The University of Virginia
Department of Engineering Systems and Environment

Integrated Assessment Modeling of Direct Air Capture for Negative CO_2 Emissions

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Abstract

Integrated assessment modeling (IAM) scenarios of the global energy, land-use, and climate systems have become increasingly reliant on future negative emissions in finding paths to limit global warming to below 2˚C. The projected requirements for so-called negative emissions technologies (NETs) are often similar in magnitude to present-day positive emissions. This dissertation explores the implications for global and country-scale food, water, and energy systems of large-scale NET deployments, and how future policy and socioeconomic developments could influence the timing and required magnitude of these deployments in meeting ambitious climate change mitigation goals. First, a critical review was conducted to explore how IAMs could improve their treatment of NETs broadly, as well as how different NETs could interact with Sustainable Development Goals set out by the United Nations. Subsequently, a framework to model direct air capture with carbon storage (DACCS) was incorporated into the Global Change Assessment Model (GCAM), and the potential role and food-energy-water side effects of DACCS in meeting a 1.5˚C temperature goal in 2100 were assessed. A case study was then conducted using this framework to understand the potential contribution of DACCS in meeting China's recently announced goal of carbon neutrality by 2060. Finally, additional model development incorporated the ability to model multiple DACCS processes across 5 Shared Socioeconomic Pathway scenarios.

Previous IAMs largely excluded DACCS and instead relied solely on bioenergy with carbon capture and storage (BECCS) and afforestation, with enormous land-use implications. The limited set of scenarios that did consider DACCS projected large deployments would need to take place at the end of the century. Here, the Global Change Assessment Model (GCAM) was extended to include a DACCS process requiring natural gas, electricity, water, and capital and operating cost input. Results indicate that DACCS could begin removing up to 3 Gt-CO_2-yr^{-1} by 2035, but only if ambitious policies to incentivize its deployment alongside conventional decarbonization efforts are rapidly implemented. DACCS was found to reduce some of the land use tradeoffs of BECCS and their market-mediated effects on food prices, but not eliminate them. Even with low-cost DACCS available, food prices could still increase up to 3-fold globally and up to 5-fold in many parts of the Global South due to remaining land competition from BECCS and afforestation. DACCS could reduce water use from bioenergy crop production and afforestation but itself could consume substantial amounts of water globally. Natural gas requirements for DACCS process heat could reach up to 115% of present-day gas consumption.

The GCAM modeling framework was then applied in a case study to understand the country-scale role of DACCS in meeting China's recently announced commitment to achieve carbon neutrality by 2060. Linearly declining constraints on CO_2 emissions were applied to China individually and the rest of the world collectively, and DACCS was allowed to freely compete with both conventional mitigation and negative emissions technologies. DACCS was projected to scale up to 1.6 Gt-CO_2-yr in China, allowing it to meet its carbon neutrality pledge at far lower cost by offsetting emissions from difficult-to-mitigate transportation and industrial sectors. DACCS could enable China to devote up to 25% less land to bioenergy crop production in its most highly productive agricultural regions, preserving this land for food production or environmental conservation. A sensitivity

analysis revealed the large projected role of DACCS to be robust across a number of modeling assumptions.

A third study further extended the modeling framework to include fully-electric DACCS processes. An extensive meta-analysis and techno-economic assessment was conducted to parametrize a fuller set of DACCS archetypes. Subsequently, assumptions regarding their future cost and efficiency improvements were harmonized with the narratives of the 5 Shared Socioeconomic Pathways. Results revealed that DACCS could play a 10-40 Gt-CO_2-yr^{-1} role in meeting both +1.5˚C and +2˚C temperature targets. The requirement for DACCS is particularly large in scenarios with delayed climate policy onset and or higher challenges to emissions mitigation, but all scenarios have large requirement for geologic carbon storage. The "sustainable development" scenarios, consistent with SSP1, have far smaller deployments of DACCS and other negative emissions owing to immediate climate policy onset, greater ease of "conventional mitigation" and tighter constraints on future negative emissions.

Together, these studies reveal that DACCS could begin making large contributions to climate mitigation in the near-future and soften, but not eliminate the negative side-effects of land-intensive NETs such as BECCS and afforestation. However, the prospect of future DACCS or other large-scale negative emissions should not serve as justification to continue delaying ambitious mitigation efforts using both conventional abatement and negative emissions technologies.

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In memory of Jesse Johnson Sr.

Table of Contents

List of Figures and Tables

Chapter 1 - Overview

1.1. Motivation and Objectives

Climate change resulting from excess concentrations of CO_2 and other greenhouse gases in the atmosphere is already causing severe disruptions to humans and the natural environment. As of 2020, global average temperatures have increased by over 1˚C from their pre-industrial average, contributing to more severe weather including droughts, heat waves, wildfires, hurricanes, and coastal flooding.[1–3] The effects of climate change will continue to worsen as long as emissions from fossil fuels and land use change continue to increase CO_2 and other greenhouse gas concentrations in the atmosphere and ocean.[4] Limiting future damage from climate change therefore requires that global emissions of CO_2 and other greenhouse gases decline to zero over the coming decades.[5,6] Despite falling temporarily due to economic disruptions associated with the COVID-19 pandemic, CO_2 emissions are expected to resume their historical growth trajectory without deliberate policies to reduce them.[7,8] The 2015 Paris Climate Agreement represented an important first step by the international community to cooperate to limit climate warming to below 2˚C above preindustrial levels, and to pursue efforts to limit warming to 1.5˚C.[9] 196 parties to the treaty committed to developing national-level policies known as Nationally Determined Contributions (NDCs) to reduce their emissions, and to periodically strengthen these commitments.[10] This later provision is critical because current emissions reduction commitments - while encouraging - will still lock the world into well over 2˚C of warming.[11,12]

Leading up to the Paris agreement was a series of reports by the Intergovernmental Panel on Climate Change that covered the causes, current and future impacts, and pathways to mitigate and adapt to climate change.[13–17] Following the adoption of the Paris Agreement, the IPCC released another comprehensive report on limiting climate warming to the treaty's aspirational 1.5˚C goal.[18] These reports were heavily informed by an ensemble of integrated assessment modeling results that detailed the extensive transitions to the global economy – in particular energy and land use - that would need to take place to meet these temperature limits.[19] As shown in **Figure 1-1**, these models found that meeting the goals of the Paris Agreement will likely only be feasible with future, globally net-negative CO_2 emissions at comparable magnitudes to present-day (positive) emissions.[20–22] The steepness with which global emissions decline over the next 15-20 years (which is in turn influenced by decisions made in the next 5-10 years) will determine the rates of future negative emissions required to still meet the same limit on climate warming. Indeed, policy and investment decisions made in the immediate future may determine whether these limits can be met at all.[23]

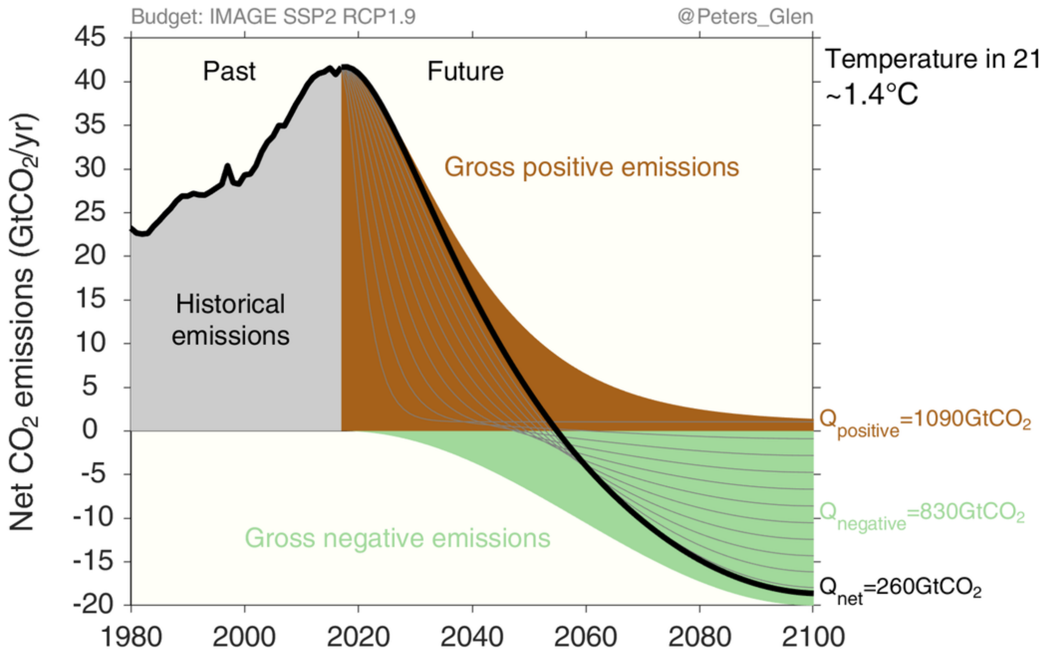

Figure 1-1: Limiting end-of-century climate warming to levels consistent with the 2015 Paris Agreement requires immediate declines in global CO_2 emissions, and future net-negative CO_2 emissions. Because warming is directly related to the cumulative amount of CO_2 and other greenhouse gases emitted to the atmosphere, every year of delay in deep mitigation efforts locks in ever-increasing commitments to future negative emissions to meet the same temperature goal.[i]

The vast majority of IAM scenarios only include two so-called negative emissions technologies (NETs): bioenergy with carbon capture and storage, and afforestation. But relying on these methods alone to achieve the levels of negative emissions envisaged would have large impacts for global land-use and be at odds with other sustainable development objectives including food production and environmental preservation.[24–26] Direct air capture is an engineered process that uses electric and/or thermal energy input to separate CO_2 from the atmosphere, with much lower land-intensity than BECCS and afforestation per unit of CO_2 removed[27,28] Cost estimates for DAC have become much more optimistic over recent years.[29–32] As a result, DAC is receiving growing attention from the IAM community and in real-world policy and corporate planning discussions. Several companies have now built pilot-scale DAC plants, and have received investment from or partnered with large corporations - including fossil fuel companies - seeking to reduce or offset their emissions.[33–39] Yet to date, DAC has not been included in most deep mitigation IAM scenarios and modeling frameworks, and those that do include it project enormous future deployments with correspondingly large dedicated energy input requirements.[40–43] Deploying different NETs as a large-scale climate mitigation strategy will have different potentials for both synergism and antagonism with other sustainable development objectives, including adaptation to climate change that is already occurring.[44–46] Given the importance of IAMs in informing international climate policy discussions, it is critical that they incorporate a fuller portfolio of NETs, clearly communicate their risks and benefits, and design scenarios to avoid excessive reliance on future NET deployments.[20,47,48]

[i] Image Source: Peters (2018).

The work presented here answers several research questions regarding negative emissions technologies generally and their treatment (or lack thereof) by integrated assessment models, as well as the potential role and side effects of large-scale DAC, in particular, on global and country-scale food energy and water systems. These questions are:

1. *What are the consequences of current treatment of negative emissions technologies by IAMs for other Sustainable Development Goals?*
2. *What are the impacts of direct air capture deployment for global food, water, and energy systems?*
3. *How can the availability of direct air capture contribute to country-scale decarbonization efforts?*
4. *How might future socioeconomic developments influence the role of and balance between direct air capture and other forms of negative emissions?*

1.2. Background

This section seeks to preface the main topics of research covered in this dissertation. Each of the subsequent chapters contains more detailed background on each of the topics presented here.

1.2.1. Negative Emissions Technologies

Negative emissions technologies (NETS) constitute a number of prospective ways to remove CO_2 from the atmosphere, and may also be referred to as carbon dioxide removal (CDR) in literature and media coverage. As shown in **Figure 1-2**, NETs differ widely in their mechanism by which they achieve negative emissions – generally by either enhancing natural carbon sinks (e.g., afforestation, soil carbon), or engineering entirely new ones (e.g., direct air capture). Correspondingly, NETs vary widely in their maximum achievable rates of CO_2 removal, degree of storage permanence, and their interaction potential with other sustainable development objectives not directly related to climate mitigation.[29,45] To date, only a limited set of NETs have been modeled by the IAM community to understand their potential role and side-effects.

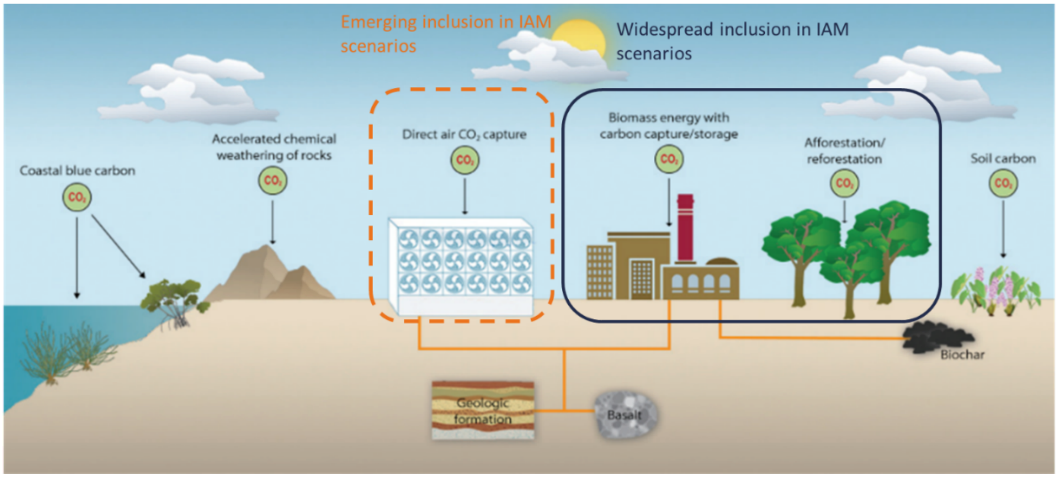

Figure 1-2: Of the large number of potential means of removing CO_2 from the atmosphere, only a select few have been included in IAM scenarios to date.[ii]

NETs are distinct from carbon capture and storage (CCS) wherein carbon dioxide is captured from a point-source combustion exhaust stream to prevent its emission to the atmosphere. However, depending on the source of the carbon (e.g., biogenic or atmospheric, as opposed to fossil), CCS can be used to generate negative emissions.[49] Prospective planetary-scale interventions in Earth's carbon cycle using NETs are also distinct from "geoengineering". That term refers to deliberately increasing Earth's albedo (reflectivity) to incoming solar radiation through atmospheric aerosol injection and/or surface-based approaches to reduce some of the impacts of increased concentrations of heat-trapping CO_2 and other greenhouse gases.[50,51] NETs could potentially be used to offset sources of positive emissions from high-temperature industrial processes, aviation and long-haul freight transportation that are expected not to be amenable to CCS or electrification.[52] Subject to their ability to scale to Gt-CO_2 removal rates and the political will to realize and maintain such massive deployments, NETs could allow reversal of historical and future damage to Earth's climate system by allowing drawdowns of previously-emitted CO_2 from the atmosphere and ocean.[53]

Interest in NETs has grown in recent years along with growing awareness of the immense gap between current emissions trajectories and those compatible with limiting climate warming to anything close to the targets agreed to in Paris and affirmed at subsequent international climate negotiations.[54,55] Several nations including China, Japan, and the United Kingdom have recently announced pledges to reduce emissions to net-zero over the coming decades, implicitly acknowledging the difficulty of fully eliminating gross-positive emissions.[56–58] Although the United States has withdrawn from and then subsequently re-entered the Paris Agreement,[59,60] it has recently implemented several policies aimed at increasing investment in carbon storage and negative emissions. A provision passed by the U.S. Congress and signed into law in 2018 provides a tax credit up to $20 per metric ton of CO_2 captured and stored in geologic reservoirs. In 2020, the U.S. joined the World Economic Forum's One Trillion Trees Initiative seeking to promote afforestation.[61] Despite these pledges and policy initiatives, global emissions are trending upwards and negative emissions activities are currently offsetting near-negligible ($\ll$ 1 Gt-CO_2-yr^{-1}) amounts of CO_2.

[ii] Image source: adapted from NRC 2018

1.2.2 Integrated Assessment Models

Integrated assessment models (IAMs) were first developed to represent greenhouse gas emissions from fossil fuel use in the energy system[62], and later expanded to include land use land use change and forestry emissions. IAMs are developed by interdisciplinary research teams and are now widely used to understand relationships between future socioeconomic developments and climate change mitigation policies.[63] Given lack of progress on mitigation efforts, there is now broad consensus among IAM results that negative emissions will be required to meet the goals of the Paris Agreement.[64–66] IAMs differ widely in their degree of technological, sectoral, and spatial detail, as well as their computational routines for determining "least-cost" approaches to meeting policy objectives. Select details of 6 major IAMs are outlined in **Table 1-1**, which reveals that most IAMs are developed by research groups in the developed world.[67] A schematic for GCAM, the IAM used for the original modeling contribution of this dissertation is shown in **Figure 1-3.**

Most IAMs include simplified representations of Earth's climate system that use dynamic equations to emulate key results (e.g., global average temperature anomaly, CO_2 concentrations) of Earth System Models (ESMs). ESMs model ocean and atmospheric circulation and biogeochemical cycling in far greater detail given some greenhouse gas emissions trajectory.[68] Given their relatively low spatial resolution, most IAM scenarios do not explicitly consider economic damages of climate change itself (e.g., coastal flooding, reduced agricultural yields), although this is an area of ongoing research effort.[69,70] This, along with discounting of future mitigation costs and potential underestimates of technological innovation rates in response to policy may be leading IAM scenarios to emphasize future negative emissions over near-term mitigation.[71–74]

Table 1-1: Overview of Major Integrated Assessment Models[iii]

Model Name (Country)	Model Category	Solution Algorithm	Model Regions
AIM (Japan)	General equilibrium	Dynamic-recursive	17
GCAM (United States)	Partial equilibrium	Dynamic-recursive	32
IMAGE (Netherlands)	Partial equilibrium	Dynamic-recursive	26
MESSAGE (Austria)	General equilibrium	Intertemporal optimization	11
REMIND (Germany)	General equilibrium	Intertemporal optimization	11
WITCH (Italy)	General equilibrium	Intertemporal optimization	13

[iii] Source: IIASA (2015)

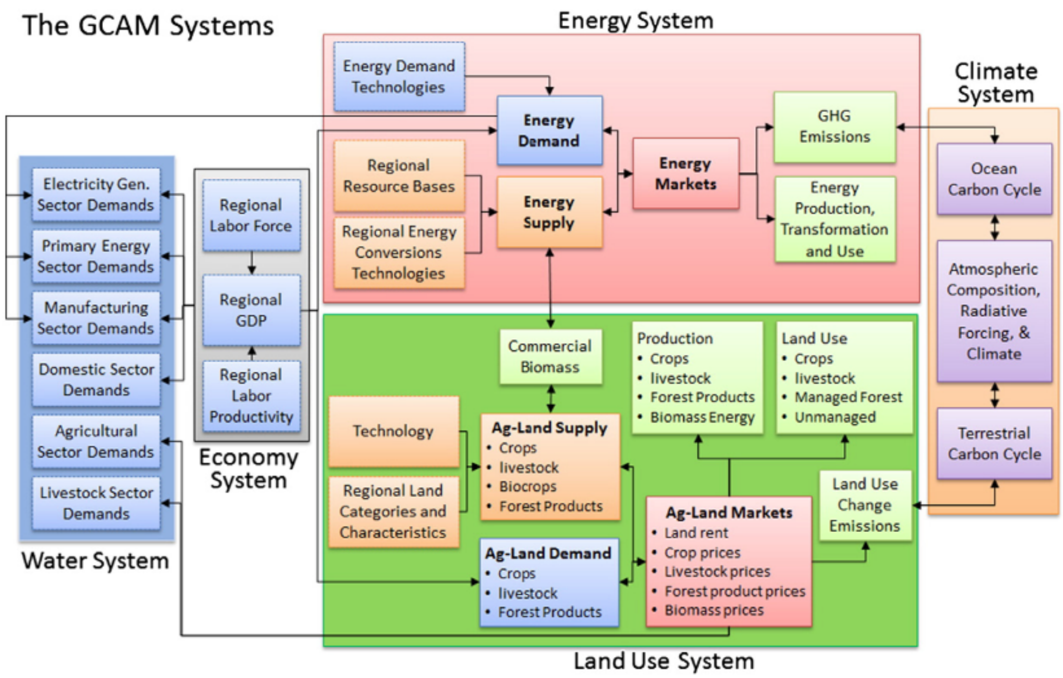

Figure 1-3: Schematic for the Global Change Assessment Model (GCAM), a dynamic-recursive IAM with detailed treatment of global energy, land, and water systems.[iv]

[iv] Image source: Hejazi et. al (2014).

Chapter 2 -Review of Intergated Assessment Modeling Treatment of Negative Emissions Technologies

2.1. Chapter Summary

Climate change mitigation strategies informed by Integrated Assessment Models (IAMs) increasingly rely on major deployments of negative emissions technologies (NETs) to achieve global climate targets. Although NETs can strongly complement emissions mitigation efforts, this dependence on the presumed future ability to deploy NETs at scale raises questions about the structural elements of IAMs that are influencing our understanding of mitigation efforts. Model inter-comparison results underpinning the IPCC's special report on Global Warming of 1.5ºC were used to explore the role that current assumptions are having on projections and the way in which emerging technologies, economic factors, innovation, and tradeoffs between negative emissions objectives and UN Sustainable Development Goals might have on future deployment of NETs. Current generation IAM scenarios widely assume we are capable of scaling up NETs over the coming 30 years to achieve negative emissions of the same order of magnitude as current global emissions (tens of gigatons of CO_2/year) predominantly relying on highly land intensive NETs. While the technological potential of some of these approaches (e.g., direct air capture) is much greater than for the land-based technologies, these are seldom included in the scenarios. Alternative NETs (e.g., accelerated weathering) are generally excluded because of connections with industrial sectors or earth system processes that are not yet included in many models. In all cases, modeling results suggest that significant NET activity will be conducted in developing regions, raising concerns about tradeoffs with UN Sustainable Development Goals. These findings provide insight into how to improve treatment of NETs in IAMs to better inform international climate policy discussions. We emphasize the need to better understand relative strength and weaknesses of full suite of NETs that can help inform the decision making for policy makers and stakeholders.[v]

2.2. Introduction

Efforts by the United Nations and others to develop a coordinated global response to climate change rely heavily on an ensemble of Integrated Assessment Models (IAMs) to make projections linking human activities to climate outcomes [17,18]. IAMs are coupled models of the global economic and climate systems, first developed to represent fossil fuel emissions from the energy system [62], and later expanded to include land use land use change and forestry emissions, as well as non-CO_2 emissions [75]. To limit global temperature change to 1.5 or 2ºC within this century, as agreed upon in the Paris Agreement on Climate Change, IAM scenarios have increasingly incorporated negative emissions technologies (NETs) to achieve carbon dioxide removal (CDR) [17,18]. NETs are a broad class of large-scale, deliberate activities for removing CO_2 from the atmosphere. While many negative emissions approaches are theoretically possible, few have been deployed commercially (with the exception of reforestation and forest management), and none at anywhere near the scales required to meaningfully contribute to climate mitigation [76–79].

NETs approaches can be broadly classified into surface-based processes that increase organic and inorganic carbon densities in the biosphere and soils, or deep-subsurface processes that store CO_2 in

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[v] This chapter was adapted from: Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W., and Clarens, A. F. "**From Zero to Hero?: Why Integrated Assessment Modeling of Negative Emissions Technologies Is Hard and How We Can Do Better**" *Frontiers in Climate* 1, (2019)

geologic formations. Surface-based NETs include afforestation and reforestation (AR), coastal blue carbon (CBC), increasing soil carbon (SC) through biochar application, and accelerated weathering (AW) of silicate minerals [29]. These surface-based NETs are generally well understood but considered more vulnerable to future disturbance or change in practice (e.g., forest fires, land-clearing, soil loss). Subsurface-based NETs include direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS). These sub-surface based approaches are less mature than surface-based approaches but are considered to be more permanent [80]. To date, IAMs have generally modeled the deployment of only BECCS and AR. Other NETs have not been considered in IAMs primarily because of connections to sectors that have not yet been included in these models, and because parameterizing these technologies is speculative given that NETs are not being deployed commercially today. A number of ocean-based approaches to remove atmospheric carbon dioxide have been proposed over the years but those have yet to be modeled by the IAM community [81].

The growing interest in NETs is driven by the recognition that efforts to limit warming to 1.5 or 2 ºC without them would require emissions reductions in the coming years that are strongly at-odds with current and intended future global climate policy [82,83]. Current deployment of climate mitigation activities that prevent CO_2 from entering the atmosphere in the first place (e.g., energy conservation, renewable energy, and fossil carbon capture and storage) is encouraging but will proceed too slowly to achieve the kinds of climate stabilization goals laid out by the UN [84,85]. Using independent modeling frameworks, a number of research groups have concluded that NETs will be needed to complement conventional mitigation activities. Even though model structures differ between IAMs (e.g., computable general equilibrium vs. system dynamics), cost and resource constraints determine the balance between traditional emissions abatement options and NETs deployment - in virtually all cases NETs play a large role.

This growing reliance on NETs in IAM projections is evident in the recent IPCC *Special Report on Global Warming of 1.5 °C* [18]. The modeling underpinning that report came from research groups from around the world using a range of different IAMs. **Figure 2-1** presents the results from the IPPC SR1.5 Scenario Database plotted in terms of peak projected NETs deployment rates versus the cumulative additional CO_2 emissions before reaching net-zero (2016 to year of net-zero emissions) [66]. Almost all the scenarios that were able to achieve a 1.5ºC future (deep purple dots) deployed significant amounts of NETs. Lighter colored model outcomes deployed far less NET capacity but also project a future with cumulative warming of 4-5ºC, which would have catastrophic impacts. To provide a frame of reference for the y-axis, annual global CO_2 emissions today are on the order of 40 Gt CO_2/yr, so the amount of NETs that these scenarios assume we would deploy is on the order of 30-50% of current emissions [86,87]. NETs present significant tradeoffs between biogeophysical or economic outcomes that have only recently begun to be studied [88–90]. Some NETs, such as BECCS, are land-use intensive, which will create competition with food, fuel and fiber [91]. Some appear to be low-cost, such as CBC, with significant co-benefits, while others are thought to be capital and energy intensive with unknown co-benefits, such as DAC. These tradeoffs are a challenge to model in IAMs given how little we know about how these technologies might be deployed at scale.

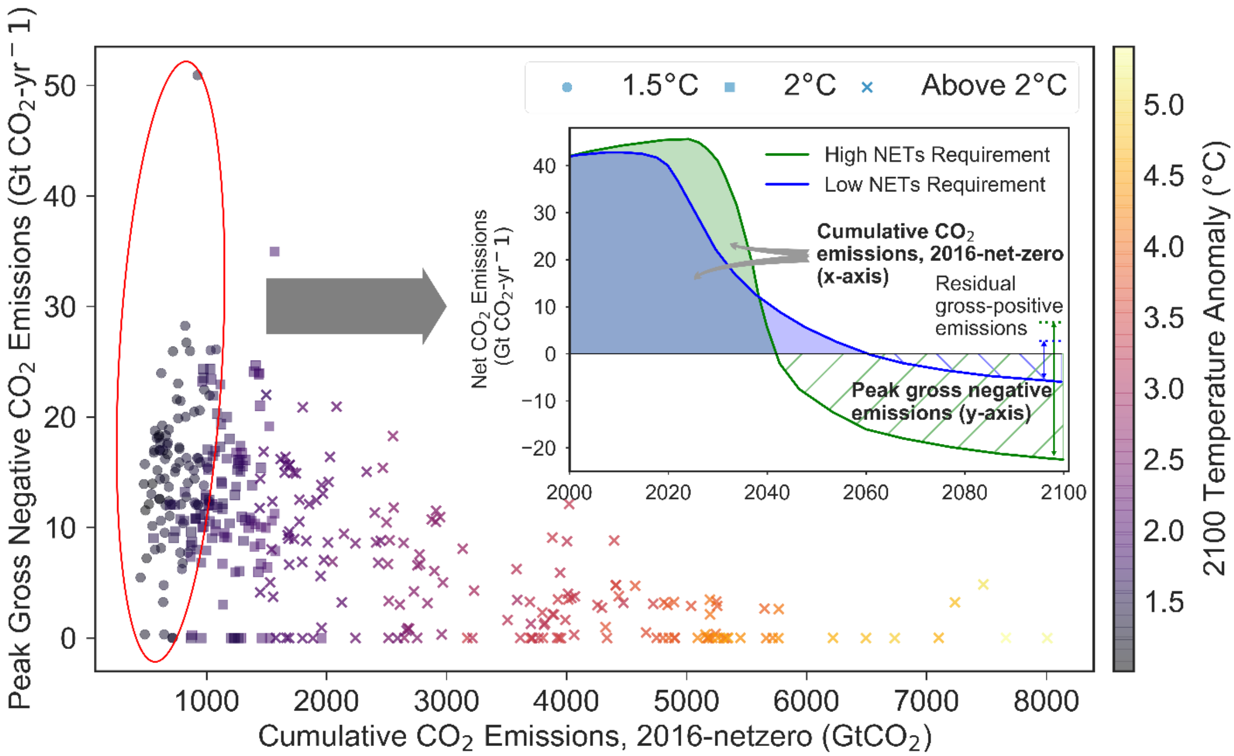

Figure 2-1. IAM scenarios consistent with limiting end-of-century warming to 1.5ºC (circles) or 2ºC (squares) above preindustrial levels have exceedingly small remaining cumulative CO_2 emissions budgets (from 2016 to year of net-zero emissions) and nearly all require significant future CO_2 removal from the atmosphere using NETs.[vi]

Most of the scenarios shown in **Figure 2-1** were developed with the objective of finding the economically least-cost means of limiting warming to a given target by 2100, without considering realistic scale-up rates of NETs, or trade-offs with other objectives (e.g., sustainable development goals). Those scenarios which applied additional design criteria and/or constraints to reflect these other factors generally find much lower NETs deployment and a greater emphasis on near-term mitigation (i.e., lower left corner of Figure 1). Such drastic mitigation required to limit future NETs deployment would need to be mediated by significant lifestyle changes, expansions in renewable energy and electrification, and reductions in non-CO_2 GHG emissions [92].

A more comprehensive handling of NETs is beginning to emerge in the climate modeling literature. Holz et al. (2018) modeled the deployment of biochar, accelerated weathering, and soil carbon management, as well as DAC, BECCS, and AR in the C-ROADS and En-ROADS system dynamics models, finding that more ambitious mitigation efforts are required for all 1.5 ºC compliant scenarios,

[vi] As illustrated in the inset, for a given temperature target (e.g., those trajectories that achieve 1.5 °C indicated by the red circle), future NET requirements are governed both by the magnitude of the greenhouse gas pulse emitted previously, as well as by residual gross-positive emissions from those sectors of the economy which are recalcitrant to decarbonization once a climate policy is implemented (e.g., air travel). Increased cumulative emissions after 2016 before reaching net-zero generally corresponds to increased peak future NETs deployment and associated impacts. Data source: Huppmann et al., 2018 (main figure); Lawrence, 2019 (inset).

especially those which assume limited availability of NETs in the future [23]. Surface based NETs (e.g. BC, AR) have been reported to exhibit storage losses, which in some scenarios required gross CO_2 removal to be maintained simply to offset storage losses from CO_2 sequestered previously in soils [93]. Creutzig et al. compared prospective impacts of BECCS and DAC on the energy system, providing analysis of the three IAM studies incorporating both. IAM assumptions and results for BECCS energy yields per tCO_2 sequestered are compared and found to differ significantly (up to 40%) in magnitude and potentially sign direction from detailed bottom-up modeling results. The authors also find that DAC costs and energy inputs may be overstated in existing IAM studies [94]. Modeling a broader portfolio of NETs can increase negative emissions capacity while reducing total policy cost [90,95].

Because of its potential to scale, DAC is increasingly the focus of a number of studies [96]. Chen and Tavoni (2013) studied DAC using the WITCH model and found that DAC could reduce total and marginal abatement costs, enable the postponement of mitigation activities, and prolong the use of oil, enabling energy-exporting countries to continue to sell low-carbon oil on the global market. This is found to provide a means to encourage energy-rich countries to participate in international climate agreements, as meeting aggressive targets is impossible without their involvement due to the mitigation burden on the remaining countries. Marcucci et al 2017 used MERGE-ETL to quantify the energy transition and economic consequences of limiting global warming to 1.5 and 2ºC by the end of the century [98]. They report that limiting warming to 1.5ºC is only possible with the use of DAC, which acts as a complement for BECCS. The authors note that, if the assumed learning rates for cost and efficiency of DAC are not met, its role could be substantially reduced. They call for additional analysis (e.g. Monte Carlo or other stochastic modeling) aimed at providing a sensitivity analyses [40]. Another recent paper used the REMIND model to evaluate tradeoffs between near-term mitigation, high transitional costs, and the need for large-scale future deployment of NETs, of which BECCS, afforestation, and DAC are available after 2030.[99] Most recently, the TIAM-Grantham and WITCH IAMs models were compared to assess the impact of DAC on meeting the 1.5 and 2 °C mitigation targets, finding the potential of DAC to reduce 2030 carbon prices by up to 50%, while noting that failing to meet the large projected scaleup rates of the technology could result in temperature overshoot of 0.8 °C by 2100 [96].

IAM projections will undoubtedly improve as the body of literature examining NETs continues to grow. We need ground-truth data, scaling economics, time-scales and barriers as well as resource demands and trade-offs to know whether these technologies will ever play as significant of a role as today's IAMs suggest. But a much more robust and defensible treatment of NETs in the IAM simulations is possible *today* if the research community focuses on improving three elements of their modeling: (1) increasing the portfolio of technologies possible; (2) improving our handling of the economics of NETs and innovation rates; and (3) consideration of the impacts that NETs will have on sustainable development goals and equity issues between nations. Here we discuss each of these and make recommendations for the research community to address these needs.

Our analysis is framed in the context of the data that is the basis for the IPCC *Special Report on Global Warming of 1.5 °C*, which provides quantitative mitigation pathways for 177 scenarios generated by 25 IAM and systems dynamics model versions (some models had different versions that are accounted for in this counting) [66,100]. Only those modeling runs that are successful in limiting end-of-century warming to 1.5 °C, both with and without intermediary temperature overshoot, were included. Within this grouping, 90 scenarios from 13 different studies meet the criteria. The data used here is available at the IAMC Scenario Explorer Portal [66]. The computer code used to process the data here is available in **Appendix A** and available online on GitHub.

2.3. Overview of Negative Emissions Technologies and their Treatment in Integrated Assessment Models

The vast majority of IAM simulations in the 1.5 ºC database find that NETs deployment will need to ramp up rapidly over the coming decades, mostly between 2020-2050, and then be sustained in order to meet climate targets (**Figure 2-2**). Almost all the modeled NETs capacity is BECCS and AR with only a small number of studies including DAC. In virtually all cases, the models assume that we can achieve rapid scale-up times and large deployments by the end of the century. Most model results show that NETs will follow a logistic growth path, where exponential growth transitions to a constant level of deployment. Other scenarios show continued exponential growth through 2100. In aggregate, these model scenarios indicate that we would deploy afforestation at an average scale of ~5 $GtCO_2$/year (range 2-10 $GtCO_2$/yr) and BECCS on average ~12 $GtCO_2$/yr (range 5-20 GtCO2/year) by midcentury and continuing through 2100. At present we are relying on reforestation for <<1 $GtCO_2$/yr and BECCS for 0 $GtCO_2$/yr, highlighting how rapidly we would need to scale up these technologies. The likely effects of these activities on fertilizer consumption, biodiversity, food prices, air quality, and water availability (to name a few) would be significant and is only beginning to be estimated.

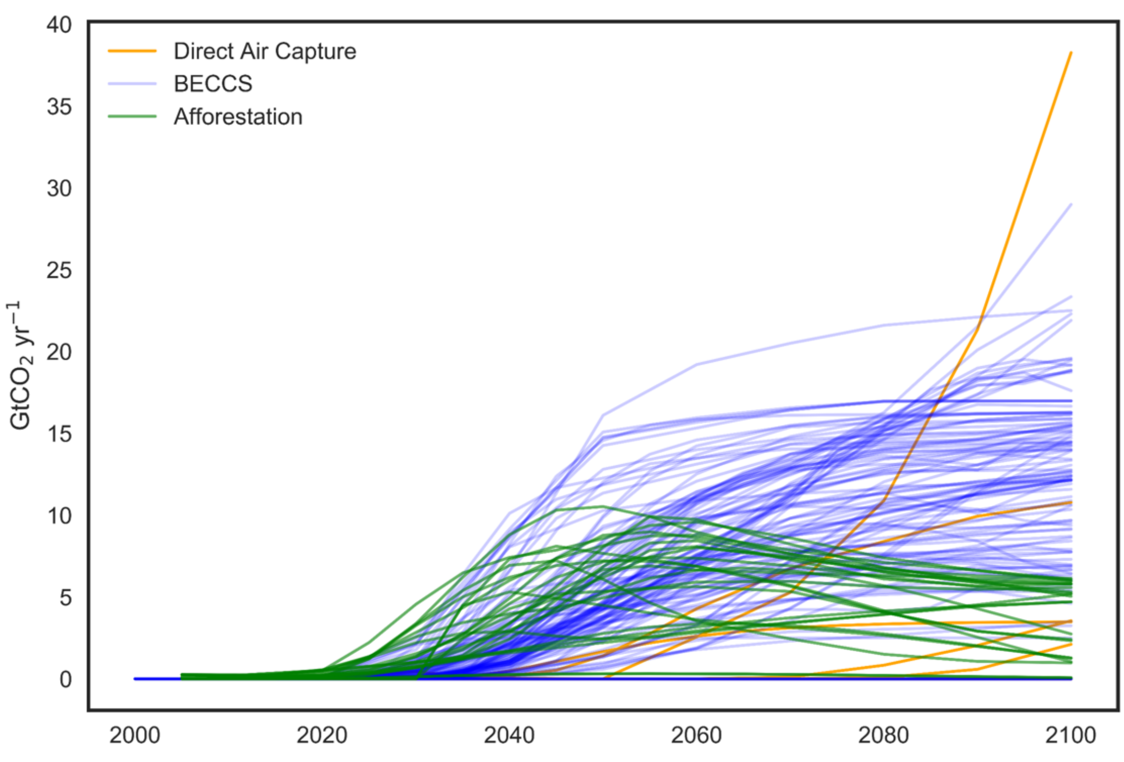

Figure 2-2. A comparison of NETs results from several different IAMs and system-dynamics models reveals that virtually all rely primarily on BECCS to limit warming to 1.5 C by 2100.

These technologies are being deployed in the models at large scales even though they have not been demonstrated at commercial scale. There is an urgent need to significantly improve the way NETs are being handled by IAMs, and incorporate a broader portfolio of technologies so that scientists, engineers, policymakers, and the public are better informed for making the best decisions possible related to NET research and development. Data Source: Huppmann et al., 2018

2.3.1. Afforestation and Reforestation

Reforestation entails allowing previously deforested lands to revert back to their natural states, while afforestation involves the growth of new forest lands where they did not previously exist (e.g., native grasslands) [101]. Both create a negative emissions pulse during the growth phase for new forests. Tradeoffs between afforestation, bioenergy, and food will limit its deployment. But unlike other forms of NETs, we have empirical evidence about how effective afforestation activities are and this will enable us to calibrate models to provide better projections [102].

2.3.2. Bioenergy with carbon capture and storage

BECCS is the most widely modeled NET to date and many models suggest it would require the planting of significant areas with bioenergy crops as well as major new infrastructure development in the form of power plants, CO_2 pipelines [103], and wells and monitoring equipment for geological sequestration [24]. The growth of biomass for BECCS, as well as for liquid fuels, in which the carbon is reemitted to the atmosphere upon combustion in non-point sources (e.g., transportation), result in large water and fertilizer demands.

2.3.3. Direct Air Capture

Even though direct air capture will require less water and land use per ton of CO_2 captured than BECCS and AF, these impacts may still be significant and need to be quantified [96]. DAC would account for a significant portion of global energy demand if the large deployments envisaged by some IAMs are achieved [96]. DAC will entail the same issues in monitoring geologically sequestered CO_2 as BECCS and post-combustion CCS of fossil fuels [104].

2.3.4. Emerging NETs

The land use requirements and other side effects of BECCS and AR are contributing to increasing discussion of other forms of NETs. These approaches have not generally been incorporated into IAMs more widely, and opportunities and challenges exist with modeling these approaches.

2.3.5. Accelerated Weathering

Accelerated weathering (AW) refers broadly to reaction of CO_2 with mineral species (primarily calcium and magnesium silicates) to form thermodynamically favorable and chemically stable solid carbonates. AW can be performed on virgin feedstocks (like basalt or olivine rock) or on waste streams (alkaline streams such as steel slag) [105]. AW is an example of a NET with large potential global capacity and co-benefits, but also significant potential side effects that have generally not yet been considered by the IAM community. Global potential for AW could be as high as 95 $GtCO_2$/yr for dunite, 4.9 $GtCO_2$/yr for basalt [106]. There is a growing body of literature focused on deploying AW on croplands, which could provide co-benefits of increased yields through enhancing soil alkalinity and structure and providing beneficial use for silicate waste materials [107]. Runoff from land application could also help offset ocean acidification [108]. The best locations for terrestrial AW are in warm and humid regions offering the potential to reduce land use stress in these regions by increasing crop yields for bioenergy and food [109]. AW also has potential for co-deployment with afforestation, reforestation, BECCS, biochar; capturing these interaction effects with IAMs could increase the total rate capacity of negative emissions while reducing costs. However, large scale deployment also risks concentrating significant environmental costs associated with surface mining, as well as soil contamination with metals, and surface water alkalinity increases in these regions.

2.3.6. Soil Carbon / Biochar

While reforestation is the most widely discussed surface-based negative emissions approach, several other forest and agricultural land management practices are lower-cost (<$10/tCO2) and also provide co-benefits in the form of improved air, water, and soil quality, and biodiversity enhancement [110]. These practices could be implemented on existing forest or agricultural lands and thus reduce land stress relative to other NETs (e.g., BECCS/AR). For forest management, accelerating regeneration of disturbed areas, extending timber rotations, and thinning to promote higher stand growth / avoid large wildfires could increase capacity of existing forest lands without significantly encroaching on other land uses. On agricultural lands, cover crops, adoption of low-till agricultural practices, conversion to perennial crops, and improved grazing land management could all result in significant atmospheric carbon removal [29]. The combined carbon cycle and economic modeling of IAMs could allow assessment of both the direct and indirect (i.e., market-mediated) effects of such activities, although substantial parametric uncertainty could affect results. Sensitivity analysis using IAMs could help highlight uncertain parameters with a greater impact on global climate results such that research funding could be better directed at better constraining these estimates.

2.3.7. Ocean-based approaches

The ocean offers near limitless potential for negative emissions even though the costs and impacts of these approaches are only beginning to be characterized [111]. Some of the research activity in this space is focused on promoting coastal ecosystems to sequester carbon in soils and sediments [112]. IAMs could highlight the opportunities to avoid further degradation of these ecosystems as a relatively low-cost climate abatement method with significant co-benefits, including climate adaptation, clean water, and biodiversity enhancement [113]. For IAMs to capture these effects, spatially explicit datasets, as well as a more detailed understanding of carbon cycle dynamics at play in these complex ecosystems is needed [114].

2.4. Influence of Near-term Investment and Policy Incentives on Negative Emissions Scaling Potential

IAMs are, at their core, economic models that make projections about technology deployments, carbon prices and emissions [115]. While some NETs, such as AR or CBC could achieve emissions reductions at costs <$100/t$CO_2$ today, these costs are still higher than most voluntary markets [90]. Many of the scenarios used for the IPCC 1.5ºC report estimate that carbon prices will exceed the costs of NETs by midcentury. This is shown for the case of DAC, commonly assumed to be one of the more expensive NETs, in **Figure 2-3**. While the costs of DAC ($100-600/t$CO_2$) are higher than carbon cost projections in the models today, by midcentury the average cost of carbon is near the upper bound of the DAC cost.

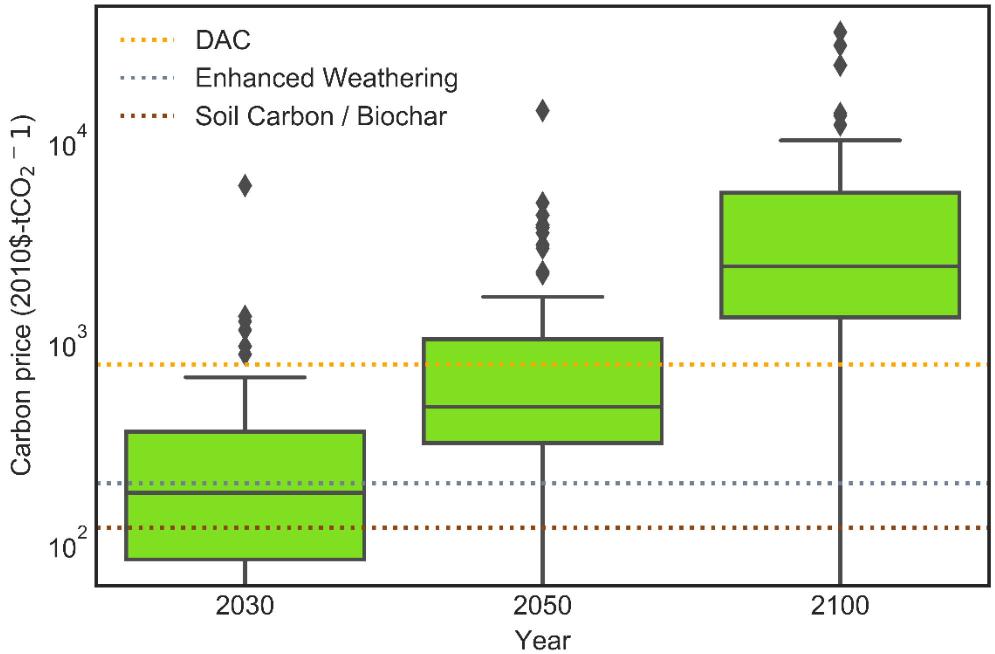

Figure 2-3: Carbon prices for 1.5 °C scenarios at three different time horizons relative to the upper bounds of cost estimates from Minx 2018 for NETs not yet widely incorporated into IAMs.[vii]

The extent to which IAMs rely on future negative emissions is largely a result of structural elements of the scenarios designed by modeling teams in order meet the targets set by policymakers, which generally focus on meeting specific temperature targets (e.g., 1.5 or 2°C) in 2100 [116]. With the promise of future NETs, near-term emissions can remain high, leading to elevated atmospheric CO_2 levels which can be drawn down later, as long as temperature returns to "safe" levels by 2100. This increases the likelihood that the emission path will temporarily overshoot the temperature target [117]. The incremental damage (e.g., from increased extreme weather) during temperature overshoot is not well understood or fully taken into account by current-generation IAMs [118]. Additionally under assumptions of increased climate sensitivity, even temporary overshoot above "safe" climate targets may have significant consequences, which even large amounts of NETs cannot reverse within decadal timescales [119]. This is made more likely by the relatively simplified climate models of IAMs that do not capture irreversible climate feedback effects (e.g., ice sheet albedo, thawing permafrost), since later carbon removal using NETs may only partially offset warming from previous emissions [120]. Finally, the use of NETs will be greater than what is optimal if NETs generate uninternalized environmental costs of their own (e.g., biodiversity loss, water contamination).

IAMs were developed to help explore sensitivity to and implications of a variety of "known unknowns", including social discount rates and rates of technological change. While imperfect, they are valuable tools to assess implications and tradeoffs of meeting the aggressive targets needed to limit catastrophic climate damages. Rather than being scrapped, they should be improved and

[vii] By 2100, most carbon prices reach well above even the most conservative estimates for DAC, which is commonly thought to be the costliest NET.

supplemented with other analytical approaches [121]. For example, a recent model incorporating future risks and policy-induced technological change inverts the conventionally accepted price path of initially-low and rising GHG emissions prices, to one of initially high and declining prices [71]. Scenarios which emphasize such prompt and aggressive action in order to limit peak, rather than end of century warming would necessarily rely less on future NETs deployment and be more in line with the text of the Paris Accord, as well as the precautionary principle of the UNFCCC [9,116,122,123].

All climate mitigation technologies, including NETs, have different capacities and assumed growth rates, which affect to what extent, and how quickly they are projected to be deployed in IAM scenarios. Some IAMs (e.g., GCAM, MESSAGE) parametrize technological growth exogenously, which allows sensitivity analysis of cost/efficiency targets for different technologies which can help inform R&D investment decisions. Others (e.g., WITCH or MERGE-ETL) handle technological growth endogenously, attempting to capture responsiveness of technological change to economic incentives. Directed technological change in the context of climate change has been framed as encouraging "clean" over "dirty" technologies, which are close substitutes in producing goods. Both a price on emissions and subsidies to R&D are required to achieve the least cost transition from the incumbent dirty process to the innovative clean process. But NETs are fundamentally different from energy production technology because demand for carbon dioxide removal is induced entirely by policy rather than demand for a final consumption good. Certainly, R&D will be needed to overcome the scale barriers to these technologies, but entirely new markets will also need to be created. The scale of these markets would exceed that of some of the largest industries in existence today. For example, the median peak projected CO_2 removal rate for IAM scenarios limiting end-of-century warming to 1.5 C (~15 Gt CO_2-yr^{-1}) is over 200% of 2018 natural gas combustion emissions, and over 133% of the total mass of fossil fuels extracted globally [124–126]. For reference, the fossil fuel industry is currently subsidized to the tune of $4.7 trillion-$yr^{-1}$ or 6.3% of global GDP [127]. This is entirely inconsistent with climatically-meaningful emissions *reductions*; let alone global-scale negative emissions. However, if the 'market' for NETs is established and scale economies are achieved, the policy cost of additional negative emissions will fall [128,129].

