Energy Outlook[36] (2019) uses 2.8$GtCO_2$/yr in 2040, which it states is equally split between the power sector and industry.

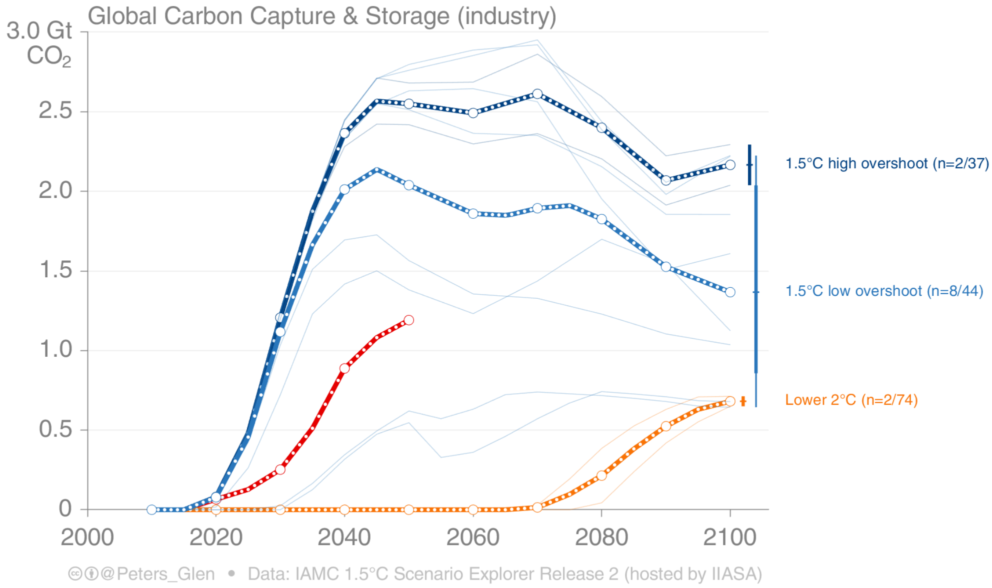

Figure 10: The scenarios that report CCS in the industrial sector in the IPCC SR15 scenario database. Only three models report this information: IMAGE is the top 6 scenarios, AIM is the bottom 4 scenarios, and the scenario ending in 2050 is from the IEA.

4.2 Paris compliant scenarios without CCS

Models can be run with different assumptions regarding technology availability. In a default case, the model will allow all technologies to be used. A sensitivity case can be run, where different technologies are removed from the model to see how costs may vary without the technology. A model could be run with and without nuclear power generation (for example), to determine if nuclear plays an important role in mitigation. These technology sensitivity analyses have been done across a range of technologies, such as nuclear, renewables, energy efficiency, bioenergy, and CCS. This section will focus on CCS.

Nearly all models analysed in the IPCC SR15 include CCS. When a model includes CCS, the technology is always deployed at some scale (we are not aware of scenarios that allow CCS but do not deploy it at all). The underlying reason why CCS is deployed at scale varies[30], but does not directly or unambiguously relate to technology costs, model structure, etc. Thus, to assess the importance of CCS to a given scenario, it is necessary to remove CCS from the model, or limit its use by a hard limit on its deployment. The quantified SSPs all allow CCS to be deployed, but there are a few scenarios in IPCC SR15 that do not allow CCS (or restrict its use) and the IPCC AR5 assessed literature that specifically removed CCS from the models to assess its importance[37].

The IPCC SR15 scenario database includes a wider range of scenarios, including models that do not allow CCS and models that are run with technology restrictions. Out of the 185 scenarios consistent with the Paris Agreement goals, 21 do not allow CCS but 6 of those have a rising temperature in 2100 (no stabilisation) and so we only consider the remaining 15 which meet the Paris goals without using CCS. There is one scenario called Low Energy Demand[38], which had the specific intention of not using CCS and focussing on aggressive demand side mitigation measures, three scenarios are from C-ROADS[39] which did not include CCS as a technology option, and the remaining 11 from AIM/CGE[40] which ran specific scenarios limiting the use of CCS. Only AIM/CGE is set up in a way such that comparisons can be made between CCS and no CCS pathways. This comparison will be done with a different set of scenarios, from the IPCC AR5 (see below).

