Re: Evidence session on CCUS
Net Zero, Energy and Transport Committee
The Scottish Parliament

Response provided by Professor Kevin Anderson - March 2022

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All views contained within this response are attributable solely to the author and do not necessarily reflect the conclusions of those within the wider Tyndall Centre or other affiliated institutions.

The response I provide here touches on all of the key questions asked by the Committee. However, given that responses to the later questions all depend on the answer to the first question, I have here aligned my response solely with Q1.

Q1. Whether CCUS has a role to play in helping the planet, and the UK and Scotland in particular, achieve net zero (with specific reference to Scotland's 2045 target):

HEADLINE RESPONSE: The first of "*the target-setting criteria*" in the Climate Change (Scotland) Act 2019 is to not exceed "*the fair and safe Scottish emissions budget [for] "holding of the increase in 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."* Set specifically within this context, **A) there is now little to no role for CCS in either power generation or blue hydrogen production; B) CCS/CCUS may have an important role in removing industrial *process* emissions of CO2, principally from cement production, but also from steel and potentially from some other industrial processes.**

The following more detailed response proceeds through a sequence of arguments that need to be understood prior to being in a position to judge the role of CCS/CCUS. These include:

- The conflicting targets within the Climate Change (Scotland) Act 2019
- The size of AR6-based global carbon budgets from 2022
- Downscaling from global to Scotland's "*safe and fair emissions budgets*" for 1.5-2°C
- The attendant mitigation and zero-CO2 dates for Scotland's "safe and fair" budgets
- Why this "*safe and fair*" framing is so far removed from "*net-zero 2045*"?
- How CDR is repeatedly misappropriated to extend the lifetime of fossil fuel use/production?
- What role is there for CCS/CCUS in delivering Scotland's "*safe and fair emissions budget/s*"?

A. Understanding the climate context is key to reasoned conclusions on CCUS

To be in a position to consider the role of CCS/CCUS for Scotland specifically (and for the "planet" more generally), it is absolutely key to understand what Scotland is obliged to deliver in terms of the "Climate Change (Scotland) Act 2019". [1]

A common summary of The Act is that it specifies Scotland's "net-zero emissions target year [as] 2045". [[1.A1(2)].

However, the Act also establishes, as the first of its *"target-setting criteria"* [5.2B(1)a)] *"the objective of not exceeding the fair and safe Scottish emissions budget". The Act defines this budget as "the aggregate amount of net Scottish emissions of greenhouse gases for the period 2010 to 2050 … contributing appropriately to the holding of the increase in 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."* [5.2B(2)]

What is absolutely key to note here, is that the Scottish Government had decided the 2045 net zero year prior to it having established its "*fair and safe Scottish emissions budget*" for either "*well below 2°C*" or "*pursuing … 1.5°C*". Put simply, the Act specified the conclusion (net zero 2045) before the analysis had been conducted to determine what the conclusion should be (i.e. it had not, at that time of the Act, established the "*fair and safe Scottish emissions budget*").

Whilst, in my view, setting the policy framing before undertaking the analysis stipulated in the Act risks setting a dangerous precedent, I am not taking issue with that here. Rather, what I want to stress, is that all my academic work relates to a careful assessment of responses to our headline commitments on climate change, not the subsidiary policy framework. In this regard my contribution here considers the role of CCS/CCUS in relation to Scotland's "*fair and safe Scottish emissions budget*" for "*holding global average temperature to well below 2°C and … pursuing 1.5°C*". Importantly, my ongoing and repeated analysis demonstrates that the rates and levels of mitigation for this "*fair and safe*" framing of the Act are very different from those associated with net zero by 2045. Acknowledging the choice of framework (i.e. either a fair 1.5-2°C carbon budget/s or net-zero 2045) is a prerequisite to offering informed guidance on the role of CCUS.

B. What are appropriate global budgets for 1.5°C and 2°C?

Based on the headline carbon budgets in IPCC AR6 [2], for this contribution to the Committee I use the following two carbon budget framings of 1.5 and 2°C.

For "*well below 2°C*" – the 83% chance of not exceeding 2°C.

For "*pursuing 1.5°C*" – the 50% chance of not exceeding 1.5°C.