Two important problems arise at this point. First, while it is not hard to imagine some harmonized global price on greenhouse gas emissions, it is less easy to imagine an internationally harmonized system for subsidizing the development of new technology. The institutional framework for the policies used in the IAMs should be consistent with our understanding of the costs of coordinating R&D policies in polycentric governance regimes. The second difficulty with NETs and the standard model of directed technical change is that many NETs have no value except for their contribution to lower GHG concentrations. These are not substitutes for some other way of producing goods. While R&D investment is required to bring NETs costs down, their use never becomes less dependent on the GHG price as is the case with renewables replacing fossil fuels. The optimal price path for inducing the development and deployment of NETs may be different from the optimal price path for inducing a shift from fossil energy to renewables. It is probably not appropriate to assume, as is often done now, that a single economy-wide GHG price can induce both an optimal mitigation path and the optimal deployment of NETs.

To explore technological growth outcomes across IAMs, we adapted the methodology of Wilson et al (2013) [130] to illustrate the projected capacity growth of negative emissions technologies for IAM scenarios limiting warming to 1.5ºC by 2100. Assuming a logistic saturation pathway for all new technologies, Wilson et al. looked for regularities in the relationship between the extent of saturation (k) and the time (t) it takes to achieve [130]. The authors compare the historical transition to new energy technologies to the modeled energy technology transitions in IAMs. We apply the same method to NET technologies in IAMs, using data from three major model comparison scenarios included in the IAMC database, SSPx-1.9 [131], ADVANCE[132], and CD-Links [133].

Here, the k-value for each technology was calculated as follows:

$$k = C_{max} - C_{2005}$$

Where: C_{2005} = the carbon sequestration capacity in 2005; and C_{max} = the maximum carbon sequestration capacity reached between 2005 and 2100, both in $GtCO_2$/yr. This is consistent with the way "cumulative capacity" for energy technologies is calculated in the 1.5ºC database and creates an analogous metric for carbon sequestration technologies to the energy generation metric in Wilson *et al*. We calculate Δt as the elapsed time in years between the capacity reaching $C_{2005} + 0.1k$ and $C_{2005} + 0.9k$

The k-values were then normalized by cumulative CO_2 emissions from 2016 until net-zero emissions ($GtCO_2$), which drives the need for NETs deployment given a temperature or radiative forcing target. The results are overlaid in **Figure 2-4** with the Wilson results (translated downwards in log-space) to illustrate how IAM results regarding NETs scale-up compare to those for energy technologies in IAMs and for historical energy technology transitions. Model output from 1.5°C compliant scenarios generally project technological growth for new NETs technologies more conservatively than historical energy system trends might suggest. This is broadly consistent with the findings that Wilson reported for the historical and projected future transitions in the energy sector. The scaleup rate and extent of some NETs with large resource demands and side effects (e.g., BECCS) is limited by land use constraints, and even then may be parametrized overly optimistically and/or limited by social factors including perceptions and concerns over equity [134,135]. At the same time, there is a risk that NETs with large potential for technological breakthrough (e.g., DAC) and/or co-benefits (e.g., AW) may not be effectively modeled in IAMs. In particular, technologies with a greater degree of modularity (e.g., DAC processes capable of using low-temperature waste heat) may have more rapid scale-up potential than "bulkier" technologies requiring more intensive investments in physical plants, supply chains, and pipeline networks (e.g., BECCS), especially in the initial phase [96,136,137]. It is clear from **Figure 2-4** that there is wide disagreement among the current models about the scalability of NETs technologies. For BECCS, the time required to achieve a similar level of diffusion varies from 20 years to a long as 65 years.

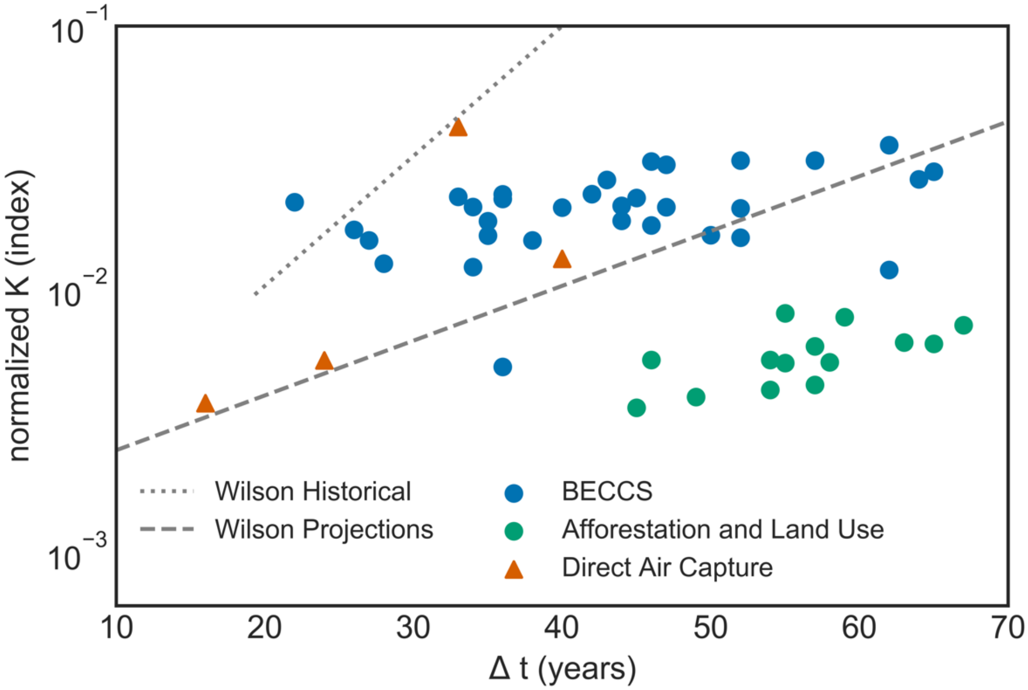

Figure 2-4 Projected capacity growth of negative emissions for IAM scenarios limiting warming to 1.5 °C by 2100.[viii]

2.5. Consideration of Sustainable Development Implications of Negative Emissions Technologies

Mitigation via emissions abatement and NETs directly contribute to climate action, one of the United Nation's Sustainable Development Goals (SDGs) [138]. SDGs are target areas that the UN has laid out to help guide policy decisions in international development. While existing Nationally Determined Contribution pledges for meeting commitments under the Paris Accord are synergistic with some SDGs (e.g., Good Health and Well-Being from reduced fossil fuel combustion emissions), they may have trade-offs with others (e.g., food and energy security). The magnitude and sign of these interaction effects can differ by geographic region [139]. The scales at which IAMs project future NETs deployment only magnifies these potential tradeoffs. Nonetheless, IAMs have already proven to be a valuable tool for analyzing tradeoffs between BECCS, AF and other mitigation activities along the dimensions of food/energy security and biodiversity preservation, as well as policy instruments used to incentivize them [26]. The use of alternative NETs will likely pose new tradeoffs and potentially ameliorate others, and it is critical for these to be considered in IAM scenario design. **Figure 2-5** summarizes potential impacts of candidate NETs in terms of their negative emissions potential, costs, side effects, co-benefits, and interaction potential with SDGs, synthesizing data and discussion from literature, and combining it with our own analysis. The full methodology and sources behind this figure are documented in **Appendix A**. NETs which restore or enhance natural processes tend to have greater synergy with SDGs but have scaling limitations and/or reversibility risks if the stored

[viii] The "historical" dotted line reflects the diffusion of 6 energy technologies globally found by Wilson et al. The "projected" dashed line reflects Wilson et al's MESSAGE-IAMF projections for Core Regions. Both overlays are translated downwards in log-space.

organic carbon is re-oxidized. NETs which require the conversion of productive agricultural lands to either forest or bioenergy production (i.e., afforestation and BECCS) pose tradeoffs with the SDGs of poverty and hunger elimination; especially at the scales envisaged by most IAM projections. More "engineered" NETs which sequester CO_2 in the subsurface or stable chemical compounds are more uncertain in terms of SDG interactions, depend heavily on implementation, and could provide co-benefits in one location and tradeoffs in another. As modeling teams begin to incorporate a fuller portfolio of NETs into IAMs, careful consideration should be given to these dimensions when designing scenarios, imposing realistic constraints on deployment, and communicating policy implications to stakeholders.

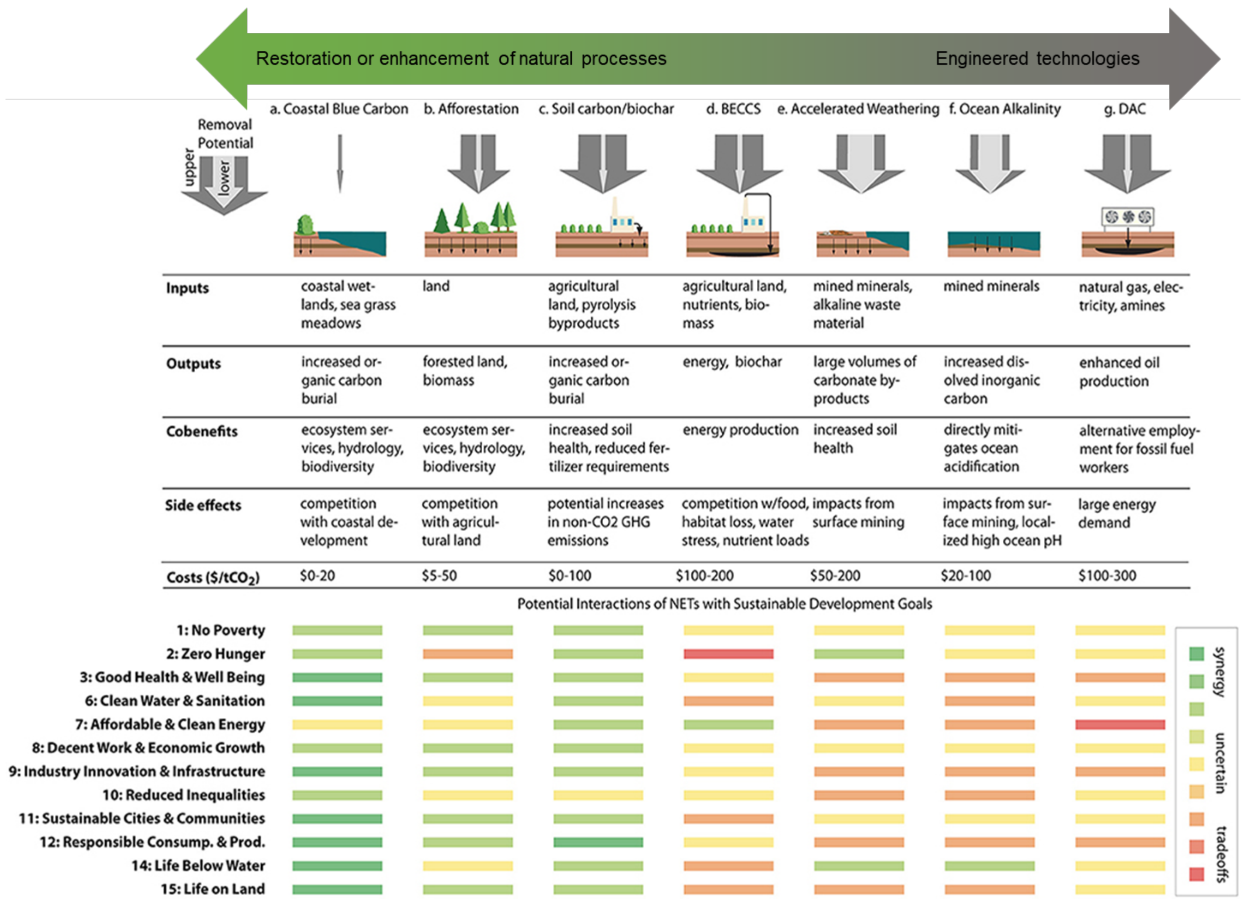

Figure 2-5 NETs each have different sequestration capacities, inputs, outputs, co-benefits and tradeoffs with Sustainable Development Goals that are not directly related to climate change mitigation.[ix]

[ix] We selected a subset of SDGs for which NETs have significant potential for synergism or antagonism, synthesizing data and discussion from literature, and combining it with our analysis. Full methodology and sources for this figure are provided in **Appendix A**. Interaction potential between many SDGs and NETs have been largely unexplored in the literature and would depend heavily on the specifics of how the technologies are implemented and the scale at which they are deployed.

Even under optimistic assumptions of agricultural intensification and use of abandoned or marginal land for bioenergy production, meeting competing land demands of climate mitigation, food and energy security, and biodiversity preservation will be challenging [140]. Although projections differ by model and scenario exactly where biomass production and AR activities would occur under aggressive global climate mitigation efforts, most model scenarios project large deployments of NETs in the developing world, which is responsible for only a small fraction of cumulative anthropogenic emissions to date. This poses obvious tradeoffs with SDG 10: Reduced Inequalities. **Figure 2-6** shows downscaled results for second-generation biofuels production in 2100 in an RCP2.6 scenario generated using GCAM, which shows large impacts on sub-Saharan Africa and portions of the northern hemisphere that are currently not major agricultural regions but could be as the planet warms [141].

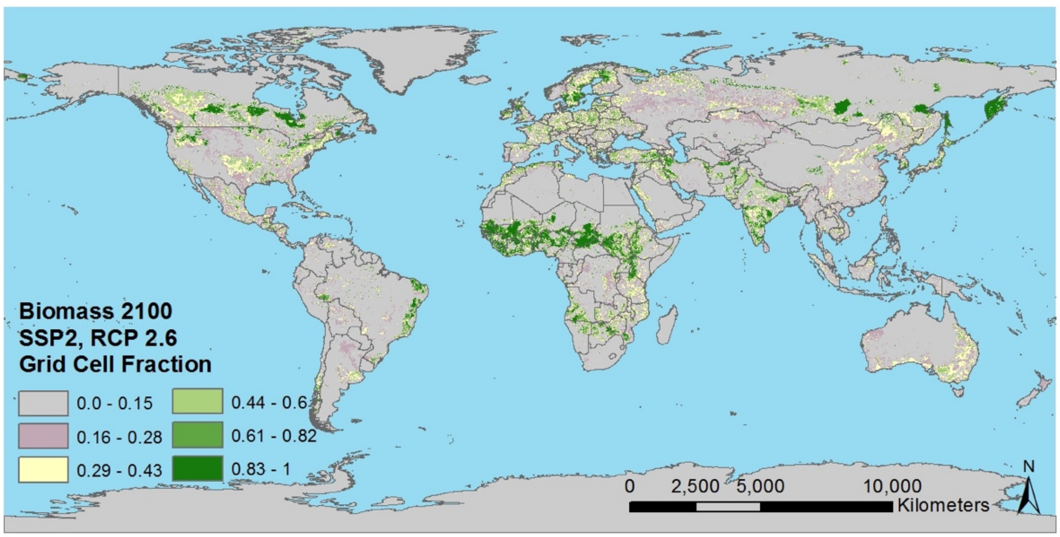

Figure 2-6: World map showing projected fraction of land area devoted to dedicated bioenergy crops in a scenario consistent with limiting warming to 2 ºC (RCP 2.6), using downscaled data from GCAM.[x]

Other models anticipate similar impacts in South America, with large portions of the Brazilian cerrado/Amazon being converted to intensive bioenergy feedstock production in aggressive mitigation scenarios [142]. **Figure 2-7** summarizes land-use impacts of afforestation and bioenergy production for 1.5 ºC scenarios, aggregated by 5 major geopolitical regions reported in the 1.5 ºC database, as well as globally. The median projection for global land area devoted to bioenergy in 2100 (with and without CCS) is 364 Mha, constituting approximately 3% of total global land area, and nearly 20% of current global cropland area (1870 Mha) [143,144]. Land use impacts of afforestation are projected to be much larger, with a median of 7% of global land area by 2100, and much of this taking place in the developing world. These large scaleups are projected to be delayed to late-century in all regions as evidenced by the difference in deployment between 2030 and 2100 results. As in Figure 1, these results are driven largely by the underlying model architectures and scenario designs, for which the objective functions are based on economic cost minimization and/or market equilibrium. Externalities such as environmental damages not directly related to climate (e.g., biodiversity loss, water quality

[x] Data source: Calvin et al., 2019b

degradation), and other considerations such as inequality and inequity are generally not included in the formulations.

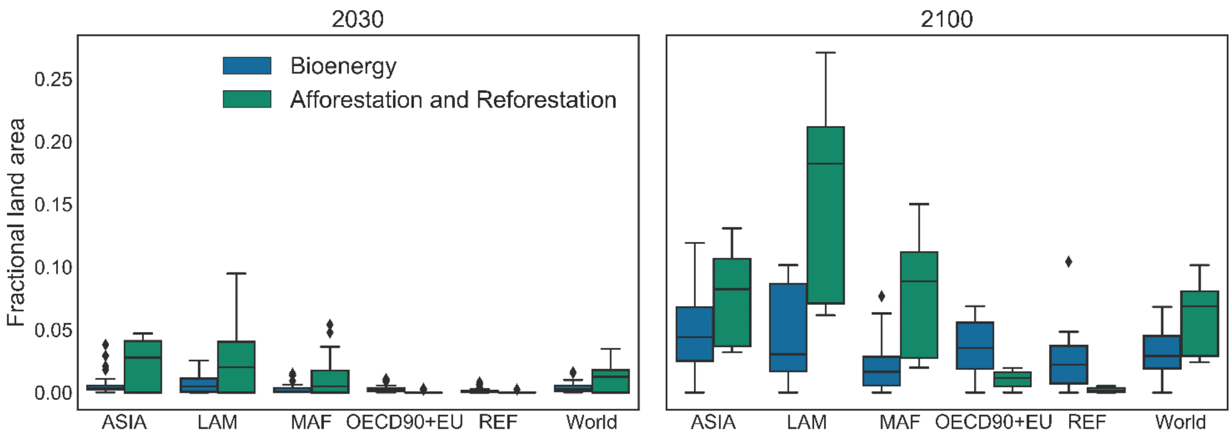

Figure 2-7: Summary of fractional land area in each region devoted to bioenergy and re/afforestation for scenarios limiting end-of-century warming to 1.5 C from 7 IAMs.[xi]

2.6. Conclusions

Existing IAM scenarios rely heavily on land-based approaches (BECCS and AR) to achieve warming targets largely because of historical artifacts associated with the way these models were developed. Most IAMs were developed around energy and emissions modeling with land-use change models added to include the role of bioenergy and forestry. Under stringent emissions constraints, the models suggested pathways using these land-based approaches [145]. Other dedicated NETs such as DAC or AW have not been widely included because the historical development paths did not have an obvious place for their inclusion. The results of our analysis suggest that the integrated assessment modeling community should consider incorporating a broader portfolio of NETs into existing model structures. Doing so would provide valuable information for a range of stakeholders and policymakers. We suggest that the IAM community evaluate the extent to which this highlights opportunities for more limited near-term deployment of potential alternative NETs, as opposed to presuming future large-scale deployment of more uncertain technologies. In particular, modelers should consider potential co-benefits and overlaps with other SDGs in conjunction with other aggressive near-term mitigation efforts. This would reduce risks associated with irreversible climate change by minimizing or eliminating carbon budget overshoot.

IAMs were developed as one of a suite of tools to assess potential coordinated international policy responses to climate change. They allow assessment of implications of and sensitivity to a wide range of parameters (e.g., technological rates of change and social discount rates) at global scales, and compliment regional and local-scale economic and energy systems models which help inform implementation of the top-line policy requirements found by IAMs with more granularity. Clearly, IAMs and their treatment of NETs needs to be improved and complimented with other analytical

[xi] The six aggregated regions included in the database are: ASIA; LAM (Latin America and the Caribbean); MAF (Middle East and Africa); OECD90+EU; REF (Reforming Economies of Eastern Europe and the Former Soviet Union).

approaches if these models are to continue to provide useful insights. Results projecting large-scale future deployment of NETs should be communicated to and interpreted by policymakers and other stakeholders as warnings of the potential impacts of the NETs themselves, rather than prescriptive licenses to delay taking action and attempt reverse the damage later. An interdisciplinary effort by economists, environmental scientists, engineers, political scientists, and ethicists will be required to improve IAMs and the policies they are meant to inform if we are to avoid the worst damages of climate change, as well as from attempts to reverse it with a speculative future NETs "moonshot".

2.7. Chapter 2 Acknowledgements

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Chapter 3 - Food-Energy-Water Implications of Negative Emissions Technologies in a +1.5°C Future

3.1. Chapter Summary

Scenarios for meeting ambitious climate targets rely on large-scale deployment of negative emissions technologies (NETs), including direct air capture (DAC). However, the tradeoffs between food, water and energy of different NETs deployment is unclear. Here we show that DAC could provide up to 3 GtCO2-yr^{-1} of negative emissions by 2035 — equivalent to 7% of 2019 global CO2 emissions — based on current-day assumptions regarding price and performance. DAC in particular could exacerbate demand for energy and water, yet it would avoid the most severe market-mediated effects of land use competition from BECCS and afforestation. This could result in staple food crop prices rising by approximately 5-fold relative to 2010 levels in many parts of the Global South, raising equity concerns about the deployment of NETs. These results highlight that delays in aggressive global mitigation action greatly increase the requirement for DAC to meet climate targets, and correspondingly, energy and water impacts.[xii]

3.2. Introduction

During the 2015 UNFCCC Conference of the Parties in Paris, world leaders agreed to limit global temperature change to well-below 2 °C and pursue efforts to meet 1.5 °C by 2100.[55,2] These targets require rapid declines in greenhouse gas emissions, reaching net-zero by mid-century.[18,146] Recent progress on mitigation has been highly inconsistent with this goal.[147,54] With emissions still rising,[148] integrated assessment modeling (IAM) scenarios of the global economy and climate system have increasingly relied on the presumed ability to deploy net-negative emissions activities in order to meet these ambitious climate targets.[20,21] There are a number of ways by which to remove already-emitted CO_2 from the atmosphere[29,88–90,149] Yet the vast majority of IAM scenarios include just two land-based negative emissions technologies (NETs): bioenergy with carbon capture and storage (BECCS) and afforestation (**Appendix B** Fig. 1).[150,151] The degree to which these NETs would compete for productive agricultural and natural land, as well as their impact on water resources if deployed at climatically-relevant (i.e., Gt-CO_2-yr^{-1}) scales has raised concerns about the viability of these approaches.[28,140,152–154,]

In light of the foreseeable tradeoffs inherent to land-based negative emissions, recent work has focused on developing direct air capture (DAC) technology. DAC is an engineered separation process that uses aqueous or amine sorbents to remove CO_2 from ambient air, compress it and inject it into geologic reservoirs. The physical footprint of these units would be much smaller than BECCS or afforestation and it would not require any particular land type, only proximity to a geologic reservoir for storage.[30,41,90] However, CO_2 exists in low concentrations in ambient air and so DAC is likely to be energy-intensive to deploy. This is intuitively the case for DAC processes that require combustion heat for which fossil fuels are currently the most economical source. However, processes that are

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[xii] This chapter was adapted from: Fuhrman, J., McJeon, H., Patel, P., Doney, S. C., Shobe, W. M., and Clarens, A. F. "**Food–Energy–Water Implications of Negative Emissions Technologies in a +1.5 °C Future**" *Nature Climate Change* (2020): 1–8.

capable of using renewable energy or waste heat would still entail large-scale construction of infrastructure (e.g., solar PV) for the purpose of disposing of CO_2 emitted previously. Due to these very high assumed costs, DAC has not been included in many integrated modeling scenarios to date.[29,31] However, multiple companies now have commercial-scale prototypes claiming much lower costs than previously estimated,[33,35,37,155,156] and several recent IAM studies have incorporated DAC into their mitigation and negative emissions portfolios.[41–43,99] In these deep decarbonization scenarios, the availability of DAC can reduce mitigation costs, avoid immediate stranding of fossil fuel assets, and benefit energy exporting countries by preserving the value of their fossil fuel reserves under stringent climate policies.[42] Meeting a 1.5 °C temperature target may now only be possible if large-scale DAC is available.[43] However, relying on future availability of DAC and then failing to achieve the rapid scale-ups to global-scale deployment could risk overshooting this target by up to 0.8º C.[41]

Increased near-term mitigation effort is required to avoid the steepest tradeoffs associated with future rapid decarbonization, and to avoid "lock-in" to large-scale NETs deployment to meet the Paris targets.[23,99] But the emergence of DAC as a possible climate mitigation strategy makes it important to gain understanding of its side-effects if deployed at $Gt\text{-}CO_2\text{-}yr^{-1}$ scales, weighed against its potential to reduce some of the undesirable impacts of BECCS and afforestation (e.g., land and water demand), and to offset emissions from expensive-to-mitigate sectors (e.g., liquid fuels for transportation).[157] The unprecedented financial transfers[47,53] (e.g., emissions offsets and direct public subsidies) that would be required to reach net-negative emissions globally make it even more critical to understand these potential side-effects in advance, and minimize the extent to which the deployment of any NET generates unintended consequences of its own.[151] Previous work on the potential benefits and side-effects of DAC has emphasized its ability to reduce energy system transition burdens (e.g., CO_2 prices), while itself requiring large amounts of energy.[41–43] It has been shown that DAC would significantly reduce water use for negative emissions in comparison to total evapotranspiration from bioenergy crop and forest cultivation, plus additional water demand for bioelectricity generation.[28,41] However, it is also important to understand how different NETs could affect water quality (e.g, thermal and chemical pollution) associated with withdrawals from surface and groundwater, as well as consumption (i.e., evaporative losses) that contribute to water scarcity.[158,159] Proper contextualization of each of these relative to other current and projected anthropogenic perturbations to water resources is also imperative to best inform policymakers and other stakeholders considering multiple environmental objectives (e.g., water conservation and climate mitigation). Land use impacts of DAC are considered negligible compared to BECCS and afforestation, but detailed quantitative assessment of implications for global agriculture systems (e.g., food prices) is largely missing from IAM literature on DAC and other NETs. In particular, spatially-disaggregated results for where different NETs might be deployed under different policies, and assessment of associated impacts on food, water, and energy systems is needed to better inform equity considerations of international policymaking.

Here, we use the Global Change Assessment Model (GCAM), a technology-rich IAM with detailed treatment of the energy, water, and land sectors[115] to evaluate impacts and tradeoffs of a portfolio of three distinct types of NETs (i.e., afforestation, BECCS, and DAC) in meeting two representative emissions pathways from the IPCC 1.5 °C Special Report.[18] We investigated whether DAC could help ameliorate costly food-water-energy tradeoffs when deployed alongside of BECCS, afforestation, and other technology options for avoiding CO_2 emissions altogether (e.g., renewables, point-source CCS). In light of recent, more optimistic estimates for the cost of DAC technology, we investigate when this technology could begin to play a role in the mitigation portfolio under aggressive near-term decarbonization policy that seeks to limit overdraft of a small and rapidly dwindling 1.5 °C global emissions budget. Additionally, the side-effects associated with increased negative emissions requirements resulting from delayed mitigation ambition, in meeting the same end-of-century temperature goal are quantified. Finally, we provide greater resolution as to where DAC and other negative emissions activities and associated side-effects could take place spatially, at the scale of geopolitical regions. Throughout our analysis, we compare land, water, and energy use for each of these NETs to other current-day and projected anthropogenic perturbations to these resources.

3.3. Methods

We used GCAM version 5.2, accessed on November 8th, 2019 and ran scenario permutations on the University of Virginia high performance computing cluster, Rivanna. We imposed two constraints on global CO_2 emissions pathways, which represent high and low overshoot trajectories of the 1.5 °C end-of-century temperature target from the IPCC Special Report on 1.5 °C. Both emissions constraints are assumed to begin in 2025. The first emissions pathway seeks to limit overshoot of the 1.5 °C temperature target, which is broadly consistent with the scenario design logic suggested by Rogelj et, al (2019).[48] Peak mean global temperature reached in this scenario is 1.56 °C above pre-industrial levels in year 2045, before subsequently declining to 1.32 °C by 2100. The second pathway allows near-term mitigation to proceed more slowly, with associated higher intermediary overshoot of the 1.5 °C temperature target, peaking at 1.78 °C in 2055, before returning to approximately the same temperature as the low-overshoot scenario by 2100. This allows direct assessment of the impact of delays in near-term ambition on longer-term tradeoffs associated with negative emissions. We emphasize that an explicit consideration in our scenario design was to reduce end-of-century warming as well as reliance on future net-negative emissions, and that both emissions trajectories are at odds with current and intended future climate action.[160]Additional delays in mitigation will increase the requirement for negative emissions in the future.[54,147] The emissions constraints imposed, as well as the resulting CO_2 concentrations and global average temperature anomaly trajectories are reported along with historical data for each of these in **Appendix B** Fig. 2.[148,161,162] GCAM endogenously calculates the CO_2 prices required to meet the emissions constraint imposed in each model period. Land use change emissions are included under the constraint and their price is determined as an exogenously-specified proportion of the fossil emissions price. This is done because whereas fossil fuels are largely a market commodity, much of the land use and agriculture occurs outside of regulatory frameworks in many countries.[163] Pricing land use change emissions immediately at 100% of the fossil carbon price therefore ignores existing institutional barriers to implementing land use emissions policy, including uncertainties in quantifying fluxes and reversal risks of biospheric carbon storage.[164–166] To represent long-term improvements in institutions for implementing land use policy, land use change emissions are priced here as a linearly increasing proportion of fossil and industrial emissions price, from 0 in 2025, to 100% by 2100.

DAC requires energy input in the form of process heat and electricity and financial inputs for capital expenditure and non-energy operations and maintenance. While some DAC processes require negligible water use and may actually produce water from humid air, the process modeled here relies on aqueous reactions between atmospheric CO_2 and a hydroxide solution and has evaporative water losses at the air contactor.[30,167–169] There is large parametric uncertainty with regard to the energy intensity and total cost of DAC, the latter of which depends heavily upon the assumed capital recovery factor, as well as the energy source.[170] We focus on DAC processes requiring high-temperature heat from natural gas combustion, rather than those using lower-quality waste heat or 100% renewable electricity, because detailed and harmonized specifications for these latter processes are not available in the literature due to commercial confidentiality. Energy and financial input parametrizations for high and low-cost DAC follow those used by Realmonte et al., (2019), representing upper and lower estimates for hydroxide-based DAC processes from recent literature.[30,41,171] Per tCO_2 sequestered from the atmosphere, for low-cost DAC we assume process heat input of 5.3 GJ, electricity input of 1.3 GJ, and non-energy financial input of $180. Parametrization and results for high-cost DAC, for which we used less optimistic parametrizations for energy and financial inputs, are provided in **Appendix B**. Electricity input for DAC is assumed to come from each region's grid; generation fuel mix and therefore cost and carbon-intensity is calculated endogenously. Financial inputs are assumed to remain constant in real terms over time. For water, we assume 4.7 tH_2O/tCO_2 following the detailed material balances provided by Keith et. al (2018), with withdrawals and consumption assumed equal.[30] Process heat for DAC is assumed to come from natural gas with a 95% capture rate for combustion CO_2 emissions, consistent with oxyfuel CCS processes.[41] For other CCS processes, the standard GCAM assumptions for CO_2 capture rates are used (85-95%).[30] The storage cost for carbon captured from DAC and other sources is calculated separately and endogenously by GCAM.

In equilibrium, DAC indirectly competes with other NETs for its share of contribution to the emissions reduction. For instance, given a constraint on emissions, GCAM will endogenously calculate the lowest cost option to achieve the goal by comparing the cost-effectiveness of BECCS (in both bioliquids and bioelectricity) and afforestation. Bioenergy crops can be used to achieve net-negative emissions by displacing the use of fossil fuels with CCS in electricity generation (bioelectricity), converted to liquid transportation fuels and sequestering the resulting high-purity CO_2 streams (biofuels), or used as feedstocks in durable products manufacture such as plastics (bioindustrial feedstocks). BECCS therefore largely competes on the energy supply side, but also competes for carbon negative subsidies. Afforestation largely competes with other land use demands, such as food crops and pasture, but also competes for carbon-negative subsidies. We placed no external constraints on the use of DAC and removed the default constraint on the amount of bioenergy used for negative emissions. BECCS was instead allowed to freely compete with other uses of land based on their costs, yield, and water demand. However, we kept in place the standard GCAM assumption that 90 percent of natural lands (non-commercial) are removed from economic competition (i.e., not available for expansion for bioenergy, food and fiber production, or afforestation). This is done to place reasonable biophysical constraints on the deployment of land-based mitigation and negative emissions, and to preserve much of the remaining natural land for biodiversity, species, watershed protection, recreation, and cultural value as reflected in the U.N. Sustainable Development Goals and many national-level policies. Descriptions of other GCAM model specifications can be found in the GCAM documentation.[172]

3.4. Effects of BECCS and afforestation

DAC deployment may never reach Gt-CO_2-yr^{-1} scales because it is too expensive or otherwise infeasible. The implications for energy, water, and food systems associated with meeting the low-overshoot emissions trajectory without the use of DAC are shown in **Figure 3-1**. The higher overshoot trajectory was infeasible without the availability of DAC due to constraints on agricultural and forested land expansion for agricultural production and climate mitigation. In the low overshoot trajectory, BECCS is used to produce 226 EJ-yr^{-1} in 2100, over 38% of current-day primary energy demand.[124] The use of modern biomass without CCS for heat, electricity generation, and liquid fuels production, as well as "traditional biomass" for fuel is projected to decline from a combined 83 EJ-yr^{-1} at initiation of the climate policy in 2025, to 16 EJ-yr^{-1} in 2100. The role of fossil fuels is substantially reduced, and the use of unabated coal rapidly declines to near-zero following initiation of the climate policy. Land for dedicated bioenergy crop production expands rapidly to over 5Mkm^2, a land area equivalent to over 50% of the land area of the United States and over 25% of present-day global cropland area.[173] Net deforestation is halted by 2025, but the largest increases in forested land area occur later in the century as institutions for pricing and enforcing land use change carbon pricing are assumed to be phased in. The increase in land devoted to bioenergy crops and afforestation comes at the expense of grasslands, pasture, and other crop production. These results are broadly consistent with previous IAM studies incorporating BECCS and afforestation to meet aggressive climate targets.[66] Evaporative losses from biomass irrigation and thermal bioelectricity generation are large, reaching a peak of 187 km^3-yr^{-1} in 2050. This is equivalent to nearly 15 percent of irrigation water consumption in 2010.[158,174] Fertilizer use for bioenergy crop cultivation peaks in 2045 at nearly 30% of current-day fertilizer demand. Such drastic increases in fertilizer demand for the purposes of climate change mitigation would have large environmental side effects, such as water quality degradation[175,176] but also climate effects that run counter to the CO_2 removal as excess soil nitrogen is converted to N_2O.[177]

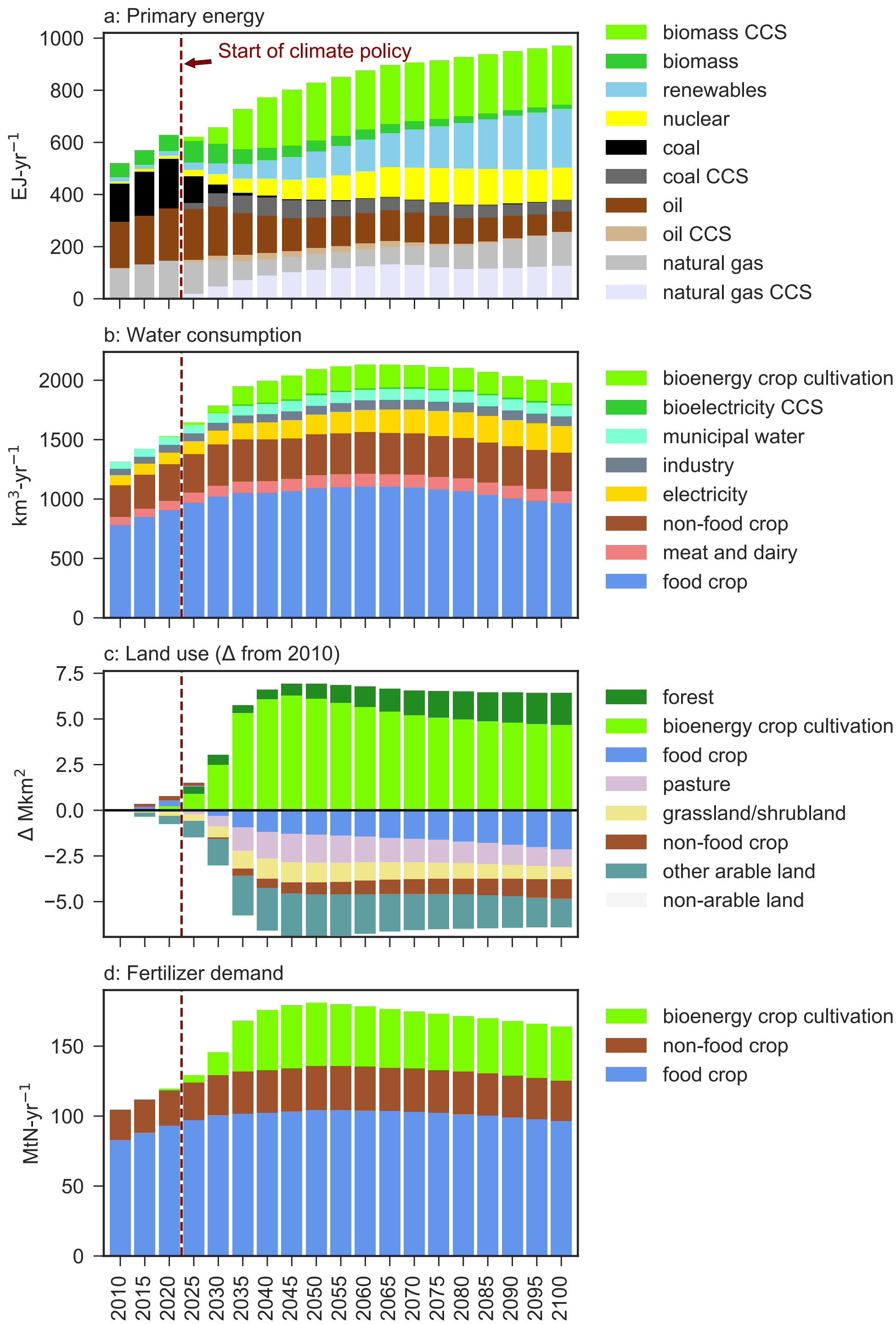

Figure 3-1: Side effects of limiting warming to below 1.5 °C without DAC available.

Projected (a) global energy, (b) water, (c) land, and (d) fertilizer demands for meeting a 1.5 °C end-of-century temperature target with low overshoot, assuming only BECCS and afforestation/reforestation will be available for negative emissions. The high overshoot case was not able to solve without the availability of DAC.

We report results for the lower (i.e., more optimistic) estimates of energy and cost inputs for DAC technology to best illustrate the potential impacts of this technology if deployed at large scale (**Figure 3-2**). Because DAC acts as a backstop to the exponential increase in CO_2 price, the mere availability of DAC in the mitigation portfolio has a much stronger effect on results than variation within the range of cost and energy inputs assessed here. In the low overshoot case, DAC is deployed at gigaton scales as early as 2035, in contrast with other IAM results which typically delay such large DAC deployments past mid-century. This primarily follows the imposition of the emission constraint, wherein we sought to model a scenario in which aggressive mitigation action is taken to limit peak temperature rise, rather than allowing the largest negative emissions requirements to be pushed far into the future to meet an end-of century target by allowing large overshoot.[48] Spatially, DAC is projected to be deployed primarily in regions such as the United States, South America, China, and Australia, which have abundant geologic storage capacity, large natural gas reserves, and the potential for inexpensive, relatively low-carbon electricity.

In all cases, much of the negative emissions requirement is driven by sectors that are recalcitrant to decarbonization (e.g., transportation). DAC displaces the use of BECCS and afforestation for negative emissions, but it also reduces the need for emissions abatement in the model. Namely, gross-positive emissions are higher in scenarios in which DAC is available, because those emissions can be offset using DAC and still meet constraints on net emissions. The negative emissions pathway of using bioliquids to manufacture durable products and thereby storing carbon (i.e., bioindustrial feedstocks) is not actively utilized when low-cost DAC is available, as the biomass and land area devoted to its growth can be more profitably used for other purposes such as transportation fuels or food crops. In the high overshoot case, even the relatively modest delays in near-term mitigation greatly increase the reliance on future negative emissions, which must be met by DAC due to constraints on land available for BECCS and afforestation. This highlights the importance of aggressive mitigation in the near-term, as DAC, and indeed all NETs have yet to be deployed at scale, and high overshoot may be irreversible if these technologies prove infeasible or incapable of keeping up with runaway climate change.[151]

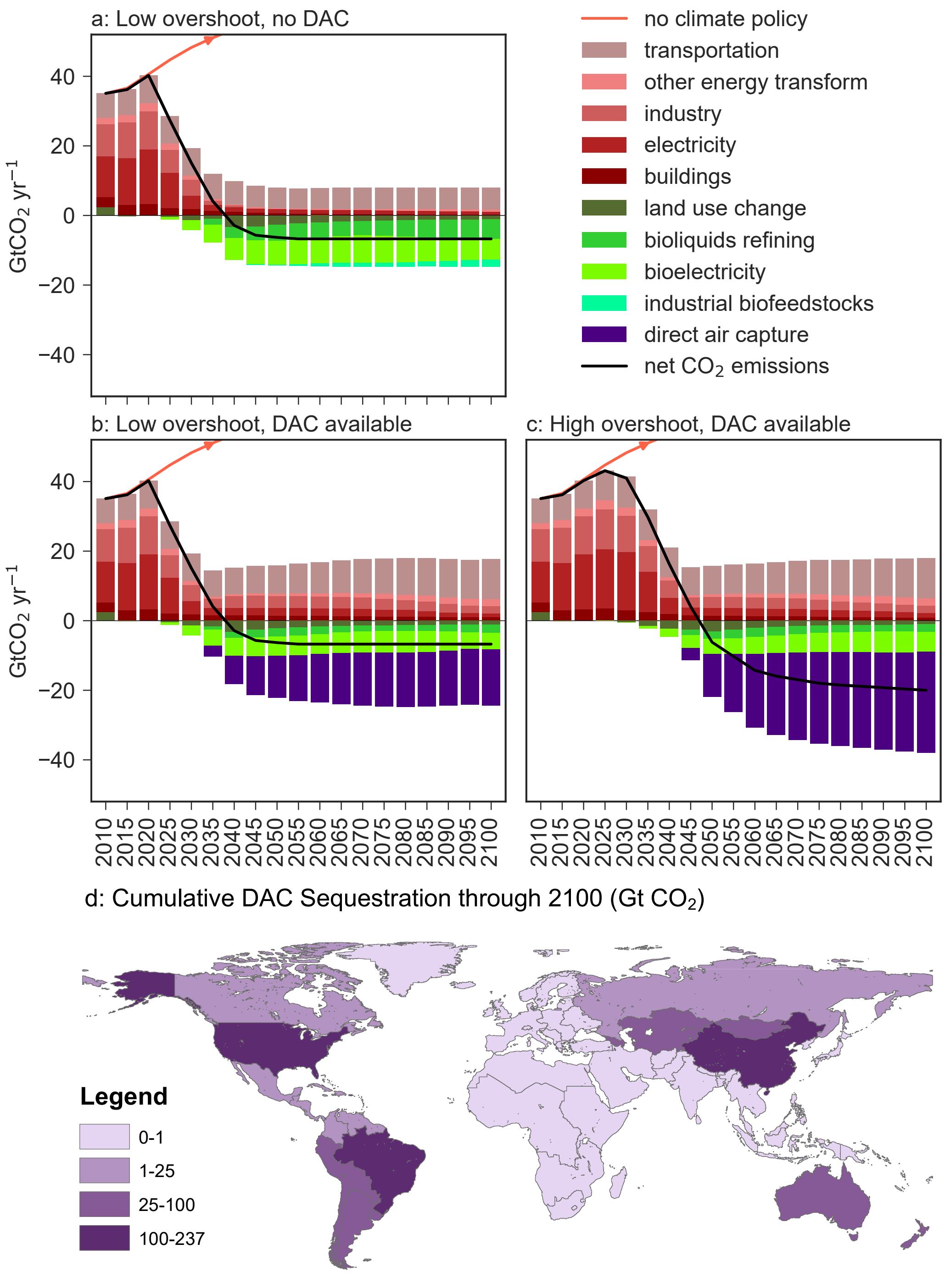

Figure 3-2: Positive and negative CO_2 emissions by sector and region.
a-c) Positive and negative CO_2 emissions by sector. d) spatial distribution of DAC deployment in the low overshoot scenario. Results from less optimistic parametrizations of DAC can be found in **Appendix B**

3.5. Crop pricing under NET deployment

We consider three major grain staple crops: corn (maize), wheat, and rice and quantity-weight the results by mass to better reflect regional differences in food supply. Food prices peak at 15% above 2010 levels in the no climate policy case due to population growth and a growing global middle class. However, this is likely an underestimate of food price increases that would occur absent climate mitigation action because GCAM does not currently consider climate damages such as reduced yields or crop failures due to extreme drought or flooding that are expected in a warmer world.[178–180] Incorporating such bidirectional feedbacks between the earth and human socioeconomic systems into GCAM is an area of cutting-edge, ongoing research.[69] Without the large-scale availability of DAC, end of century food prices are projected to increase to over 7-fold of 2010 levels (**Figure 3-3-a**). Food price impacts are regionally heterogeneous, and are projected to be most heavily concentrated in sub-Saharan Africa. The availability of low-cost DAC attenuates the most severe effects of land-intensive negative emissions on food markets, but food prices still increase by approximately 3-fold globally relative to 2010 levels and regional disparities remain, owing to still-large land use for BECCS and afforestation. These severe food price increases are largely attributable to the imposed constraint on the ability of "commercial land" (e.g., agricultural and forestry activities for food, fiber and bioenergy production) to expand into otherwise "natural" uses of land (**Figure 3-3**-**b**). If this land protection constraint is relaxed, food price impacts would be less severe in both the DAC and no-DAC scenarios, but at the expense of even larger-scale conversion of natural lands to agricultural production and managed forest.

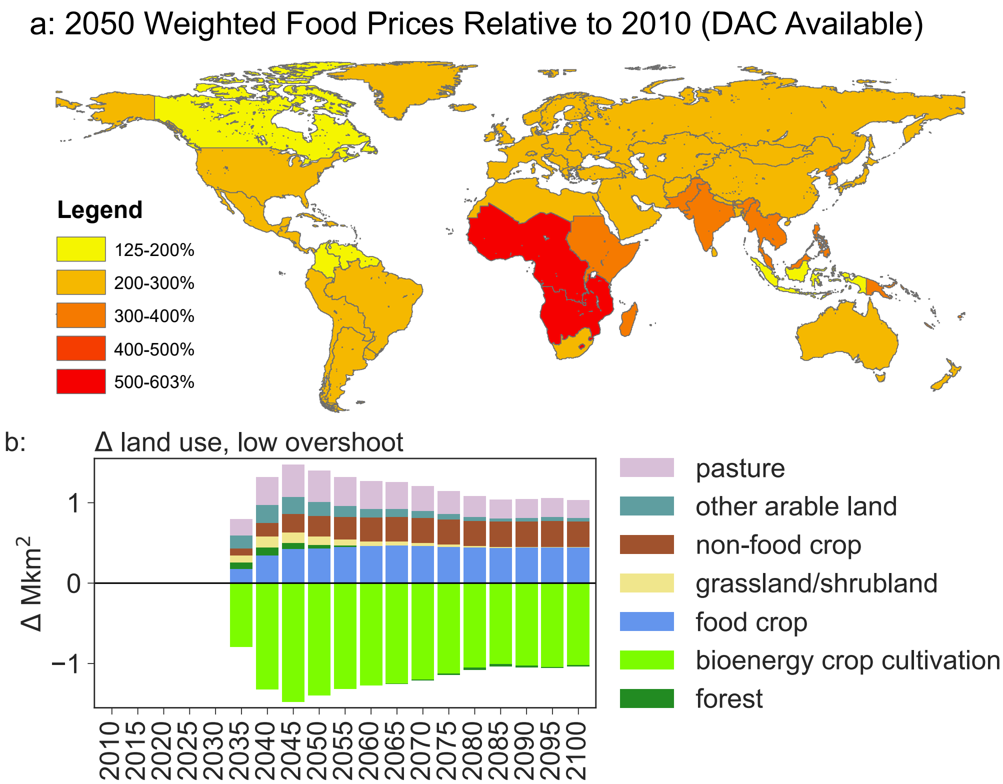

Figure 3-3: Food crop price and global land use impacts of NET deployment.
a) Regionalized food crop prices relative to 2010 levels. b) differential land use between DAC and no-DAC available scenarios. Combined land use devoted to BECCS and afforestation in the no-DAC scenario is over 5 Mkm^2 (see Figure 1). The availability of low-cost DAC can reduce this requirement by approximately 1 Mkm^2 in 2050, freeing up more land for food production and ameliorating the most severe food price impacts.