Figure 11 shows a comparison of scenarios with CCS and scenarios without CCS assessed in IPCC SR15. Scenarios without CCS generally have more rapid short-term reductions in energy demand and CO_2 emissions. The Low Energy Demand scenario has the lowest energy demand out of all scenarios, which was the idea behind the analysis: to see how far radical reductions in energy demand could feasibly go. C-ROADS is the only modelling framework that completely decarbonises the energy system leading to zero CO_2 emissions, while AIM has relatively high residual emissions after 2050. All the scenarios without CCS have CO_2 removal through afforestation. While it is possible to reach 1.5°C or 2°C without CCS, the challenges are higher.

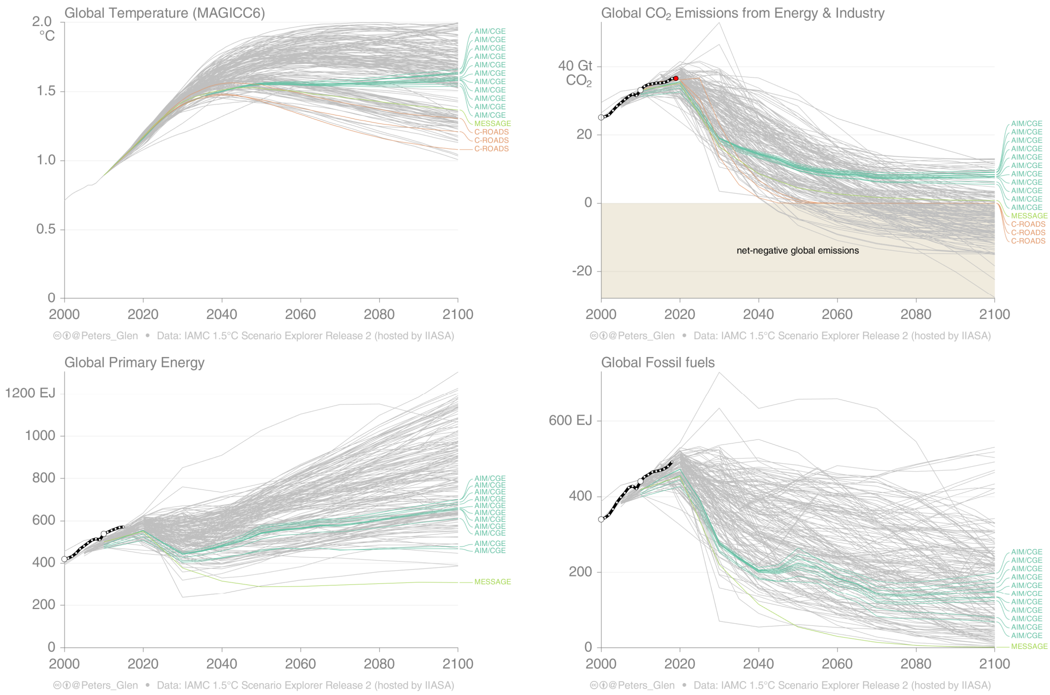

Figure 11: A comparison of 1.5°C and 2°C scenarios with CCS (in grey) and without CCS (in colours) assessed in IPCC SR15. Most of these scenarios come from AIM (green) with three from C-ROADS (orange), and one Low Energy Demand from MESSAGE (light green). Note that C-ROADS did not report primary energy demand.