I then update these to the start of 2022 and remove a relatively small allowance for non-energy based CO2 emission. This gives a 1.5°C energy-only carbon budget of 366GtCO2 and a 2°C value of 676GtCO2, both from the start of 2022. It Is worth noting that from the start of this year we have already emitted a further 8 billion tonnes of CO_2, that is to say in just ten weeks we have shrunk the remaining budgets by a further 8GtCO_2[1]. This context helps frame the urgency and timeline within which we need to cut emissions and against which we need to evaluate the role of CCUS

For details on the method behind this global assessment, see A Factor of Two [3] with updated numbers in a recent University of Manchester report 'Phaseout Pathways for Fossil Fuel Production within Paris-compliant carbon budgets'.[4]

C.What is Scotland's "fair and safe" carbon budget for 1.5°C and 2°C?

From the above global budgets, and again building on the method in A Factor of Two [3] and an earlier report "Quantifying the implications of the Paris Agreement: What role for Scotland", [5] a provisional assessment of Scotland's "fair and safe" carbon budget, using AR6 carbon budgets and updated to the start of 2022 suggests:

For a 50% chance of 1.5°C: 142MtCO_2 from 2022
For an 83% chance of 2°C: 288MtCO_2 from 2022

The value for 2°C is within the range I provided during an evidence session to the Scottish Climate Assembly in 2021 [6]. The value for 1.5°C is, of course, considerably less than this.

D. What is Scotland's "fair and safe" mitigation pathway for 1.5°C and 2°C?

On a territorial basis, and including emissions from international aviation and shipping, Scotland's current annual emissions of carbon dioxide are in the region of 33.5MtCO_2. At this this rate, Scotland will consume its "fair and safe" carbon budget for 2°C in under nine years and for 1.5°C in a little over four years. Another way of thinking about this is, if Scotland was to begin reducing its emissions immediately, when would it need to achieve zero emissions. A simple straight-line reduction from 33.5MtCO_2 to zero CO_2, would see Scotland reach *real* zero CO_2 for the 2°C carbon budget by around 2039; for the 1.5°C budget, this would be by 2031. Alternatively, following a pathway of constant annual reductions (to stay within the budgets), would require over 10% p.a. cuts year on year, starting from today, to remain in the 2°C budget. For the 1.5°C budget, the year on year cuts rise to over 19% p.a.

In reality, there will be some inertia in beginning such deep cuts in emissions, whether via the straight-line on annual reduction rate pathway. Consequently, it is reasonable to interpret Scotland's requirement under the "safe and fair" criteria of the Act to establish **a 'real zero' date for its energy-related CO_2 emissions as being 2037/38 for 2°C, and 2029/30 for 1.5°C.**

[1] Based on an annual energy-only CO_2 emissions level of 36 to 37GtCO_2 (as per estimates provided by the Global Carbon Project https://www.globalcarbonproject.org/carbonbudget/21/highlights.htm)

E. Why is this so removed from what is typically assumed?

The two heuristic mitigation pathways proposed here for Scotland, and the zero emission dates for "*well below 2°C*" and "*pursuing … 1.5°C*", are all far removed from the advice of the CCC and indeed many of the high-level global scenarios. For the CCC, as they specifically noted in their sixth carbon budget report [7], they no-longer consider it appropriate to downscale from global carbon budgets to provide national carbon budgets, choosing instead to be guided by what they judge to be "*highest possible ambition*"[2]. By contrast, the approach here very specifically downscales to the UK and Scotland, with clear sequential reasoning and transparent assumptions.

In comparing the budgets here with those of the CCC specifically, and high-level global scenarios more generally, two key differences arise.

The first relates to the treatment of equity between nations, as defined in the UNFCCC concept of 'common but differentiated responsibilities and respective capabilities' (CBDR-RC)[8]. This concept is embedded as a key criteria in the Scottish Act (2019), where it notes that the "*fair and safe Scottish emissions budget*" needs to be "in line with the principles set out in article 3 of the United Nations Framework Convention on Climate Change"[5.2B.(2)]. Article 3 of the UNFCCC includes the key concept and framing of CBDR-RC.

Within Anderson et al [3] we detail how the CCC approach essentially ignores the CBDR-RC framing of equity, choosing instead a very weak interpretation 'fairness'. Understanding this is important in appreciating just how tight the mitigation timeframe is, and hence the role of CCUS.