3.6. Water and energy use of NETs

Water consumption for DAC is comparable to that of bioenergy crop irrigation. This result is in contrast to a previous report[41] where BECCS and afforestation sequestration was scaled by a water use factor[28] that included total evapotranspiration of unirrigated bioenergy crop cultivation, without subtracting the evapotranspiration of the food crops as well as native vegetation the bioenergy crops would be replacing. GCAM calculates water consumption, water withdrawals, and crop evapotranspiration for agricultural and industrial sectors endogenously. This treatment of water use produces a result that might be non-intuitive if the water-intensity of each NET was simply scaled. DAC reduces demand for negative emissions from BECCS, but also allows for increased positive emissions to the atmosphere, which are then offset by DAC. Therefore, even though DAC is still less water-intensive than bioenergy crop irrigation, large DAC deployments result in increased total water use for negative emissions – a phenomenon analogous to a rebound effect. Further, irrigated cropland that would be used for BECCS if DAC were not available is then freed up for other agricultural production, further increasing water demand. To meet the same low-overshoot emissions constraint, the availability of DAC results in a net increase in total water consumption of nearly 35 km^3-yr^{-1} in 2050, approximately 35% of current-day evaporative losses for electricity production globally (**Figure 3-4**). Increased late-century negative emissions requirement in the high-overshoot scenario, which is met by DAC, increases water consumption even further. Input assumptions and calculated intensity factors (tH_2O/tCO_2 sequestered) are reported in **Appendix B**.

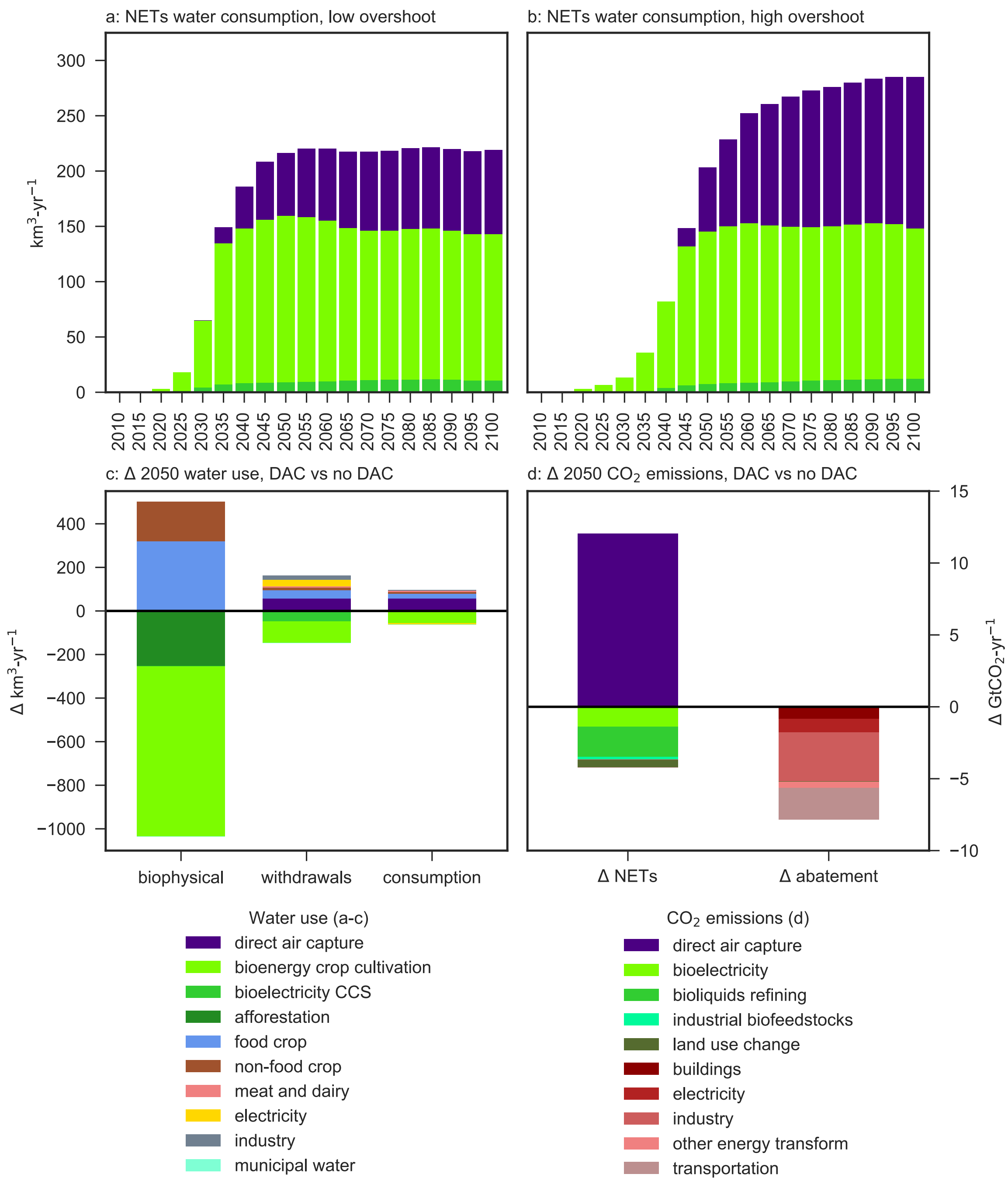

Figure 3-4: Water use and displacement of emissions abatement of large-scale DAC.
Global consumptive water use for BECCS and DAC under a) low, and b) high overshoot of the 1.5 °C temperature target. Differences in the year 2050 for biophysical water demand, withdrawals, and consumption by sector for low overshoot scenarios in which DAC is and is not available are shown in (c). The availability of DAC decreases evapotranspiration related to human activities but increases overall withdrawals and consumption. This occurs because DAC allows reductions in NET deployments but also decreases abatement effort as illustrated in (d).

Results for primary energy consumption by source for low (a) and high (b) overshoot of the 1.5 °C temperature target are reported in **Figure 3-5**. As in the no-DAC scenario, fossil fuels continue to play a large role in the global energy system, but their emissions are mostly abated using CCS technology (i.e., CO_2 emissions are captured at point sources). Even with DAC, unabated coal shows precipitous drop-offs at the initiation of the climate policy, while unmitigated oil and gas continue to be used for transportation and industrial processes that are recalcitrant to decarbonization. In the low overshoot case, process heat and electricity requirements for DAC together account for 100 EJ-yr^{-1} of energy demand by 2100, with process heat requirements accounting for 85 EJ-yr^{-1} of this. For context, global natural gas demand in 2018 was approximately 130 EJ.[124] Even relatively modest delays in aggressive mitigation in the high-overshoot scenario results in increased energy demand from DAC to remove previously-emitted CO_2. Differences between low overshoot scenarios in which DAC is and is not available are shown in (c). Increases in demand for other fuels (e.g., conventional natural gas and oil) occur because DAC availability allows other industries to abate their emissions less aggressively and be offset by DAC. Additional demand for natural gas CCS is due to DAC process-heat requirements.

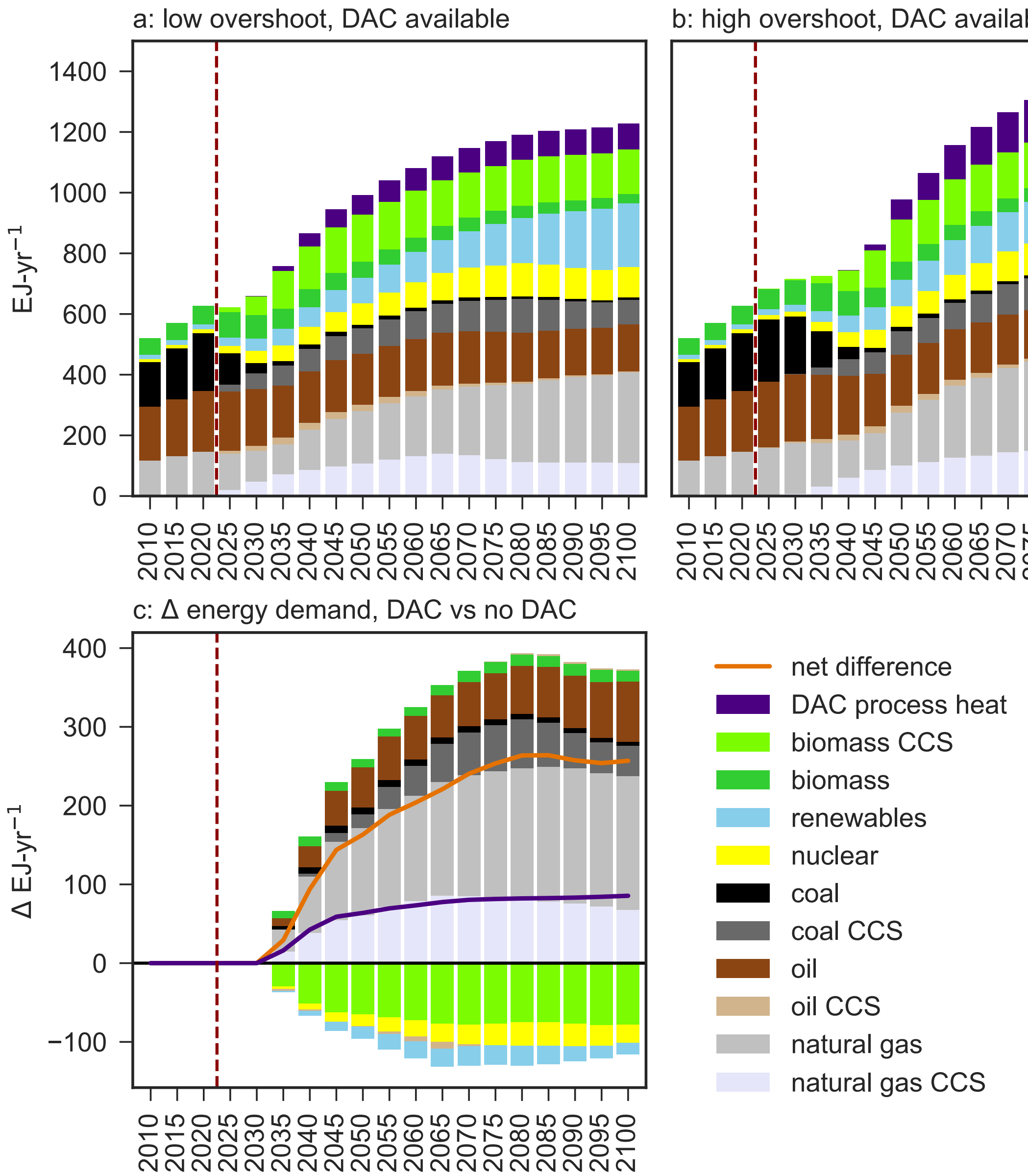

Figure 3-5: Effects of DAC on primary energy consumption

Primary energy consumption by source for a) low, b) high overshoot scenarios with DAC available. Natural gas with CCS for DAC process heat is subtracted to avoid double-counting and shown separately in purple. Differences between two low overshoot scenarios in which DAC is and is not available is shown in (c). Virtually all increase in natural gas CCS in (c) is driven by DAC. Increases in energy demand from other sources occurs because low-cost DAC enables less aggressive emissions abatement. Electricity consumption for DAC is a secondary energy demand and is not shown separately.

3.7. Conclusions

Model results obtained using GCAM suggest that DAC technology can make substantial contributions before mid-century to the deep emissions reductions necessary to meet a 1.5 °C end-of-century temperature goal. Given global ambition to aggressively mitigate climate change in the near-term, DAC could begin removing multiple $GtCO_2$-yr^{-1} from the atmosphere as early as 2035, even assuming present-day financial and energy inputs. The availability of DAC can reduce the steepest tradeoffs associated with land and fertilizer use for BECCS and afforestation. However, even with large-scale DAC availability, BECCS and afforestation deployment will still have large effects on other commodity markets, food in particular, with expected impacts concentrated heavily in the Global South. We also find that reductions in bioenergy crop irrigation withdrawals and consumption are largely offset by increased water use for DAC. In the case of water consumption, evaporative losses from DAC are over 100 percent of the reduction in BECCS-related consumptive water use that DAC technology enables. This is due to a "water rebound effect" where the less water-intensive technology (DAC) is used at higher rates because it displaces emissions abatement, increasing overall water use. Indeed, much of the negative emissions requirement in all scenarios is driven intratemporally by offsets for recalcitrant sectors (e.g., liquid fuels for transportation). Thus, research and policies aimed at avoiding emissions from these distributed sources in the first-place could substantially reduce the projected tradeoffs associated with all NETs. This highlights the importance of detailed consideration of interaction effects between NETs and emissions abatement by policymakers and the models informing them, as well as environmental impacts (e.g., water use) not directly related to climate. IAM research into NETs with potential co-benefits (e.g., agricultural soil carbon, coastal wetlands protection and restoration) could further highlight ways to alleviate negative side-effects associated with planting trees, growing bioenergy crops, or building industrial facilities solely for the purpose of large-scale carbon removal. It is crucial however, that modeling results projecting large-scale future deployments of "more sustainable" negative emissions are communicated so as to not justify further delays in implementing ambitious mitigation policy in the near-term.[181]

Consistent with other IAM studies of DAC, we find that this technology will require large energy input, up to 115% of current-day natural gas consumption for process heat alone.[124] Any robust climate policy including DAC in the mitigation portfolio should therefore consider natural gas life cycle emissions (e.g., leakage during extraction and transport) to avoid offsetting the climate benefit of the CO_2 removal.[182] The fundamental issue of increasing future energy requirements for CO_2 removal in order to compensate for failure to decarbonize in the near-term exists even with DAC processes that can use renewable energy for process heat and electricity. The magnitude and distribution of food price increases projected to result from land-based carbon removal, even with the large-scale deployments of DAC, raises profound intra and inter-generational equity concerns. While these concerns have been well-covered in the literature with respect to the risks and burdens of climate change itself (e.g., refs.[183,184]) additional attention is needed to address the distribution of burdens of negative emissions intended to mitigate it. Most critically, we emphasize the need for urgent action on decarbonization policy that is the precondition for any kind of large-scale mitigation activity, let alone global-scale net-negative emissions. Just as climate impacts (e.g., sea level rise, extreme weather events) will continue to become more severe with delayed action, the food, energy, and water tradeoffs of

DAC and other negative emissions technologies will only increase in magnitude the longer mitigation is delayed and the need for their deployment increases.

3.8. Chapter 3 Acknowledgements

I wish to thank Katherine Holcomb of the UVA Advanced Research Computing Service for her assistance with setting up GCAM on UVA's High Performance Computing Cluster. I'd would also like to thank the University of Virginia's Office of the Vice President for Research—3 Cavaliers Program, the University of Virginia Environmental Resilience Institute, and the Global Technology Strategy Program for supporting this work.

Chapter 4 -The role of negative emissions in meeting China's 2060 carbon neutrality goal

4.1. Chapter Summary

China's pledge to reach carbon neutrality before 2060 is an ambitious goal and could provide the world with much-needed leadership on how to achieve a +1.5°C warming above pre-industrial levels by the end of the century. But the pathways that would achieve net zero by 2060 are still unclear, including the role of negative emissions technologies. We use the Global Change Analysis Model to simulate how negative emissions technologies, in general, and direct air capture (DAC) in particular, could contribute to China's meeting this target. Our results show that negative emissions could play a large role, offsetting on the order of 3 $GtCO_2$ per year from difficult-to-mitigate sectors such as freight transportation and heavy industry. This includes up to a 1.6 $GtCO_2$ per year contribution from DAC, constituting up to 60% of total projected negative emissions in China. But DAC, like bioenergy with carbon capture and storage and afforestation, has not yet been demonstrated at anywhere approaching the scales required to meaningfully contribute to climate mitigation. Deploying NETs at these scales will have widespread impacts on financial systems and natural resources such as water, land, and energy in China.[xiii]

4.2. Introduction

On September 22, 2020 China announced that it would pursue a plan to achieve "carbon neutrality" in its economy by 2060.[58] China has previously committed to peaking its CO_2 emissions before 2030,[186] and its new carbon neutrality commitment greatly strengthens its nationally determined contributions (NDCs) under the Paris Climate Agreement. There are a number of studies that have explored China's decarbonization pathways,[187–192] but not much attention has been given to the role that negative emissions technologies (NETs) could play, especially the availability of direct air capture (DAC). In our recent paper, we assessed the negative emissions requirement for meeting a +1.5°C target globally.[193] Our results indicated that DAC could play a large role with much of that activity concentrated in the US and China because of their substantial capacity to carry out geologic carbon storage.[193]

The number of countries, regional governments, and corporations that have been making carbon neutrality commitments has been accelerating.[194] While China is distinct from many of the other countries and institutions making decarbonization pledges because of its size, its announcement was similar to other national commitments such as the United Kingdom's and Japan's that have provided few details about implementation and enforcement.[56,57,195] China today produces approximately one-third of global greenhouse gas emissions, but up to 30 percent of these emissions result from production of goods that are exported to other regions of the world.[196–200] In addition, energy consumption in China is currently highly carbon intensive with most of its primary energy supply coming from coal combustion.[201,202] Wang et. al., (2019a) examined pathways to decarbonize China's power sector, including the use of BECCS, and the early retirement of coal-fired generation units.[203] But China has recently invested in 38 GW of new coal capacity in 2020 and has indicated intention to build hundreds of new coal-fired power plants in its most recent 5-year plan.[204–206] This is at odds with its stated efforts to decarbonize, as well as those to improve air quality. As reported by

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xiii This chapter is adapted from: **Fuhrman, J.,** Clarens, A. F., McJeon, H., Patel, P., Ou, Y., Doney, C., Shobe, W. M., and Pradhan, S. "The Role of Negative Emissions in Meeting China's 2060 Carbon Neutrality Goal" Oxford Open Climate Change (2021): 1–15.

Wang et. al., (2019b), China's late-stage industrial sector could rapidly reduce CO_2 emissions over the coming decades under global climate policy with a combination of energy efficiency improvements, fuel switching, and CCS. However, owing to its size relative to other large economies such as Western Europe, and the prohibitive expense of fully decarbonizing some industrial processes (e.g., iron and steel), China's industrial sector could have over 1 Gt-CO_2 of residual emissions by 2050.[207] Transportation in China and elsewhere is expected to remain recalcitrant to decarbonization relative to other sectors, owing to continued dominance of petroleum-derived liquid fuels, especially for freight.[208–210] Like other large economies, China's CO_2 emissions declined temporarily due to the COVID-19 pandemic. However, emissions in China and elsewhere are rebounding and are likely resume their historic growth trajectory without investment in lower carbon technologies and deliberate policy action to reduce them.[7,8] In order to achieve its carbon-neutrality target, China will need to rapidly decarbonize its power, transportation, and industrial sectors in the near term and will likely have to seek opportunities for negative emissions in the long term.[211,212]

To achieve carbon neutrality, a country needs to balance emissions and sinks. For any large and complex economy, there will be sources of emissions that will be recalcitrant to decarbonization, such as aviation, freight transport, and high temperature heat applications in industry. For this reason, there is growing interest in approaches for actively removing emissions from the atmosphere.[213] So-called negative emissions technologies (NETs) are a suite of engineered or natural approaches such as DAC, bioenergy with carbon capture and storage (BECCS), and afforestation that remove carbon from the atmosphere and could play an important role in offsetting recalcitrant emissions, and/or reaching net-negative emissions globally or regionally. China has attempted afforestation projects to combat desertification and soil erosion in the past, with mixed success in initial phases.[214–216] Adapting forest protection and afforestation approaches based on lessons learned could reduce negative impacts on biodiversity and water availability, and some studies indicate that the expanding forest cover in China may be generating large carbon sinks from the atmosphere.[217] Preventing further deforestation and restoring previously deforested land to its natural state has potential environmental and human health co-benefits, in addition to storing carbon from the atmosphere.[218] However, China's experience with afforestation highlights the potential challenges of further expanding of this approach for large-scale climate mitigation due to measurement uncertainties inherent to natural and managed forest systems, competition with agricultural land demands, opposing goals of carbon storage and timber harvest, large land and water footprints, and the potential lack of permanence of forest carbon stocks in a warming world.[29,219] As China's government seeks to increase the standard of living for its citizens, large-scale bioenergy crop cultivation could also compete with food production, as well as environmental conservation objectives.[25,166,220] DAC is an emerging technology with a far lower land footprint than BECCS or afforestation, but large energy demand due to the thermodynamic unfavourability of separating atmospheric CO_2 at ~415 PPM.[28,221] With recent, more optimistic cost estimates for DAC, several large European and U.S. based companies have made investments in commercial DAC technologies, and still others have committed to using negative emissions including DAC to draw down their historical emissions from the atmosphere.[33,37–39,222] Given China's currently large emissions, its capacity for geologic storage,[223] and the large share of its carbon-intensive exports in the global economy, DAC could potentially play a large role in deep decarbonization there. Yet there has not yet been modeling performed to understand the role and tradeoffs of DAC and other negative emissions in China in achieving its recently-announced climate ambitions.

At a global scale, integrated assessment models (IAMs) have been used to explore deep decarbonization pathways.[224] IAMs incorporate economic, geophysical, demographic, and climate modules to study future policy scenarios. The International Panel on Climate Change (IPCC) uses a suite of IAMs to explore different scenarios and inform international commitments, including those laid out in the 2015 Paris Agreement.[224] Over the past several years, IAMs have been used to explore what it would take to limit future anthropogenic climate change to +1.5ºC warming relative to pre-industrial levels. All the IAMS used by the IPCC show that, in order to meet these aggressive decarbonization scenarios, NETs will be needed to help offset recalcitrant emissions. BECCS and afforestation are the most widely modeled technologies with median projected global deployments of respectively, 4 and 2 Gt CO_2 per year, projected by 2050 to limit warming to below 2 C in 2100.[225] Several recent modeling studies have also assessed engineered NETs such as DAC, with even higher projected deployments to actively draw down atmospheric CO_2 levels.[97,131,193,226] Such large deployments of these NETs will entail enormous transitions for energy and land, as well as water use patterns, and it is critical to understand how these might unfold at the country-level.[193]

The goal of this paper is to estimate the potential role of DAC and other forms of negative emissions to help China meet its carbon neutrality goal, as well as their interactions with mitigation efforts. In particular, we examine how the availability of different NETs might affect the required decarbonization of different sectors and the extent to which each type of NET could be deployed. We estimate the costs and tradeoffs for land, water, and energy systems of negative emissions deployment in China. The scale at which they could be needed in order to meet this target is quite large, so it is crucial to understand the tradeoffs these technologies would represent. These results could also provide baseline cost estimates to inform where to target investments in innovation. To perform this analysis, we used the Global Change Analysis Model (GCAM)[227], a technology-rich integrated assessment model with embedded simplified versions of global climate and carbon dynamics. We modeled three main scenarios featuring estimates for DAC cost and energy intensity to assess how China might achieve its carbon neutrality target in 2060. In addition, we conducted a sensitivity analysis to understand how key model assumptions could influence the projected role of DAC in China. These results provide insight about the technological transitions, as well as financial, environmental, and human health impacts that could result from NETs deployments in China.

4.3. Methods

We used the latest release of GCAM 5.3[227], enhanced with the capability to model DAC, to simulate different paths by which China individually, as well as the rest of the world, collectively might reach net-zero emissions by 2060. We followed the near-term to net-zero ("NT2NZ") approach described in Kaufman et al.[228] We assumed a linearly declining net CO_2 emissions trajectory from 2021 until reaching zero net CO_2 emissions in 2060 for both China separately and the rest of the world together. This modeling approach for net-zero CO_2 emissions pathways accommodates uncertainties and measurement difficulties while also helping guide near-term policy design. Specifically, while the prospective future availability of DAC and other NETs would tend to delay mitigation in modeling scenarios where the CO_2 price rises at an assumed interest rate, this could prove to be a risky bet for real-world decision makers if NETs and other uncertain technologies prove unable to scale up as rapidly as expected, and/or as impacts from climate change itself worsen.[47,228,229] With this CO_2 constraint, we evaluated three parametrizations for the cost, efficiency and availability of DAC (i.e., high-cost DAC, low-cost DAC, and no DAC available). Population and GDP input assumptions follow the "middle of the road" scenario and can be found in **Appendix C**. Prices on land-use change and correspondingly, subsidies for afforestation, are specified as an increasing proportion of the fossil and industrial carbon emissions price, reaching 100% of the fossil carbon price by 2100. This is intended to represent gradually improving institutions for pricing land-use change emissions, given that agriculture and land-use decisions now largely occur outside of regulatory frameworks in most countries.[163,193]

Table 4-1: Description of the CO_2 emissions constraint trajectories run in GCAM to understand the role DAC in meeting these constraints

Scenario Name	Description
No climate policy	A reference scenario with no climate mitigation policy (i.e., pricing or constraints on CO_2 or other GHG emissions), but improving technological efficiency
China + rest of the world (ROW) net-zero 2060	China, along with the rest of the world, achieve net-zero CO_2 by 2060 in a linearly declining emissions trajectory. China's emissions are individually constrained, but emissions from the remaining regions in the rest of the world are allowed to be individually greater than or less than a separately imposed emissions constraint, so long as their sum is less than or equal to this constraint.

We modeled DAC as a process that uses an aqueous reaction between atmospheric CO_2 and a hydroxide solution that has evaporative water losses at the air contactor.[230–232] The DAC technology requires energy input in the form of high-temperature process heat and electricity, and financial inputs for capital expenditure and non-energy operations and maintenance, given in Table 2. For low-cost DAC, financial and energy inputs are assumed to decline linearly between their 2020 and 2050 parametrizations, then remain constant after 2050. In the high cost DAC cases, the technology is assumed to remain costly and energy-intensive over time. We assume that the process heat is high-temperature heat from natural gas combustion and not lower temperature waste-heat or renewables. While there are other DAC archetypes that can use renewable electricity and/or waste heat input and do not consume water,[233] we focused our analysis on this high temperature process because it appears to be the most inexpensive and commercially mature at present.[226,230] Geological carbon storage costs are treated endogenously by GCAM. Note that DAC is assumed to behave as a quasi-backstop technology, with no external constraints on its deployment outside the availability of energy, carbon storage, and its cost relative to other mitigation and negative emissions technologies in meeting a binding cap on CO_2 emissions. No constraints were imposed on the scaling rate of DAC or any other technology. We assumed a median lifetime for DAC plants of 40 years. No other technological, institutional or legal limitations are modeled with respect to DAC, which we assume can be deployed rapidly at scale in the model under appropriate conditions. Because of these assumptions, the simulated rate of DAC deployment at the costs specified may be considered as an upper bound.

Table 4-2: Input parameters for DAC technology[193,230]

Technology	Natural Gas (GJ/tCO_2)		Electricity (GJ/tCO_2)		Non-Energy Cost (2015 $/$tCO_2$)		Water (m^3/tCO_2)
	2020	**2050**	**2020**	**2050**	**2020**	**2050**	**-**
Low cost DAC	8.1	5.3	1.8	1.3	300	180	4.7
High cost DAC	8.1	8.1	1.8	1.8	300	300	4.7

Note: For low-cost DAC, we assume that the energy efficiency of the technology improves between 2020 and 2050. The energy and non-energy cost inputs are assumed decline linearly between year 2020 and 2050 and thereafter remain constant. For the high cost DAC scenario, we assume that the technology will remain costly and energy-intensive.

4.4. Results

Figure 4-1 presents the results for (a) global average temperature anomaly, (b) atmospheric CO_2 concentration, and (c) CO_2 emissions over time for China as well as globally. The CO_2 emission trajectories after 2020 follow directly from the constraints imposed. If China and the rest of the world together reduce their emissions to net-zero by 2060, this results in approximately +1.8°C of warming in 2100. Scenarios in which DAC is deployed show slightly higher warming in 2100 despite meeting the same CO_2 emissions cap, owing to fugitive methane emissions from the production of natural gas which DAC takes as an input, as well as higher residual non-CO_2 emissions from difficult-to-mitigate sectors. In all scenarios, criteria air pollutant emissions in China (e.g., black carbon, VOC, NOx, and SO_2) are projected to decline drastically from their current levels due to the phase-down of coal as an energy source, regardless of the availability of DAC. Relative to their 2010 levels, black and organic carbon particulate emissions each decline by over 80%, NOx emissions decline by 73%, and SO_2 emissions decline by 95%, highlighting important environmental and public health co-benefits of CO_2 emissions reduction policy. Detailed projections for non-CO_2 emissions for our three main scenarios are provided in **Appendix C**.

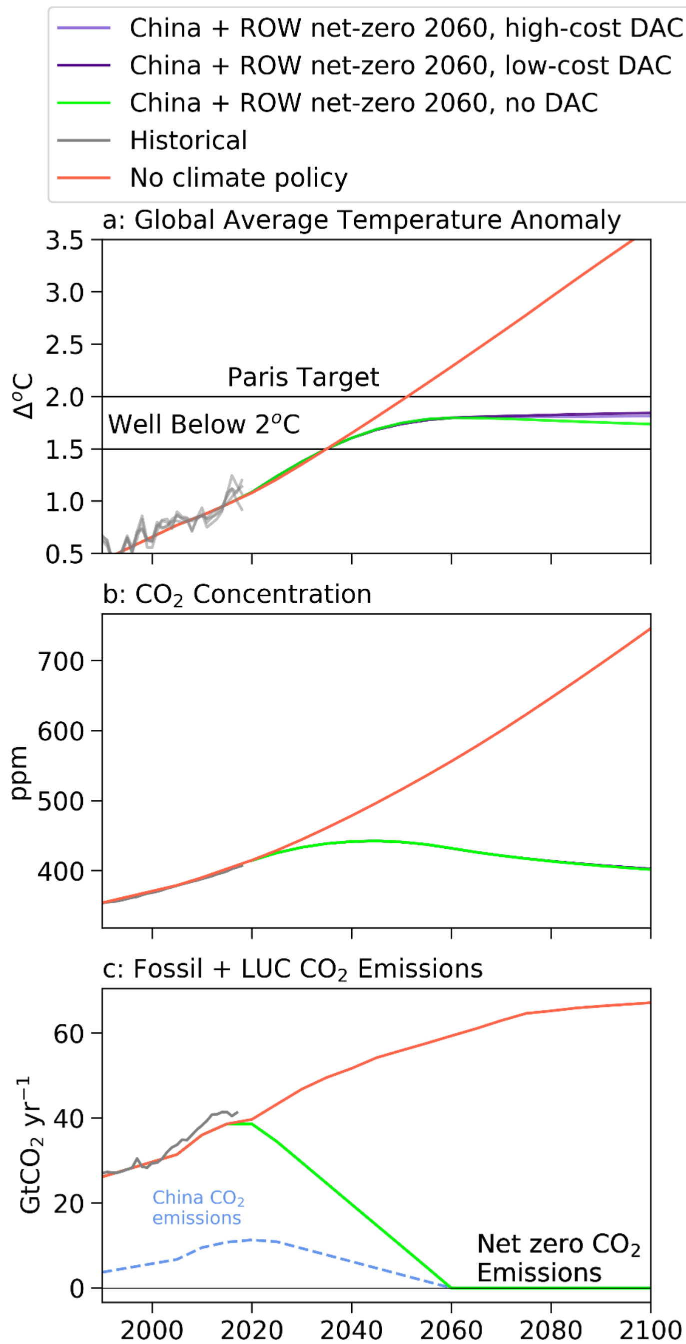


Figure 4-1: Model results show different trajectories for global temperature anomaly (a), even though CO_2 concentration (b), and net CO_2 emissions (c) over time are the same for the 3 scenarios simulated here. Globally net-zero emissions could limit end-of-century warming to below +2C, but more ambitious near-term mitigation and/or future net-negative emissions is required to meet a below +1.5°C goal.[xiv]

[xiv] Historical data for emissions,[148] CO_2 concentrations,[161] and temperature anomaly[162] are indicated by grey lines. Four data sources were used to report recorded historical temperature anomaly; the darker grey "line" indicates overlap or especially high agreement between different observations, which were plotted with slightly increased transparency for clarity.

Figure 4-2 illustrates the extensive transformation China will need to make to its economy in order to achieve its 2060 net-zero target. The panel on the left shows the dominant current emission sectors: transportation, industrial, and electric power. On the right, the panel shows the results of three permutations of the China + rest of world net-zero 2060 scenario; one in which no DAC is available, one in which DAC is available but continues to be expensive, and one in which DAC is available and gradually improves in cost and energy efficiency by 2050 (see Table 2). In all three cases, China will rely on significant deployment of negative emissions to achieve its net-zero target.

Our results show that getting China and the rest of the world to net-zero by 2060 without DAC, would require China to deploy at least 1 Gt-CO_2 per year of negative emissions from BECCS and AR, which is in line with a recent study by Yu et al.[211] Achieving the net-zero CO_2 target without DAC available, that is, relying only on BECCS and afforestation for negative emissions, would result in a marginal cost of over \$800 per tCO_2 in 2060 (\$2015 price). With DAC available, the world along with China could achieve net-zero CO_2 emissions by 2060 at much lower marginal costs, in the range of US\$ 200 - 400 per tCO_2. This carbon price corresponds to the sum of the capture + carbon storage costs for DAC, both of which become gradually more costly over time as geologic storage reservoirs and energy resources are consumed. Full carbon emissions price paths are reported in **Appendix C.**

Under the low-cost DAC deployment, China would require about 3 GtCO_2 per year of negative emissions to reach net-zero by 2060, much of it coming from DAC, with the remainder coming from BECCS and AR. If DAC does not improve in cost and energy-efficiency, it would make up a smaller percentage of the negative emissions portfolio, which would still total 2 GtCO_2 per year. Residual, positive CO_2 emissions from difficult-to-mitigate sectors require multiple Gt-CO_2 of negative emissions to offset them in all scenarios. In the no DAC scenario, the industrial sector becomes a net sink of CO_2 largely through hydrogen production from bio-feedstocks and CCS. Low-cost DAC availability allows up to 1 Gt-CO_2 emissions from industrial energy use in China to be offset at lower cost. Transportation is projected to be recalcitrant to decarbonization across all scenarios. While passenger transportation can decarbonize through electrification and hydrogen fuel cells, freight trucks using both liquid and natural gas fuels under the carbon policy result in large residual emissions. An electrified and/or hydrogen fuel cell freight truck fleet in China and elsewhere could substantially reduce the need to deploy NETs to offset their emissions. Transportation emissions are slightly higher in the DAC scenarios due to higher service demand because the lower carbon emissions prices lead to correspondingly lower fuel prices. There is also less need to switch from vehicles using petroleum-derived fuels to more costly lower-emissions electric, natural gas, and hydrogen fuel cell vehicles if DAC is available to offset these distributed emissions. Detailed breakdowns of industrial and transportation CO_2 emissions in China, as well as transportation demand are made available in **Appendix C**

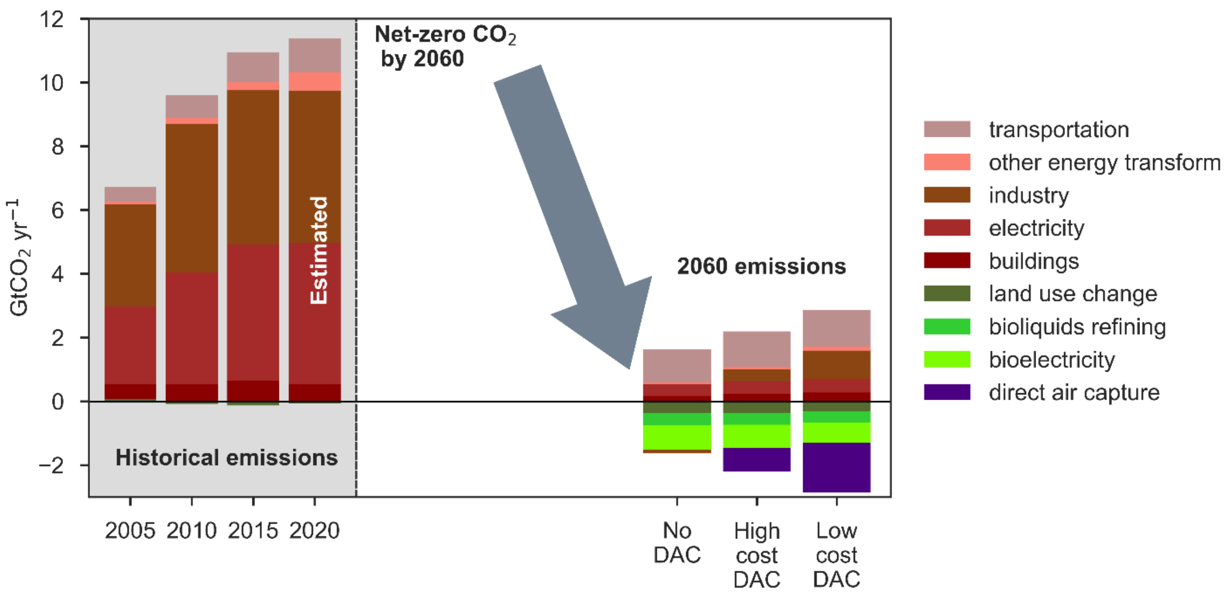


Figure 4-2: Pathways for China to reach net-zero CO_2 emissions by 2060 all involve deep emissions reductions and CO_2 removal. The availability of DAC technology in China enables less use of BECCS and also offsets emissions from difficult-to-mitigate sectors such as transportation and industry, allowing higher emissions from these sectors relative to the no DAC case. Results shown here are for the China + rest of the world (ROW) net-zero 2060 scenario, which results in approximately 1.8º C of warming from preindustrial in 2100.

Figure 4-3 shows the projected primary energy transitions for China to reach net-zero CO_2 emissions by 2060. At present, China relies heavily on coal and oil for its primary energy. To achieve net zero CO_2 emissions will require a substantial rollout of renewable energy over the coming 40 years in addition to very large deployment of fossil carbon capture and storage. For the three negative emissions cases described in Figure 3 for the China + rest of world net-zero by 2060 scenario (no DAC available, high cost, and low-cost DAC) we see important differences in energy consumption patterns. Notably, the deployment of DAC consumes natural gas for process heat on the same order of magnitude as all of China's present day gas consumption. The primary energy consumption of coal declines from 67% share in 2020 to 21% in 2060 without DAC. This includes 2% conventional coal and 19% coal-based carbon capture and storage. With low-cost DAC deployment, the share of coal would decline to 22% in 2060 with 4% conventional coal and 18% coal-based carbon capture and storage.

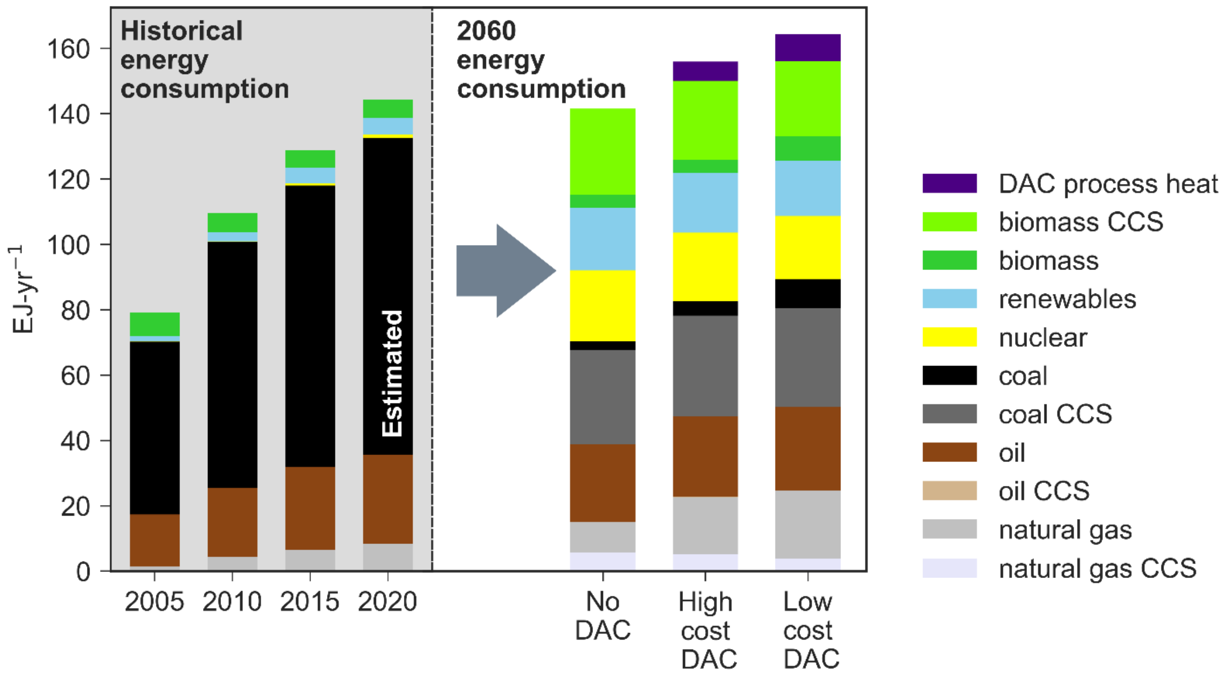


Figure 4-3: Historical and projected primary energy by fuel for China showing values for recent historical periods and for net-zero CO_2 emissions in 2060 scenarios.[xv]

Figure 4-4 shows potential water consumption patterns for China in meeting its net-zero CO_2 emissions by 2060 goal. Irrigation for agriculture comprises most of the historical and projected water consumption, and evapotranspiration from rainfed agriculture is not included in this figure. Agricultural water consumption is projected to decline slightly by 2060 owing to technological improvements and exogenous assumptions of population peaking and then declining by mid-century. In all cases, irrigation for bioenergy crop cultivation expands from near-zero level in present day, to substantial fractions of overall water use in 2060. If no DAC is available, bioenergy crop irrigation grows to 7 km^3 per year in 2060, which is nearly 3% of projected water consumption for that year. If low-cost DAC can be deployed at scale in China, this could reduce bioenergy irrigation consumption to approximately 5 km^3 per year. But, evaporative losses from DAC itself are projected to consume large amounts of water, over 7 km^3 per year in 2060, nearly 80 percent of municipal water consumption in China in 2015.

[xv] Process heat for DAC (i.e., the primary energy from natural gas CCS devoted solely to CO_2 removal) is reported separately in indigo (dark purple at top of bars) and subtracted from natural gas CCS to avoid double counting.

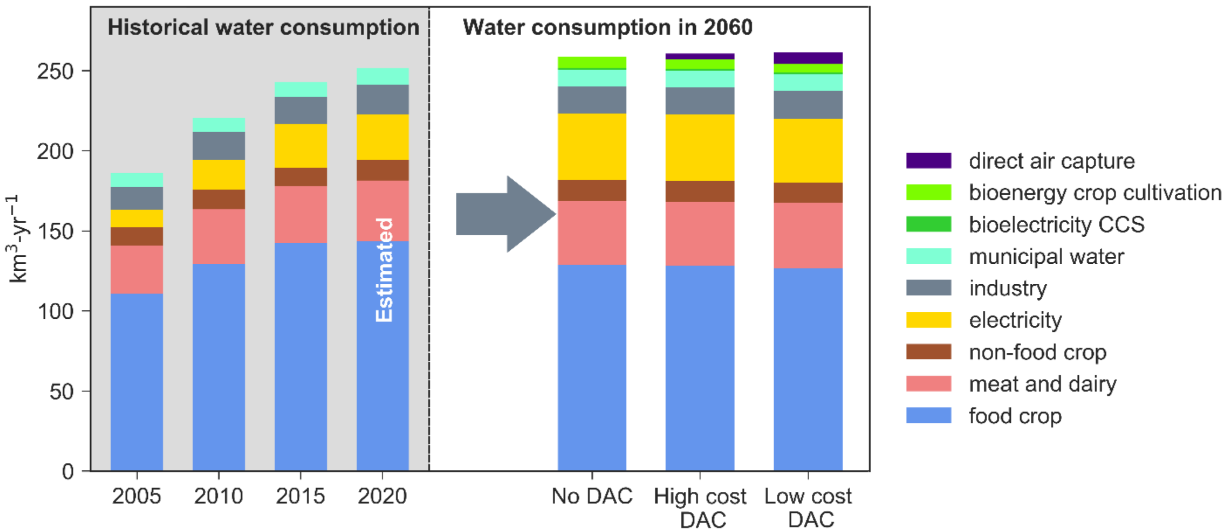
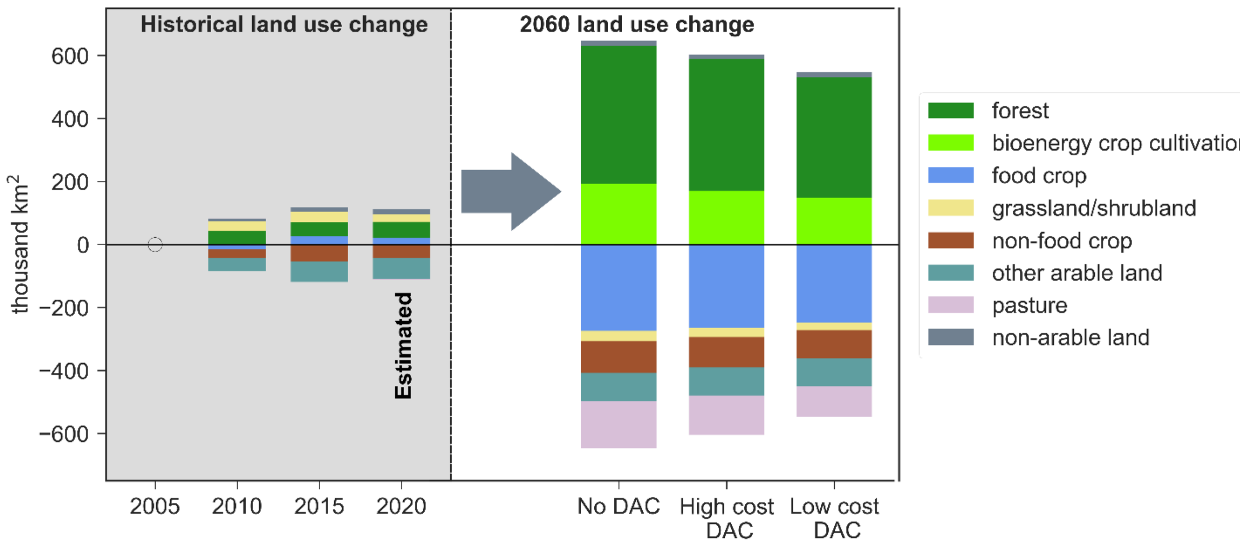


Figure 4-4: Recent historical and projected water consumption for China for net-zero CO_2 emissions by 2060.

Figure 4-5 reports historical and projected land-use for China if it and the rest of the world reach net-zero emissions by 2060, relative to a 2005 base year. The existing historical trend of gradual forest expansion is greatly accelerated, whereas grasslands see a reversal of recent historical growth as bioenergy and afforestation are scaled up. Land area for food cultivation (i.e., grains and staple crops) is projected to decline by nearly 100,000 km^2 from 2005 levels in China in 2060 in the no DAC scenario, while bioenergy crop production expands to over 190,000 km^2 and forested area gains approximately 430,000 km^2. Low-cost DAC can reduce the decline in food production land slightly, to approximately 90,000 km^2, with 148,000 km^2 being used for bioenergy crop cultivation, and 380,000 km^2 net gain in forest area from 2005 level. Without DAC available, weighted prices for major staple grain crops increase to 300% of their 2010 levels (200% increase) due to land competition from BECCS and AF. Low-cost DAC availability reduces this increase to approximately 175% of their 2010 levels (75% increase). Figure 5 also reports how the availability of DAC could reduce biomass cropland area required for mitigation and negative emissions in major river basins in China. In the most productive agricultural regions in eastern China, the availability of DAC could reduce biomass cropland area by 20-25%, freeing up more land for other agricultural activity or environmental conservation. Fractional land area devoted to biomass cropland in each water basin is reported in **Appendix C.**

a) Land-use change from 2005 for net-zero by 2060 scenarios



b) Impact of DAC on biomass cropland area by major river basin

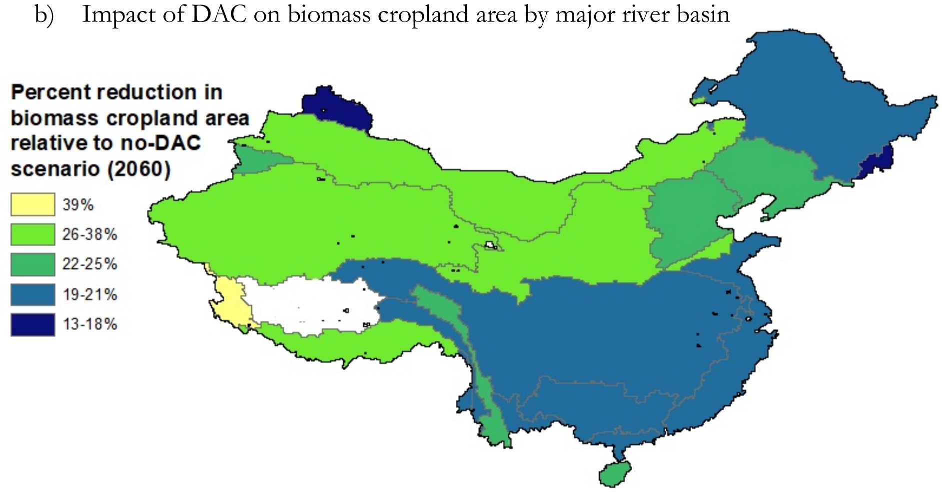


Figure 4-5: Historical and projected land-use changes from 2005 in China for net-zero CO_2 emissions by 2060 scenarios (a). Difference in biomass cropland area in major river basins in China between no DAC and low-cost DAC scenarios (b).[xvi]

4.5. Sensitivity analysis

To more fully assess the sensitivity of our projections for DAC deployment in China to input assumptions, we individually varied the cost and energy input parameters for DAC itself, as well as other model assumptions that are external to DAC but directly influence its cost and/or requirement for its deployment. Table 3 summarizes the assumptions for our sensitivity analysis. Parametrizations for geologic carbon storage supply curves used in this sensitivity study, as well as population and GDP input assumptions for the "central" and "low residual emissions" scenarios may be found in **Appendix C**. **Figure 4-6** reports how parametric variations from **Table 4-3** influence DAC deployment in China in 2060. All scenarios are compared against the "Low-cost DAC" scenario and hold all other input assumptions constant except for the indicated change. Assumptions for capital

[xvi] White coloring indicates zero biomass cropland area in both scenarios and thus no change between them.

and non-energy operating costs have large impacts on the projected level of DAC deployment, with a 56% reduction in non-energy cost (i.e., from $180 to $78 in 2060) leading to over an 80% increase in deployment. Conversely, a 66% increase in non-energy cost (i.e., from $180 to $300) reduces the potential of DAC in China by approximately 40%. The role of DAC is reduced by over 60% if land available for bioenergy, afforestation, and agricultural expansion is unconstrained, which could be at odds with other objectives such as environmental conservation. The requirement for DAC could also be reduced by 45% if lower population growth and improved mitigation technologies reduce the amount of residual CO2 that needs to be offset with DAC and other NETs. Increasing the geologic carbon storage cost by a factor of 10 reduces DAC deployment by 30%. This substantial but relatively small response to such a large parametric variation occurs due to the small contribution of storage to the overall cost of DAC, as well as because it similarly increases costs for abatement using fossil carbon capture and storage. Process heat and electrical input efficiencies remaining at the upper bounds of today's literature instead of improving over time could reduce the role of DAC by 20 and 10%, respectively.