Another aspect of scenarios without CCS is how they change the costs of mitigation. One study compared the change in costs of mitigation when technologies were removed or restricted from a model (EMF27[37]). This study was assessed in IPCC AR5 and found that for a 2°C scenario, out of 10 models that could keep warming below 2°C in a default setting, only four could get to 2°C if CCS was not allowed. In the latter scenarios, mitigation costs more than doubled. Figure 12 shows the *change* in the energy mix in the four model runs that specifically exclude CCS, together with the cost increases relative to the default case. Overall, all the models show a short-term decrease in energy use and a long-term increase in energy use when CCS is excluded from the model. The energy source with the largest increase is bioenergy, in a need to generate carbon neutral fuels. Non-fossil energy sources increase, and the models used for this analysis either increase solar or nuclear (other models might increase other energy sources). Coal, oil, and gas decline more quickly when CCS is excluded from the models. Any residual emissions need to be offset by CO_2 removal from afforestation as BECCS is not available.

The removal of CCS from the models shows that fossil fuel use decreases, while non-fossil sources increase. Essentially, CCS allows the continued use of fossil fuels. Similar outcomes occur whenever any technology is removed from a model, another energy source must replace it, which demonstrates why mitigation costs are lower if all technologies are available. Models that don’t deploy or restrict the use of CCS have higher mitigation costs, if they can even reach the climate target without the use of CCS. Restricting the deployment of CCS removes flexibility from a model and makes mitigation harder and more costly, which is a key reason that the scientific literature finds that it is important to keep a broad range of technologies available. It is worth noting that this study is from 2014, and the models were run some years earlier than that, suggesting the models may now find it harder to reach 2°C without CCS or have different energy mixes dependent on changing technology costs. The study has not been repeated with the latest generation of scenarios.

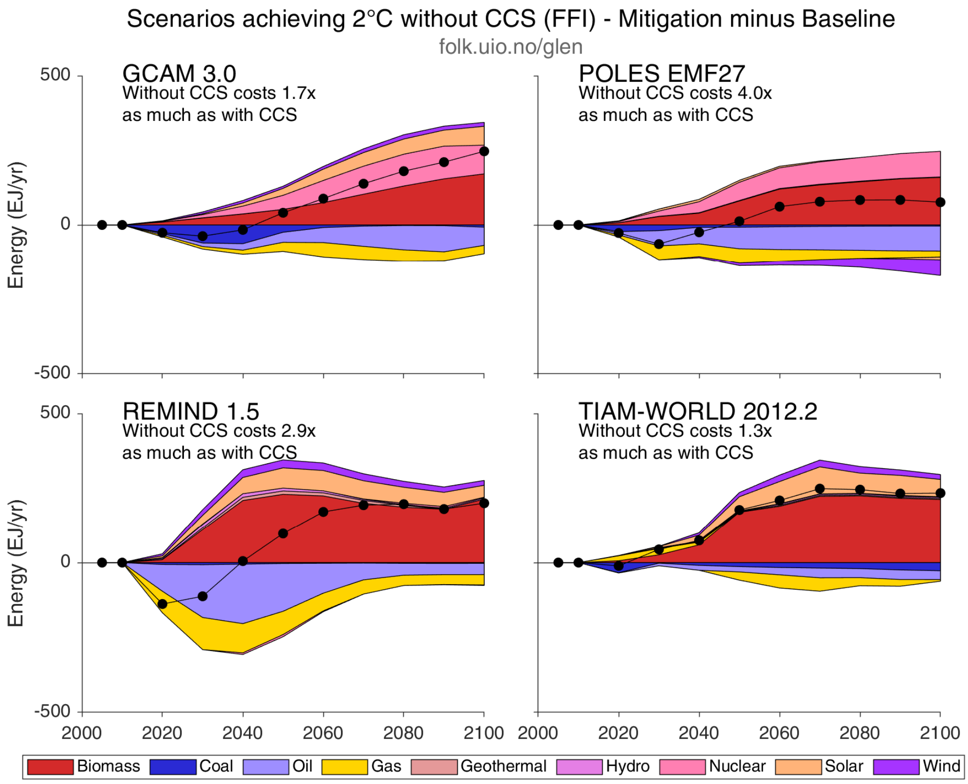

Figure 12: The change in the energy mix in four models that could get to 2°C without CCS, showing also the cost increases relative to the default technology assumption (in text). The figure shows the difference between the mitigation scenario without CCS and the scenario with the default technology assumption with CCS. Positive values show the energy sources that increase in the scenarios without CCS, and the negative values show energy sources that decrease in the scenarios without CCS.