Second, and further differentiating the CCC's approach and the Act's "*net-zero 2045*" framing, from Scotland's "*safe and fair emissions budget*", arises from the assumption that future generations will develop and deploy technologies to remove many hundreds of billions of tonnes of this generations carbon dioxide directly from the atmosphere. This is assumed by the CCC (and most high-level scenarios) to begin in earnest by around 2035, increasing through 2050 and out to and beyond the end of the century. This reliance on future generations to deploy what are still highly speculative technologies (at scale) at an unprecedented planetary level has the expedient effect of increasing the carbon budget space, and thereby the timeline within which CCS/CCUS can be usefully deployed.

The following section borrows heavily from the report referred to earlier "*Phaseout Pathways for Fossil Fuel Production within Paris-compliant carbon budgets*"[4], in particular the section on "*What role for Carbon Dioxide Removal and Carbon Capture and Storage?*" Here, the critique of 'Carbon Dioxide Removal is critical to understanding why the mitigation pathway associated with Scotland's "*safe and fair*" contribution to 1.5-2°C is far more onerous than Scotland's "*net zero 2045*" framing. This then places a very different context and timeline within which CCUS needs to be considered.

[2] For example, see [7] p.428.

What role for Carbon Dioxide Removal and Carbon Capture and Storage?

1. The case for CDR and CCS

Since the IPCC's first major report in 1990 and the UNFCCC entering into force in 1994[3] [8], the rates of mitigation needed to "*prevent dangerous anthropogenic interference with the climate system*" have increased substantially. From 2013 the IPCC's reports began to include explicit carbon budgets for various probabilities of different temperatures [9], [10], [2]. These budgets have provided a means to robustly quantify the widening gulf between real action to reduce emissions on the one hand, and political commitments on climate change on the other.

Coincident with the rapid decline in the remaining carbon budgets, improvements in climate science have led to a reduction in the temperature at which 'dangerous' impacts are forecast to occur [11]. This combination of dwindling budgets and a focus on lower temperatures (i.e. a stronger emphasis on 1.5°C) has prompted many mitigation scenario modellers to include increasing levels of future 'carbon dioxide removal' (CDR) and the deployment of 'carbon capture and storage' (CCS) technologies. Within a given carbon budget, the adoption of CDR reduces the necessary rates of mitigation by effectively increasing the available emissions space. The inclusion of CCS has the effect of reducing the carbon intensity of fossil fuel energy (e.g. the grams of CO2 emitted per kWh of energy produced) and thereby increase the total quantity of fossil fuels that may be combusted for any given carbon budget.

2. Why we should not expand the carbon budgets through CDR

Within this submission, CDR, both in the form of 'negative emissions technologies' (NETs) and 'nature-based solutions' (NbS), is not used to increase the size of the remaining carbon budgets associated with fossil fuel use. This position reflects several key concerns arising from the almost ubiquitous adoption of CDR within high-level emission scenarios. The following subsections provide a succinct account of why, within this submission, CDR is not used to expand the emission space available for fossil fuel combustion.

2.1 NETs: too speculative for inclusion

As of today, NETs are either in the form of small pilot demonstrators capturing just a few thousand tonnes of carbon dioxide[4] [12], [13] or remain in the imagination of

[3] The UNFCCC was adopted at the UN in New York in May 1992, opened for signatures in Rio in June 1992 and finally entered into force in March 1994.

[4] For example, the new (Sept 2021) Orca power plant in Iceland, which captures around 4000 tonnes of CO_2, or the equivalent of around 0.00001% of global CO_2 emissions from fossil fuels. Ostensibly higher levels of actual removal occur at the ADM bioethanol plant in Illinois in the USA. Here in the region of 0.5MtCO_2/yr have been successfully captured and stored, with the operational capacity to increase to 1MtCO_2/yr [60]. However, there is little full life-cycle information available to determine the net levels of CO_2 removal, with the plant's total CO_2 emissions actually rising in recent years (to over 4MtCO_2/yr), likely due in part to the wider activities it undertakes, but also the energy required for the capture and storage. The ADM plant certainly demonstrates how, when rich CO_2 streams exist from biomass processing, it is possible to capture and store the CO_2. However, the application of CCS on the *combustion* of biomass (or indeed fossil fuels) presents a very different engineering challenge (with

modelers and engineers. Despite this, virtually all high-level mitigation analyses assume that in coming decades NETs will be deployed at huge, planetary scale, increasing significantly post-2050 and extending well beyond the end of the century. Certainly, there is merit in a well-funded research and development programme on NETs. Moreover, provided any promising designs meet stringent ecological and social sustainability criteria, a rapid process of large-scale testing and subsequent deployment should commence.