Table 4-3: Assumptions for Sensitivity Analysis.

Scenario Name	Description
Central	DAC energy and cost inputs follow the trajectory defined in the "Low cost DAC" scenario (Table 2). Socioeconomic assumptions follow the "middle of the road" scenario in the GCAM core release. 90% of non-commercial land is assumed protected from agricultural expansion.
Best-case DAC capex + non-energy opex	Non-energy cost inputs decline linearly to \$78 per tCO_2, the most optimistic value found in today's literature[230]
High DAC capex + non-energy opex	Non-energy cost inputs do not improve between 2020 and 2060, remaining at \$300 per tCO_2
High DAC process heat input	Natural gas process heat requirement for DAC does not improve between 2020 and 2060, remaining at 8.1 GJ per tCO_2
High DAC electricity input	Electricity input requirement for DAC does not improve between 2020 and 2060, remaining at 1.8 GJ per tCO_2
Unconstrained land for BECCS/afforestation/agriculture	Removed 90% protection constraint on non-commercial lands, freeing up more land for bioenergy, forestry, and other agricultural activity.
Low carbon storage availability	Cost curves for geologic carbon storage follow the "highest cost CCS" assumption from the GCAM core release. Offshore carbon storage reservoirs are assumed unavailable.
High carbon storage availability	Cost curves for geologic carbon storage follow the highest availability of CCS assumed in the GCAM core release.
Low residual emissions	Population growth, technological improvement, and social preferences generally follow the "sustainable development" scenario. Geologic carbon storage supply curves and land protection constraints are the same as in the central scenario.

Note: all other input assumptions other than the one described in each scenario are held constant, including the CO_2 emissions constraint.

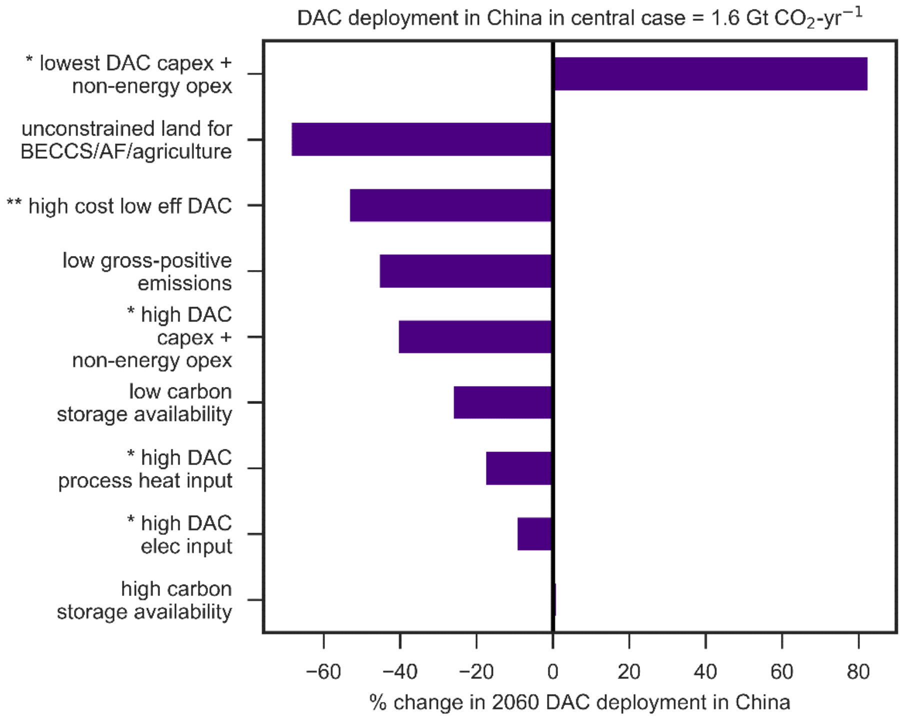


Figure 4-6: Sensitivity analysis for DAC deployment in China in 2060.[xvii]

4.6. Conclusions

In 2018, the IPCC released a report describing what it would take to limit end-of-century global warming to +1.5ºC above preindustrial levels, recognizing this target would require ambition and coordination far beyond what we have seen to date.[224] The recent pledge from China to achieve carbon neutrality by 2060 provides a major contribution towards limiting climate change to below +2ºC above pre-industrial levels. The rest of the world joining China's carbon neutrality pledge would help achieving the common goal of limiting climate warming to below +2ºC, but greater near-term emissions cuts and/or long-term future net-negative emissions would be required to meet the below +1.5ºC goal. We modeled these different futures in an effort to understand the role of negative emissions technologies (NETs) in helping to achieve the net-zero by 2060 target. Negative emissions technologies are being developed to offset recalcitrant emissions from transportation and industry and potentially draw down atmospheric CO_2 levels in the future, even though they are generally considered to be more expensive than conventional decarbonization activities. We analyzed China's options to achieve net-zero CO_2 emissions using the Global Change Assessment Model (GCAM) with three major sources of negative emissions: bioenergy with carbon capture (BECCS), afforestation, and direct air capture (DAC).

Our findings show that DAC can play a large role in China to achieve its net-zero emissions target. The extent to which DAC is deployed depends on its cost, which is expected to decrease over time as

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[xvii] Items marked with an asterisk (*) indicate direct changes to DAC input assumptions such as natural gas for process heat, electricity, and non-energy cost. The "high-cost low efficiency DAC" scenario is marked with two asterisks (**) and is the same as the "high-cost DAC" scenario in Figures 4-2 through 4-5. Scenarios with no asterisks indicate changes to other GCAM assumptions that directly influence the cost and/or requirement for DAC.

technologies improve with widespread implementation. However, some of the radiative forcing benefit of CO_2 removal with DAC is offset by fugitive methane emissions from its natural gas process heat requirement, and non-CO_2 emissions from increased residual fossil fuel use. Because of these effects, the global average temperature anomaly in 2100 is approximately 0.1 ℃ higher in the low-cost DAC scenario than in the no-DAC scenario, despite having the same CO_2 emissions trajectories. If the leakage rate of the natural gas supply chain is higher, the net radiative forcing benefit of large-scale natural gas-fired DAC deployment would be correspondingly lower. Without DAC, China could reach net-zero CO_2 emissions by 2060 with 1.5 $GtCO_2$ per year negative emissions, but this would need to come from BECCS and afforestation at an increasingly higher marginal cost per tCO_2 than if DAC could be deployed alongside them. With DAC widely available, China's carbon neutrality can be supported by more than 2-3 $GtCO_2$ per year negative emissions to get to the net-zero CO_2 emissions by 2060. Scaling up DAC to this level would require investment on the order of US$ 200-280 billion per year in 2060, which is about 1-2% of China's GDP in 2019 and 0.5-0.7% of its projected GDP in 2060.

Our results indicate that up to 30-60% of China's negative emissions requirement could be fulfilled by DAC, with the remainder fulfilled by BECCS and AR. These results provide insight into the country-scale changes in water, energy, and land-use when different forms of negative emissions are used in China. We also assessed sensitivity of DAC deployment to key parameters such as its cost, energy efficiency, (lack of) constraints on land for BECCS and forest expansion, carbon storage costs, and ability to reduce gross-positive CO_2 emissions that need to be offset with DAC and other NETs. Improvements in DAC non-energy costs could increase its deployment in China by up to 80 percent. We also find that DAC still plays an important role even under more pessimistic assumptions regarding its future cost and energy efficiency improvements, as well as under more optimistic assumptions for future gross-positive emissions reductions. This is due to high costs of decarbonizing the industrial and freight transportation sectors. DAC availability could reduce biomass cropland area in major river basins in China by up to 25 percent, freeing up more land for agricultural production and environmental conservation. While DAC reduces the extent of land-use dedicated to climate mitigation (i.e., for afforestation and bioenergy), they remain large. DAC also reduces the need for irrigation water consumption for bioenergy crops, but itself consumes large amounts of water. This results in little change to overall water consumption in China if DAC is available, but DAC availability may be able to shift water use away from agricultural regions with growing water stress. The large remaining land and water tradeoffs of negative emissions with DAC availability result from its displacement of emissions abatement, which offsets the impacts of reducing the need for other forms of negative emissions. In addition to improvements which reduce the financial and natural resource intensity of DAC and other NETs themselves, greater investment in technologies to enable emissions avoidance such as transport and industrial electrification could also reduce the tradeoffs of negative emissions for offsets.

4.7. Chapter 4 Acknowledgements:

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Chapter 5 -The Role of Direct Air Capture and Negative Emissions Technologies in the Shared Socioeconomic Pathways towards +1.5˚C and +2˚C Futures

5.1. Chapter Summary

The development of the Shared Socioeconomic Pathways (SSPs) and associated integrated assessment modeling (IAM) exercises did not include direct air capture with carbon storage (DACCS) in their scenarios. Recent progress in DACCS commercialization suggests it could be a viable means of removing CO_2 from the atmosphere with far lower land intensity than bioenergy with carbon capture or afforestation but with a higher energy demands. In addition, several forms of DACCS are in development, with different costs and energy demands, as well as potential for future efficiency improvements. Here, we use the Global Change Analysis Model (GCAM) to understand the role of DACCS across all 5 SSPs for the below 2˚C and below 1.5˚C end-of-century warming goals. We assess DACCS deployment relative to other carbon capture methods, and its side effects for global energy, water, land systems. We find that DACCS could play a 10-40 Gt-CO_2-yr^{-1} role in many of these scenarios, particularly those with delayed climate policy and or higher challenges to emissions mitigation. Our "sustainable development" scenarios, consistent with SSP1, have far smaller deployments of DACCS and other negative emissions owing to immediate climate policy onset, greater ease of "conventional mitigation" and tighter constraints on future negative emissions.[xviii]

5.2. Introduction

The Intergovernmental Panel on Climate Change's Special Report on Global Warming of 1.5 ˚C marked a turning point for integrated assessment modeling (IAM) scenarios. This report – as well as the 2015 Paris Agreement, in which nations agreed to pursue efforts to limit warming to below +2 ˚C in 2100 – were heavily informed by an ensemble of IAM scenarios that featured deep (that is, tens of Gt CO_2-scale) negative CO_2 emissions.[17,18] There are many potential negative emissions technologies (NETs) that could be used to deliberately remove CO_2 from the atmosphere. [29,88–90,149] IAM scenarios to date have relied almost universally on bioenergy with carbon capture and storage (BECCS) and afforestation for negative emissions, largely because the structures for modeling these pathways (for example, bioenergy with carbon capture and storage) already existed.[218] But these land-intensive strategies could have large impacts on global agricultural and natural biological systems if deployed at the scales envisaged.[26,145,154,234] Direct air capture with carbon storage (DACCS) is an engineered process that is receiving increasing attention from policymakers and major corporations[33,37,39,222,235–238] for separating and geologically storing atmospheric CO_2. A small number of recent IAM studies – including our recent work[185] – have shown that DACCS could increase global capacity for negative emissions, reduce abatement costs, and soften the sharpest tradeoffs of land-intensive negative emissions due to its much smaller physical footprint.[40–43] But DACCS itself could require large amounts of energy and water, especially if it is mainly used to offset high levels of residual emissions.[185] Delaying mitigation efforts in anticipation of future large-scale DACCS deployment, and then failing to realize such deployment risks lock-in to irreversible warming well above the long-term international goals.[41] Near-term incentives for investing in DACCS could reduce the risks of extreme-scale emergency deployments later in the century.[239] Given the emerging role of DACCS in the deep-negative emissions scenario ensemble, it is critical to more fully understand the factors that influence

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[xviii] This chapter was adapted from: Fuhrman, J., Clarens, A. F., Calvin, K. V., Doney, S. C., Edmonds, J., O'Rourke, P., Patel, P., Pradhan, S., Shobe, W., and McJeon, H. "**The Role of Direct Air Capture and Negative Emissions Technologies in the Shared Socioeconomic Pathways towards +1.5˚C Future**" *Submitted for review* (2021)

both the availability of and requirement for different archetypes of DACCS and other forms of negative emissions. These factors include near and long-term policy ambition and other global socioeconomic developments.

Given the goal to limit climate warming and its impacts to an "acceptable" level, the requirement for negative CO_2 emissions – both to draw down atmospheric CO_2 stocks over time, and to offset ongoing positive emissions – will be driven by socioeconomic and policy developments that are somewhat external to the negative emissions technologies themselves. The Shared Socioeconomic Pathways (SSPs) were developed to explore the implications of different socio-economic futures along the dimensions of challenges to mitigation and challenges to adaptation.[240] This set of qualitative and quantitative assumptions regarding population, growth, human development, economy and lifestyle, policies and institutions, technologies, and environment and natural resources is used to provide an internally consistent framework across integrated modeling scenarios.[63]

The SSP framework defines five storylines that strongly differ in the challenges for mitigation and adaptation, resulting in different levels of long-term warming in the absence of global climate policies.[240] SSP1 represents a "sustainable development" pathway marked by improved land use and other resource efficiency, a preference for renewable energy and other sustainable production methods, and investment in human development that together result in low challenges to both mitigation and adaptation.[241] In contrast, SSP5 is an energy and resource-intensive trajectory in with high levels of growth in fossil fuel consumption that result in improving human welfare and thus capacity for adaptation, but very high challenges to mitigation.[242] SSP2 is a "middle of the road" scenario describing intermediate challenges to both mitigation and adaptation in which socioeconomic and technological developments generally continue along their historical trajectories.[243] SSP4 describes a scenario of deepening inequality, especially between the rich and poor world, which result in relatively low challenges to mitigation but high challenges to adaptation.[164] SSP3 describes a "rocky road" scenario in which continued fossil fuel and particularly coal dependency, poor land management practices, and poor levels of international cooperation result in high challenges to both mitigation and adaptation.[244] On a second axis of the scenario matrix are representative concentration pathways (RCPs) of atmospheric greenhouse gases resulting in different global-mean, radiative forcing perturbations relative to pre-industrial (for example, $+2.6\ W/m^2$, $+8.5\ W/m^2$) in 2100.[245] Finally, the shared climate policy assumptions (SPAs) describe the climate mitigation policy environment (for example, beginning of mitigation efforts, land-use policy) for the different SSPs in reaching a given radiative forcing level from the RCPs.[246]

Recent work by van Vuuren et. al combined assumptions from the SSP2 "middle of the road" scenario with some from the SSP1 "green growth" scenario and found that alternative pathways that include lifestyle change, additional reductions of non-CO_2 greenhouse gases, and more rapid electrification of energy demand could substantially reduce the need for negative emissions in meeting the 1.5 $^{\circ}$C target, but not fully eliminate it.[92] Assessing the need for negative emissions as well as the relative contributions of different forms such as direct air capture and other negative emissions technologies across the full set of SSPs remains a gap in the literature. Here, we use the Global Change Analysis Model (GCAM), a technology-rich IAM with detailed treatment of the energy, water, and land sectors, to assess the requirement for, and relative share of two land-intensive NETs (BECCS and afforestation) as well as DACCS across the 5 shared socioeconomic pathways and 2 end-of-century radiative forcing targets (for a total of 10 scenarios). We harmonized assumptions regarding future potential improvements in the cost and efficiency of DACCS technology, as well as potential constraints on its deployment, with the narrative storylines of each of the SSPs. Subject to different levels of ambition for limiting warming in 2100, we assessed how the availability of DACCS could influence emissions trajectories and feasibility of ultimately meeting these targets. We also assessed how the side-effects on global energy, water, and land systems of different forms of DACCS, as well as their shares relative to other forms of carbon capture for each of the feasible mitigation scenarios.

5.3. Methods

We used GCAM version 5.3 enhanced with the capability to model direct air capture with carbon storage.[185] We conducted scenario permutations on the University of Virginia high performance computing cluster, Rivanna. Two constraints were imposed on end-of-century radiative forcing increases from the pre-industrial levels: +2.6 W/m^2, consistent with limiting warming in 2100 to below +2 ˚C, and +1.9 W/m^2, consistent with limiting warming to below 1.5 ˚C in 2100 [131,247,248]. GCAM solved for the lowest-cost, exponentially increasing (5% y/y growth rate) CO_2 price-path that meets the end-of-century radiative forcing constraint.[249,250] By default, GCAM imposes a constraint on financial transfers for negative emissions equivalent to 1% of GDP. In our scenarios, DACCS, BECCS and afforestation are all included under this constraint, which serves to indirectly limit the size of any temperature overshoot that might occur. For the SSP1 "sustainable development" scenarios, this constraint on financial transfers for negative emissions was reduced by a factor of 10, to 0.1% of GDP to further limit reliance on future negative emissions.[21,47,48] We did not otherwise limit the magnitude of the forcing overshoot, so long as 2100 radiative forcing returned to at or below its respective target in 2100.[115] This design choice was made to explore the implications of potential socioeconomic and policy developments on the requirement for and the side-effects of DACCS and other NETs, as well as the magnitude of overshoot of the long-term radiative forcing targets. The two radiative forcing constraints were permuted across the 5 shared socioeconomic pathways, with each SSP containing assumptions for potential improvements to the cost and energy efficiency of DACCS that are consistent with its respective storyline.

In our recent work, we assessed how a DACCS process requiring high temperature heat from natural gas combustion, electricity, and water could contribute to both ambitious near-term and delayed mitigation scenarios that limit end-of century warming to below +1.5 ˚C.[185] There are several additional DACCS processes which have also been demonstrated at commercial or pilot scale.[35,155,156] These processes are estimated to have higher initial capital and/or operating expenses, but do not require natural gas combustion for process heat, and have the potential to be fully-powered by very low or zero-carbon electricity.[169] The removal efficiency of DACCS is influenced in part by the carbon intensity of its electricity supply.[251] In our scenarios, the electricity input for DACCS comes from each region's grid, with the fuel mix and therefore carbon intensity, other environmental performance, and cost of the electricity supply solved for endogenously by GCAM. High-temperature DACCS relies on aqueous reactions between atmospheric CO_2 and hydroxide solutions and has evaporative water losses at the air contactor.[167,168,252] The low-temperature DACCS process is assumed to use solid sorbents and not require water input.[28]

Table 5-1: Parametrizations for DACCS Technologies.

Technology	**Scenario**	**Natural Gas (GJ/tCO_2)**		**Electricity (GJ/tCO_2)**		**Non-Energy Cost (2015 $/tCO2)**		**Water ($m^3/tCO2$)**	
		2020	2050	2020	2050	2020	2050	2020	2050
High temp. DACCS (natural gas)	SSP1 - Sustainable Development		5.3		1.3		$185		
	SSP2 - Middle of the Road		5.3		1.3		$185		
	SSP3 - Rocky Road	8.1	8.1	1.8	1.8	$296	$296	4.7	
	SSP4 - Inequality		5.3		1.3		$78		
	SSP5 - Fossil Fueled Development		5.3		1.3		$78		
High Temp DACCS (fully electric)	SSP1 - Sustainable Development				5		$186		
	SSP2 - Middle of the Road				5		$186		
	SSP3 - Rocky Road	-		6	6	$384	$384	4.7	
	SSP4 - Inequality				5		$101		
	SSP5 - Fossil Fueled Development				5		$101		
Low Temp DACCS (electric heat pump)	SSP1 - Sustainable Development						$235		
	SSP2 - Middle of the Road				3.8		$235		
	SSP3 - Rocky Road	-		5.5	2.5	$402	$402	-	
	SSP4 - Inequality				2.5		$137		
	SSP5 - Fossil Fueled Development				2.5		$137		

Table 5-1 reports the parametrizations used for DACCS technologies. In developing our parametrizations, we generally followed the detailed methodology of Fasihi et. al,[233] adjusting financial discount rate assumptions for more conservative estimates of especially the early costs of these emerging technologies. For low-temperature DACCS, we converted the required low-temperature thermal energy to electricity by assuming an electric compression heat pump plant with a coefficient of performance equal to 3 and accounted for its additional levelized financial input. Where this was not accounted for, we added the additional electrical energy requirement of compressing the captured CO_2 to pressures required for subsurface injection. Full details of our derivation of high, intermediate, and low-cost estimates are reported in **Appendix D**. Given the lack of obvious biophysical constraints on global-scale DACCS deployment, even the lower bounds that we selected for financial and energy inputs represent conservative estimates for the future development of this technology relative to other literature.[169,253] We varied assumptions regarding the potential improvements in energy and financial inputs over time to be consistent with each SSP storyline, as outlined below. External to DACCS, the assumptions with respect to the timing of global climate policy, the efficacy of land-use policies, and key technological developments follow the Shared Policy Assumptions[246] and their implementation protocols.[254] (**Table 5-2**). In all scenarios, we imposed an absolute constraint of 40 $GtCO_2\text{-}yr^{-1}$ on CO_2 removal by DACCS, equivalent to 120% of energy-related CO_2 emissions in 2019.[255]

Table 5-2: Summary of climate policy, land use policy, and key technology assumptions

Scenario	Initiation of Global CO_2 Emission Price	Land use policy	Commercial Biomass: Tech Development	Commercial Biomass: Social acceptance	CCS technology: Tech Development	CCS technology: Social acceptance
SSP1 – Sustainable Development	2025	Strong	High	Low	Intermediate	Low
SSP2 – Middle of the Road	2040	Intermediate	Intermediate	Intermediate	Intermediate	Intermediate
SSP3 -Rocky Road	2040	None	Low	High	Intermediate	Intermediate
SSP4 - Inequality	2025	Regionally fragmented	High	High	High	Regionally fragmented
SSP5 – Fossil Fueled Development	2040	Strong	High	Intermediate	High	Intermediate

In SSP1, social acceptance of new technologies is low, with the exception of non-biomass renewable energy [241]. As an energy-intensive process devoted to capturing and disposing of atmospheric CO_2, DACCS, especially the natural gas-fired process is assumed to be available but with very low social preference weighting. This mirrors the treatment of BECCS in SSP1, with both commercial biomass and CCS technology having low social acceptance. In these scenarios, global society relies mostly on sustainable development to reduce inequities, as well as rapid technological change directed towards environmentally-friendly processes such as lower carbon energy sources. High productivity of agriculture reduces deforestation pressure and can allow large-scale reversion of previously cultivated land to its natural state.[256] Climate policies are assumed to begin immediately after the year 2020 (that is, 2025 is the first GCAM model period with carbon pricing). Strong policies are assumed to be put into place for pricing carbon emissions from land-use change. To represent transaction costs and long-term improvements in institutions for implementing land use policy, land use change emissions pricing is represented in GCAM as a linearly increasing proportion of the fossil carbon price beginning after 2020, reaching 50% of the fossil carbon price by 2050 and remaining constant through 2100.[164]

In SSP2, social, economic, and technological trends are assumed to not shift markedly from historical patterns [256]. DACCS technology is therefore assumed to have high costs initially [41,171], with energy and financial input requirements declining gradually over time to intermediate estimates from present-day by 2050 and remaining constant thereafter.[30] Global climate policies do not begin until 2040 [257]. Land-use policy is assumed weaker here than in SSP1, beginning at the initiation of the global carbon pricing in 2040 and increasing to a 25% proportion of the fossil carbon price by 2065, remaining constant thereafter, reflecting higher transaction costs of pricing land use change emissions than in SSP1.

SSP3 is marked by slow improvements in technology and low levels of international cooperation.[258] As such, DACCS technologies are assumed to remain energy-intensive and costly. Climate policy does not begin in earnest until 2040. Land-use policy in this scenario is poorly coordinated, and as such no pricing on land-use change emissions is assumed.[164]

SSP4 is defined by inequities and divisions, especially between high and low-income nations.[164] Governments of nations with advanced economies and large multi-national corporations are assumed to have the capacity to make investments to rapidly improve technology over time in order to offset their emissions. DACCS technologies are therefore assumed high cost initially, with energy and financial input requirements declining markedly over time, reaching the most optimistic estimates from present-day by 2050 and remaining constant thereafter. DACCS systems may be installed anywhere in the world, including in less-developed regions, based solely on the availability of resources such as carbon storage, energy, and water. Land-use policy in SSP4 is regionally fragmented, and is generally stronger in the rich world (reaching 50% of fossil carbon price by 2050) and weaker in middle-income nations (reaching 25% of fossil carbon price by 2050). In low-income nations, land use change emissions are assumed unpriced.[164]

SSP5 is a scenario marked by continued growth in fossil fuel use, but a more inclusive and globalized economy that is able to rapidly improve technologies.[259] As in SSP4, DACCS costs are assumed to decline to the most optimistic estimates from present-day by 2050. A wealthier and more equal global society is assumed to be able to have a large capacity to devote large supply of dedicated energy to negative emissions with DACCS under ambitious mitigation policies. Here, the initiation of global land-use and climate policy is assumed to be delayed until 2040. Prices on land-use carbon emissions increase to 50% of the fossil carbon price by 2065.

5.4. Results

Figure 5-1 reports results for global average temperature anomaly (a), CO_2 concentrations (b), and net CO_2 emissions (c) for the no-policy and ambitious mitigation (that is, below +2˚C and below +1.5˚C in 2100) scenarios. All +2˚C and +1.5 ˚C scenarios are projected to require future, globally net negative CO_2 emissions. No model in previous studies of the shared socioeconomic pathways found feasible solutions to limit warming to below +2˚C in the SSP3 "Rocky Road" scenario.[257] Here, we find that even the prospective availability of Gt-CO_2 scale DACCS does not enable meeting the below +2˚C target in 2100 in this fragmented and economically poor world. Hereafter, scenarios will be denoted by their SSP-RCP combination as well as the assumed availability or lack thereof of DACCS technology. For example, SSP2-DACCS-2.6 denotes the SSP2 scenario with DACCS available that limits radiative forcing in 2100 to under +2.6 W/m^2. Climate results for the default GCAM SSP-forcing target scenario permutation (that is, without DACCS included in the model) are compared to the DACCS scenarios in **Appendix D**. All scenarios temporarily overshot the +1.5˚C end-of-century target, including those without DACCS assumed available. This is driven in part by the assumed discount rate combined with prospective future negative emissions tending to delay the "optimal" timing of mitigation. More ambitious near-term mitigation could limit or avoid overshoot altogether. In most scenarios, the availability of DACCS allows delayed mitigation and thus larger overshoot of a given temperature or forcing target. The only exception is SSP1, where we tightened the constraint on the total financial transfers for all negative emissions, with the explicit goal of limiting overshoot magnitude and subsequent large-scale DACCS and other negative emissions deployment at the end of the century.

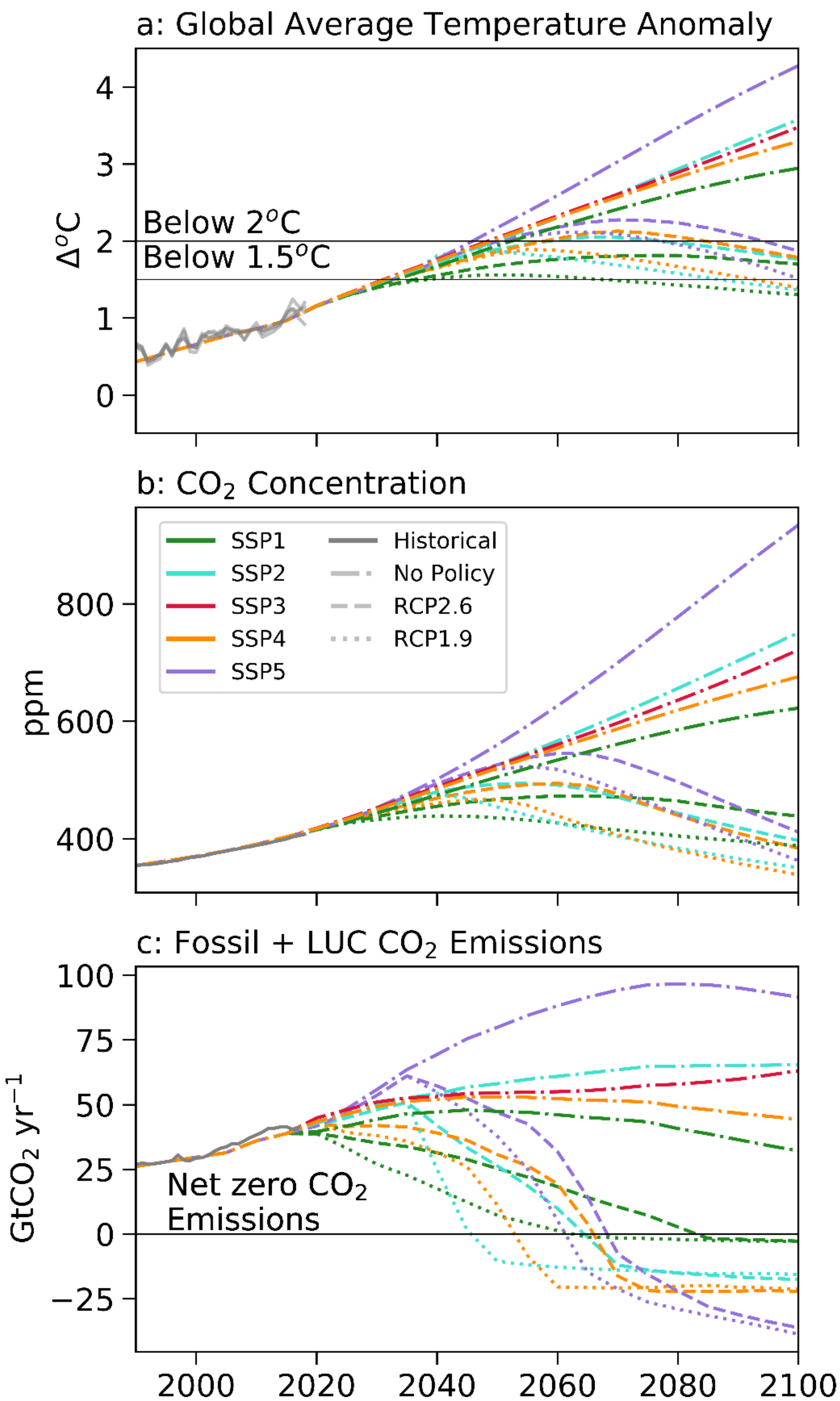

Figure 5-1: Trajectories for (a) global average temperature anomaly, (b) CO_2 concentrations, and (c) net CO_2 emissions for deep mitigation scenarios with DACCS available, and no-policy scenarios.[xix]

[xix] Historical data for emissions,[148] CO_2 concentrations,[161] and temperature anomaly[162] are indicated by grey lines.

Figure 5-2 reports positive and negative CO_2 emissions by sector for below +2°C in 2100 scenarios and below +1.5 °C in 2100 scenarios. For this and all remaining figures, the teal dashed line represents present-day (that is, 2020), while the dashed magenta lines indicate the first model period of assumed global CO_2 policy in each scenario.

In the SSP1 "Sustainable Development" scenarios, improvements in agricultural productivity and globally coordinated land-use policy allow massive CO_2 uptake from reforestation, peaking at approximately 10 $GtCO_2$ per year. This is opposite in sign and nearly two times the magnitude of present-day land-use change emission rates [148]. In SSP1-DACCS-2.6, CO_2 emissions reach net-zero around 2080, before reaching more than 10 Gt CO_2 per year of net negative emissions by 2100 as BECCS is scaled up. SSP1-1.9 requires steeper declines in near-term CO_2 emissions, as well as a longer period of sustained net negative emissions, beginning in approximately 2065. DACCS deployment in the SSP1-DACCS-2.6 scenario peaks at 0.5 $GtCO2\text{-}yr^{-1}$ in 2085 and is slightly lower in SSP1-DACCS-1.9, reaching 0.4 $GtCO2\text{-}yr^{-1}$ in 2070. These very low deployments of DACCS relative to other scenarios are driven by tighter constraints placed on all negative emissions, and low assumed social preference for DACCS in particular for this scenario.

In SSP2, delays in mitigation efforts until 2040 lead to a requirement for more rapid declines to net zero emissions, and deeper net negative emissions thereafter, reaching over 20 Gt CO_2 per year by 2100. Over the remainder of the century, DACCS contributes to negative emissions along with bioenergy and afforestation. For SSP2-DACCS-2.6, global DACCS deployment begins at Mt CO_2 per year levels (tens of DAC facilities globally) upon initiation of the climate policy in 2040. DACCS grows quickly (peak y/y growth of 47%) to Gt-CO_2 scales (thousands of DACCS facilities) by 2050, reaching a peak of over 16 Gt CO_2 per year globally by 2070. Thereafter, DACCS and other negative emissions decline slowly as population declines, reducing the need for DACCS and other negative emissions to offset positive CO_2 emissions. SSP2-DACCS-1.9 requires even steeper near-term emissions declines, which in turn leads to earlier Gt CO_2-scale DACCS deployment beginning in 2040. After initiation of the climate policy in 2040 in the SSP2-DACCS-1.9 scenario, land-use change emissions spike to 8 Gt CO_2 per year as land is cleared for bioenergy crop cultivation. Peak deployment of DACCS is reduced relative to the SSP2-DAC-2.6 case, at 9 Gt CO_2 per year.

In SSP4, poor global land-use policy substantially reduces the contribution of afforestation to negative emissions relative to other shared socioeconomic pathways. On the other hand, DACCS can scale up more rapidly owing to high investment in this 'tech fix' and quickly becomes the dominant form of negative emissions. In the SSP4-DACCS-2.6 scenario, DACCS deployment increases at a rate of over 50% per year after 2030 to reach Gt-CO_2 scale in 2050. For context, the compound annual growth rate of natural gas extraction via hydraulic fracturing in the U.S. was approximately 43% per year between 2007 and 2011.[260] DACCS deployment then declines slowly following the retirement of the inefficient units installed earlier. Technological advances in other sectors reduces the need for overall negative emissions later in the century. In the SSP4-DAC-1.9 scenario, DACCS scales even more quickly, but peak deployment requirement is reduced slightly.
In SSP5, delayed onset of climate mitigation policies as well as difficulties in mitigating gross-positive emissions lead to a large future requirement for DACCS and other forms of negative emissions. Broad social acceptance for DACCS and other negative emissions globally results to very low financial costs to deploying this technology. This in turn enables other sectors to mitigate even less aggressively than they would without DACCS available. In the SSP5-DAC-2.6 scenario, DACCS over 50% per year to

reach Gt-CO_2 scale deployment in 2050, reaching the 40 Gt CO_2 per year constraint on its deployment in 2065. Such large deployments of DACCS might be achieved by oil and gas industries quickly pivoting to take advantage of this potentially enormous source of revenue once global action on climate becomes a reality.

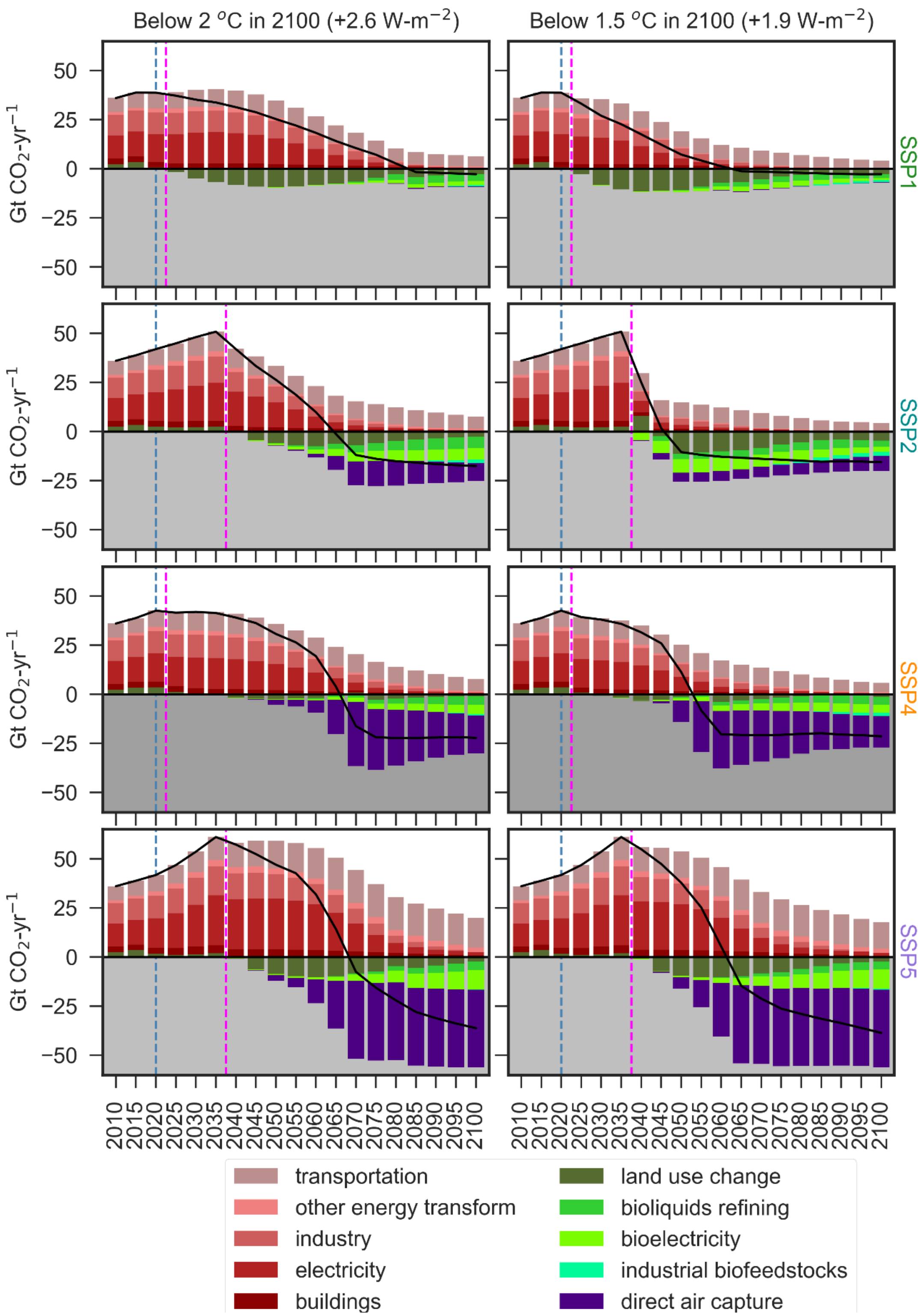

Figure 5-2: Positive and negative CO_2 emissions by sector for deep mitigation scenarios with DACCS available. Gray shading indicates net CO_2 removal. The dashed teal lines indicate present-day levels (that is, 2020). The dashed magenta lines indicate the start of global CO_2 emissions pricing.

In addition to understanding sources of positive and negative CO_2 emissions, it is also critical to understand how the use of negative emissions technologies, and geologic carbon storage more generally, might vary depending on socioeconomic developments. **Figure 5-3** reports global deployment of geologic carbon storage by SSP and end-of-century warming target combination. For the three different archetypes of DACCS modeled, CO_2 captured from the atmosphere is represented by purple shades, while sequestered combustion CO_2 from the natural gas process heat for DAC are indicated in orange. The emphasis on renewable energy in SSP1 results in the lowest use of geologic carbon storage of all the SSP scenarios, especially early-on in the century. But even SSP1 still requires large deployment of carbon storage towards the end of the century of over 10 Gt CO_2 per year, mostly from bioliquids refining for transportation fuels. SSP5 requires rapid scale-up of carbon storage, reaching over 75 Gt CO_2 per year by 2100. Over half of this is projected to come from DACCS and its process heat, with the remainder coming largely from fossil fuel and biomass electricity generation, with a smaller proportion coming from industry and bioliquids refining. In SSP4, there are still large requirements for geologic storage, reaching over 50 Gt CO_2 per year in both the +1.5° and +2° C end of century warming target. Sequestration from DACCS and its process heat again constitute the majority of geologic CCS in SSP4. The earlier initiation of climate policy (that is, immediately after 2020) reduces the need for DACCS and other forms of CCS to scale up as quickly as they do in SSP5. In SSP2, the use of geologic carbon storage falls between that of SSP1 and SSP4 and 5. Here, DACCS, bioenergy, and fossil CCS are relatively well-balanced, with no one technology dominating.

Figure 5-3 also reveals important dynamics in the breakdowns of different DACCS technologies, which we find to vary depending on the prevailing socioeconomic assumptions. In both SSP4 and SSP5, the DACCS process requiring high-temperature combustion heat from natural gas dominates, with the lower-temperature fully electric DACCS process playing a much smaller but still substantial role due to its higher capital and non-energy operating expenses. In SSP2, the share of natural gas-fired versus fully-electric DACCS is split more evenly because the electric grid decarbonizes more rapidly in these scenarios. In fact, in the SSP2-DAC-1.9 scenario fully-electric DACCS comes to dominate by the end of the century. With the non-energy cost and electricity inputs we assumed, fully-electric high-temperature DACCS does not play a substantial role in any scenario. All scenarios project tens of Gt CO_2-scale geologic storage based upon the assumption of a global CCS market which has not yet emerged. For reference, global deployment of geologic CCS was 0.04 Gt-CO_2-yr^{-1} in 2020.[261]

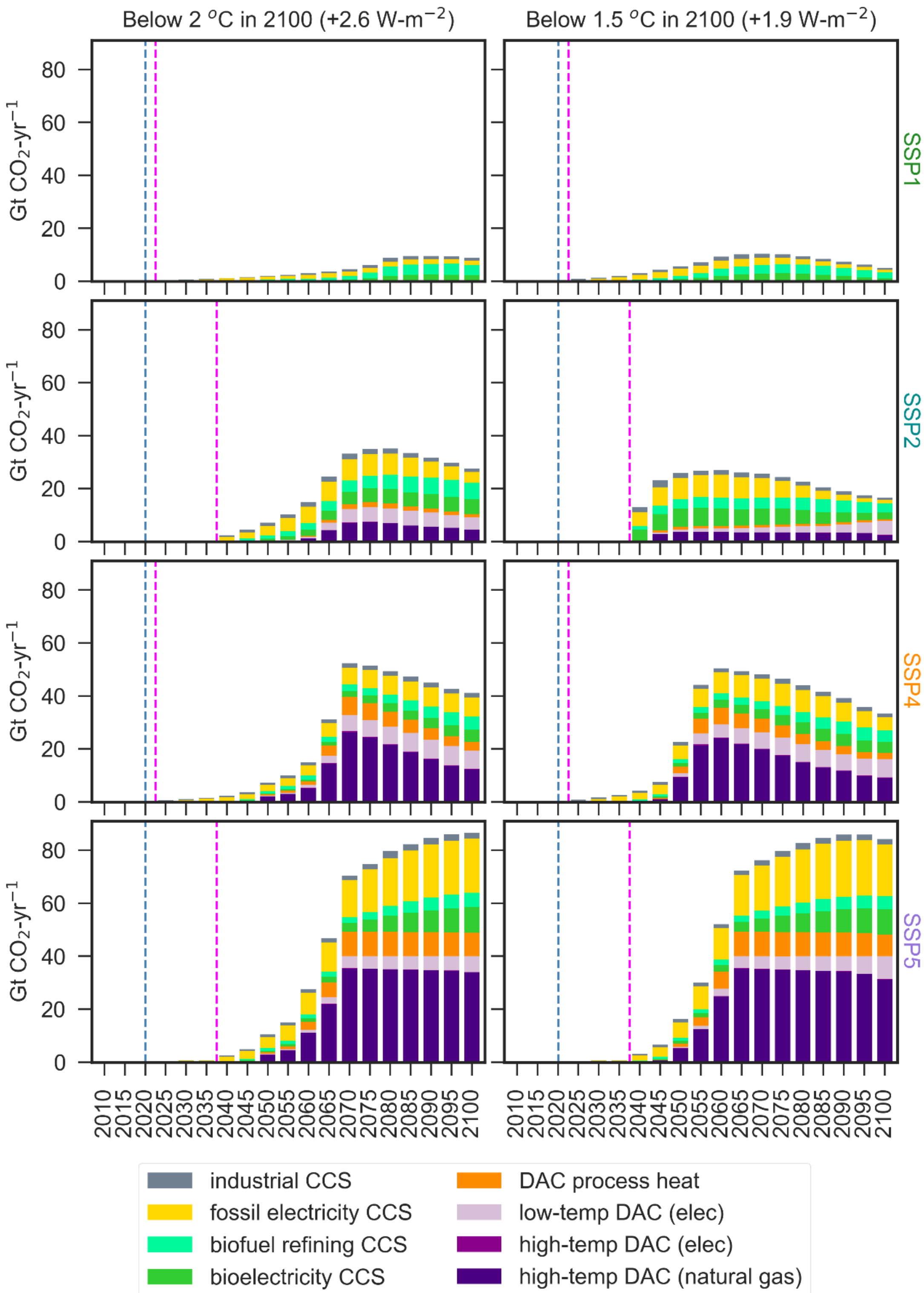

Figure 5-3: Global geologic carbon storage by sector for deep mitigation scenarios with DACCS available. The dashed teal lines indicate present-day levels (that is, 2020). The dashed magenta lines indicate the start of global CO_2 emissions pricing.

Figure 5-4 reports global primary energy consumption by fuel for all feasible scenarios. The consumption of natural gas with carbon capture and storage for high-temperature DACCS process heat is indicated by indigo coloring and is subtracted from other natural gas CCS to avoid double counting. Electricity use for DACCS is a secondary, rather than primary energy consumption, and is not reported separately but is included in the mix of primary fossil, biomass, nuclear, and renewable energy. Results for electricity generation and consumption are reported in **Appendix D**. SSP1 is projected to have low energy demand growth, with the gradual phase-down of most fossil fuels, especially coal. Renewables and BECCS dominate primary energy consumption by the end of the century. In SSP5, the use of fossil fuels continues to grow globally, even after global CO_2 pricing begins in 2040. Emissions are largely abated with carbon capture and storage, as well as offset with negative emissions from DACCS and BECCS. Together, DACCS and biomass with CCS comprise a large fraction of global primary energy consumption. In SSP4, energy demand grows more modestly due to reduced welfare corresponding with the inequality in this scenario. DACCS process heat and BECCS again grow to comprise a substantial fraction of global primary energy consumption by the end of the century. In SSP2, primary energy consumption falls between that of SSP1 and SSP5, with DACCS comprising a modest but still substantial fraction of primary energy consumption compared to SSP5. Of particular note is the abrupt phase-down of unabated coal in the SSP2-DACCS-1.9 scenario when global CO_2 pricing begins. This would be highly disruptive and highlights the risks of delayed mitigation efforts and continued growth in coal, even with large-scale negative emissions available in the future.