Another way to show how CCS affects the energy system is to look at how the effective 'carbon budget' changes. Figure 13 shows different components of the carbon budget using scenarios assessed in IPCC AR5. If fossil fuels are used with CCS, or BECCS is used to remove CO_2 from the atmosphere, then the total amount of fossil fuels that can be used (in terms of the equivalent CO_2 emissions) increases. Scenarios that use CCS can use more fossil fuels than what is otherwise permitted by the carbon budget when CCS is not used. In scenarios where CCS is not used, the total amount of fossil fuels that can be used are very similar to the size of the carbon budget. In effect, the use of CCS allows the increased use of fossil fuels if the fossil CO_2 is captured and stored.

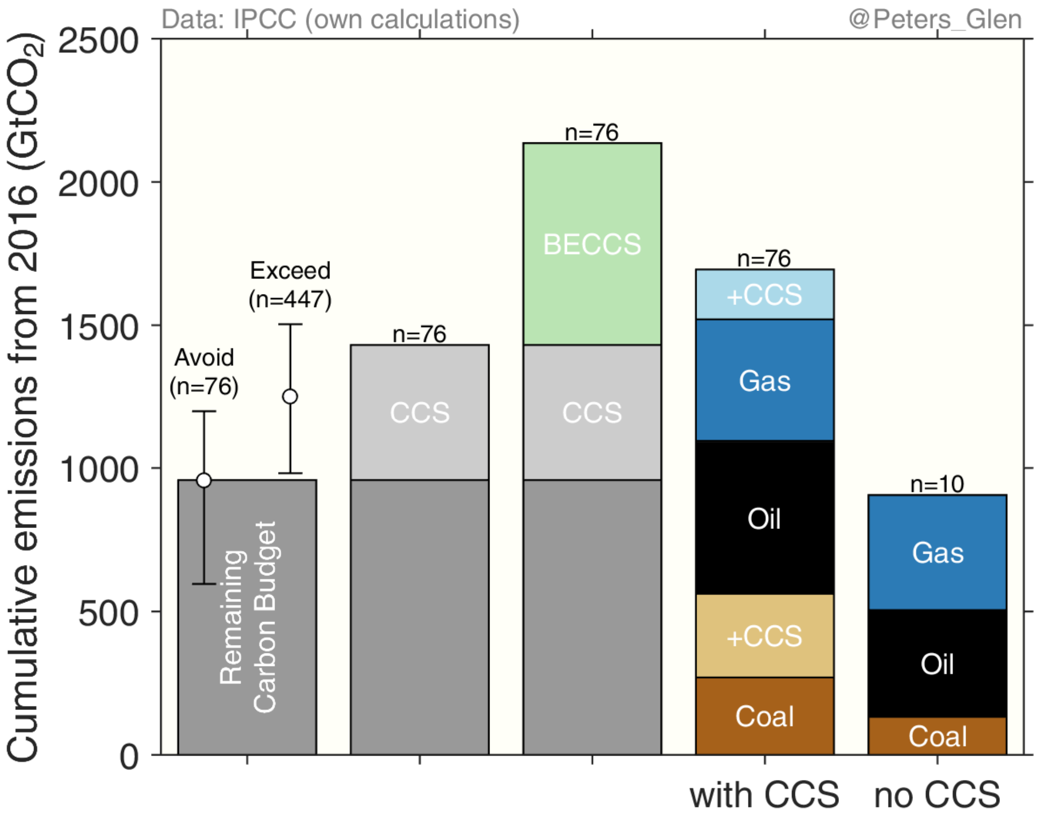

Figure 13: The carbon budget gives an indication of how much fossil fuels can be used to stay within a given target. The first column shows the carbon budget to stay below 2°C based on scenarios assessed in IPCC AR5, the whiskers represent the uncertainty range. If CCS is used either on fossil fuels or bioenergy, then the effective carbon budget (measured in terms of effective CO_2 emissions) increases. This is shown in the second and third columns. Using CCS means that the total amount of fossil fuels that can be used measured in CO_2 emissions (fourth column) is larger than the carbon budget indicates, with the gap between the maximum carbon budget (third column) representing the effect of non-CO_2 emissions. If no CCS is used, then the total CO_2 that can be emitted is similar to the carbon budget (last column).