Such deployment of NETs in a small suite of more exotic scenarios would add an important family of model outputs to complement those using existing technologies and understood processes of social change. However, and despite the fledgling state of NETs, their ‘unproblematic’ use to remove many hundreds of billions of tonnes of carbon dioxide across the century is now pervasive.

2.2 BECCS: ecological and sustainability implications

Within existing models and scenarios, the approach that dominates the NETs assumption is bioenergy with carbon capture and storage (BECCS). In this approach the growing of organic material (biomass) absorbs atmospheric CO2, with the biomass subsequently combusted as fuel in a conventional thermal power station from which the CO2 is captured and stored rather than emitted.

Ostensibly BECCS confers considerable advantages to models seeking to cost-optimise their responses to climate change, as it substitutes for other mitigation options deemed to have higher marginal costs. However, the scale of mono-cropped[5] biomass necessary to deliver the billions of tonnes of removal through BECCs imposes considerable ecological and societal risks. In important respects, the cure could be as bad if not worse than the disease. One estimate puts the “loss of terrestrial species (from high levels of BECCS) perhaps worse than the losses resulting from a temperature increase of about 2.8°C above pre-industrial levels.” [14]. Another estimate puts the land take associated with the levels of BECCS in many models at between 380 and 700 million hectares [15], equivalent to one-and-a-half times the combined area of the EU’s twenty-seven countries, or up to twice the area of India. Further to such high-profile impacts, BECCS at scale also has major implications for water use, land-rights, global shipping and wider transport demands, as well as those associated with the integrity of carbon dioxide storage.

From the perspective of this submission, the particular details of returning to a global economy powered, in significant part, by the combustion of plant material with the emissions subsequently captured and buried, is largely beside the point. As noted in §2.1, this analysis does not explicitly adopt any form of NETs as a means for directly expanding the available carbon budget space for fossil fuels. Nevertheless, as discussed in §2.4 below, some form of CDR is indirectly assumed to compensate for warming arising from those residual agricultural emissions that cannot be eliminated.

much lower concentrations of CO_2 and more contaminants), yet it is this approach that dominates the high-level mitigation models.

[5] Or at least a crop with very limited biodiversity.

2.3 Forestry as a 'nature-based solution' to rising emissions

Another approach increasingly mooted as having potential to expand the available carbon budget, and thereby reduce the rates of immediate and early mitigation, is the adoption of high levels of forestry. This typically takes the form of afforestation and reforestation, but in analyses that draw on specialist forestry expertise, notably extends to include the regeneration of degraded forests [16].

While there is certainly significant potential for the uptake of carbon dioxide into additional forestry cover, what is critical for this submission is that "the rates and amounts of net carbon uptake are slow and low compared to the rates and amounts of carbon dioxide we release by fossil fuel combustion. Hence, removal of carbon dioxide from the atmosphere does not compensate for the release of fossil fuel emissions" [26, p. 10]. This key point was reiterated at COP26. Based on the publication of the 'New Insights in Climate Science 2021' [17], Professor Rockström (one of the report's authors) stated clearly "we need nature-based solutions, but we cannot use them to slow down the pace of emission reductions from fossil fuels" [18].

Further to this, the simple reduction of the myriad complexities of trees and forests to one of carbon, risks missing a much more nuanced suite of climate-related issues that remain, to an important degree, unsettled[6] [19].

For this submission the breadth of forestry-related issues – from how terrestrial carbon is always vulnerable to re-emission (i.e. issues of permanence), through to temporal differences in land and fossil-fuel carbon cycles – are considered sufficient reason to exclude NbS from compensating directly for fossil fuels emissions.