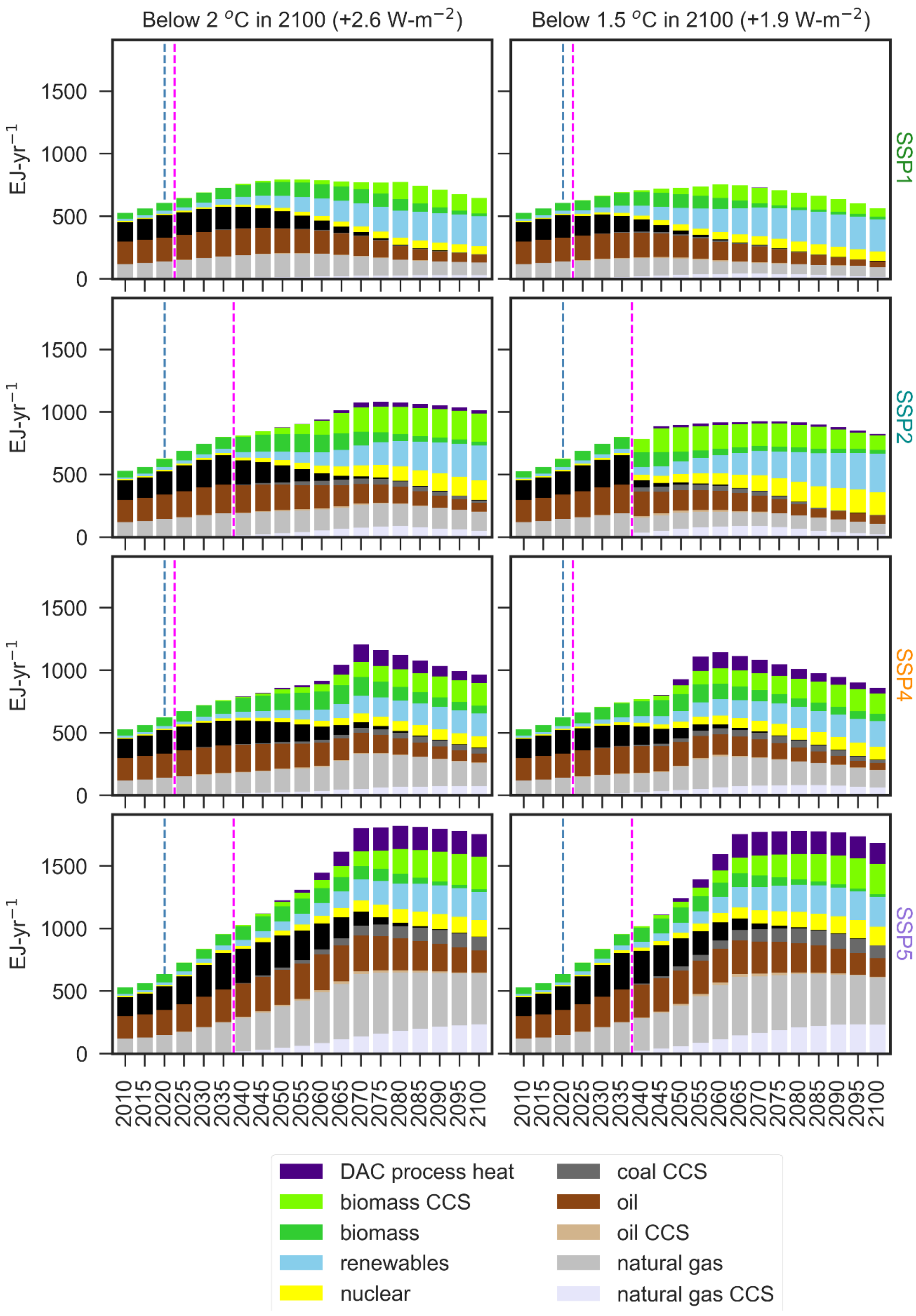

Figure 5-4: Global primary energy consumption by source for deep mitigation scenarios with DACCS available. Natural gas process heat for high-temperature DACCS is shown in purple and subtracted from other natural gas with CCS (light gray) to avoid double counting. The teal dashed lines indicate present-day levels (that is, 2020). The magenta dashed lines indicate the assumed initiation of global CO_2 emissions pricing.

Figure 5-5 reports water consumption (that is, water that is lost to evaporation or otherwise consumed by humans or livestock)[262] for each of the feasible mitigation scenarios. Water withdrawals (that is, water that is withdrawn from ground or surface water resources and then later returned to the natural environment) are reported in **Appendix D**. In all scenarios, irrigation for agriculture dominates global water consumption, with irrigation for bioenergy crop cultivation constituting a substantial additional water demand. In the SSP1-DACCS-2.6 and SSP1-DACCS-1.9 scenarios, process water for DACCS is small, owing to the small deployments of DACCS generally, and aqueous DACCS processes in particular. In the "middle of the road" scenarios, process water for DACCS reaches 34 km^3-yr^{-1} in 2075 for the SSP2-DACCS-2.6 scenario, with a lower peak of 18 km^3-yr^{-1} in 2055 in the SSP2-DACCS-1.9 scenario. For the SSP4 scenarios defined by growing inequality, DACCS process water consumption is much higher, peaking at 125 km^3-yr^{-1} in 2070 for SSP4-DACCS-2.6, and 113 km^3-yr^{-1} in SSP4-DACCS-1.9. In both SSP5 scenarios, water consumption for DACCS reaches 166 km^3-yr^{-1} by 2070, when DACCS is bound by the 40 Gt-CO_2-yr^{-1} constraint we placed on its deployment. This is equivalent to 10% of estimated global water consumption for 2020. DACCS process water requirements for the SSP4 and SSP5 scenarios are higher than in SSP1 and SSP2 because of the larger negative emissions usage overall, the higher share of DACCS amongst negative emissions, and the higher share of aqueous processes relative to the solid sorbent ones that do not require water input. Additional water consumption associated with electricity generation for DACCS is included under electricity and bioelectricity CCS in Figure 5. GCAM endogenously models many thermoelectric and non-biomass renewable generation technologies with varying water intensity; these values are reported in **Appendix B**

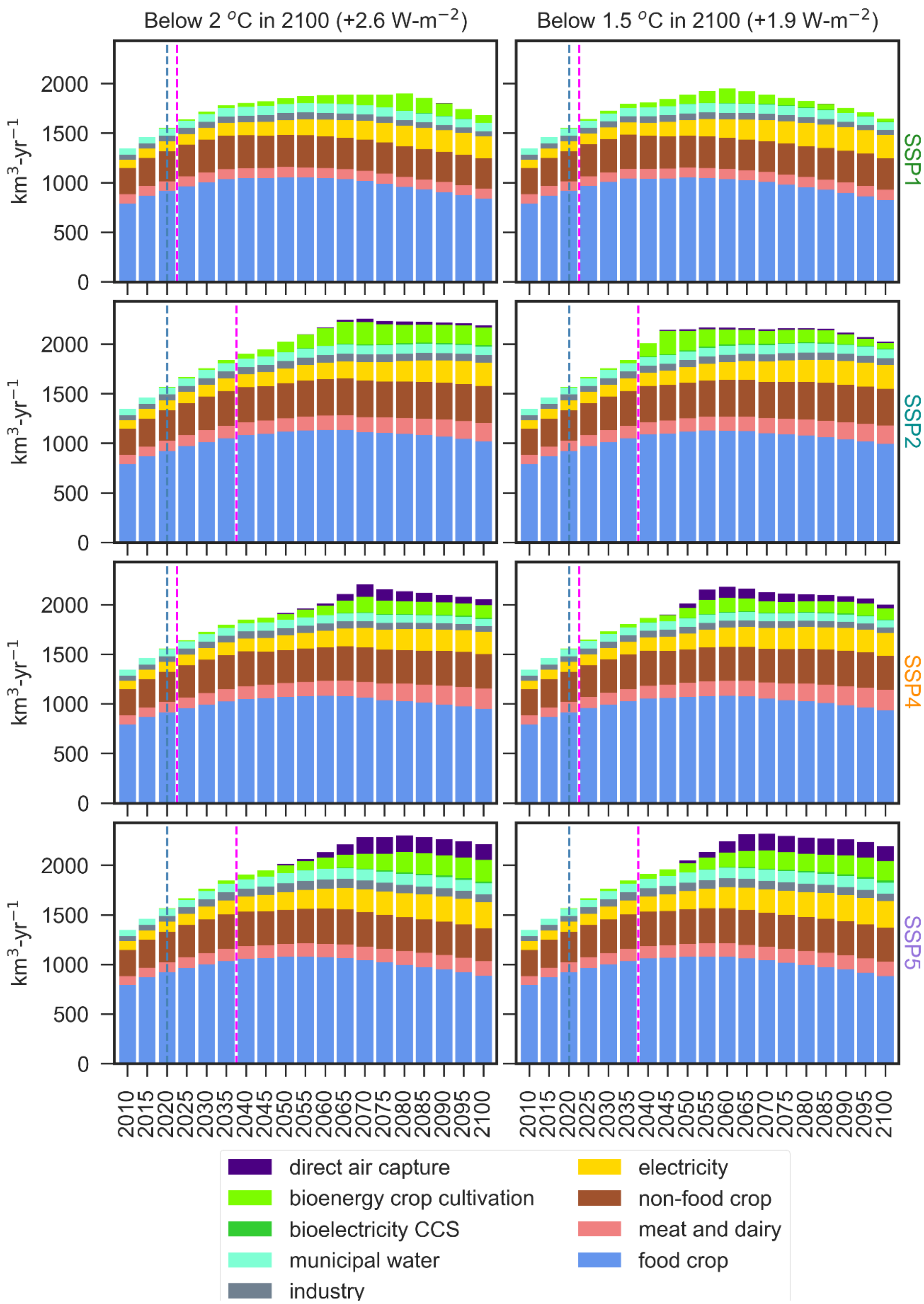

Figure 5-5: Water consumption by sector for deep mitigation scenarios with DACCS available. The dashed teal lines indicate present-day levels (that is, 2020). The dashed magenta lines indicate the assumed start of global CO2 emissions pricing.

Figure 5-6 reports changes in global land use from 2010 for each of the 8 feasible SSP-DACCS scenarios. Land use change projections for scenarios without DACCS available are reported in **Appendix D.** In all scenarios, tens of millions of km^2 of land are projected to be devoted to climate mitigation in the form of forests and bioenergy crop cultivation, even with DACCS available. But, DACCS reduces the land use requirement for bioenergy and allows more land for afforestation in all scenarios. The balance and timing of forest vs bioenergy expansion, as well as which land types are displaced to make room for them, varies by SSP and long-term climate target. In both SSP1 and SSP5, there is large reforestation of agricultural lands that are no longer needed due to improved efficiency, leading to declines in land required for food production. However, the inequities and poor land management practices in SSP4 lead to increases in land use for food and other agricultural production, and decreases afforestation. In SSP2 and SSP5, expansion of bioenergy cropland is projected even before global CO_2 pricing begins in 2040. Also in SSP5, greater emphasis on more technology-heavy bioenergy with CCS correspondingly reduces forest expansion.

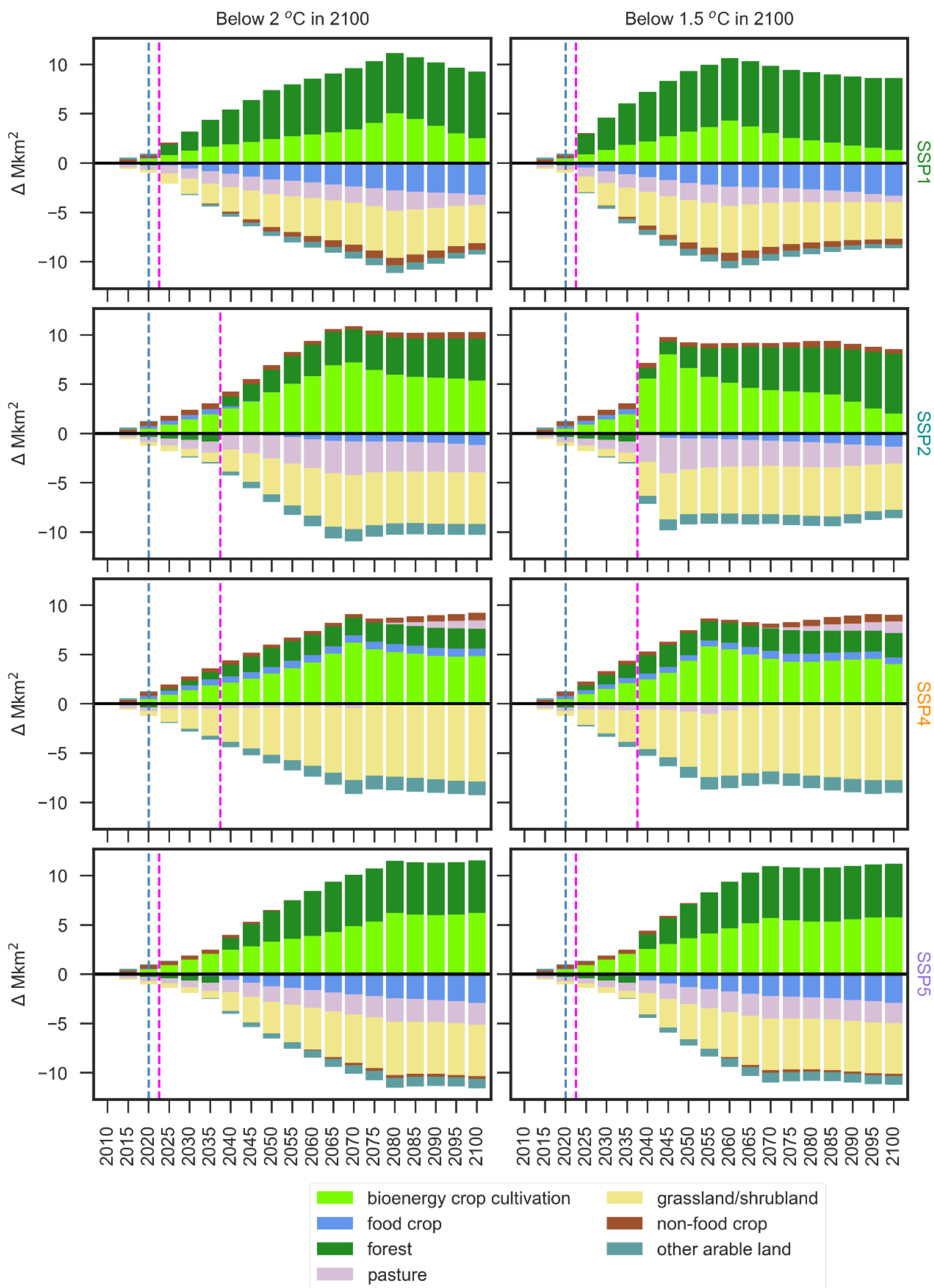

Figure 5-6: Change in global land use from 2010 for deep mitigation scenarios with DACCS available. The dashed teal lines indicate present-day levels (that is, 2020). The dashed magenta lines indicate the assumed start of global CO_2 emissions pricing.

5.5. Conclusions

The development of SSPs and associated modeling exercises were both undertaken before DACCS was demonstrated at commercial scale and emerged as such a large potential source of negative CO_2 emissions in the IAM scenario literature. With the window to limit global warming to below +2˚C and especially to only +1.5˚C in 2100 rapidly closing, IAMs have been forced to represent scenarios with deep negative CO_2 emissions. These scenarios relied almost solely on BECCS and afforestation because structures for modeling alternative pathways were not included, constituting a limitation in these scenario designs. As a prospective large-scale negative emission technology that consumes rather than produces energy (as is the case with BECCS), DACCS poses unique interactions with socioeconomic and policy factors that have not yet been explored in the SSP literature. We have sought to fill this gap by modeling DACCS and other forms of negative emissions with consistent SSP storylines using GCAM.

Our results indicate that the requirement for and balance of negative emissions are highly sensitive to scenario assumptions. The side effects on energy, water, and land systems will also correspondingly differ among these potential trajectories. Delays in mitigation and continued growth in fossil fuel use (for example, in SSP5) lead to large overshoot, with corresponding risks of not being able to ultimately meet the 2100 climate goal if DACCS and other negative emissions prove unable to scale up. Higher residual use of fossil fuels such as in SSP5 leads to a higher requirement for additional energy use for DACCS to offset these emissions, leading to compounding increases in energy use. The role of the land sector is especially sensitive to the assumed ability to price land use emissions, with fragmentation between rich and poor nations, as in SSP4, greatly diminishing its contribution. Land use plays an enormous role in mitigation even with large-scale DACCS deployment, consistent with previous studies (for example, ref [150]). While emphasis on renewables and lower consumption lifestyles as in the "sustainable development" SSP1 scenario can greatly reduce negative emissions requirement, future geologic carbon storage rates 10+ Gt CO_2 per year are required in all scenarios by 2100. The SSP1 scenario is the only one of the below +2˚ C scenarios we assessed that did not temporarily overshoot this warming target, and all scenarios temporarily overshot the +1.5˚ C target. This highlights the importance of strengthened near-term policy ambition in case negative emissions prove unable to scale up quickly enough to reverse overshoot of a less ambitious goal. We found the "rocky road" SSP3 scenario to be infeasible, even with prospective large-scale DACCS availability. Given the emerging emphasis on DACCS in deep negative emissions scenarios, we propose that the IAM community more fully integrate this technology into future SSP scenarios such that opportunities to reduce reliance on future negative emissions can be highlighted.

5.6. Chapter 5 Acknowledgements

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Chapter 6 - Conclusions and Future Work

6.1 Conclusions

This dissertation explored the potential role and side effects of direct air capture and other forms of negative CO_2 emissions in meeting the ambitious mitigation goals required to avoid the most severe impacts of climate change. Integrated Assessment Modeling (IAM) scenarios informing international negotiations and policy to meet these goals were found in Chapter 2 to rely heavily on future deployments of a limited set of negative emissions technologies (NETs), at odds with other objectives for sustainable development including (near-term) climate action. This work showed that if policies consistent with meeting international agreements to limit climate warming to "well-below" +2˚C are put into place, economic incentives would exist to deploy NETs that are not yet receiving widespread treatment by IAMs. This includes NETs such as direct air capture with carbon storage (DACCS) that were previously thought too costly to be a financially viable mitigation option. In Chapter 3, a framework was developed to model DACCS in the Global Change Assessment Model (GCAM) and then applied to understand its potential role and implications for global food energy and water systems. Chapter 4 assessed the role of DACCS in meeting China's recently-announced commitment to reach net-zero CO_2 emissions by 2060 and how its availability could affect key economic sectors as well as land, water, and energy demand in China. Chapter 5 further extended the DACCS modeling framework to understand how potential socioeconomic and policy futures could influence the requirement for different DACCS processes, and other forms of negative emissions. This section will summarize the main contributions presented here by returning to the four research questions posed in Chapter 1:

Research Questions

1. *What are the consequences of current treatment of negative emissions technologies by IAMs for other Sustainable Development Goals?*
    - A critical review of integrated assessment modeling results underpinning two of the IPCC's most recent consensus reports shows that virtually all scenarios consistent with limiting climate warming to +1.5˚C above pre-industrial rely heavily on future negative emissions from afforestation and bioenergy with carbon capture and storage (BECCS), with removal rates comparable to present-day positive CO_2 emissions.
    - Deploying BECCS and afforestation at these scales would entail enormous changes to global land-use patterns, especially in the developing world, at odds with other objectives for sustainable develpment.
    - End-of-century CO_2 emissions prices in +1.5˚C compliant scenarios exceed even conservative cost estimates of alternative negative emissions approaches that are not yet being modeled by the IAM community
    - Modeling a fuller portfolio of negative emissions technologies could highlight realistic opportunities for near-term deployments that are synergistic rather than antagonistic with other sustainable development objectives, and reduce risks of relying too heavily on any one approach.

2. *What are the impacts of direct air capture deployment for global food, water, and energy systems?*
   - A framework for modeling direct air capture technology was developed for the Global Change Assessment Model (GCAM) and used to understand the potential role and side-effects of DACCS in meeting a +1.5˚C end-of-century warming goal in both immediate and delayed mitigation scenarios. The large future negative emissions capacity made possible by DAC enabled meeting the +1.5˚C goal after delayed mitigation, which was infeasible without it.
   - DACCS could begin removing up to 3 $GtCO_2$ by 2035, up to 50% of 2019 U.S. CO_2 emissions, subject to incentivizing policies being put in place for aggressive decarbonization efforts.
   - DACCS was found to soften the sharpest land-use impacts of relying solely on land-intensive BECCS and afforestation, but not eliminate them. With DAC available, prices for major staple grain crops still rise by approximately three-fold globally and over 5-fold in many parts of the Global South due to remaining land competition from still-large deployments of these land-intensive negative emissions strategies
   - DACCS enables large reductions in irrigation water consumption and withdrawals, as well as biophysical water demand for bioenergy crops and afforestation. However, at global scale these reductions in consumption and withdrawals are offset partially or wholly by water use for DACCS itself, given its displacement of emissions abatement in addition to the use of these other negative emissions technologies.
   - Natural gas consumption for DACCS process heat could reach up over 65% of present-day global gas demand by 2100, with delayed mitigation and greatly increasing the requirement for DACCS and its associated energy and water impacts.

3. *How can the availability of direct air capture contribute to country-scale decarbonization efforts?*
   - The modeling framework developed for DACCS was applied to assess how China might meet its recently announced pledge to reach net-zero CO_2 emissions by 2060, both with and without large-scale DACCS availability.
   - Subject to their ability to scale, DACCS, BECCS, and afforestation could contribute up to 3 $Gt\text{-}yr^{-1}$ of negative emissions in China by 2060, with up to a 1.6 $Gt\text{-}yr^{-1}$ contribution from DACCS, offsetting expensive-to-mitigate sectors such as industry and freight transportation.
   - DACCS availability could reduce biomass land cropland area required to reach net-zero CO_2 emissions by up to 25% in the most productive agricultural regions in eastern China, freeing up more land for food production and environmental conservation.
   - The large projected role of DACCS in China in meeting its net-zero goal is found to be robust to variation of a number of parametric assumptions, including reduced geologic carbon storage availability, greater ease of "conventional" decarbonization efforts, and (lack of) improvements in future cost and energy efficiency.

4. *How might future socioeconomic developments influence the role of and balance between direct air capture and other forms of negative emissions?*
   - A meta-analysis was conducted to develop detailed paremetrizations for three direct air capture processes: an aqueous solvent process requiring natural gas combustion heat; an aqueous solvent process requiring high-temperature (>900˚C) heat provided by electricity; and solid sorbent process using an electric heat pump to provide low-temperature heat for sorbent regeneration. This meta-analysis was then used to develop narratives about how improvements in DACCS cost and energy efficiency might proceed, building upon existing Shared Socioeconomic Pathway model development that previously excluded DACCS.
   - Two end-of-century radiative forcing targets, consistent with limiting warming to below +1.5˚C and below +2˚C were permuted across five Shared Socioeconomic Pathway scenarios with the newly-added ability to model DACCS:
     - SSP1: "Green Growth"
     - SSP2: "Middle of the Road"
     - SSP3: "A Rocky Road"
     - SSP4: "A Road Divided"
     - SSP5: "Fossil Fueled Development"
   - DACCS was found to have an enormous potential role in SSP4 and SSP5, up to tens of $Gt\text{-}CO_2\text{-}yr^{-1}$ and enable delays in mitigation, at the risk of being ultimately unable to meet the long-term targets should real-world deployment fail to reach the massive scales projected. DACCS had a much smaller, but still substantial role in SSP1 of approximately 0.5 $Gt\text{-}CO_2\text{-}yr^{-1}$ owing to explicit consideration given to limiting reliance on all future negative emissions in this scenario's design. Even with prospective large-scale DACCS availability, limiting climate warming to below +2˚C in the SSP3 scenario was found to be infeasible.

6.2 Future Work

The original modeling contributions of this dissertation assessed the potential role and side effects at global and national scales of direct air capture with carbon storage (DACCS) technologies that require a dedicated energy supply to capture CO_2 from the atmosphere. But, as detailed in Chapter 2, there are several additional NETs – including DACCS processes that can use waste heat produced as a byproduct of industrial activities – that have not yet received widespread treatment in integrated assessment models. Developing realistic modeling structures and parametrizations for these NETs could highlight near-term carbon removal opportunities that are synergistic – or at the very least – minimally antagonistic with other sustainable development goals. For DACCS, such research could develop supply curves of waste heat availability with spatially explicit treatment of industrial sources and geologic carbon storage availability. Future IAM development could also seek to incorporate a more complete life-cycle accounting of energy and environmental impacts of DACCS, including from those from solvent and sorbent production. While this is now difficult due to the proprietary nature of many commercial DACCS processes, such research would build a more complete picture of the potential co-benefits and tradeoffs of DACCS, and may help reconcile the tens of $Gt\text{-}CO_2$ scale projections from many IAM results with expectations of more limited near-term scale-ups from many DACCS companies themselves. Given its energy demand and obvious overlaps in expertise required for fossil fuel extraction from the subsurface, of particular interest for DACCS is its potential role in a "just transition" for otherwise-displaced fossil fuel workers. Interdisciplinary research could highlight opportunities to deploy this technology in an environmentally and socioeconomically sustainable way, ensuring long-term good-quality jobs in climate remediation as opposed to carbon extraction.

As detailed in Chapters 3-5, much of the requirement for NETs including DACCS, and consequently the side-effects resulting from their deployment was driven by the need to offset residual emissions sources, especially from the freight transportation sector's continued use of liquid fuels. However, electrification of freight transportation may be far less costly than previously estimated, and several large companies and the United States Postal Service have recently made investments in electrifying their fleets. Passenger vehicle electrification is also accelerating, with a growing number of automakers committing to phasing out production of vehicles with internal combustion engines. Additional model development and scenario exercises could assess interactions between accelerated rollout of transport electrification and the requirement for negative emissions.

If policy incentives consistent with meeting international climate objectives are put into place, it is likely that more complex industrial ecology relating to the use of captured CO_2 would emerge before devoting such large amounts of resources solely to negative emissions activities. Rather than acting solely as an atmospheric waste disposal service, commercial direct air capture operations would likely seek value-added uses for their captured CO_2. This would compete with CO_2 captured from higher-concentration, and thus more energetically favorable, waste streams. For example, synthetic fuels derived from Fischer-Tropsch reactions of captured CO_2 and hydrogen could be largely drop-in replacements for petroleum-based liquids. But the source of the CO_2 (i.e., atmospheric, biomass, or fossil), hydrogen (e.g., water electrolysis or natural gas), both affect the life cycle cost and energy burdens, as well as the extent to which the fuel is truly zero or ultra-low carbon after it is combusted. CO_2 from DAC and industrial sources could also be used to cure high-strength cement or produce other long-lived materials. These pathways to develop a "circular economy for CO_2" hold promise but have not yet been studied comprehensively for their global potential or interactions with other sectors of the economy.

Corresponding to their development in the run-up to the Paris Agreement, the objective functions in IAM scenarios are often specified to meet a specific temperature target in 2100. They generally do not account for the co-benefits of CO_2 emissions reductions (e.g., reduced local air pollution), the additional damages resulting from "overshooting" the warming target, or the externalities and co-benefits of NET deployments themselves. Future development could incorporate climate and local air and water pollution damage functions into technology-rich IAMs and evaluate how this influences the "optimal" timing and magnitude of policy efforts. Together, these efforts could emphasize opportunities for more sustainable near-term deployments of NETs, as well as to maximize the extent that future NETs deployments are drawing down atmospheric CO_2 concentrations over time.

Appendix A - Supplementary Information for Chapter 2: Review of Integrated Assessment Modeling Treatment of Negative Emissions

Here, we provide the method we used to assess the sequestration potential, cost, and SDG interaction effects of candidate NETs. We score each NET on a scale of -2 (high potential for tradeoffs) to 2 (high potential for synergies) based primarily on Smith et al., 2019, as well as well as the IPCC's Special Report on 1.5 C (IPCC, 2018). Figure 5.2 from the IPCC report is translated to tabular form and further supplemented with sources from the literature and synthesis by the authors, as neither the IPCC nor Smith 2019 assess all the NETS evaluated here for SDG interactions. The scores assigned based on our qualitative assessment are translated to a color-coded table for the figure in the main text using Microsoft Excel. SDG 4: Quality Education, SDG 5: Gender Equality, SDG 16: Peace Justice and Strong Institutions, and SDG 17: Partnerships for the Goals were excluded from our analysis, as based on existing literature we did not foresee direct interaction mechanisms between any of the NETs and those SDGs. More research is required to consider more indirect effects between these SDGs and NETs. All interaction effects are heavily-dependent on scale, wherein very large-scale deployment would shift the balance towards a higher potential for negative tradeoffs for all combinations of NETs and SDGs. All NETs positively contribute to SDG 13: Climate Action by removing CO_2 from the atmosphere, coinciding with the sequestration potential of each NET.

Table A-1: Assessment of SDG-NET Interaction Potential

	Coastal Blue Carbon	**Afforestation**	**Soil Carbon / Biochar**	**BECCS**	**Accelerated Weathering**	**Ocean Alkalinity**	**DA C**
Sequestration Capacity (Gt CO2/yr)	0.13* [29]	0.5-3.6 [89]	Soil Carbon: 0-5 (subject to saturation) Biochar: 0.5-2 [29,89]	0.5-5 [89]	2-4 [89]	3.6** [111]	0.5-5 [89]
Inputs	coastal wetlands, sea grass meadows	land	agricultural land, pyrolysis byproducts	agricultural land, nutrients, biomass	mined minerals, alkaline waste material	mined minerals	natural gas, electricity, amines
Outputs	increased organic carbon burial	forested land, biomass	increased organic carbon burial	energy, biochar	large volumes of carbonate byproducts	increased disolved inorganic carbon	enhanced oil production
Co-benefits	ecosystem services, hydrology, biodiversity	ecosystem services, hydrology, biodiversity	increased soil health, reduced fertilizer requirements	energy production	increased soil health	directly mitigates ocean acidification	potential alternative employment for fossil fuel workers
Side-effects	competition with coastal development	competition with agricultural land	Potential increases in non-CO2 GHGs	competition with food, habitat loss, water stress, nutrient loading	impacts from surface mining	impacts from surface mining, localized	large energy demand

	Coastal Blue Carbon	Afforestation	Soil Carbon / Biochar	BECCS	Accelerated Weathering	Ocean Alkalinity	DAC
						high ocean pH	
Costs ($/tCO₂)	\$0-20 [29]	\$5-50 [89]	\$0-100 [89]	\$100-200 [89]	\$50-200 [89]	\$20-100	\$100-300 [30,89]
1: No Poverty.	Restored wetlands could provide habitat for fish and shellfish, an important protein source [263,264] **Score: 1**	"There is relatively little literature that explicitly examines the impact of AR on SDGs 1 and 2 across the globe, but there are indications that AR programs can contribute to local livelihoods and decreasing poverty" [263]. **Score: 1**	"Healthy soil can produce more food and goods, thereby contributing positively to food security and incomes for the world's poorest people" 'For SDG 1, No Poverty, reducing costs and dependency on external resources together with the increase in crop productivity would help farmers to be self-sufficient while increasing incomes."[263]. **Score: 1**	More land-efficient per unit CO2 sequestered than afforestation, but still displaces productive agricultural land [265]. Construction of new infrastructure for biomass energy and CO2 transport may provide value-added employment **Score: 0**	Certain silicate minerals could increase soil health, enhancing agricultural productivity if applied to croplands. [107,108]. Mining could provide employment opportunities but the industry has a poor track record of alleviating local poverty [263] **Score: 0**	Reductions in ocean acidification impacts could enhance fisheries, which can contribute to nutrition [111]. Mining could provide employment opportunities but the industry has a poor track record of alleviating local poverty [263] **Score: 0**	Lowers policy costs (i.e., CO2 prices) of aggressive mitigation pathways relative to land-based CDR alone [96]. But this is only relative to other NETs. DAC could provide employment opportunities but development is likely to occur in areas that have geologically appropriate formations (e.g., fossil fuel reserves and associated infrastructure) (Author assessment) **Score: 0**
2: Zero Hunger	Restored wetlands could provide habitat for fish and shellfish, an important protein source. [263,264] **Score: 1**	Very large land footprint competes with agriculture, especially at the scales envisaged by IAMs [18] [140]. But some AR practices (e.g., agroforestry can affect food supply positively [263] **Score: -1**	Healthy soil can produce more food and goods, thereby contributing positively to food security and incomes for the world's poorest people.. food security will benefit from higher yields and higher agroecosystem resilience [263]. **Score: 1**	Likely to displace productive agricultural land for food production, especially at the scales envisaged by IAMs [25,153] **Score: -2**	Certain silicate minerals could increase soil health, enhancing agricultural productivity if applied to croplands [107]. **Score: 1**	Reductions in ocean acidification impacts could enhance fisheries, in particular calcifying shellfish, providing nutrition. But localized pH increases may harm	May lower costs (i.e., CO2 prices) of aggressive mitigation pathways relative to land-based CDR alone, but this is only relative to other NETs. **Score: 0**

	Coastal Blue Carbon	Afforestation	Soil Carbon / Biochar	BECCS	Accelerated Weathering	Ocean Alkalinity	DAC
						ecosystems [111] **Score: 0**	
3: Good Health & Well Being	Ecosystem services provide natural water filtration [266–268] **Score: 2**	Restoration of previously deforested land could provide ecosystem services [29] **Score: 1**	"by increasing crop yields, aiding soil remediation and water purification, [soil carbon enhancement] and biochar application to soils can contribute significantly to peoples' nutritional health". [263] **Score: 1**	Reductions in mortality and morbidity from air pollution are possible if BECCS displaces fossil fuels for energy. However increases in air and water pollution are likely from incentivization of commodity agriculture **Score: 0** [139]	Environmental degradation and health impacts of mining for silicate minerals [29]. **Score: -1**	Environmental degradation and health impacts of mining activity [111]. **Score: -1**	If energy comes from fossil fuels, environmental degradation from fossil fuel extraction. **Score: -1**
4: Quality Education							
5: Gender Equality							
6: Clean Water & Sanitation	Ecosystem services provide natural water filtration. [266–268] **Score: 2**	Ecosystem services provide natural water filtration [263]. However, the scales envisaged by some IAM scenarios could require drylands to be converted to forest, which requires irrigation, in potential competition with drinking water	Reduced soil erosion. [263] **Score: 1**	N-fertilizer runoff could contaminate drinking water resources [140]. **Score: -1**	Could decrease irrigation requirements for agriculture, but mining water requirements (e.g., dust suppression) could impact local water resources. [263] **Score: 0**	Mining water requirements (e.g., dust suppression) could impact local water resources. [263] **Score:-1**	Water-consuming DAC processes could result in local scarcities but lower water impacts compared to biofuels [28]. Places with plentiful low-carbon energy may be water-stressed (e.g., deserts). (Author assessment) **Score: 0**

	Coastal Blue Carbon	Afforestation	Soil Carbon / Biochar	BECCS	Accelerated Weathering	Ocean Alkalinity	DAC
		resources (Jobbágy and Jackson, 2004; Ornstein et al., 2009, IPCC, 2018) **Score: 0**					
7: Affordable & Clean Energy	No obvious direct pathways for interaction **Score: 0**	Sustainably-harvested timber from (re)afforested land could be used for biofuel, but forested land competed directly with dedicated bioenergy crops [29]. **Score: 0**	"give people access to Affordable and Clean Energy (through energy crops)." [263] **Score: 1**	Provides energy services in addition to carbon sequestration, but incentives based around carbon credits alone could end up incentivizing highly inefficient BECCS plants to consume and sequester as much biomass C as possible [271] **Score: 1**	Consumes energy for mineral transport and grinding [29]. **Score: -1**	Consumes energy for mineral transport and grinding. "Sequestering 10% of current emissions would require all of global shipping capacity" [111] **Score: -1**	Large energy impacts. [96] **Score: -2**
8: Decent Work & Economic Growth	"Wetland construction for treatment of wastewater, and various other wetland restoration approaches , to deliver the wide range of high-value NCPs discussed above, could	"AR programs could create new income opportunities for rural land owners Taking into account the suitability of the tropical basins for reforestation to remove CO2 (8), this could also imply financial transfers from	Through the combination of improved agricultural productivity, improved water and air quality, and the potential of soil (organisms) to provide medicines, SCS can contribute positively to SDG 3, Good Health and Well-being.	Construction of new infrastructure for biomass energy and co2 transport may provide value-added employment [263]. But risks making developing world communities dependent on global biomass agricultural	Alternative employment for coal mining industry workers. But could also entrench extractive industries with associated occupational health and safety risks (Author assessment). **Score: 0**	Alternative employment for coal mining industry workers. But could also entrench extractive industries with associated health and safety risks. "~2 tonnes of mineral per tonne of CO2 draw-down	Alternative employment for oil and gas workers. But could also entrench extractive industries with associated occupational health and safety risks (Author assessment) **Score: 0**

	Coastal Blue Carbon	Afforestation	Soil Carbon / Biochar	BECCS	Accelerated Weathering	Ocean Alkalinity	DAC
	provide significant employment in developing and developed countries in support of Decent Work and Economic Growth." [263] But there does exist potential for competition with coastal development (Author assessment) **Score: 1**	North to South under global carbon." [263]. **Score: 1**	This may also help to achieve Decent Work and Economic Growth and Industry" [263]. **Score: 1**	commodity market. (Author assessment) **Score: 0**		requires massive mining and transportation efforts." [111] **Score: 0**	
9: Industry Innovation & Infrastructure	Sustainably designed engineered wetlands could provide coastal flood protection and compliment "hard infrastructure" [272,273] **Score: 2**	"Depending on the mode of implementation, AR could lead to enhanced forest infrastructure. This could provide a positive impact on forest industries." [263] **Score: 1**	Biochar could provide carbon negative energy with value-added coproduct. More resilient soil can dampen the effect of climate hazards [263] **Score: 1**	"On the one hand, newly generated agricultural income options could lead to lower investments in innovation and manufacturing in other sectors, especially in biomass producing countries. On the other hand, due to the cleaner energy provided by BECCS, CO2 emission of industrial production	Creation/expansion of new extractive industry to reverse effects of previous and ongoing extractive industries (Author assessment). "Creating tailings solely to consume labile Mg for rapid CO2 capture from air and solid storage would produce 5 to 50 Gt of tailings (2 to 17 km3) per Gt of CO2 captured. To put these volumes in context, this corresponds to a layer… 10 to 100 m thick	Creation/expansion of new extractive industry to reverse effects of previous and ongoing extractive industries. [111] **Score: -1**	Could "lock in" fossil fuel infrastructure (e.g., natural gas pipelines) for the purpose of CO2 removal. Methane leakage from natural gas could offset radiative forcing reductions [274]. **Score: -1**

	Coastal Blue Carbon	Afforestation	Soil Carbon / Biochar	BECCS	Accelerated Weathering	Ocean Alkalinity	DAC
				would be lower.” [263] **Score: 0**	over Washington, D.C. (177 km2), per Gt of CO2 captured from air and stored.” [29] **Score: -1**		
10: Reduced Inequalities	Targeted investment in could provide environmental co-benefits in the developing world.[263] Figure 2 (Author assessment) **Score: 1**	Depending on implementation, could provide environmental restoration to disadvantaged communities, but scaling incentives would likely result in disproportionate burdens of CDR on the developing world, resulting in much higher food prices [25,153]. **Score: 0**	Not directly impacted by SCS or biochar [263], but global carbon market could provide means of financing sustainable agriculture in the developing world (Author assessment) **Score: 0**	Economic incentives alone could result in BECCS feedstock cultivation being pushed to the developing world where land is "cheap" resulting in disproportionate burdens so that the developing world can avoid mitigating as aggressively in both the near and long term [25]. **Score: -1**	Could improve agricultural productivity in the global tropics [107] but could also exacerbate inequalities with lower skilled workers employed in mining sector, especially with regard to silicate health impacts (Author assessment) **Score: -1**	Alkalinity additions could mitigate ocean acidification impacts on fisheries in the developing tropics [18]. However the mining required could also exacerbate inequalities with lower skilled workers employed in mining sector [263]. **Score: -1**	Alternative employment for oil and gas workers, but investment in DAC infrastructure is could take place mostly in places where fossil fuel infrastructure already exists, which could exacerbate inequalities. Environmental impacts associated with energy requirements (Author assessment). **Score: -1**
11: Sustainable Cities & Communities	Sustainably designed engineered wetlands could provide coastal flood protection and compliment "hard infrastructure". [263,272,273,275 276] **Score: 2**	Restored forest lands could provide ecosystem services (e.g., flood prevention) [263] **Score: 1**	“This may also help to achieve Decent Work and Economic Growth and Industry, Innovation and Infrastructure, which in turn might contribute to developing Sustainable Cities and Communities” [263] **Score: 1**	May provide employment in agricultural communities but also risks making them dependent on international commodities markets (Author assessment). **Score: 0**	Creation of new extractive industry to reverse effects of previous and ongoing extractive industries (Author assessment). **Score: -1**	Creation of new extractive industry to reverse effects of previous and ongoing extractive industries (Author assessment). **Score: --1**	Use of energy (at least some of which is likely to come from fossil fuels) to reverse impacts of previous and ongoing fossil fuel extraction (Author assessment). **Score: -1**

	Coastal Blue Carbon	Afforestation	Soil Carbon / Biochar	BECCS	Accelerated Weathering	Ocean Alkalinity	DA C
12: Responsible Consump. & Prod.	Restored wetlands could provide habitat for fish and shellfish, a valuable protein source.[263,264] **Score: 2**	Opportunities for sustainable forestry, but scale-dependent.[29]. **Score: 1**	Carbon markets could offer pathway to finance more sustainable agriculture.[263]. **Score: 1**	If thoughtfully-implemented, could displace fossil fuels for carbon-negative energy, but could also incentivize agricultural products as a global commodity, with corresponding incentives for unsustainable practices[263] **Score: 0**	May reduce fertilizer requirements[263]. However if primary goal is CO2 removal, would imply the creation of new extractive industry to reverse effects of previous and ongoing extractive industries. (Author assessment). **Score: -1**	Creation of new extractive industry to reverse effects of previous and ongoing extractive industries. (Author assessment). **Score: --1**	Use of energy (at least some of which is likely to come from fossil fuels) to reverse impacts of previous and ongoing fossil fuel extraction (Author assessment). **Score: -1**
14: Life Below Water. *Note that all NETs would reduce ocean acidification with CO_2 removal*	Habitat restoration for coastal species[263,275]. **Score: 2**	"Life below water not directly impacted by AR"[263] **Score: 0**	"SCS can help to prevent erosion and polluted substances from reaching water bodies."[263] **Score: 1**	N fertilizer runoff[263]. **Score: -1**	Directly ameliorates ocean acidification, but could have localized environmental degradation (e.g., trace metals)[107,277] **Score: 1**	Directly ameliorates ocean acidification, but could have localized environmental degradation where alkalinity is applied[111]. **Score: 1**	No obvious direct interaction pathways **Score: 0**
15: Life on Land	Coastal ecosystem restoration.[275] **Score: 2**	Restored forest lands could increase biodiversity, but afforesting non-native ecosystems (e.g., graslands) could reduce biodiversity[265]. **Score: 1**	"SCS can help to improve soil health, thereby enhancing potential for biodiversity and healthy ecosystems."[263] **Score: 1**	Large land use impacts biodiversity[28,140] **Score: -1**	Mining environmental impacts[149]. **Score: -1**	Mining environmental impacts[149] **Score: -1**	Much smaller footprint than land-based NETs. Potential impacts of natural gas pipelines for energy supply (Author assessment) **Score: 0**
16: Peace, Justice and Strong							

	Coastal Blue Carbon	Afforestation	Soil Carbon / Biochar	BECCS	Accelerated Weathering	Ocean Alkalinity	DAC
Institutions							
17: Partnerships for the Goals							

Appendix B - Supplementary Information for Chapter 3: Food-Energy-Water Implications of Negative Emissions Technologies in a +1.5°C Future

As shown in **Figure B-1**, the ensemble of IAM scenarios underpinning the IPCC 1.5 °C Special Report assume enormous deployment scales for BECCS, afforestation, and DAC. In the median case, afforestation is deployed on the order of current-day deforestation emissions, which would require massive changes to global land use practices, along with robust enforcement policies to prevent the release of previously sequestered carbon.[278,279,150] BECCS is the most widely-modeled NET, and shows even higher assumed sequestration potential. The projected role of DAC is more limited owing to high cost assumptions and constraints on its deployment in the relatively few modeling exercises incorporating it to date. However, in several scenarios the availability of DAC is projected to enable CO_2 removal at rates approaching or exceeding that of current-day positive emissions from fossil and land use change sources (i.e., lower-right of Figure 1).

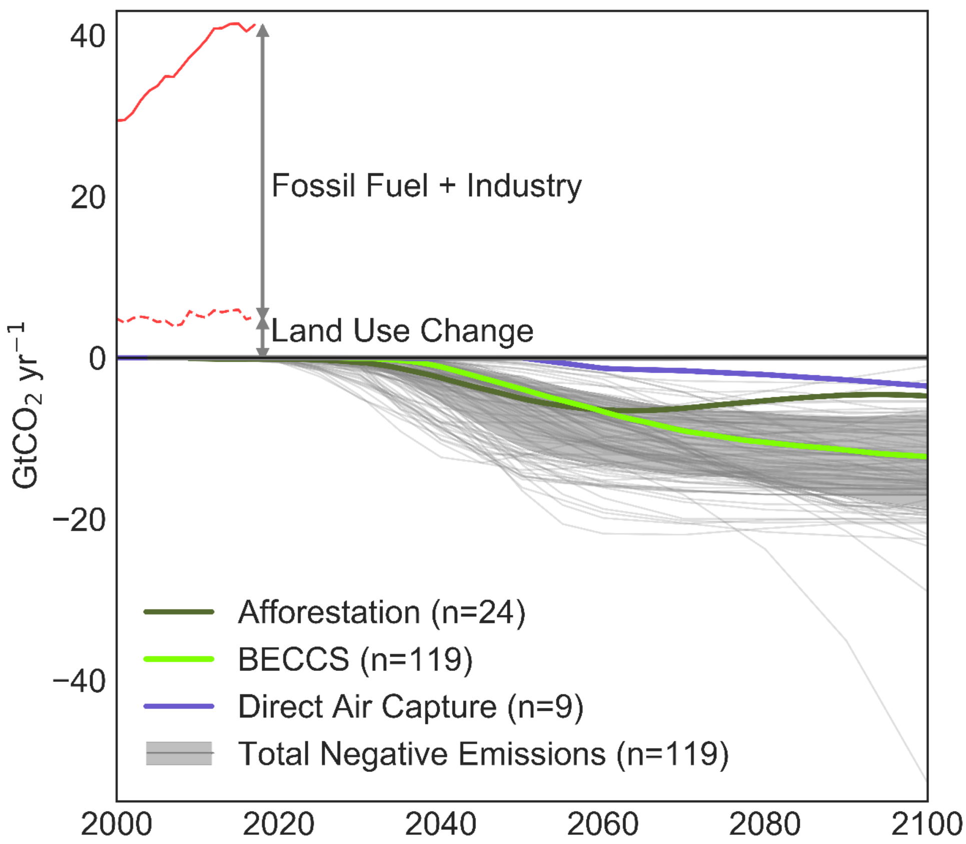

Figure B-1: Projected NET deployments to limit global warming to 1.5 °C.

Modeling results underpinning the IPCC's Special Report on Global Warming of 1.5 °C.[66] The thicker coloured lines show the median projected deployments of the individual afforestation, BECCS, and DAC technologies, for those model results which report them. The thin grey lines represent the combined negative emissions deployment for individual scenarios. The grey shading represents the 68% confidence interval (+/- 1 standard deviation) on combined negative emissions deployment.

Figure B-2 reports a) global average temperature anomalies, b) atmospheric CO_2 concentrations, and c) CO_2 emissions constraints applied in this study to represent high and low-overshoot of the 1.5 °C end-of-century warming target.

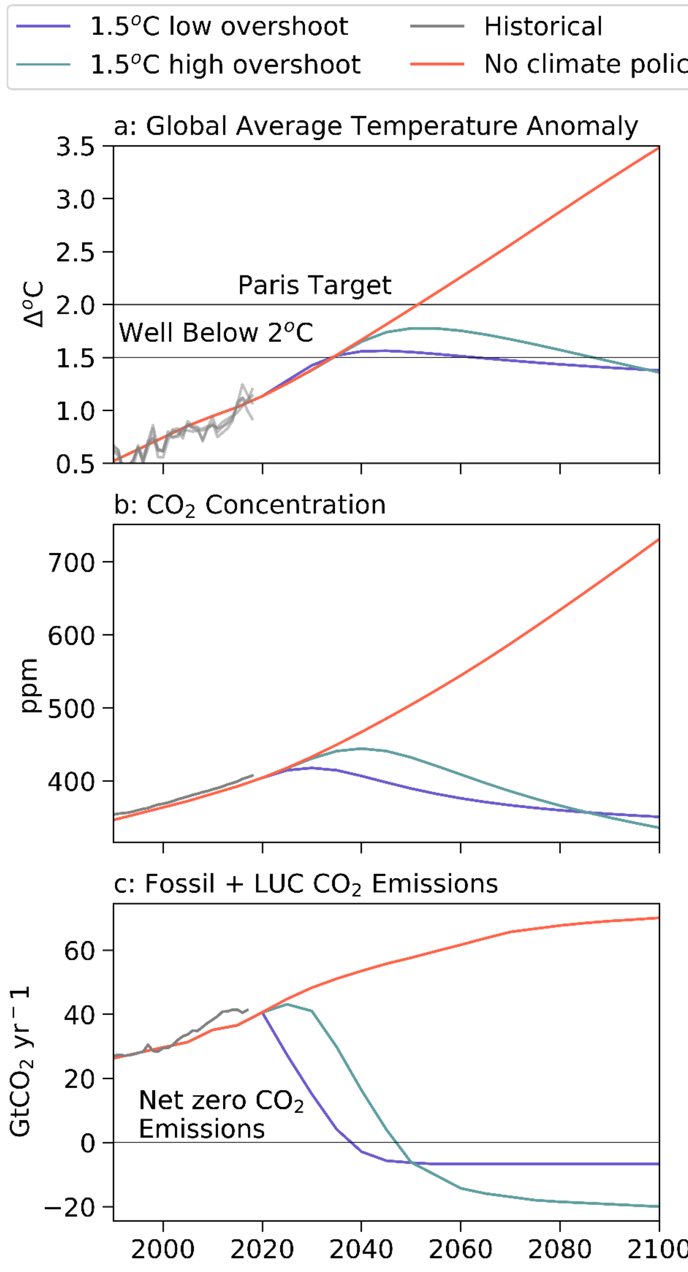

Figure B-2: Representative high and low overshoot trajectories of the 1.5 °C end-of-century temperature target.

a) Temperature anomalies from pre-industrial, b) CO_2 concentrations, and c) emissions trajectories. Historical data for emissions,[148] CO_2 concentrations,[161] and temperature[162] are indicated by grey lines. The "no climate policy scenario" is the GCAM reference scenario.