5 Concluding remarks

CCS has been in the spotlight for over 20 years[41]. Despite early interest in the 2000's and an IPCC Special Report on CCS[42], CCS deployment has been less than expected[41]. Norway was one of the first countries with an interest in CCS and started the Sleipner CCS facility in 1996. Over the last 20 years, scenarios have increasingly stressed the importance of CCS to meet climate goals, most recently in the IPCC Special Report[21] on Global Warming of 1.5°C to meet the Paris Agreement's 'well below 2°C' goal. However, deployment of CCS has lagged far behind what is necessary[1]. It could be argued that the slow progress after initial optimism was due to a lack of coordination between major projects, which limited learning[43]. Big budgets for single projects were also a risk, more so as cheaper and smaller-scale solar and wind projects took off over the last decade. The emergence of the rapid growth in wind, solar, and natural gas displacing coal in electricity production, particularly in developed countries, has also required a shift in focus for CCS away from coal power generation and towards industry. A broader recognition of the challenges in hard-to-mitigate sectors[8] has shifted the focus of CCS to more diverse niche applications such as in industry and some forms of power generation (e.g. gas, hydrogen production, air-to-fuels). This diversity emphasises the need for greater coordination and cooperation to facilitate learning and ultimately scaling[43].

While CCS has received some criticism for potentially prolonging the life of fossil fuels, or potentially delaying mitigation action when used in combination with bioenergy for CO_2 removal[31] (negative emissions), scenarios continue to show a critical role for CCS in meeting climate stabilisation targets. CCS is deployed at scale in emissions scenarios and is used in power generation and industry, for bioenergy and fossil fuels, and across world regions. Scenarios that restrict the use of CCS show much higher costs (about double), and many cannot reach 'well below 2°C' targets without the use of CCS. Even if a case is made that scenarios rely too much on CCS, it is hard to argue against the necessity for CCS to deal with some hard-to-mitigate sectors[8]. The young age of coal infrastructure, much of which is an Asia, would need to be retired well before their commercial lifetime to meet a 1.5°C climate target[44,45]. Indeed, the IEA's World Energy Outlook[36] (2019) argues that retrofitting existing coal facilities in Asia with CCS is necessary in order to follow their Paris-compliant Sustainable Development Scenario (WEO Figure 1.12). Thus, the question is not really *whether* CCS is needed, but at what *scale* it can be deployed given political realities.

There is no one technology, or silver bullet, that can solve the climate problem. CCS is one of many silver 'buckshots' needed to meet the climate mitigation challenge. The IEA's World Energy Outlook[36] (2019) shows that CCS covers 9% of the gap in 2040 between the Stated Policies Scenario and the Paris-compliant Sustainable Development Scenario (WEO Figure 2.1). This is important. While CCS is a critical technology for mitigation, it must be deployed in parallel with other technologies. According to the IEA[36], the gap between the Stated Policies Scenario and the Sustainable Development Scenario in 2040 is covered by energy efficiency (37%), renewables (32%), fossil fuel switching such as coal to gas (8%), nuclear (3%), CCS (9%), and other technologies (12%). After 2040, and as net-zero and eventually net-negative emissions are reached around 2050 or soon after, the contribution of CCS will necessarily grow in importance. Just as climate change is a global commons problem, where all countries need to act, the same applies at the technology level, where all technologies need to play a role for a 'well below 2°C' world to become a reality. CCS is one of those key technologies, which needs to play a critical role alongside other technologies.

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