2.4 CDR to balance residual emissions from agriculture

A key caveat to the role of CDR in relation to carbon dioxide budgets and fossil fuels is that emissions of all long-lived greenhouse gases need to reduce to zero, or warming from any residual emissions must be compensated for. In this regard, this submission assumes a vital role of some form of CDR in balancing ongoing warming from residual agricultural emissions of nitrous oxide (N2O) and methane (CH4). While such emissions can be significantly reduced from their current rate, they cannot be entirely eradicated. With a rising global population, alongside changes in the climate, rainfall patterns, etc, there will very likely be additional demand for fertiliser use to maintain and potentially increase yields. Overall, a combination of much improved agricultural practices and a fundamental shift away from meat consumption is here assumed to result in total global agricultural emissions in the order of 4 to 7 GtCO2e/year [20], [21] – not too dissimilar to estimates of future CDR.

Acknowledging the need for significant levels of CDR to address those emissions impossible to eliminate (in contrast to just 'difficult' to decarbonise) highlights the jeopardy of 'double-counting' such removals to offset emissions from fossil fuels. Thus, the analysis within this submission is developed without recourse to future CDR for the energy system.

[6] For example, issues of albedo and 'volatile organic compounds' (VOCs). See [29] for more details.

3. Why do we not expand the use of fossil fuels through CCS?

Having provided point by point reasoning as to why Scotland's carbon budgets (as developed in §C) cannot be increased through CDR, it is now possible to consider the role of CCS/CCUS in delivering Scotland's commitment to not to exceed it "*fair and safe emission budgets*" for 1.5-2°C.

The prospect of CCS has, since the late 1970s [22], been proposed as a potential means for reducing the emissions per kilowatt hour of fossil-fuel-fired power generation. More recently, it has also been offered as a technology with the potential to unlock the production of 'blue hydrogen'. However, while CCS has remained central to most orthodox system-level mitigation scenarios, in practice the fossil fuels industries have demonstrated very little belief in its long-term prospects, having constructed just a few small pilot schemes over the past two decades.

In 2010 the IEA's CCS Roadmap (as part of its low carbon 'Blue' scenario) [23] envisaged sixty large scale CCS projects by 2020, rising to around 500 by 2030 and over 1800 by 2050. In its 2021 report, the Global CCS Institute noted there were twenty-seven plants operational, with four more currently under construction [24]. Total capture was estimated at a little under 37 MtCO2, or less than 0.1% of total fossil-fuel CO_2 emissions. If those future plants designated by the Global CCS Institute as in a stage of "advanced development" were all to proceed to construction and then full operation, capture rates could rise by an additional 47 $MtCO_2$, bringing the total to a little over 0.2% of current annual fossil fuel emissions. However, these values include both geological storage and the use of captured CO2 for 'enhanced oil recovery'. **Considering only CO2 actually stored geologically reduces the 37 MtCO2 to a little over 7 MtCO2, or under 0.02% of energy-related CO2 emitted in 2021.** As for the future projects, and again assuming they all proceed to full operation, then in terms of storage, by **2030 the total is set to rise to around 45 MtCO2, or a little over 0.1% of current emissions** [25].

All of this is far-removed from the long-standing enthusiasm for CCS as a cornerstone of the decarbonisation agenda. Yet, and despite the long history of over-promising and under-delivering [26], this enthusiasm remains unchecked.

3.1 CCS: too little too late

The primary remit of this submission is reducing emissions in line with not exceeding 1.5 -2°C. This entails rapid decarbonisation, beginning now and being all but complete within one to two decades. Such a tight timeframe is inconsistent with any realistic interpretation of the roadmaps of CCS-based power generation or blue hydrogen production.

Furthermore, power generation is the one area of energy supply where very low or zero carbon alternatives actually exist, and at prices that are already competitive. Adding both the significant capital cost of CCS to existing or even new facilities, alongside the major energy penalty of CCS-based generation (i.e. much higher costs/kilowatt hour), further reinforces the cost-competitiveness (and energy security benefits) of renewables.

As such, bolting on what is in effect an inefficient and expensive filter to prolong the life of fossil fuels is very much an ‘end-of-pipe’ approach, more reminiscent of the last century than the system-level considerations of this century.