Figure B-3 shows the distribution of peak global average surface temperature rise from pre-industrial for all scenarios in the Integrated Assessment Modeling Consortium (IAMC) database that meet a 1.5 °C end-of-century temperature target.[19] The majority of scenarios allow large overshoot (i.e., have peak temperatures well above 1.5 °C), implying large deployments of negative emissions technologies to return temperatures to 1.5°C or below. **Figure B-4** compares the peak temperature overshoot from our two scenarios to those of other scenarios in the IAMC database which project non-zero deployments of DAC.[23,40,43] Our low overshoot scenario resulted in 1.56 °C peak temperature anomaly and our high-overshoot scenario resulted in 1.78 °C peak temperature rise from the pre-industrial period.

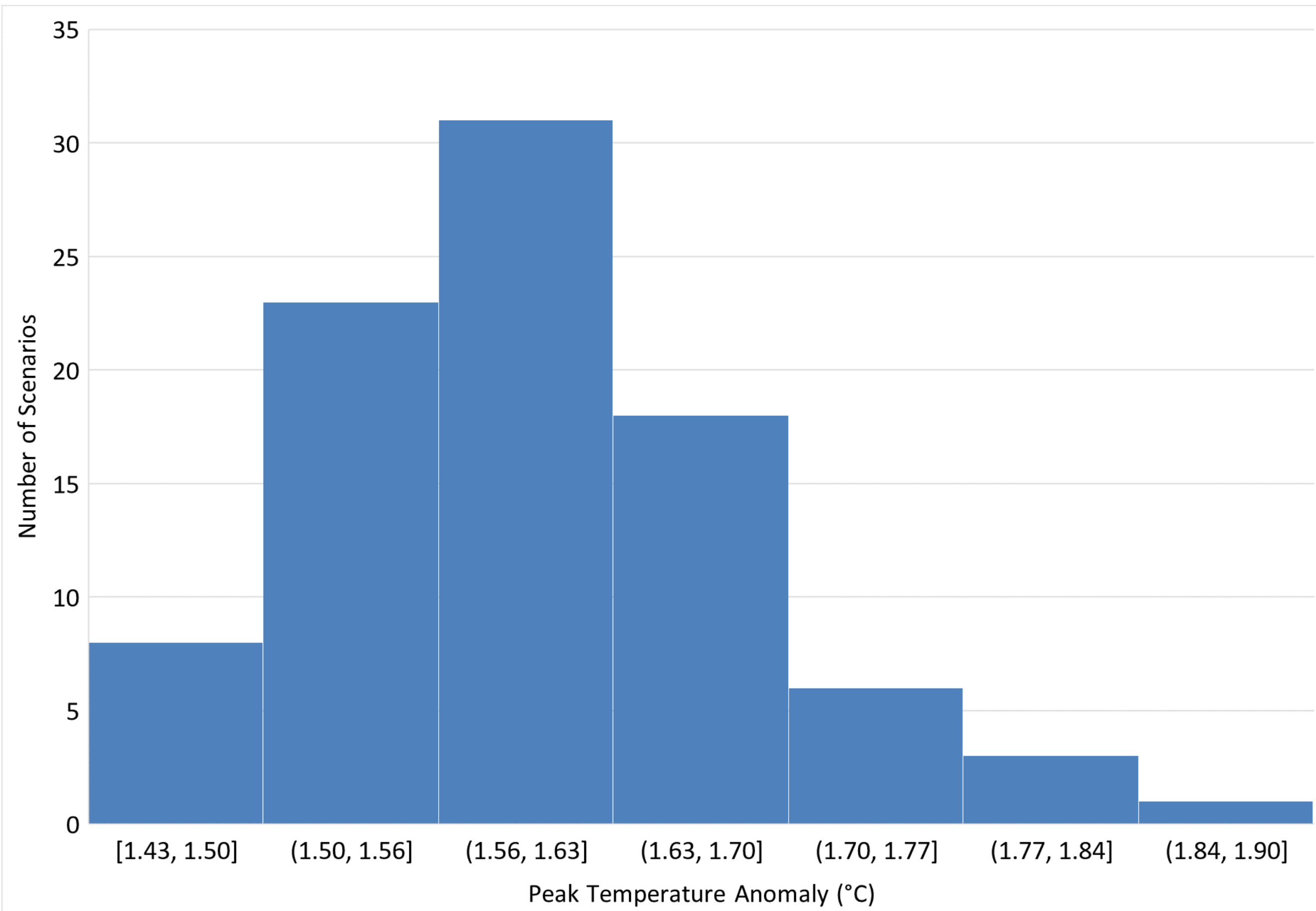

Figure B-3: Distribution of peak temperature anomalies in the IAMC database for scenarios meeting a 1.5 C end-of-century temperature target

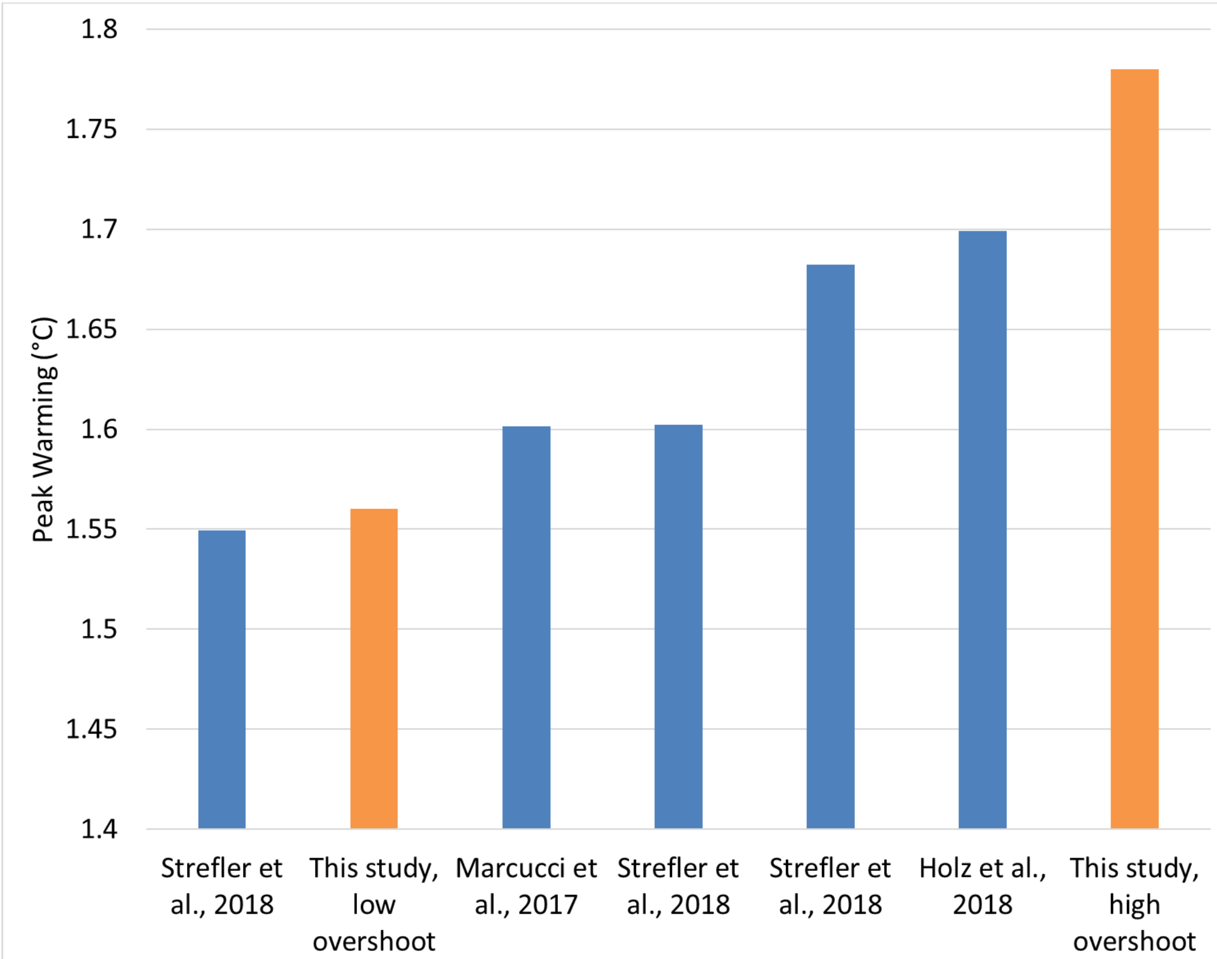

Figure B-4: Peak temperature anomalies for scenarios projecting non-zero deployments of DAC and meeting a 1.5 °C end-of-century temperature target.

Figure B-5 reports differences in global land use between the GCAM reference scenario, in which no climate policy is implemented, and the below 1.5 °C low-overshoot scenario in which no DAC is available.

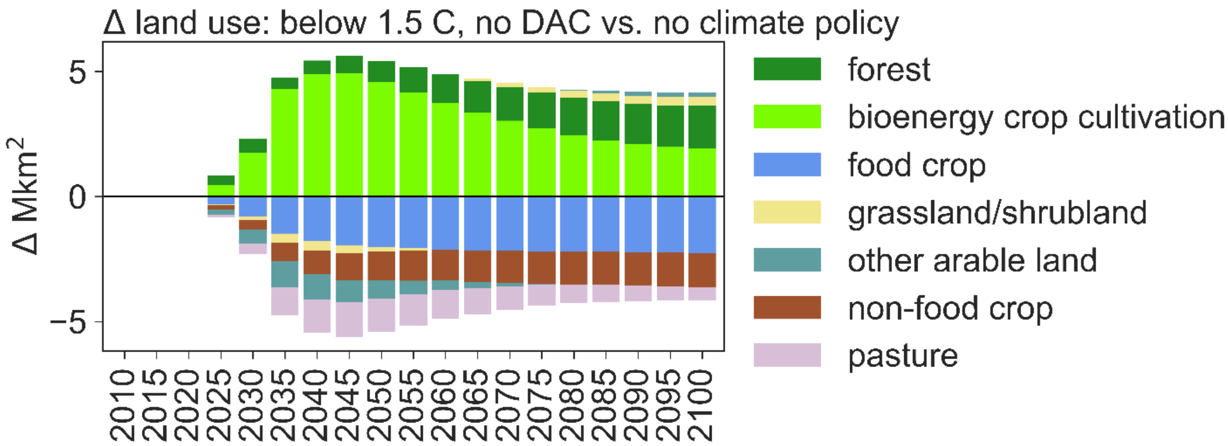

Figure B-5: Differences in global land use between the below 1.5 °C low overshoot scenario, and the GCAM no climate policy (reference) scenario, which results in ~3.5 C of warming by 2100.

Figure B-6 shows cumulative geologic carbon storage supply curves for onshore and offshore storage resources by region. For this figure, GCAM regions with small geologic storage capacity are aggregated together (e.g., Africa, Europe, South America excl. Brazil). We used the default geologic carbon storage market parametrization in the GCAM 5.2 release. Each region's onshore geologic storage supply curve is parametrized from updates to Dooley and Friedman (2005)[280,281] and includes deep saline sedimentary and basalt formations, depleted oil and gas fields, and unmineable coal seams, following Dahowski (2011).[282] Offshore storage is assumed be an unlimited resource where cost is a larger barrier to deployment than physical limits on repository availability. The offshore storage cost estimate of \$96/tCO_2 is not intended to serve as an exact point estimate but rather to represent a backstop reservoir for CCS when regions exhaust their land-based storage. Therefore, a conservative estimate is used (several times the \$32/tCO_2 estimate from Decarre et. al., 2010)[283] owing to the large uncertainty of both offshore and onshore carbon storage costs and availability.

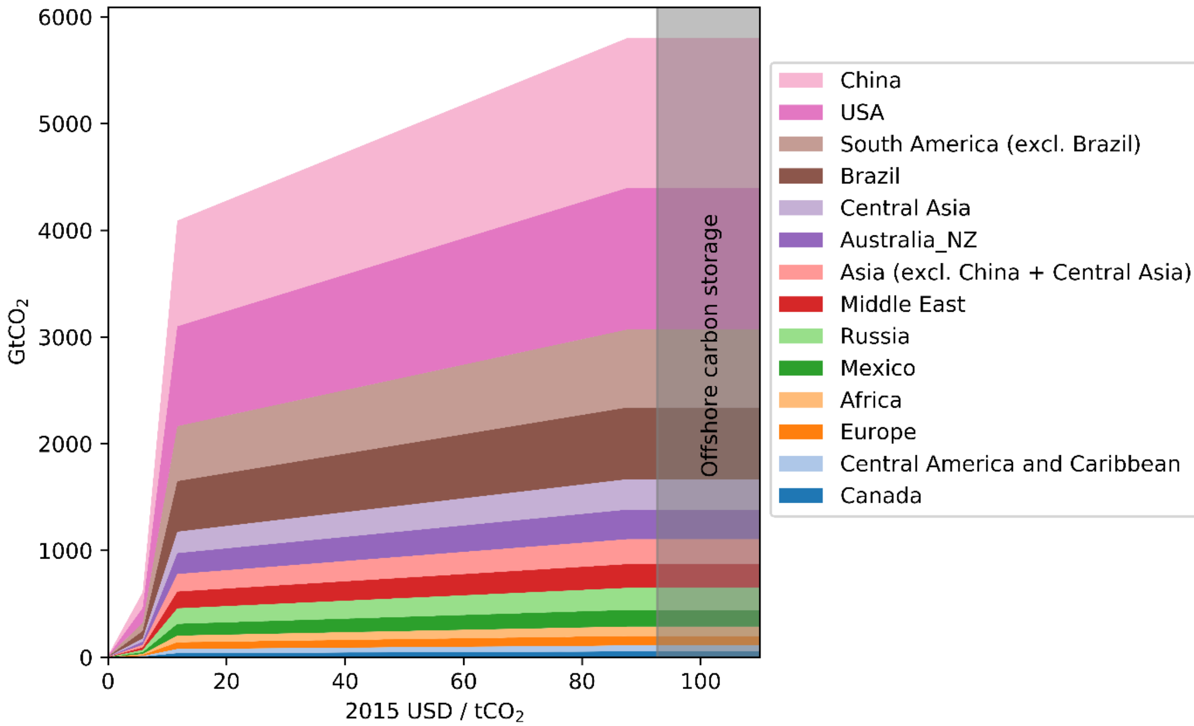

Figure B-6: Geologic carbon storage supply curve parametrization

Table B-1 reports input assumptions for DAC technology. Process heat is assumed to come from natural gas combustion, with 95% of emissions captured. Fuels and associated carbon-intensity for grid electricity inputs, as well as geologic carbon storage costs are solved for endogenously by GCAM.

Table B-1: DAC technology parametrizations for process heat, electricity, water, and financial inputs

Technology	Natural Gas (GJ/tCO_2)	Electricity (GJ/tCO_2)	Water (m^3/tCO_2)	Non-Energy Cost (2015 $\$/tCO_2$)
Low cost DAC (in main)	5.3	1.3	4.7	180
High cost DAC	8.1	1.8	4.7	300

Figure B-7 shows projected costs by region in 2050 for low-cost DAC in the low overshoot scenario, reported in 2015 dollars. The total cost of DAC is calculated from the GCAM results by summing the natural gas, electricity, non-energy financial input, and carbon storage costs for DAC in each region. The price per GJ for electricity and natural gas inputs is multiplied by their respective intensity factors (GJ/tCO_2) from Table 1. Inflation adjustment factors of 3.57 ($1975 to $2015 for energy and financial inputs and results) and 1.61 ($1990 to $2015 for GCAM carbon storage markets) were obtained from the St. Louis Federal Reserve website.[284]

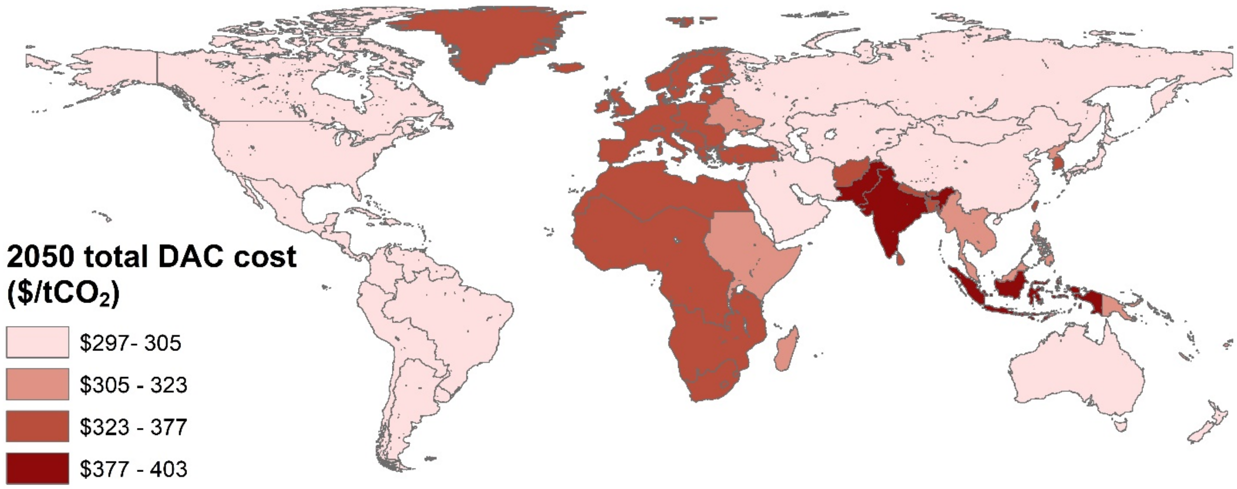

Figure B-7: Total DAC costs in 2050 by region ($2015, low-cost DAC)

Figure B-8 reports the CO_2 emissions price paths in each of the high and low overshoot and no-DAC, high-cost DAC and low-cost DAC scenarios. The availability of DAC acts as a backstop to exponential increases in CO_2 price in both the high and low-cost DAC parametrizations. In the high overshoot scenarios, (dotted lines), delayed mitigation results in lower emissions prices in the near-term, before quickly increasing to the long-term emissions prices of the low-overshoot scenario with the same DAC parametrization.

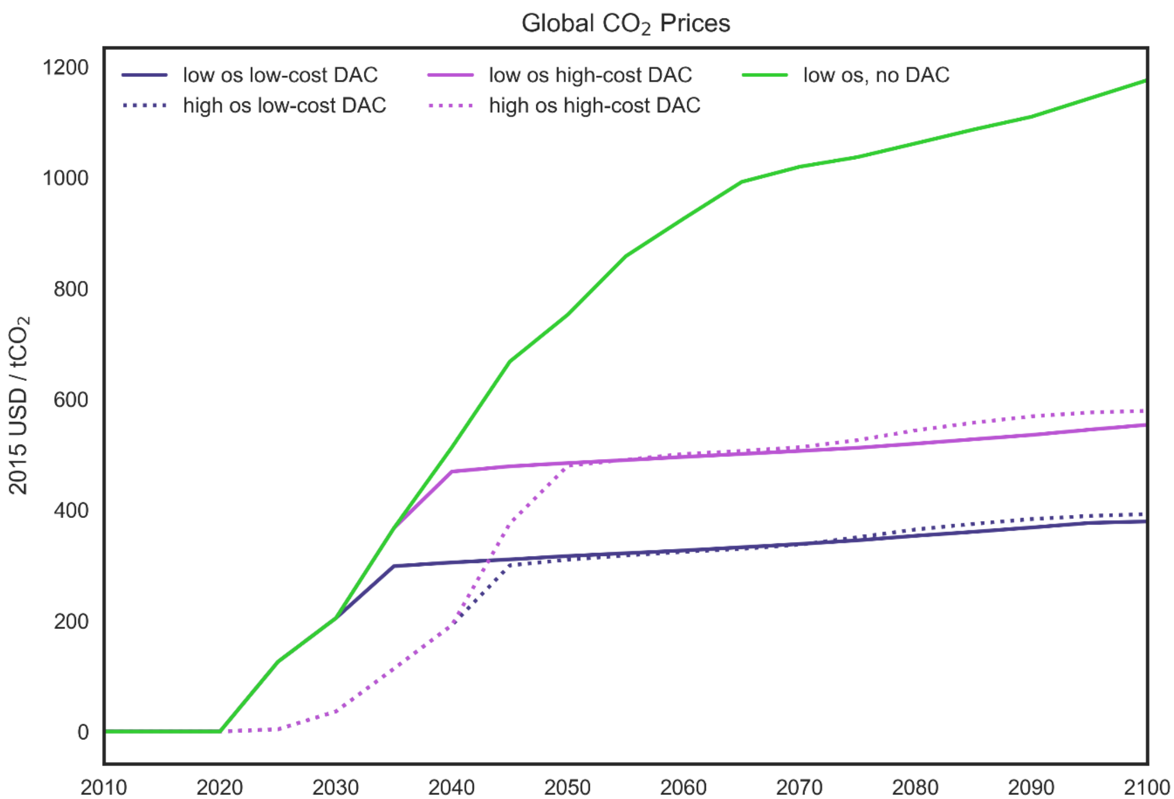

Figure B-8: CO_2 price paths.

Figure B-9 reports emissions results with high-cost DAC available in the low (a) and high (b) overshoot scenarios. High-cost DAC delays initiation of deployment from 2035 in the low-cost case, to 2040. DAC still sees rapid scale-up to large deployment by mid-century.

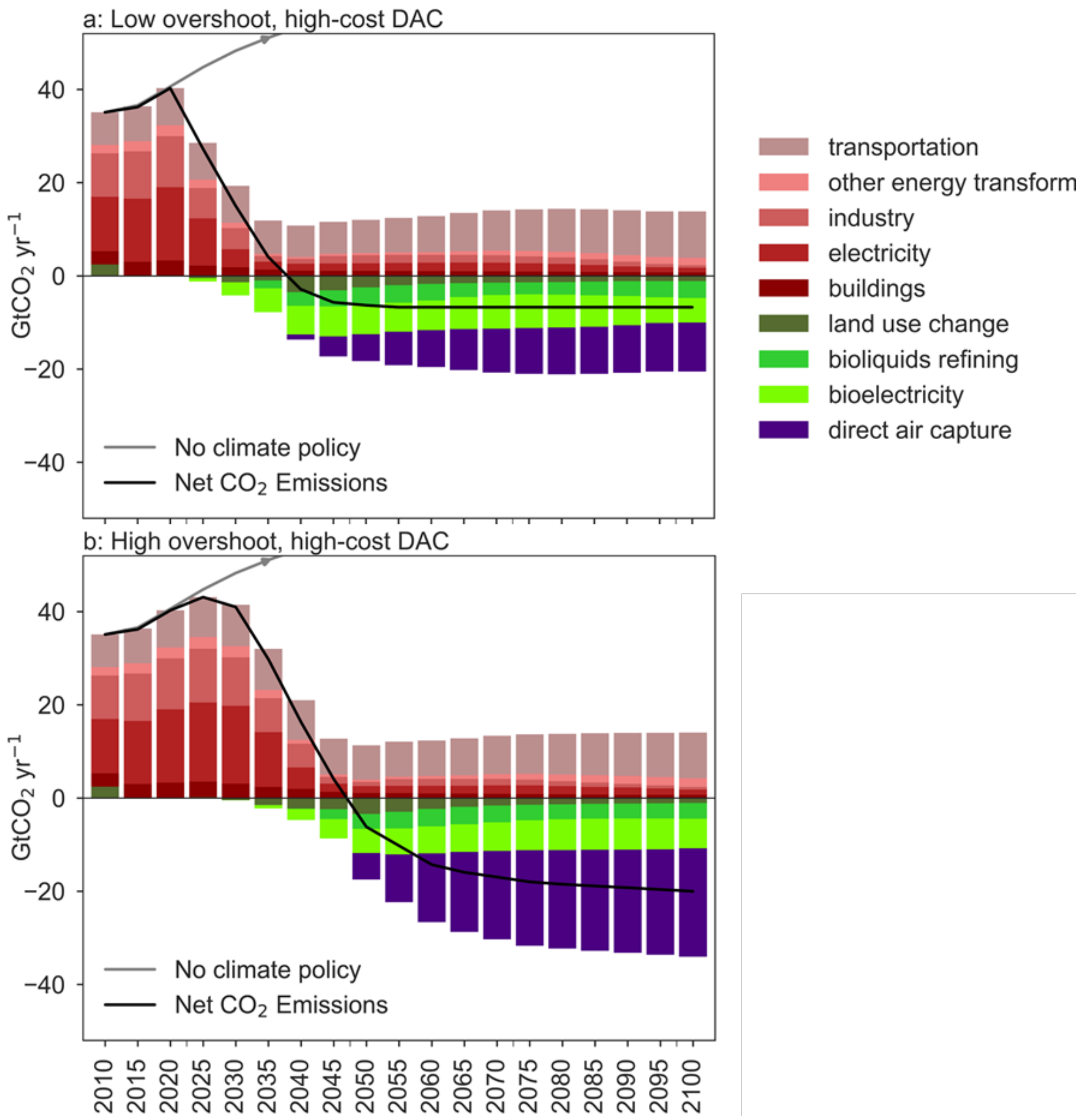

Figure B-9: CO_2 emissions by sector for scenarios with high-cost DAC

There are several different metrics with "water use" with relevance to natural and economic systems. Water withdrawals refer to water that is extracted from a surface or groundwater resources. Some portion of the withdrawn water is returned to the environment, but the quality may be degraded by thermal pollution (e.g., from cooling thermoelectric generating units) or chemical pollution (e.g., runoff of irrigation water). Water consumption refers to the portion of water that is withdrawn but not returned to the environment due to evaporation, consumption by humans or livestock, or incorporation into products or crops.[262] Finally, evapotranspiration, or biophysical water demand, refers to the consumption of soil moisture which occurs both in natural ecosystems and irrigated and non-irrigated croplands.[285]

Figure B-10 shows the water intensity input assumptions for evapotranspiration for bioenergy crop cultivation and afforestation, as well as water use of DAC technology applied by Realmonte et. al., 2019 (indicated by orange boxing), and this study.[41] These input values are compared to endogenously calculated average water withdrawals and consumption for BECCS from this study. Afforested land in GCAM is assumed to be unirrigated. The water withdrawal and consumption coefficients for irrigation in each of the water basins,[285–287] as well as for thermoelectric generation by technology are exogenously defined.[288,289] But the locational and technological mix of bioenergy crop cultivation (e.g., irrigated vs. rainfed) and electricity generation is determined endogenously by GCAM. The water intensity assumptions for each of the bioelectricity CCS technologies in GCAM are summarized in **Table B-2**. We estimate average water intensity for the CCS component of BECCS by dividing global water withdrawals and consumption for bioelectricity CCS generation by the total CO_2 sequestered by bioelectricity CCS technologies in 2050 in the no DAC scenario. The average water intensity for BECCS irrigation is estimated by dividing global water withdrawals and consumption for bioenergy crops by the total CO_2 sequestered by, bioelectricity, bioliquids refining, and bioindustrial feedstocks. Total evapotranspiration for bioenergy crop cultivation is much larger than water use for DAC, however the differential value, as well as endogenously calculated irrigation water withdrawals and consumption are much closer to those of DAC per unit CO_2 removed.[28] In this study, we assume withdrawals and consumption for DAC process water are equivalent.

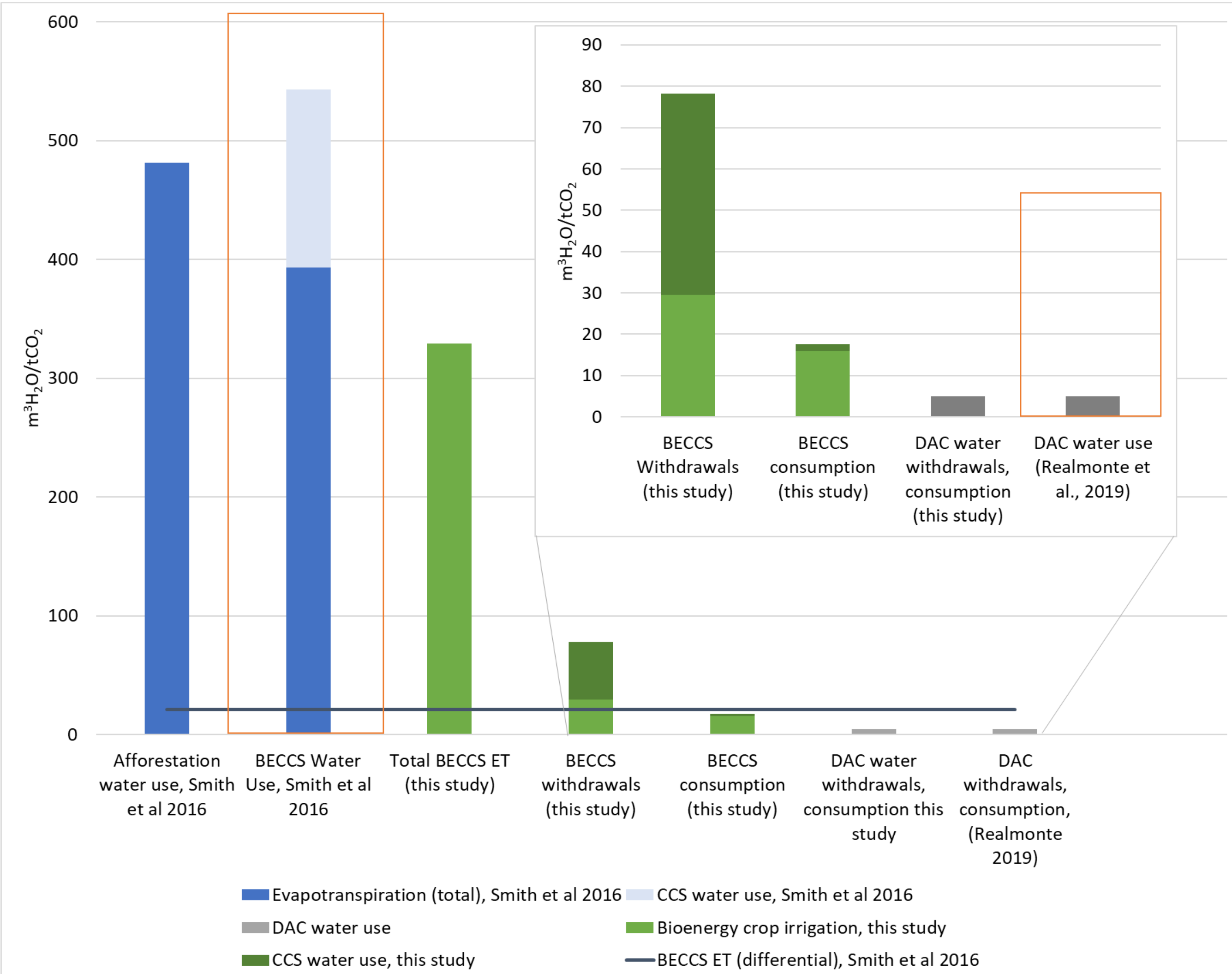

Figure B-10: Comparison of input assumptions and endogenously calculated values for water use for negative emissions

Table B-2: GCAM water intensity input assumptions for bioelectricity CCS technologies

Technology	Cooling System	m^3H_2O/GJ-electricity	efficiency (GJ electricity/GJ biomass)	tCO_2/GJ biomass	post-combustion capture rate	m^3H_2O/tCO_2 sequestered
Withdrawals						
biomass (conv CCS)	dry cooling	0.32	0.196			**0.8**
biomass (conv CCS)	once through	54.67	0.196			**141.3**
biomass (conv CCS)	recirculating	1.34	0.196			**3.5**
biomass (IGCC CCS)	dry cooling	0.32	0.262	0.084	0.9	**1.1**
biomass (IGCC CCS)	once through	51.56	0.262			**178.1**
biomass (IGCC CCS)	recirculating	0.62	0.262			**2.1**
Consumption						
biomass (conv CCS)	dry cooling	0.25	0.196			**0.7**
biomass (conv CCS)	once through	0.33	0.196			**0.9**
biomass (conv CCS)	recirculating	0.99	0.196			**2.6**
biomass (IGCC CCS)	dry cooling	0.29	0.262	0.084	0.9	**1.0**
biomass (IGCC CCS)	once through	0.11	0.262			**0.4**
biomass (IGCC CCS)	recirculating	0.57	0.262			**2.0**

Figure B-11 reports total biophysical water demand for (a) low overshoot, low-cost DAC, (b) high overshoot, low-cost DAC, and (c) no DAC available scenarios. A first-order estimate of afforestation biophysical water demand is obtained in by multiplying the LUC negative emissions result by 1765 tH_2O/tC from Smith et. al, 2016.

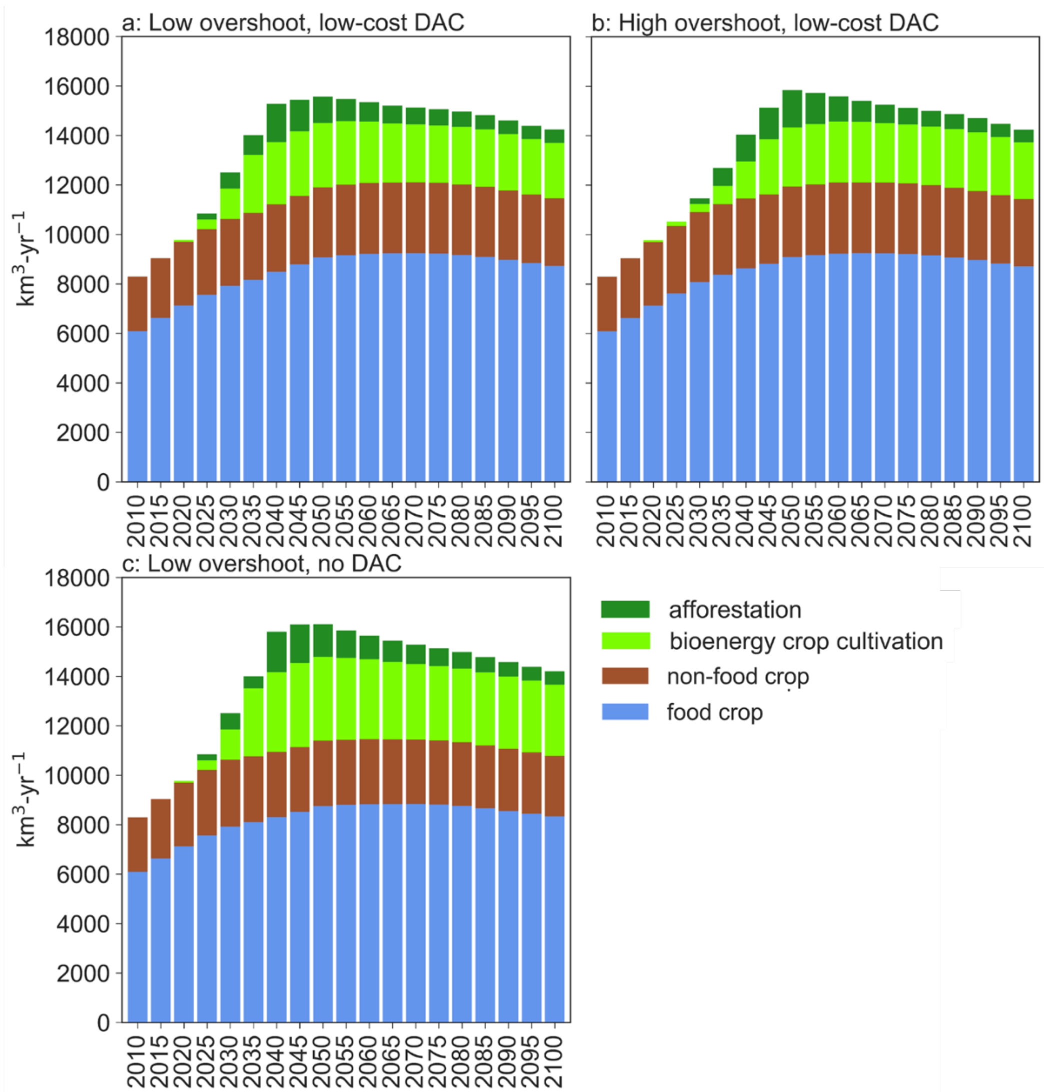

Figure B-11: Total biophysical water demand for agricultural activities and afforestation

Figure B-12 reports global consumptive water use for all sectors for (a): low overshoot, low-cost DAC; and (b) high overshoot, low-cost DAC. Because most global agriculture including projected bioenergy crop cultivation is rain-fed, irrigation water requirements are far less than evapotranspiration losses. Irrigation water consumption for bioenergy crops therefore constitutes a large additional stress on water resources but is comparable to that of other sectors. Consumptive water use for the low overshoot, no DAC scenario appears in the main text, in Figure 3b.

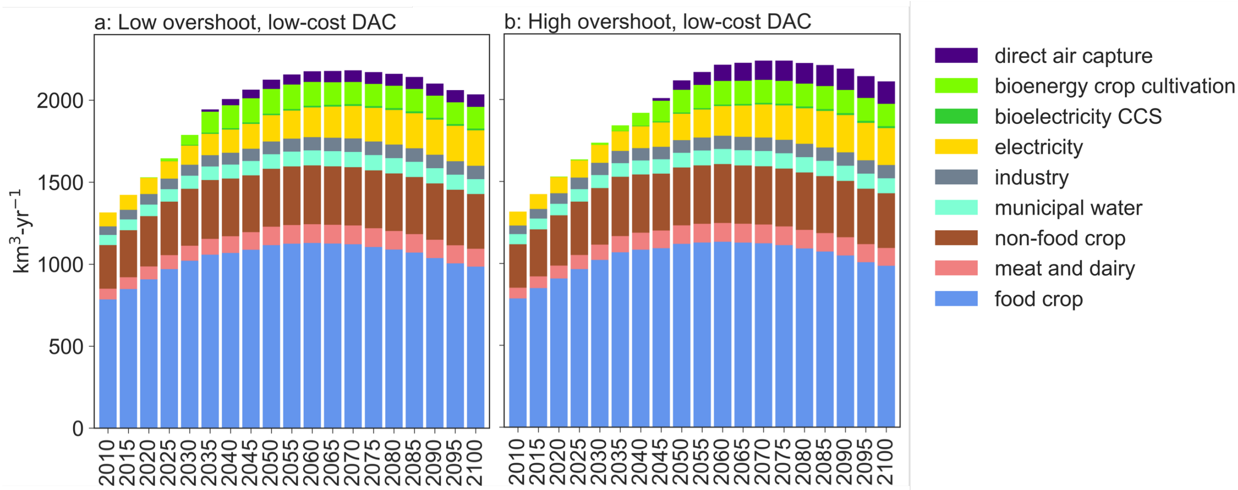

Figure B-12: Global consumptive water use for all sectors in low-cost DAC scenarios

Figure B-13 reports global water withdrawals for all sectors for (a): low overshoot, low-cost DAC; (b) high overshoot, low-cost DAC; and (c): low overshoot, no DAC available scenarios. Water withdrawals are over 200% of consumptive water use globally.

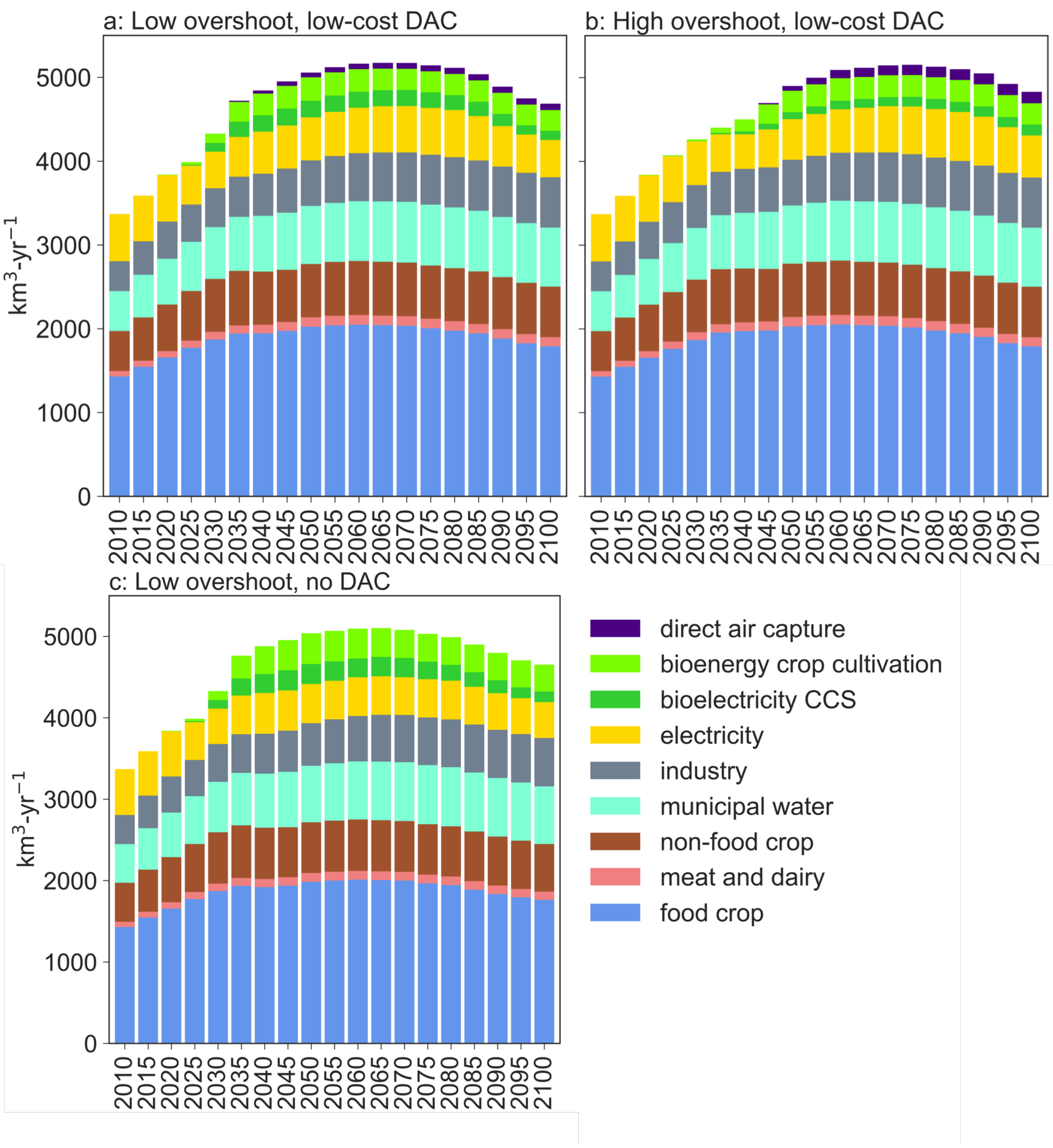

Figure B-13: Global water withdrawals for all sectors

Figure B-14 reports global water withdrawals for negative emissions only, for (a) low overshoot, low-cost DAC, (b) high overshoot, low-cost DAC, and (c) low overshoot, no DAC available scenarios. *Consumptive* water use for negative emissions is reported in the main text, Figure 6a and b

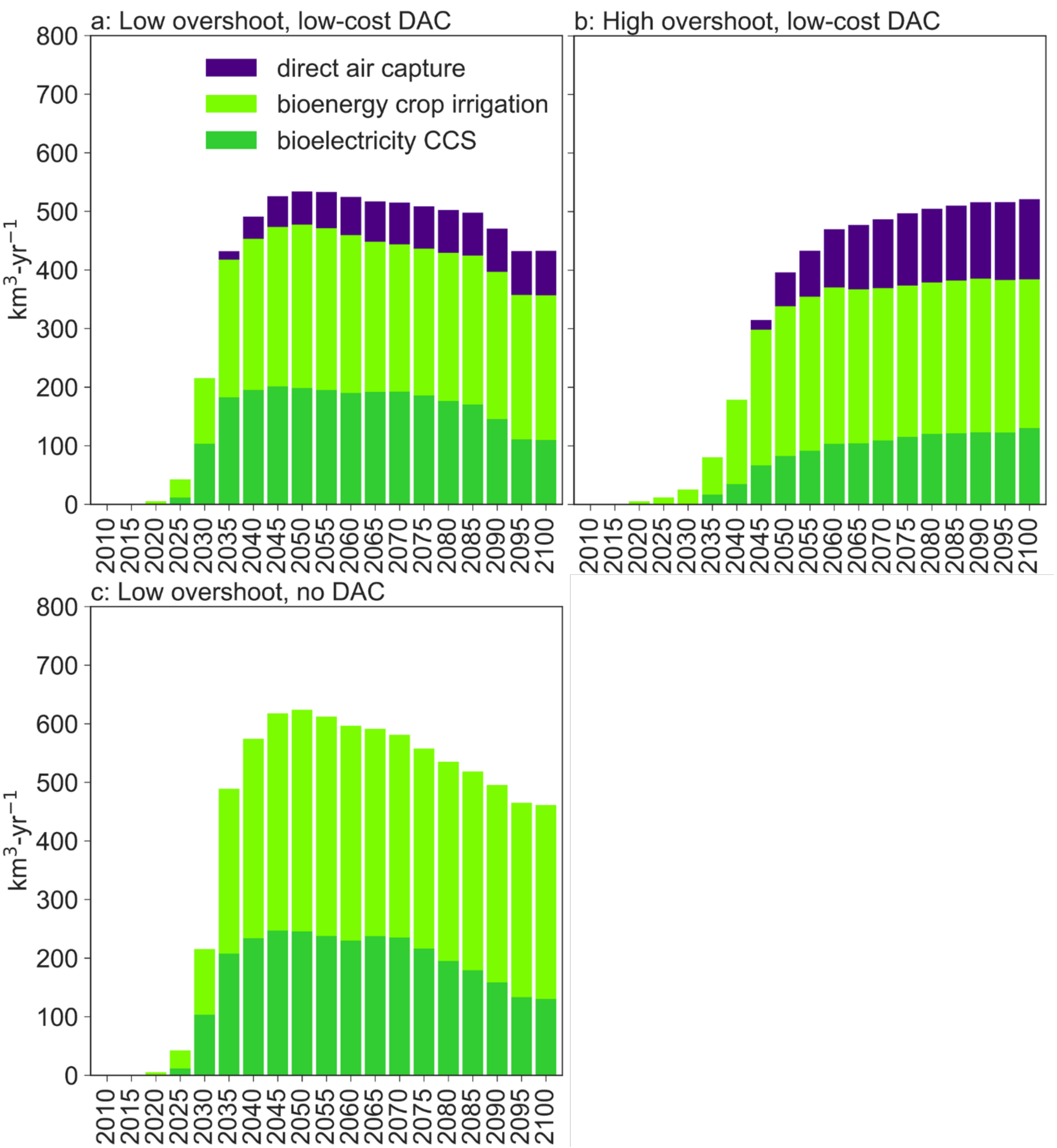

Figure B-14: Global water withdrawals for negative emissions

Figure B-15 reports primary energy demand for (a) low overshoot, and (b) high overshoot scenarios with high-cost DAC available. End-of-century energy demand for DAC is similar to the low-cost DAC scenarios because of the higher assumed energy-intensity for both process heat and electricity.

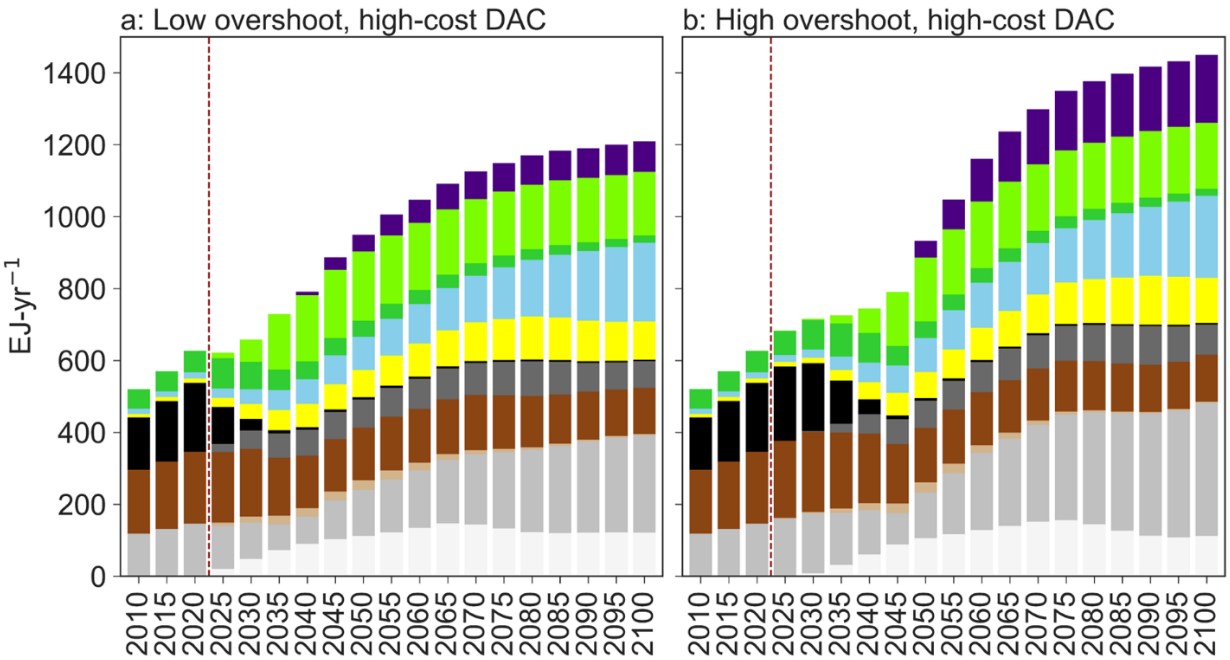

Figure B-15: Primary energy demand by fuel for high-cost DAC scenarios

Figure B-16 reports global methane emissions from natural gas production using a 100-year GWP value of 21 to estimate the CO_2-equivalent emissions from the natural gas supply chain. Methane is an even more potent greenhouse gas in the short-term, and applying the 20-year GWP of 86 would correspondingly increase the CO_2 equivalent emissions estimate.[17] Increased natural gas use for DAC results in increased fugitive methane emissions, which offsets some of the radiative forcing reduction achieved by the CO_2 removal. GCAM fully accounts for the transient and long-term temperature effects of methane and other non-CO_2 greenhouse gas emissions with its embedded climate model, Hector.[290] GCAM's assumption of 2% fugitive methane emissions rates from global natural gas production follows EPA (2011) and Venkatesh (2011).[291,292] Other studies have reported substantially higher leakage rates for specific regions (e.g., refs[274,293,294]), which would correspondingly further reduce the radiative forcing benefit of DAC and natural gas fuel switching more broadly.[295] Minimizing fugitive supply chain emissions will be critical for coupled DAC and natural gas systems to be a viable climate strategy.

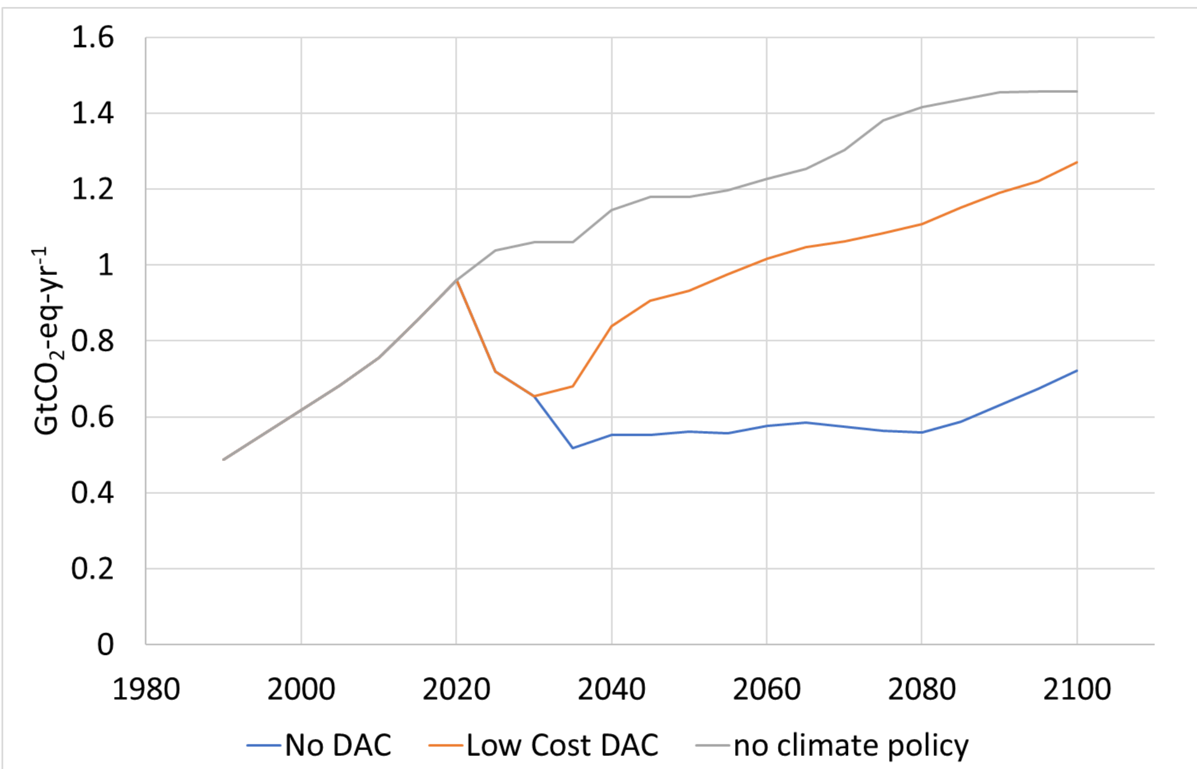

Figure B-16: Global fugitive methane emissions from natural gas extraction

Appendix C - Supplementary Information for Chapter 4: The role of negative emissions in meeting China's 2060 carbon neutrality goal

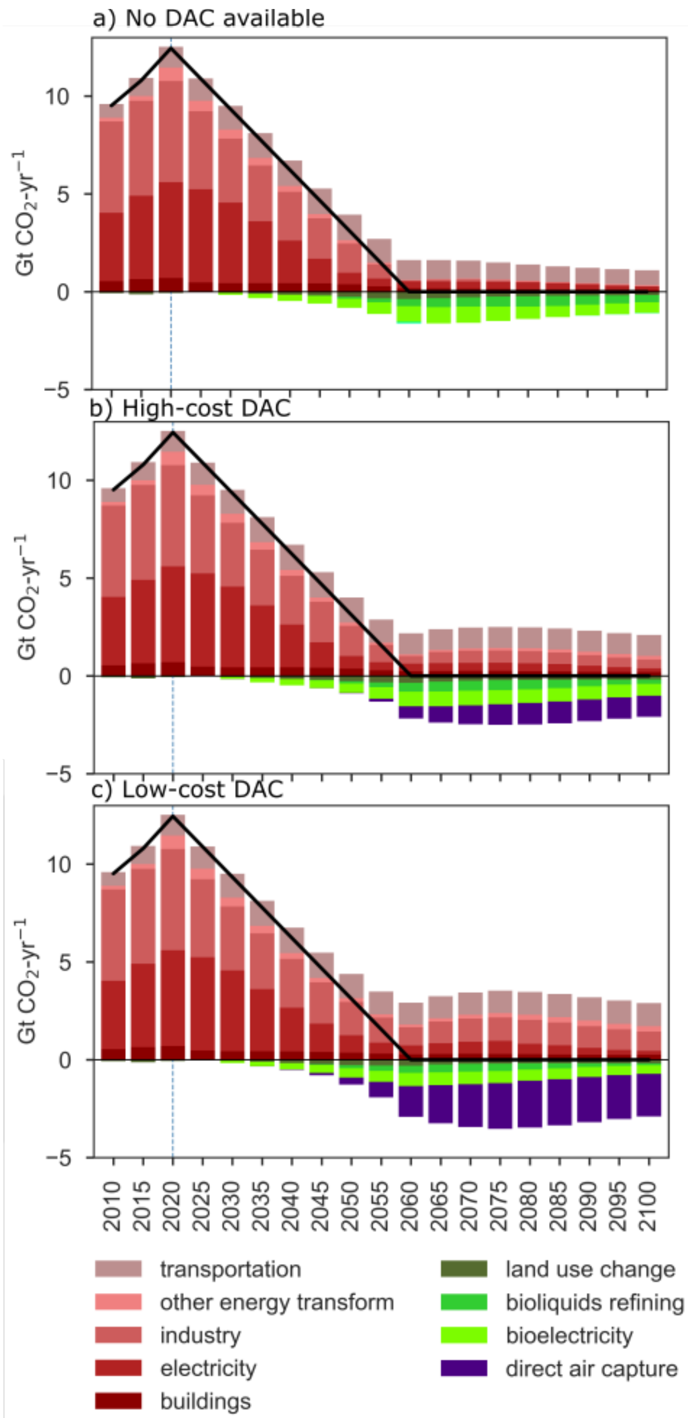

Figure C-1: CO_2 emissions by sector in China from 2010 to 2100

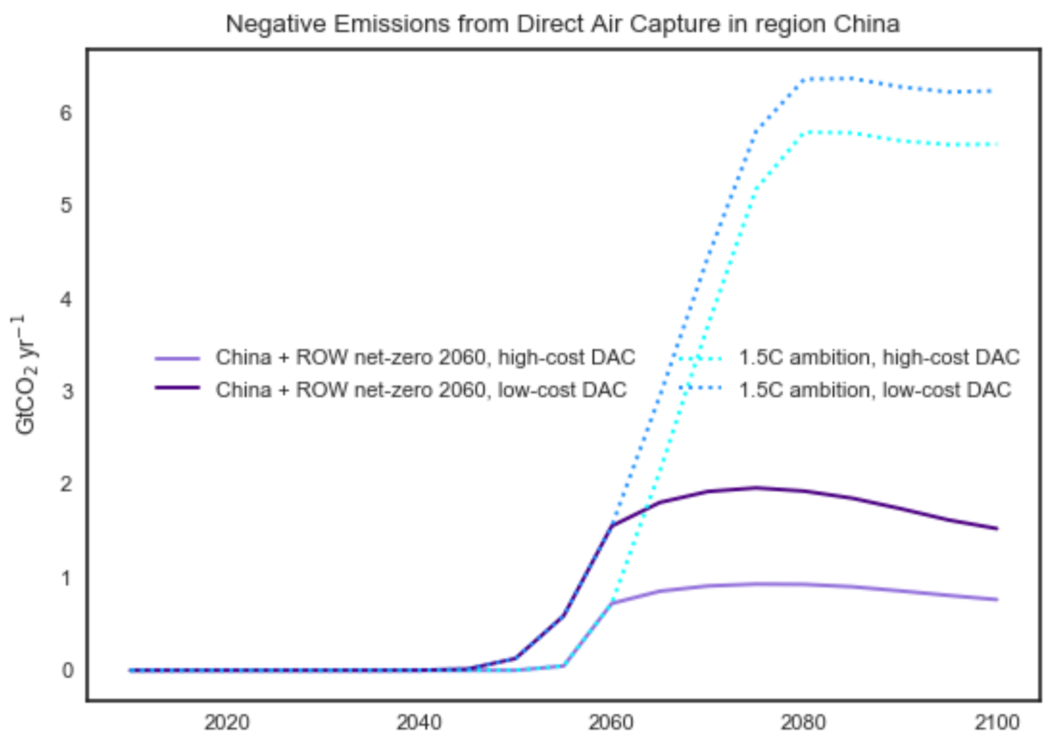

Figure C-2: DAC deployment in China by scenario.

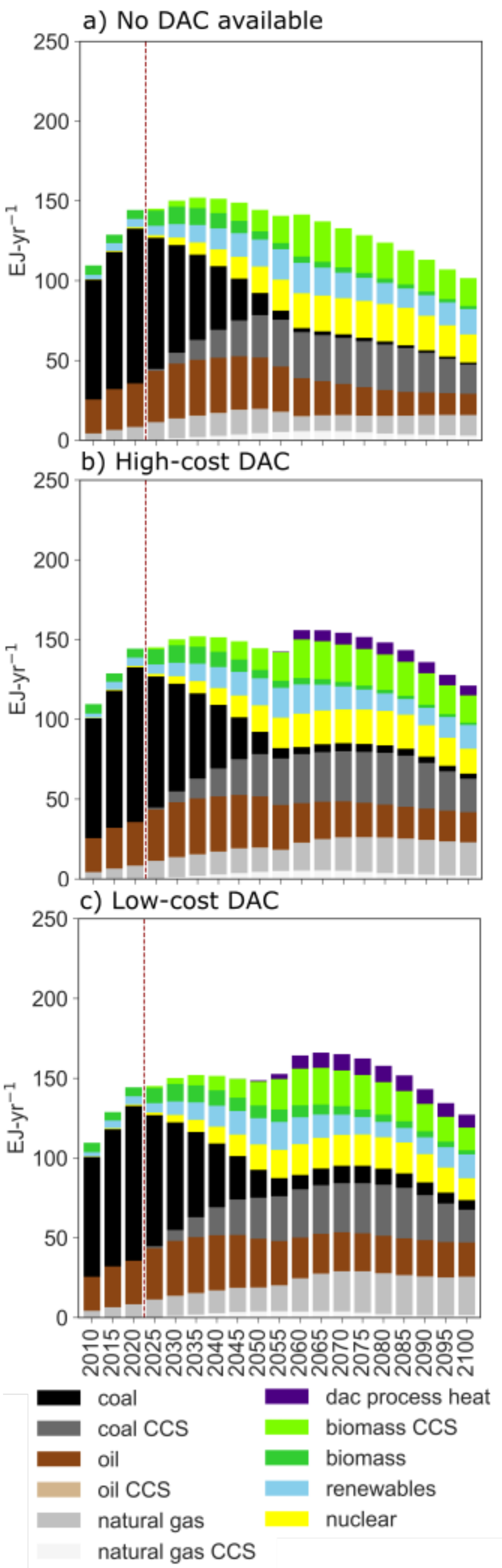

Figure C-3: Primary energy consumption by fuel in China

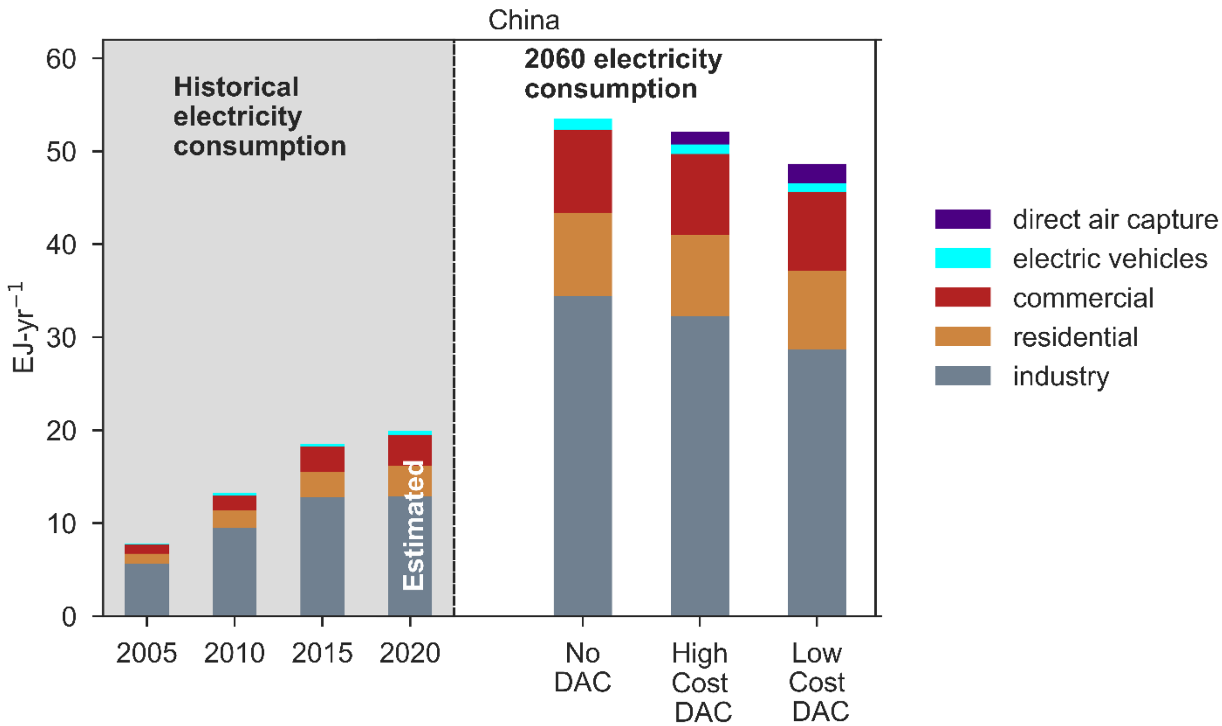

Figure C-4: Historical and projected electricity demand in China

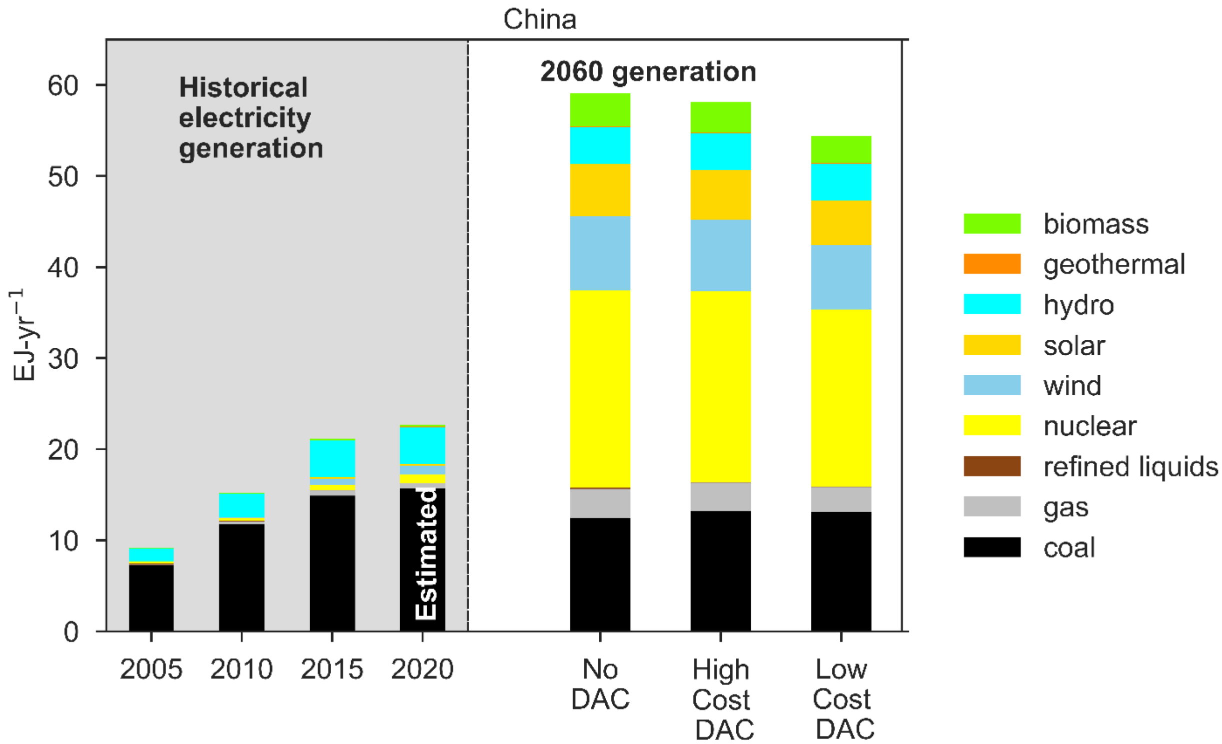

Figure C-5: Historical and projected electricity generation by fuel source in China

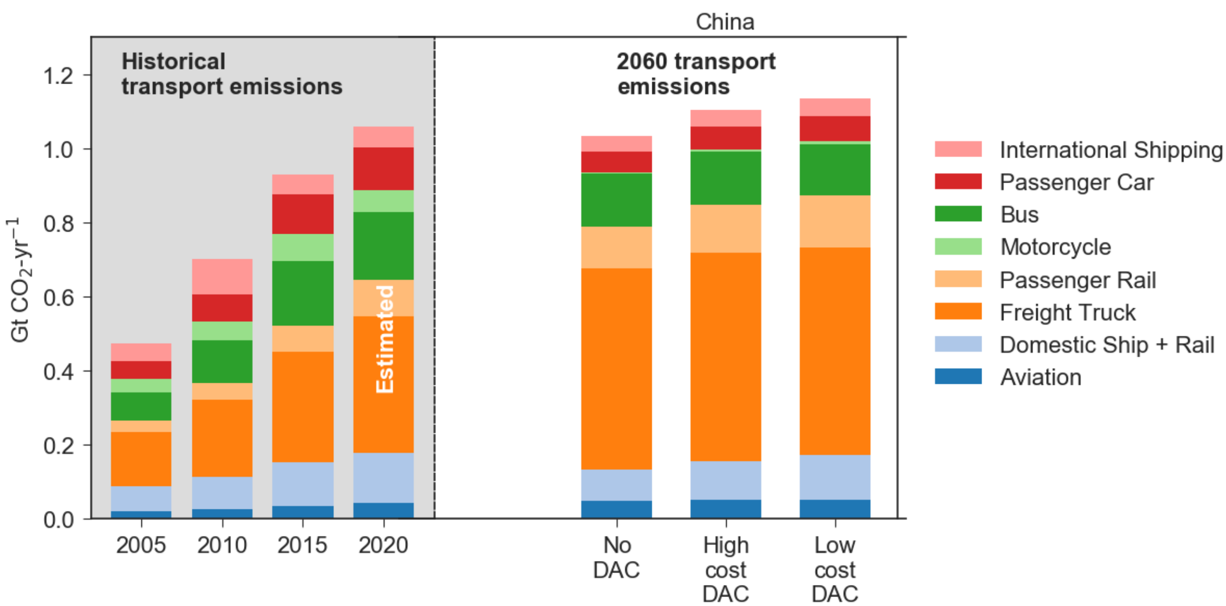

Figure C-6: Historical and projected transportation emissions in China

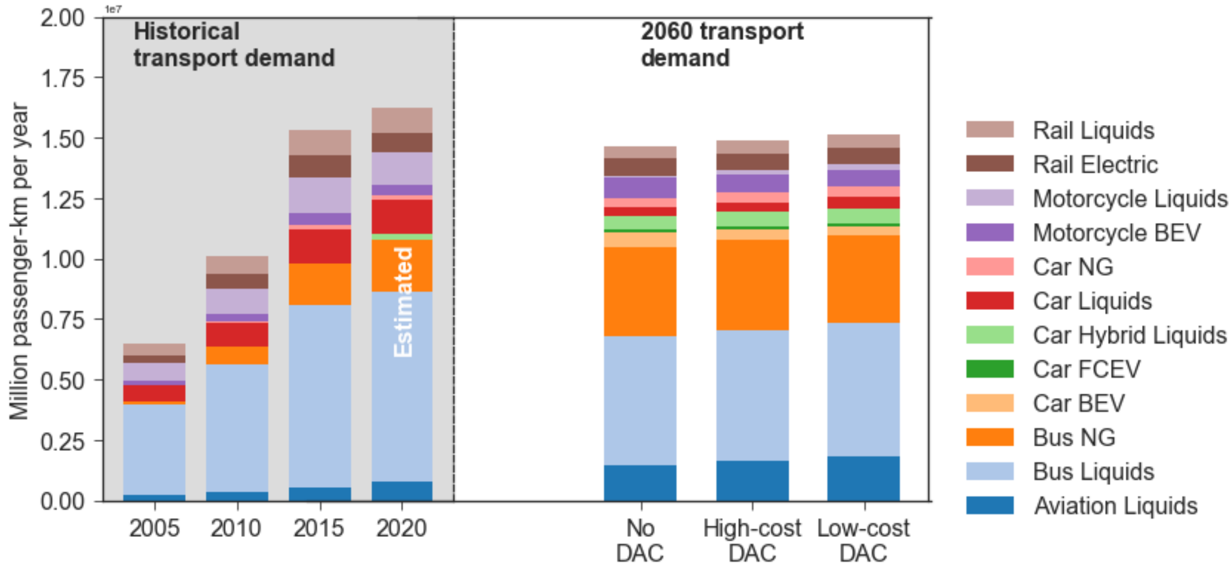

Figure C-7: Historical and projected passenger transportation demand in China

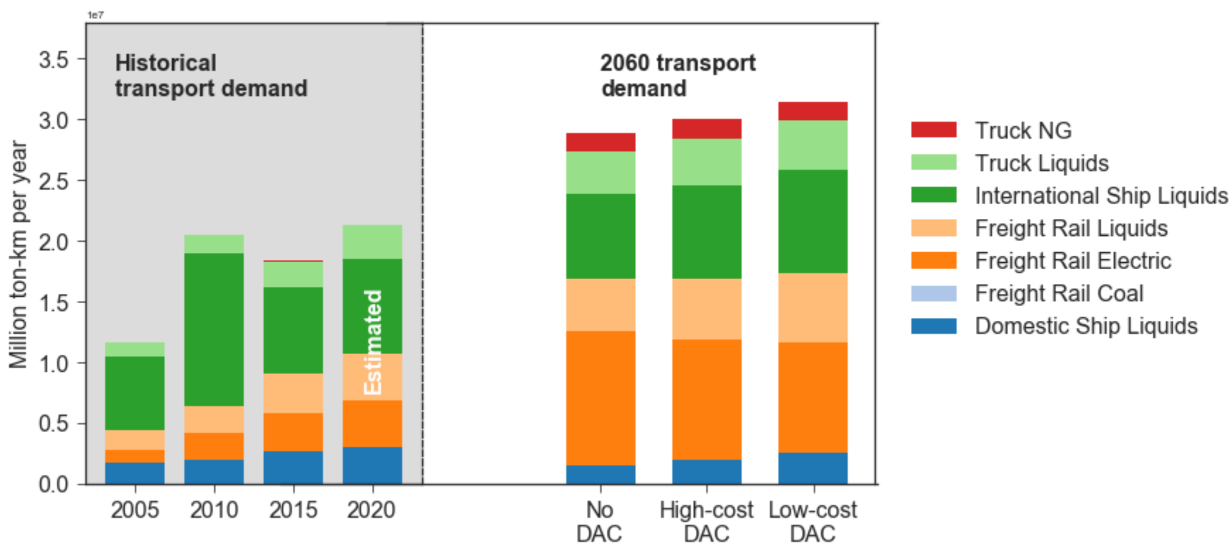

Figure C-8: Historical and projected freight transportation demand in China

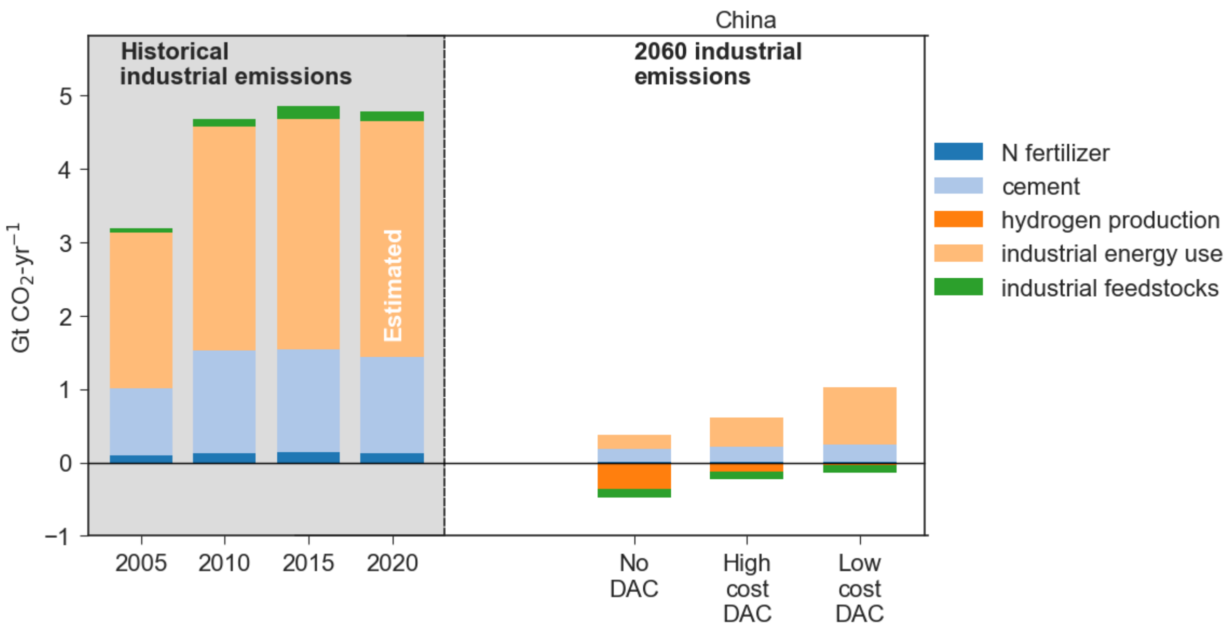

Figure C-9: Historical and projected industrial CO_2 emissions in China

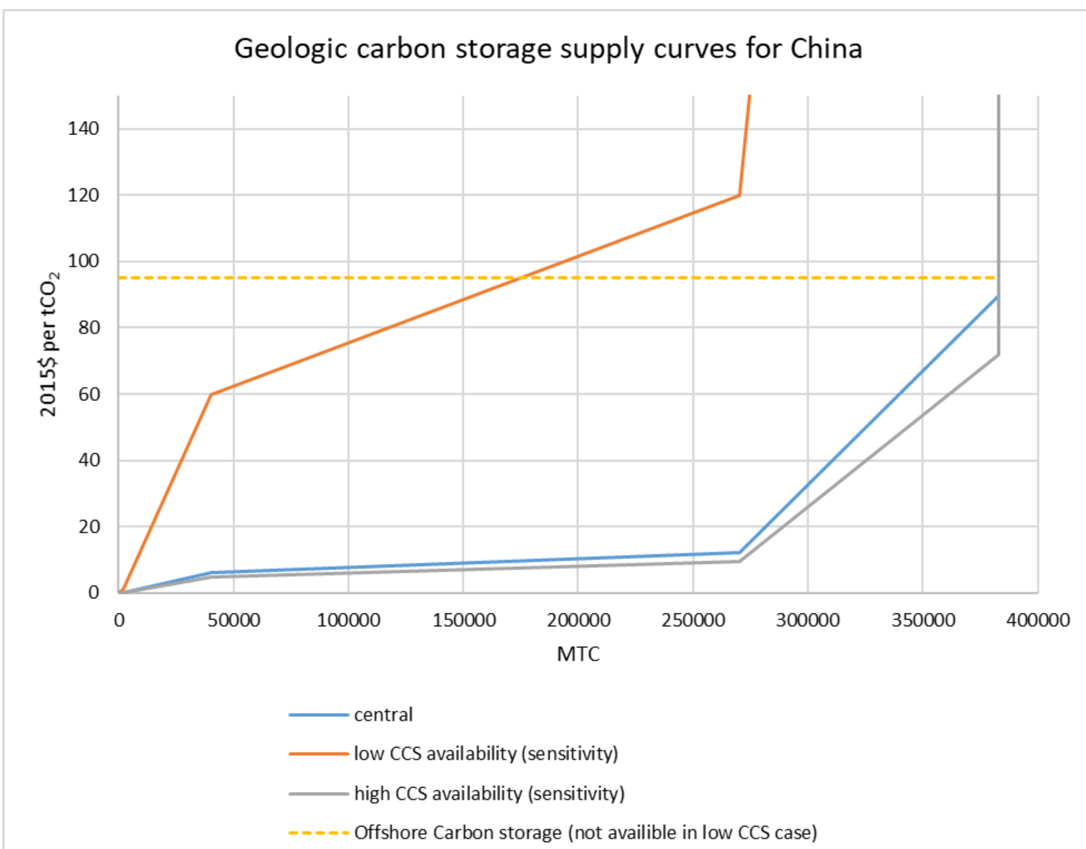

Figure C-10: Geologic carbon storage curves for China

Figures 11-17 report non-CO_2 air pollutant emissions in China for the three main net-zero CO_2 by 2060 scenarios. All scenarios show drastic reductions in air pollution resulting from the phase-down of coal and other fossil fuel consumption, demonstrating important co-benefits of climate action for air quality and human health. Emissions of most air pollutants are slightly higher when DAC is available owing to direct emissions from natural gas combustion for DAC process heat, as well as higher residual coal and other fossil fuel use.