3.2 The very high lifecycle emissions of CCS

While it may be possible to reduce operational emissions of CO_2 by around 90%, this still leaves a significant residue of CO_2 released to the atmosphere[7] [27]. Given the need for all GHGs to be eliminated globally, with only residual emissions from agriculture remaining, then **the high lifecycle emissions associated with CCS (typically 100–300 gCO_2e/kWh [28]) make it unsuitable for all but very marginal roles.**

3.3 A tonne emitted from CCS is a tonne that cannot be emitted elsewhere

A further consideration in terms of CCS within the energy system is how low- or zero-CO_2 options for power generation are far more advanced than are the alternatives for fossil fuels in other sectors, particularly transport. **Consequently, every tonne of CO_2 emitted from a power station (even with CCS) is a tonne that cannot be emitted from transport or industry. Since electricity generation has many more options for easier and earlier decarbonisation, this misappropriation of the scarce carbon budget works against a system-level transition to zero carbon energy.**

3.4 The potential merits of CCS on cement

The role of CCS in eliminating process emissions from industry, particularly cement manufacture, is subject to different conditions to that for power generation. As it stands, **CCS looks set to be a key technology in addressing the 4% of global CO_2 emissions released from the chemical reactions in cement production.**

4. CDR and CCS: summary

In short, this submission eschews the substitution of deep cuts in emissions today for CDR and CCS tomorrow. Rather, it suggests we face the mitigation challenges head on, navigating the highly constrained space between an equitable and practical distribution of Scotland’s rapidly dwindling “*safe and fair emissions carbon budgets*”.[1]

[7] Sustained capture rates above 90% are possible theoretically, but would very likely go along with a significant increase in both indirect greenhouse emissions and cost.

Degree of confidence in this submission

It is certainly possible to 'fine tune' some of the assumptions that underpin the quantitative analysis within this a submission. However, within the tight IPCC AR6 carbon budgets for 1.5–2°C, and with serious attention paid to the UN framing of equity, the key messages outlined here are sufficiently robust to provide a strong guide to mitigation policy.

A potential exception to this is whether it is considered appropriate or not to expand the IPCC's carbon budgets through future 'carbon dioxide removal', deployed at planetary scale and principally in the second half of the century. This issue receives careful attention within the submission. Specifically, in relation to emissions of carbon dioxide from the energy sector, the inclusion of highly-speculative-at-scale CDR is judged inappropriate, as it works against the tenets of precaution. Moreover, whilst CDR is now ubiquitous in mitigation analyses, the IPCC's estimates of additional feedbacks, potentially reducing carbon budgets, are seldom if ever included. For this submission, a conservative approach is adopted, neither easing the mitigation burden through CDR nor increasing it through additional feedbacks.

References

[1] Climate Change (Emissions Reduction Targets) (Scotland) Act 2019
https://www.legislation.gov.uk/asp/2019/15/contents/enacted

[2] Working Group 1 of the IPCC, "Climate Change 2021, The Physical Science Basis, Summary for Policymakers," 2021. doi: 10.1260/095830507781076194.

[3] Kevin Anderson, John F. Broderick & Isak Stoddard (2020) A factor of two: how the mitigation plans of 'climate progressive' nations fall far short of Paris-compliant pathways, Climate Policy, 20:10, 1290-1304, DOI: 10.1080/14693062.2020.1728209

[4] Calverley, D. and Anderson, K. (2022), Phaseout pathways for fossil fuel production within Paris-compliant carbon budgets. Tyndall Centre, University of Manchester. To be published 17th March 2022

[5] Kuriakose, J., Anderson, K., & Mclachlan, C. (2018). Quantifying the implications of the Paris Agreement: What role for Scotland?

[6] Anderson, K. Evidence provided to the 2021 Scottish Climate Assembly (2021) [VIDEO LINK REMOVED AS CANNOT PUBLISH]

[7] Committee on Climate Change. Sixth Budget Report (2020)
https://www.theccc.org.uk/publication/sixth-carbon-budget/

[8] United Nations Framework Convention on Climate Change (1992). Article 3. pp.4-5. https://unfccc.int/resource/docs/convkp/conveng.pdf
[9] IPCC, "Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change," 2018. [Online]. Available: https://www.ipcc.ch/sr15/

[10[IPCC, “Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,” Cambridge University Press, Cambridge, UK, and New York, USA, 2013. [Online]. Available: https://www.ipcc.ch/report/ar5/wg1/

[11] J. B. Smith *et al.*, “Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) “‘reasons for concern.”’” [Online]. Available: www.pnas.orgcgidoi10.1073pnas.0812355106

[12] Climeworks.com, “Orca is Climeworks’ new large-scale carbon dioxide removal plant.” https://climeworks.com/roadmap/orca (accessed Feb. 16, 2022).

[13] The Economist, “The world’s biggest carbon-removal plant switches on | The Economist.” https://www.economist.com/science-and-technology/2021/09/18/the-worlds-biggest-carbon-removal-plant-switches-on (accessed Feb. 16, 2022).

[14] P. Williamson, “Emissions reduction: Scrutinize CO2 removal methods,” *Nature*, vol. 530, no. 7589, pp. 153–155, 2016, doi: 10.1038/530153a.

[15[P. Smith *et al.*, “Biophysical and economic limits to negative CO2 emissions,” *Nature Climate Change*, vol. 6, no. 1, pp. 42–50, 2016, doi: 10.1038/nclimate2870.

[16] E. W. Littleton *et al.*, “Dynamic modelling shows substantial contribution of ecosystem restoration to climate change mitigation,” *Environmental Research Letters*, vol. 16, no. 12, p. 124061, Dec. 2021, doi: 10.1088/1748-9326/AC3C6C.

[17] Future Earth, The Earth League, and WCRP, “10 New Insights in Climate Science 2021,” Stockholm, 2021. Accessed: Feb. 15, 2021. [Online]. Available: https://doi.org/10.5281/zenodo.5639539

[18]]   UN Climate Change, *Johan Rockström at #COP26: 10 New Insights in Climate Science*, (2021). [Online Video]. *[VIDEO LINK REMOVED AS CANNOT PUBLISH]*

[19] G. Popkin, “How much can forests fight climate change?,” *Nature*, vol. 565, no. 7739, pp. 280–282, Jan. 2019, doi: 10.1038/D41586-019-00122-Z.

[20] T. Searchinger, R. Waite, C. Hanson, and J. Ranganathan, “World Resources Report. Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050,” Washington, DC, USA, 2019. [Online]. Available: https://agritrop.cirad.fr/593176/1/WRR_Food_Full_Report_0.pdf

[21] A. Bows-Larkin *et al.*, “Importance of non-CO2 emissions in carbon management,” *Carbon Management*, vol. 5, no. 2, pp. 193–210, Mar. 2014, doi: 10.1080/17583004.2014.913859.

[22] C. Marchetti, “On geoengineering and the CO2 problem,” *Climatic Change*, vol. 1, no. 1, pp. 59–68, 1977, doi: 10.1007/BF00162777.

[23] IEA, “Technology Roadmap: Carbon Capture and Storage in Industrial Applications,” Paris, 2011. [Online]. Available: www.iea.org/reports/roadmap-carbon-capture-and-storage-in-industrial-applications

[24] Global CCS Institute, “The Global Status of CCS: 2021,” Australia, 2016. [Online]. Available: https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf

[25] E. Martin-Roberts, V. Scott, S. Flude, G. Johnson, R. S. Haszeldine, and S. Gilfillan, “Carbon capture and storage at the end of a lost decade,” *One Earth*, vol. 4, no. 11, pp. 1569–1584, Nov. 2021, doi: 10.1016/J.ONEEAR.2021.10.002.

[26] N. Wang, K. Akimoto, and G. F. Nemet, “What went wrong? Learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects,” *Energy Policy*, vol. 158, p. 112546, Nov. 2021, doi: 10.1016/J.ENPOL.2021.112546.

[27] IEAGHG, “Towards zero emissions CCS from power stations using higher capture rates or biomass,” 2019. [Online]. Available: https://climit.no/app/uploads/sites/4/2019/09/IEAGHG-Report-2019-02-Towards-zero-emissions.pdf

[28] T. Gibon, A. Arvesen, and E. G. Hertwich, “Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options,” *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 1283–1290, Sep. 2017, doi: 10.1016/J.RSER.2017.03.078.