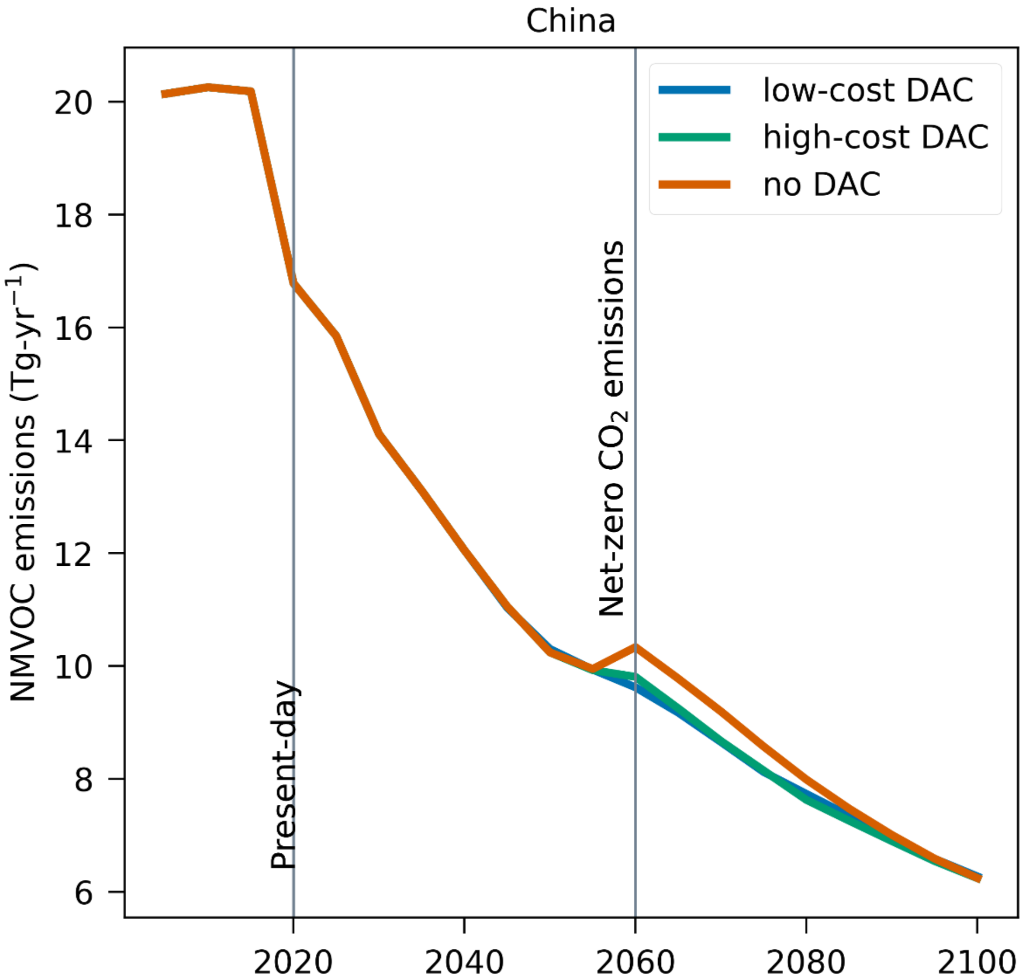

Figure C-11: Non-methane VOC emissions in China

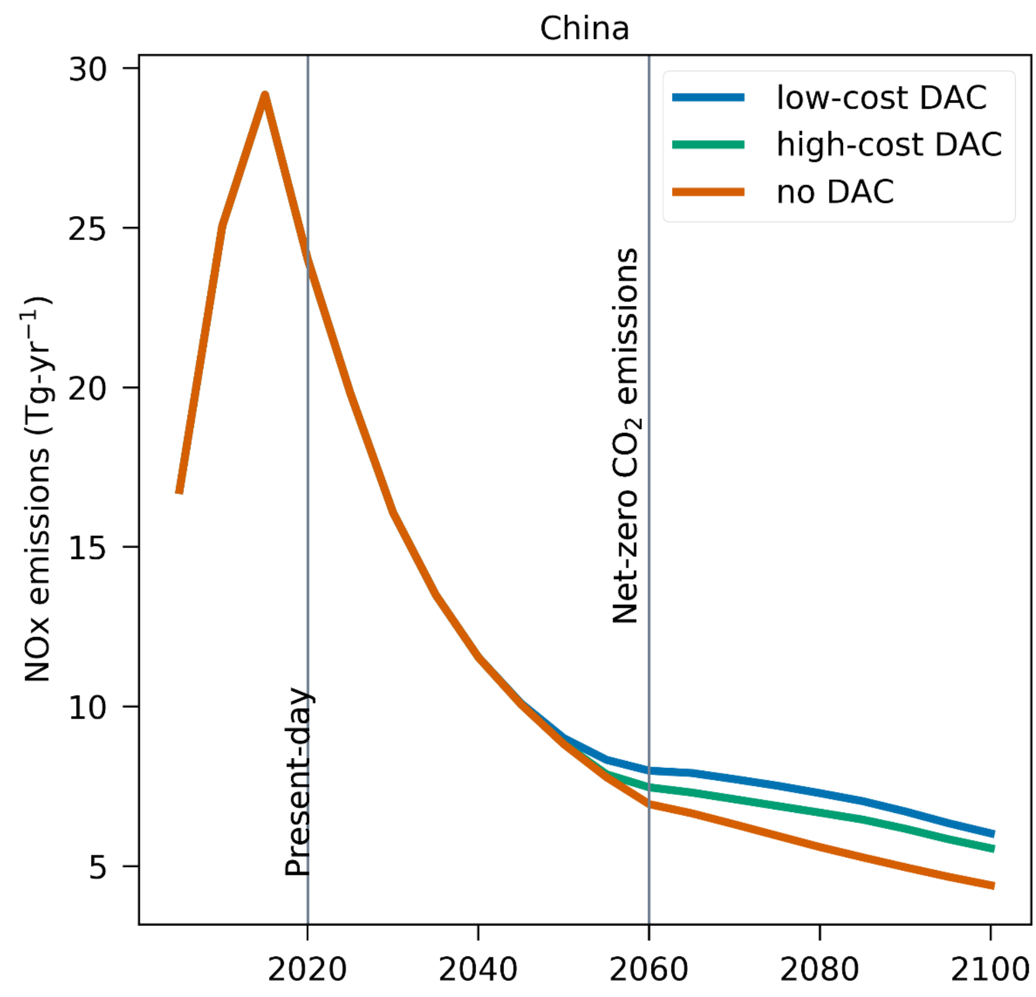

Figure C-12: NOx emissions in China

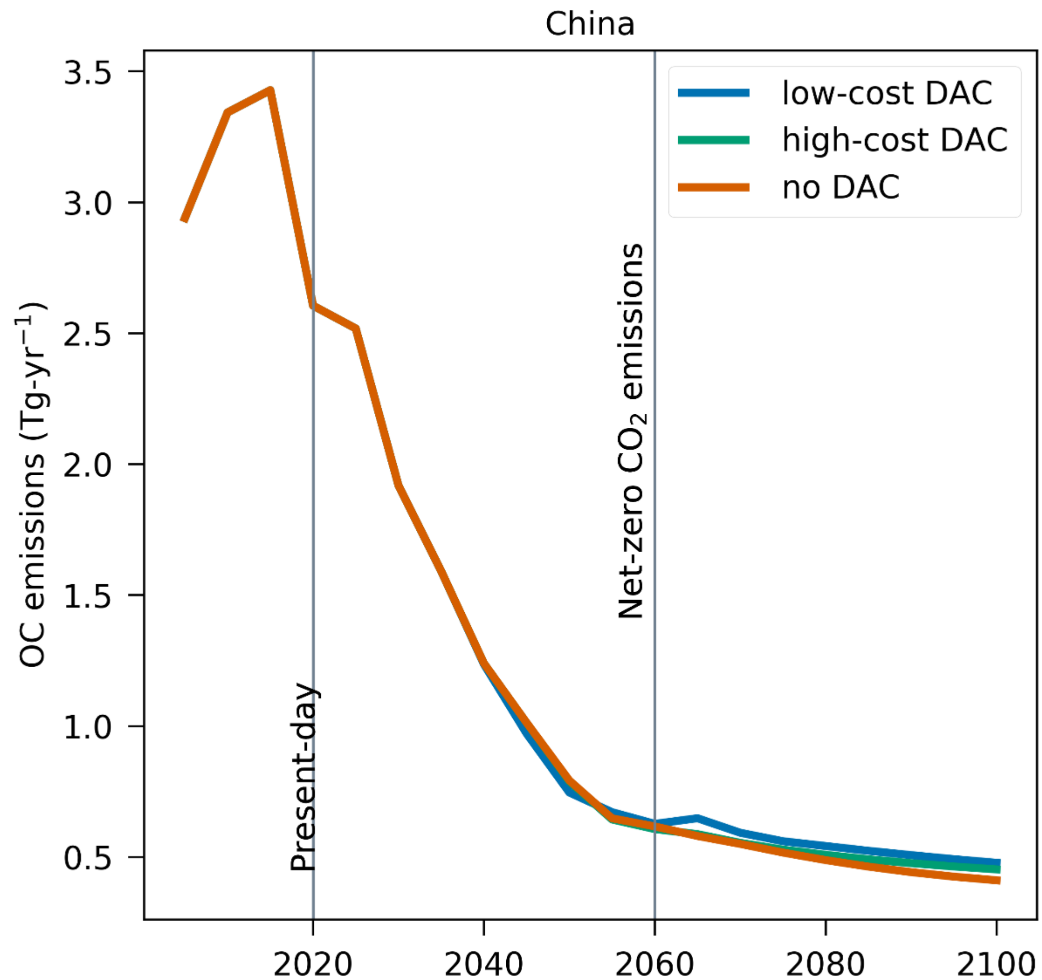

Figure C-13: Organic carbon particulate emissions in China

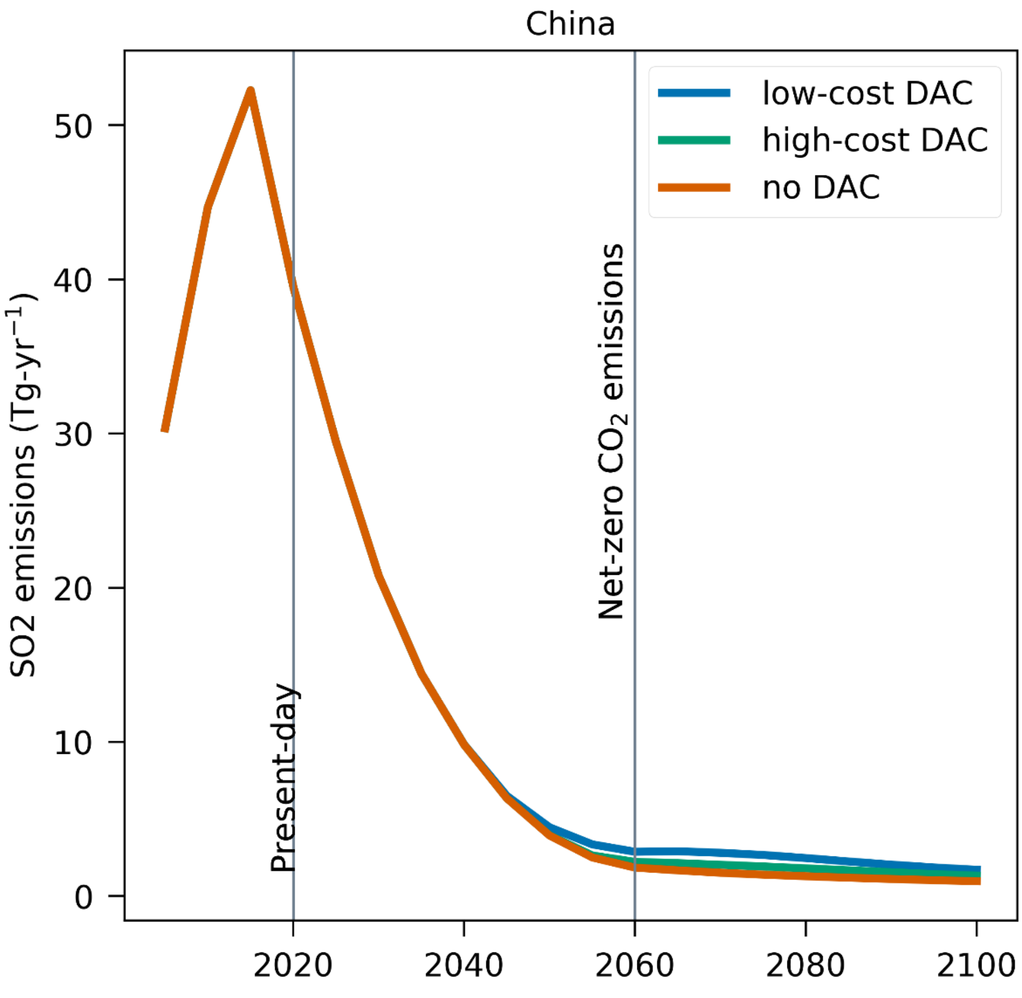

Figure C-14: Organic carbon particulate emissions in China

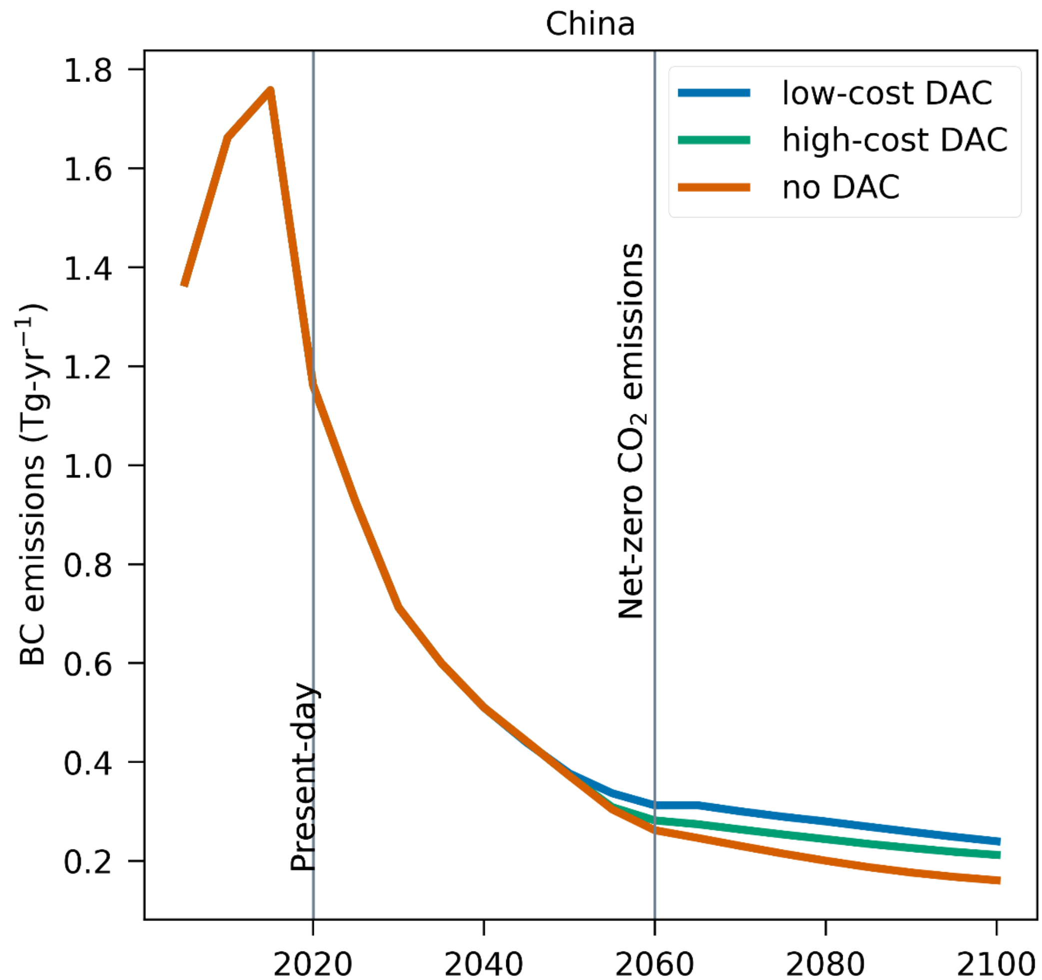

Figure C-15: Black carbon particulate emissions in China

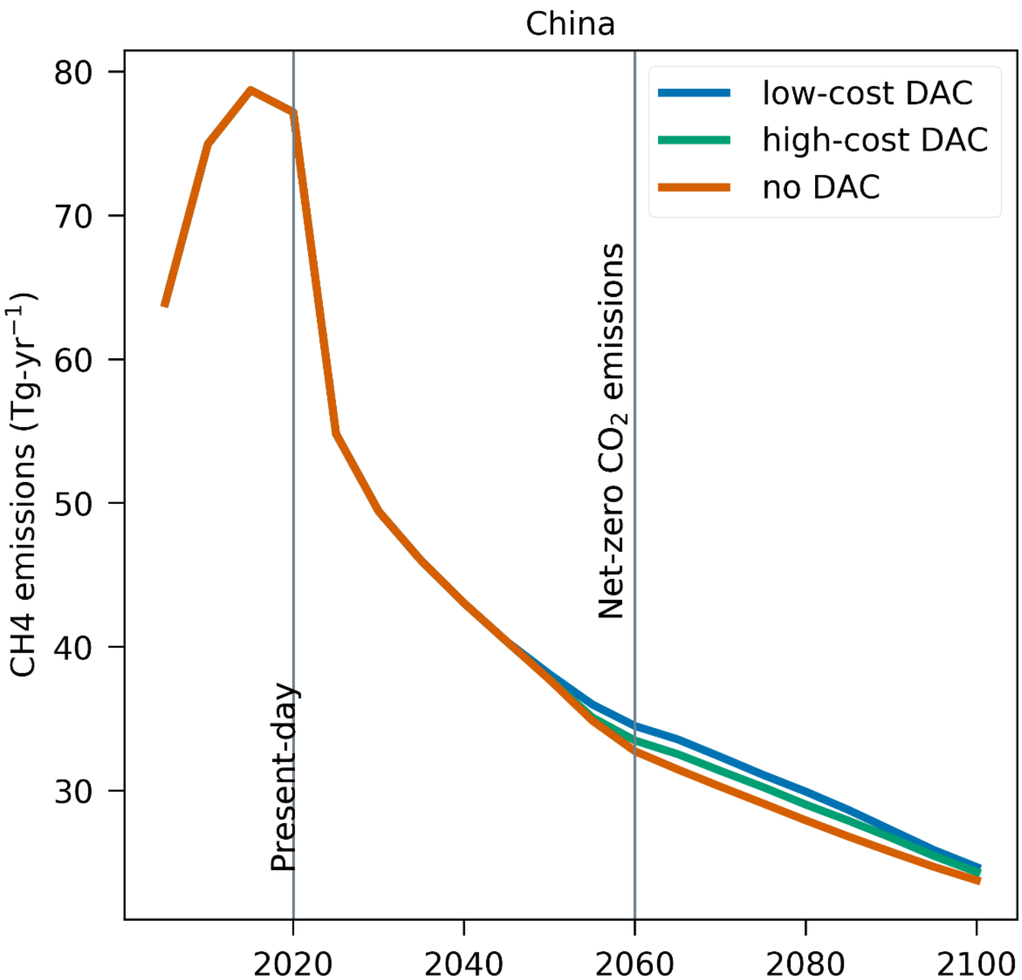

Figure C-16: Methane emissions in China

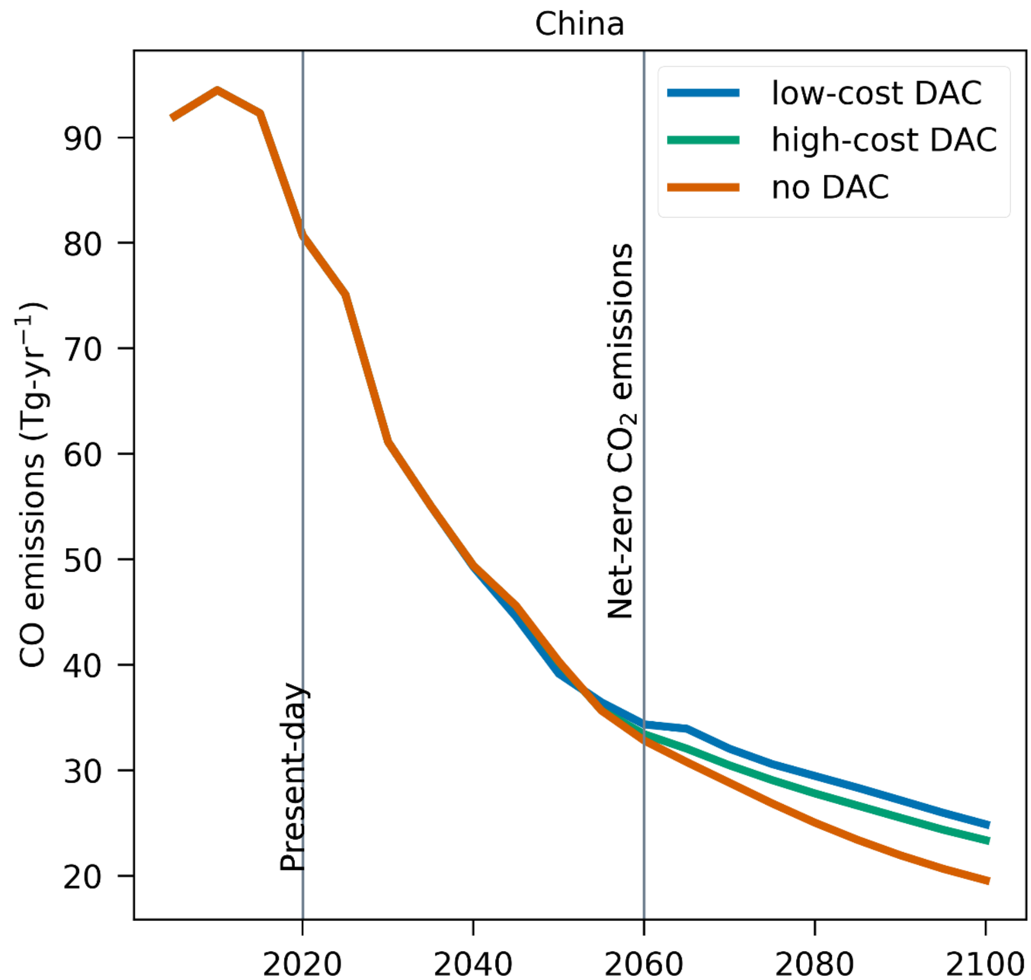

Figure C-17: Carbon monoxide emissions in China

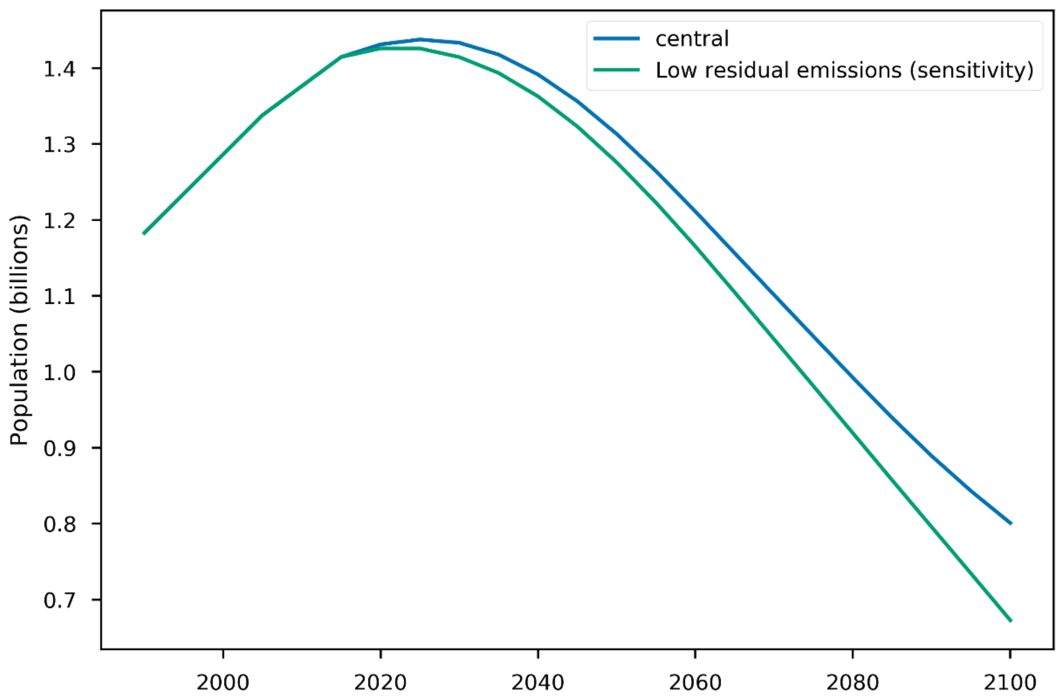

Figure C-18: China population assumptions for central and low-residual emissions sensitivity scenarios

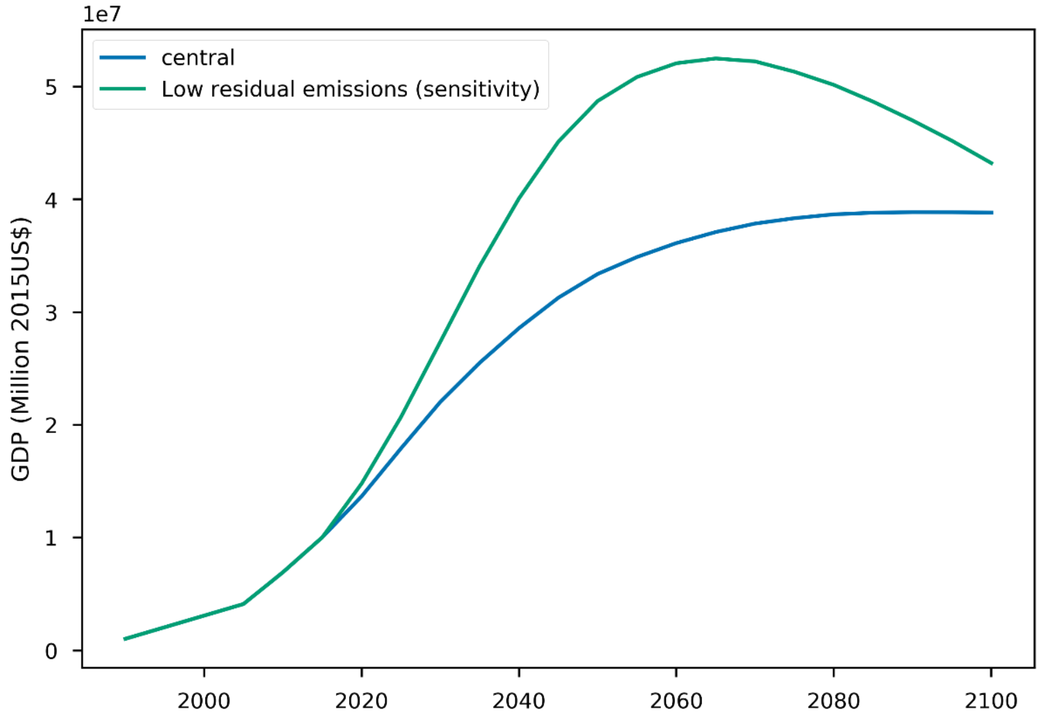

Figure C-19: China GDP input assumption for central and low-residual emissions scenarios

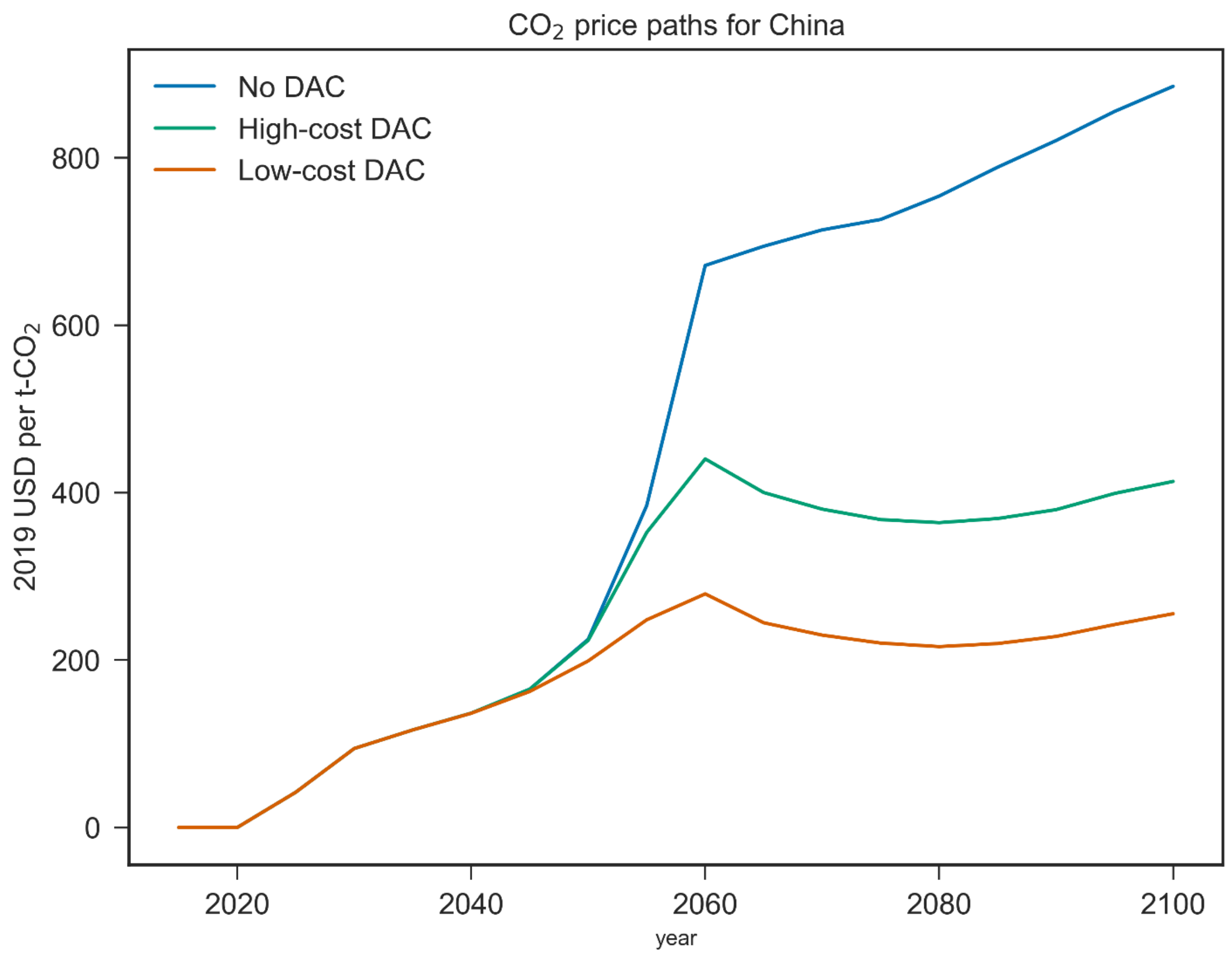

Figure C-20: CO_2 emissions price paths in China

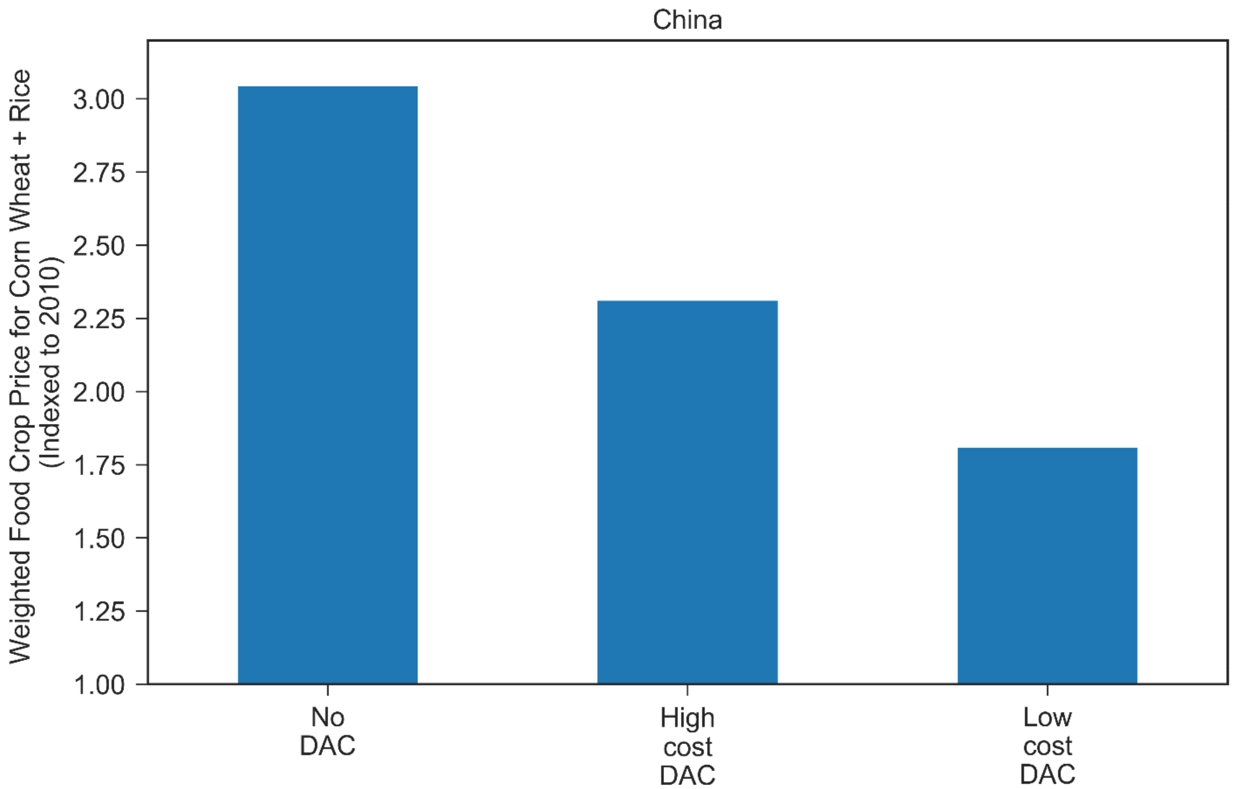

Figure C-21: Food price index results for China

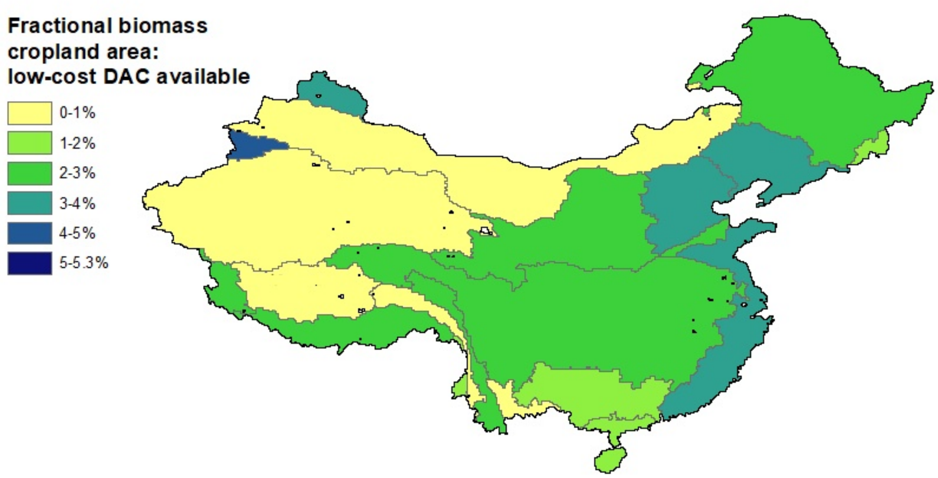

Figure C-22: Fractional land area for biomass cropland in 2060 for major river basins in China – no DAC scenario

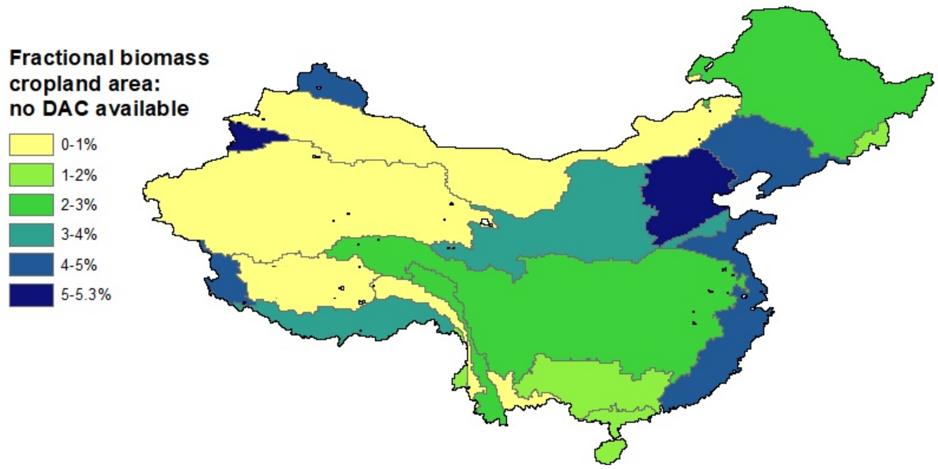

Figure C-23: Fractional land area for biomass cropland in 2060 for major river basins in China – Low-cost DAC scenario

Tables 1-6 report GCAM input assumptions for transportation, cement production, hydrogen production, electricity generation, and refined liquids production technologies for the year 2060. As an open source model, GCAM's full set of input assumptions for all model periods and technologies may be accessed on Github[296] Dollar values are converted from $1975 to $2015 using an inflation factor of 3.61[284]

Table C-1: Passenger vehicle purchase price input assumptions in China (2060)

	Vehicle purchase price (2060)	**Units**
Liquids	$ 22,010	2015$/vehicle
Hybrid Liquids	$ 22,863	2015$/vehicle
NG	$ 23,896	2015$/vehicle
BEV	$ 19,596	2015$/vehicle
FCEV	$ 36,056	2015$/vehicle

Table C-2: Freight truck cost input assumptions in China (2060)

	Fuel	**2060 CAPEX + non-energy opex**	**Units**
Truck (0-6t)	Liquids	$ 0.49	2015$/vkt
Truck (0-6t)	Natural Gas	$ 0.61	2015$/vkt
Truck (6-14t)	Liquids	$ 0.55	2015$/vkt
Truck (6-14t)	Natural Gas	$ 0.67	2015$/vkt
Truck (>14t)	Liquids	$ 0.57	2015$/vkt
Truck (>14t)	Natural Gas	$ 0.71	2015$/vkt

Table C-3: Input assumptions for cement production technologies (2060)

technology	input	coefficient	CCS capture fraction (if applicable)
cement	electricity (GJ/t)	0.5	
	limestone (t/t)	1.5	
	process heat (GJ/t)	3.4	
	non-energy cost ($2015/t)	$ 18	
cement CCS	electricity (GJ/t)	0.5	0.9
	limestone (t/t)	1.5	
	process heat (GJ/t)	3.4	
	non-energy cost ($2015/t)	$ 38	

Table C-4: Input assumptions for hydrogen production technologies (2060)

sector	technology	input	coefficient	CCS capture fraction (if applicable)
H2 central production	biomass to H2	biomass (GJ/GJ)	2.04	
H2 central production	biomass to H2	non-energy cost ($2015/GJ)	$8.23	
H2 central production	biomass to H2 CCS	biomass (GJ/GJ)	2.04	0.94
H2 central production	biomass to H2 CCS	non-energy cost ($2015/GJ)	$10.83	0.94
H2 central production	coal chemical	coal (GJ/GJ)	1.44	
H2 central production	coal chemical	non-energy cost ($2015/GJ)	$8.28	
H2 central production	coal chemical CCS	coal (GJ/GJ)	1.57	0.94
H2 central production	coal chemical CCS	non-energy cost ($2015/GJ)	$10.83	0.94
H2 central production	electrolysis	electricity (GJ/GJ)	1.42	
H2 central production	electrolysis	non-energy cost ($2015/GJ)	$26.70	
H2 central production	natural gas steam reforming	natural gas (GJ/GJ)	1.36	
H2 central production	natural gas steam reforming	non-energy cost ($2015/GJ)	$2.97	
H2 central production	natural gas steam reforming CCS	natural gas (GJ/GJ)	1.43	0.94
H2 central production	natural gas steam reforming CCS	non-energy cost ($2015/GJ)	$4.30	0.94
H2 central production	thermal splitting	GenIII nuclear fuel (GJ/GJ)	0.85	
H2 central production	thermal splitting	non-energy cost ($2015/GJ)	$16.04	
H2 forecourt production	electrolysis	electricity (GJ/GJ)	1.48	
H2 forecourt production	electrolysis	non-energy cost ($2015/GJ)	$26.70	
H2 forecourt production	natural gas steam reforming	natural gas (GJ/GJ)	1.58	
H2 forecourt production	natural gas steam reforming	non-energy cost ($2015/GJ)	$16.01	

Table C-5: Input assumptions for thermal electricity generation technologies (2060)

technology	input	coefficient	CCS capture fraction (if applicable)
biomass (conv CCS)	capital ($2015/kW)	$ 6,715	0.9
biomass (conv CCS)	OM var ($2015/MWh)	$ 13	0.9
biomass (conv CCS)	OM fixed ($2015/kW/yr)	$ 122	0.9
biomass (conv CCS)	biomass (GJ/GJ)	2.76	0.9
biomass (conv)	capital ($2015/kW)	$ 4,068	
biomass (conv)	OM var ($2015/MWh)	$ 8	
biomass (conv)	OM fixed ($2015/kW/yr)	$ 55	
biomass (conv)	biomass (GJ/GJ)	2.90	
biomass (IGCC CCS)	capital ($2015/kW)	$ 7,249	0.9
biomass (IGCC CCS)	OM var ($2015/MWh)	$ 13	0.9
biomass (IGCC CCS)	OM fixed ($2015/kW/yr)	$ 112	0.9
biomass (IGCC CCS)	biomass (GJ/GJ)	2.32	0.9
biomass (IGCC)	capital ($2015/kW)	$ 5,209	
biomass (IGCC)	OM var ($2015/MWh)	$ 15	
biomass (IGCC)	OM fixed ($2015/kW/yr)	$ 143	
biomass (IGCC)	biomass (GJ/GJ)	2.34	
coal (conv pul CCS)	coal (GJ/GJ)	2.00	0.9
coal (conv pul CCS)	OM var ($2015/MWh)	$ 10	0.9
coal (conv pul CCS)	OM fixed ($2015/kW/yr)	$ 6	0.9
coal (conv pul CCS)	capital ($2015/kW)	$ 5,025	0.9
coal (conv pul)	coal (GJ/GJ)	2.05	
coal (conv pul)	OM var ($2015/MWh)	$ 4	
coal (conv pul)	OM fixed ($2015/kW/yr)	$ 10	
coal (conv pul)	capital ($2015/kW)	$ 2,949	
coal (IGCC CCS)	coal (GJ/GJ)	1.91	0.9
coal (IGCC CCS)	OM var ($2015/MWh)	$ 6	0.9
coal (IGCC CCS)	OM fixed ($2015/kW/yr)	$ 17	0.9
coal (IGCC CCS)	capital ($2015/kW)	$ 5,332	0.9
coal (IGCC)	coal (GJ/GJ)	1.92	
coal (IGCC)	OM var ($2015/MWh)	$ 4	
coal (IGCC)	OM fixed ($2015/kW/yr)	$ 25	
coal (IGCC)	capital ($2015/kW)	$ 3,473	
gas (CC CCS)	natural gas (GJ/GJ)	1.55	0.9
gas (CC CCS)	OM var ($2015/MWh)	$ 6	0.9
gas (CC CCS)	OM fixed ($2015/kW/yr)	$ 30	0.9
gas (CC CCS)	capital ($2015/kW)	$ 1,819	0.9

technology	input	coefficient	CCS capture fraction (if applicable)
gas (CC)	natural gas (GJ/GJ)	1.55	
gas (CC)	OM var ($2015/MWh)	$ 10	
gas (CC)	OM fixed ($2015/kW/yr)	$ 97	
gas (CC)	capital ($2015/kW)	$ 1,069	
gas (steam/CT)	natural gas (GJ/GJ)	2.29	
gas (steam/CT)	OM var ($2015/MWh)	$ 7	
gas (steam/CT)	OM fixed ($2015/kW/yr)	$ 43	
gas (steam/CT)	capital ($2015/kW)	$ 762	

Table C-6: Input assumptions for refined liquids production technologies (2060)

sector	technology	input	coefficient	CCS capture fraction (if applicable)
refining	biodiesel	biocrude (GJ/GJ)	1.03	
refining	biodiesel	natural gas (GJ/GJ)	0.06	
refining	biodiesel	non-energy cost ($2015/GJ)	$ 7	
refining	cellulosic ethanol	biomass (GJ/GJ)	1.91	
refining	cellulosic ethanol	non-energy cost ($2015/GJ)	$ 17	
refining	cellulosic ethanol CCS level 1	biomass (GJ/GJ)	1.99	0.26
refining	cellulosic ethanol CCS level 1	non-energy cost ($2015/GJ)	$ 18	0.26
refining	cellulosic ethanol CCS level 2	biomass (GJ/GJ)	2.11	0.9
refining	cellulosic ethanol CCS level 2	non-energy cost ($2015/GJ)	$ 25	0.9
refining	coal to liquids	coal (GJ/GJ)	2.04	
refining	coal to liquids	non-energy cost ($2015/GJ)	$ 19	
refining	coal to liquids CCS level 1	coal (GJ/GJ)	2.12	0.82
refining	coal to liquids CCS level 1	non-energy cost ($2015/GJ)	$ 22	0.82
refining	coal to liquids CCS level 2	coal (GJ/GJ)	2.24	0.9
refining	coal to liquids CCS level 2	non-energy cost ($2015/GJ)	$ 23	0.9
refining	corn ethanol	electricity (GJ/GJ)	0.03	
refining	corn ethanol	natural gas (GJ/GJ)	0.32	
refining	corn ethanol	non-energy cost ($2015/GJ)	$ 9	
refining	FT biofuels	biomass (GJ/GJ)	1.85	

sector	technology	input	coefficient	CCS capture fraction (if applicable)
refining	FT biofuels	non-energy cost ($2015/GJ)	$ 28	
refining	FT biofuels CCS level 1	biomass (GJ/GJ)	1.92	0.82
refining	FT biofuels CCS level 1	non-energy cost ($2015/GJ)	$ 31	0.82
refining	FT biofuels CCS level 2	biomass (GJ/GJ)	2.04	0.9
refining	FT biofuels CCS level 2	non-energy cost ($2015/GJ)	$ 32	0.9
refining	gas to liquids	natural gas (GJ/GJ)	1.59	
refining	gas to liquids	non-energy cost ($2015/GJ)	$ 14	
refining	oil refining	electricity (GJ/GJ)	0.01	
refining	oil refining	natural gas (GJ/GJ)	0.02	
refining	oil refining	non-energy cost ($2015/GJ)	$ 3	
refining	oil refining	oil (GJ/GJ)	1.04	
refining	sugar cane ethanol	non-energy cost ($2015/GJ)	$ 7	

Appendix D - Supplementary Information for Chapter 5: The Role of Direct Air Capture and Negative Emissions Technologies in the Shared Socioeconomic Pathways towards +1.5˚C and +2˚C Futures

D3.1 Shared Socioeconomic Pathway Driving Assumptions

Figure D-1 is from O'Neill et. al (2014)[246] and shows a conceptual diagram of the SSP scenario matrix which in turn informs the quantitative assumptions of the scenarios themselves. The matrix spans a "challenges space" defined by challenges to mitigation and challenges to adaption.

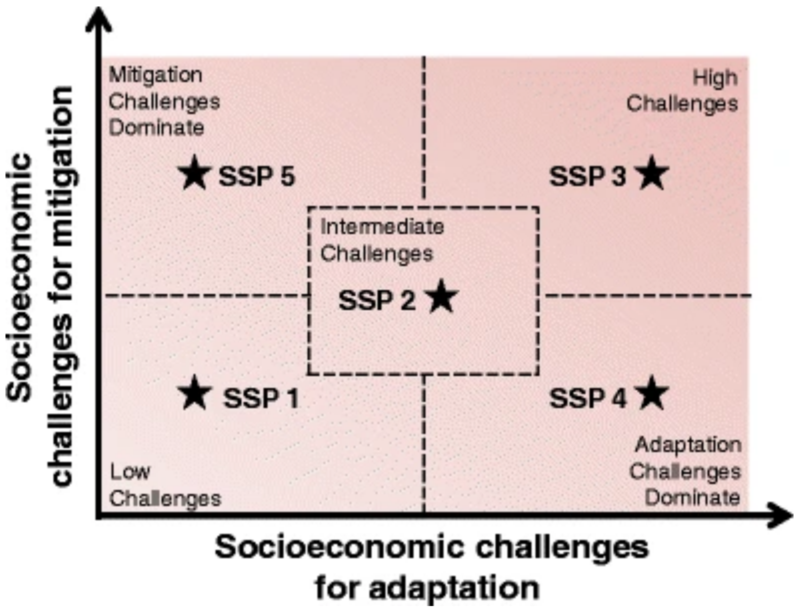

Figure D-1: Challenges to mitigation and adaptation by shared socioeconomic pathway.

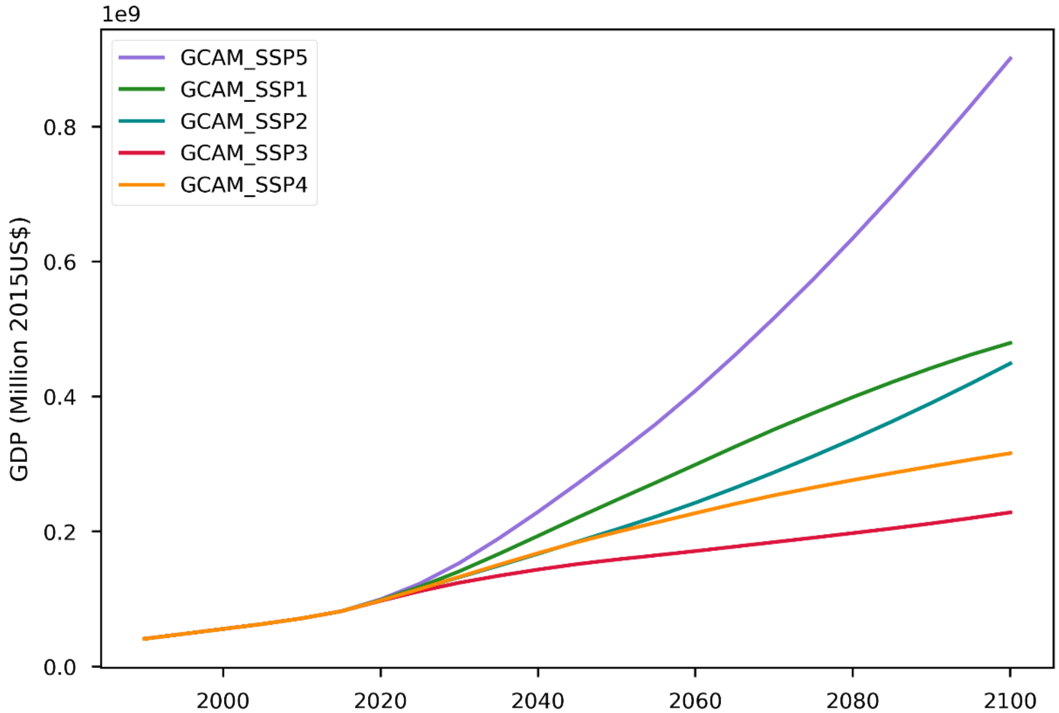

Figure D-2: GDP by shared socioeconomic pathway

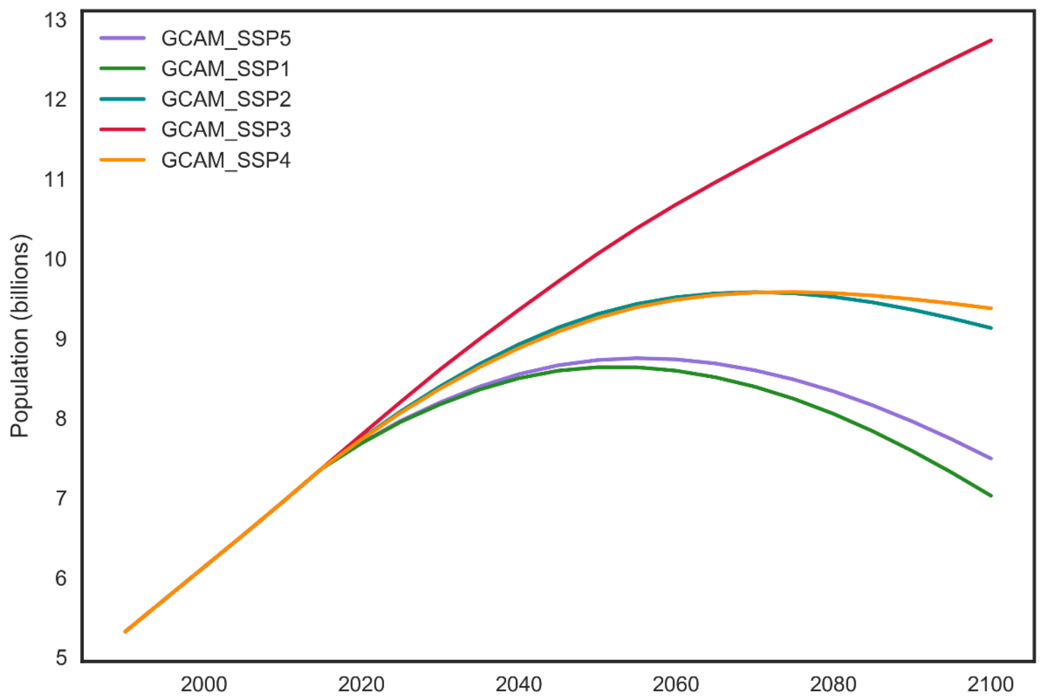

Figure D-3: Population by SSP

D3.2 Detailed derivation of DACCS cost and energy input assumptions

Table 1 reports detailed cost and energy input data for high and low temperature DACCS processes. To derive inputs to GCAM, we generally followed the methodology of Fasihi et. al (2018)[169] , adding several new references and adjusting capital return factor assumptions upward for more conservative estimates of especially the early costs of this emerging technology. We also added additional 132 kWh/tCO_2 electrical input requirement to compress CO_2 to subsurface injection pressure[30] where this was not accounted for in the original literature source. For low-temperature DACCS processes using solid sorbents, we converted the thermal energy requirement to electrical energy assuming a heat pump with coefficient of performance (COP) equal to 3.[253] We added an additional levelized cost component for capital and operational expenditures for the electric heat pump plant using Equation 1[169,253]:

$$Capex_{HP}\left(\frac{\$}{tCO_2}\right) = \left(\frac{Capex_{HP} * CRF}{FLh} + Opex_{HP,var}\right) * H \quad (1)$$

Where:

H = low-temperature thermal energy input requirement (KWh_{th}/tCO_2)

$Capex_{HP}$ = *Capital expenditure for heat pump (\$733/*kW_{th}*)*[297,298]

$Opex_{HP,fixed}$ = *Fixed operating cost of heat pump (\$2/*kW_{th}*)* [297,298]

$Opex_{HP,var}$ = *Variable operating cost of heat pump (0.001 \$/*kWh_{th}*)* [297,298]

FLh = Full load hours per year (4000) [169,253]

Table D-1: Derivation of Cost and Energy Input assumptions for DACCS

	Capex	Lifetime	CRF	Capex	Opex	Electricity demand	Heat/fuel demand	Heat pump cost	Cost reported (total)	Recalculated GCAM Non Energy Cost	Comment / Reference
	\$/tCO2\$-a	*years*	*%*	*\$/tCO2*	*\$/tCO2*	*GJ/tCO2*	*GJ/tCO2*	*\$/tCO₂*	*\$/tCO2*		
HT aqueous		20	9.4%						\$500		[157]
HT aqueous			-						\$343		[299]
HT aqueous	\$ 2,105	20	9.4%		**\$84**	**1.8**	**8.1**		\$411		Optimistic [31]
HT aqueous	\$ 2,774	20	9.4%		**\$111**	**1.8**	**8.1**		\$525		Pessemistic [31]
HT aqueous			-				**6.6**		\$ 376-399		[171]
HT aqueous			-			**5.4**			\$ 100-150		[155]
HT aqueous	\$ 1,146	25	8.6%		**\$42**		**8.8**		\$ 168-232		[30]
HT aqueous	\$ 793	25	8.6%		**\$30**		**8.8**		\$ 127-170		nth plant [30]
HT aqueous	\$ 694	25	8.6%		**\$26**	**1.3**	**5.3**		\$ 122-163		nth plant [30]
HT aqueous	\$ 609	25	8.6%		**\$23**	**0.3**	**5.3**		\$ 94-97		nth plant, not compressed to injection pressure, free O2[30]
HT aqueous	\$ 905	25	8.6%		**\$33**	**6.0**	-				Electric-only. Added additional electricity demand to reflect compression to injection pressure [169]
HT aqueous	\$ 2,060		11%		**\$76**	**1.8**	**8.1**		-		Literature review for integrated modeling study [96]
HT aqueous	\$ 1,146		11%		**\$42**	**1.3**	**5.3**		-		Literature review for integrated modeling study [96]
HT aqueous	\$ 700		11%		**\$27**	**1.3**	**5.3**		-		Literature review for integrated modeling study [96]
HT aqueous (natural gas)	\$ 1,763		13%	**\$220**	**\$76**	**1.8**	**8.1**			**\$296**	**Upper estimate for HT DAC using natural gas (2020 starting point, 2050 values for SSP3)**
HT aqueous (natural gas)	\$ 1,146		13%	**\$143**	**\$42**	**1.3**	**5.3**			**\$185**	**Intermediate estimate for HT DAC using natural gas (2050 values for SSP1, SSP2)**
HT aqueous (natural gas)	\$ 694		8%	**\$52**	**\$27**	**1.3**	**5.3**			**\$78**	**Optimistic estimate for HT DAC using natural gas (2050 values for SSP4, SSP5)**
HT aqueous	\$ 2,300		13%	**\$299**	**\$85**	**6.5**	**-**			**\$384**	**Upper estimate for fully-electric HT DAC (2020**

	Capex	Lifetime	CRF	Capex	Opex	Electricity demand	Heat/fuel demand	Heat pump cost	Cost reported (total)	Recalculated GCAM Non Energy Cost	Comment / Reference
	$/tCO2$-a	*years*	*%*	*$/tCO2*	*$/tCO2*	*GJ/tCO2*	*GJ/tCO2*	*$/tCO$_2$*	*$/tCO2*		
(fully electric)											**starting point, 2050 values for SSP3)**
HT aqueous (fully electric)	$ 1,146		13%	**$143**	**$42**	**5.1**	**-**			**$186**	**Intermediate estimate for fully-electric HT DAC (2050 values for SSP1, SSP2)**
HT aqueous (fully electric)	$ 905		8%	**$68**	**$33**	**5.1**	**-**			**$101**	**Optimistic estimate for fully-electric HT DAC (2050 values for SSP4, SSP5)**
LT solid sorbent	$ 1,623	25				**2.5**	**7.5**				Assumes free waste heat [300]
LT solid sorbent	$ 971	25				**2.5**	**7.5**				Assumes free waste heat [300]
LT solid sorbent						**0.5-0.9**	**4.2-5.0**		$113		[169]
LT solid sorbent						**0.5-0.10**	**4.2-5.0**		$ 11-38		[36,301,302]
LT solid sorbent		20				**0.72-1.1**	**5.4-7.2**				[35]
LT solid sorbent									$83		[35]
LT solid sorbent	$ 810	20	9.4%	**$76**	**$32**	**0.9**	**6.3**			$109	Assumes free waste heat [169]
LT solid sorbent	$ 750	15	12%	**$89**	**$260**	**1.1**	**7.2**			$349	Literature review for integrated modeling study [96]
LT solid sorbent	$ 430	15	12%	**$51**	**$150**	**0.6**	**4.4**			$201	Literature review for integrated modeling study [96]
LT solid sorbent	$ 110	15	12%	$13	$37	0.6	4.4			$50	Literature review for integrated modeling study [96]
LT solid sorbent		12-20				**1.4**	**5.8**				Long-term goal [32]
LT solid sorbent						**1.8**	**9.0**		$600		Current estimate of total cost [303]
LT solid sorbent							**7.0**		$200		Expected cost reduction after 3-5 years (Factor of 3 from previous estimate); Expected improvements in energy efficiency [303]
LT solid sorbent (heat pump)		20	13%	**$89**	**$260**	**5.5**	-		**$53**	**$402**	**Upper estimate for LT DAC w/ electric heat pump with COP of 3[297,298] (2020 starting point, SSP3)**
LT solid sorbent (heat pump)		15	10%	**$51**	**$150**	**2.5**	-		**$33**	**$235**	**Intermediate estimate for LT DAC w/ electric heat pump with COP of 3[297,298], 2050 values for SSP1, SSP2**
LT solid sorbent (heat pump)		15	10%	**$43**	**$17**	**2.5**	-		$27	**$136**	**Optimistic estimate for LT DAC w/ electric heat pump with COP of 3[297,298], 2050 values for SSP4, SSP5**

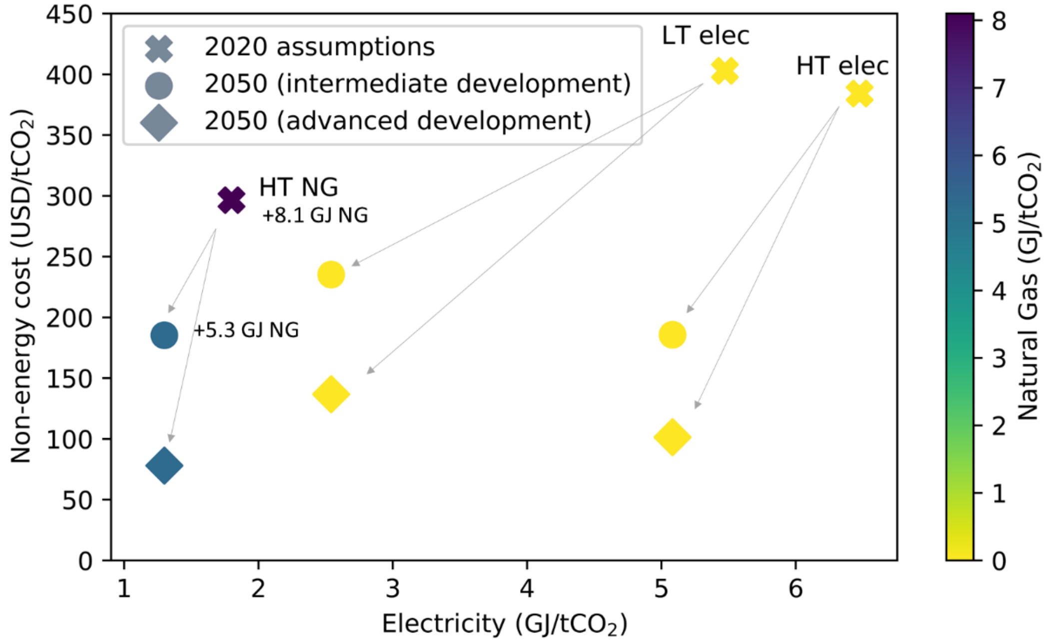

Figure D-4: Tradeoffs between energy intensity, source, and cost for DACCS archetypes.[20]

D3.3 Economic choice function for DACCS technologies

DACCS indirectly competes in GCAM against (a) emissions abatement; and (b) other negative emissions technologies based on its cost and the subsidy paid for CO_2 removal (i.e., the carbon price). This is implemented in GCAM by creating a DACCS sector with several competing technology options.[304,305] The first is a "null" technology which does not capture carbon and has zero cost. This competes against DACCS technolgies which intake electric and/or thermal energy, and a non-energy cost. These technologies remove CO_2 from the atmosphere and send it to geologic storage, along with any captured combustion emissions from process heat. We use GCAM's logit choice model for economic choice between DACCS technologies. This includes the "choice" to not deploy DACCS and instead use other mitigation or negative emissions technologies (i.e., the "null" DACCS technology). The share s_i of any DACCS technology with price p_i is computed as follows:

$$s_i = \frac{\alpha_i \exp(\beta p_i)}{\sum_{j=1}^{N} \alpha_j \exp(\beta p_j)} \qquad (2)$$

[20] HT NG = high-temperature DACCS requiring natural gas; HT elec = high-temperature fully-electric DACCS; LT elec = low-temperature fully-electric DACCS (thermal energy requirement met by heat pump).

Where:

α_i = the shareweight of the technology.

β = the logit coefficient, which determines how large a cost difference is required to produce a given difference in market share.

Shareweights are used to represent societal preferences, infrastructure buildup, barriers to market entry.[227] Consistent with GCAM's treatment of other new and emerging technologies, we set shareweights for DACCS technologies to zero in 2020, and linearly increase to 1 by 2100 for most scenarios. This means that by 2100, DACCS technologies are competing solely based on their cost minus the subsidy for removing carbon dioxide from the atmosphere (again, equal to the carbon price). For the SSP1 "sustainable development" scenarios, we reduced the final 2100 shareweight to 0.1 for electric-only DACCS technologies, due to an assumed social preference against relying on future energy and financially intensive negative emissions to make up for slow near-term mitigation progress.[47,48] We futher reduced the shareweight for DACCS processes requiring natural gas to 0.01 in these scenarios, assuming an even lower preference for depending directly on fossil fuel extraction to remediate the climate in the future.

D3.4 Additional GCAM-SSP-DACCS scenario results

Figure 4 reports net CO_2 emissions and primary energy consumption in 2100 for the scenarios from this study (large coloured markers), relative to the SSP marker scenarios which did not include DACCS technology (smaller coloured markers). The small light gray markers indicate other below 1.5 degrees C and below 2 degrees C scenarios in the IIASA 1.5 degree scenario database, while the darker gray markers indicate those scenarios in which DACCS is represented and has non-zero deployment in the scenario.[66] Relative to the SSP scenarios developed without the capability to model DACCS, the GCAM SSP-DACCS scenarios generally allow deeper negative emissions in 2100 and lead to higher primary energy consumption. This is due to both direct energy consumption of DACCS itself, as well as less aggressive emissions abatement allowing higher energy consumption.

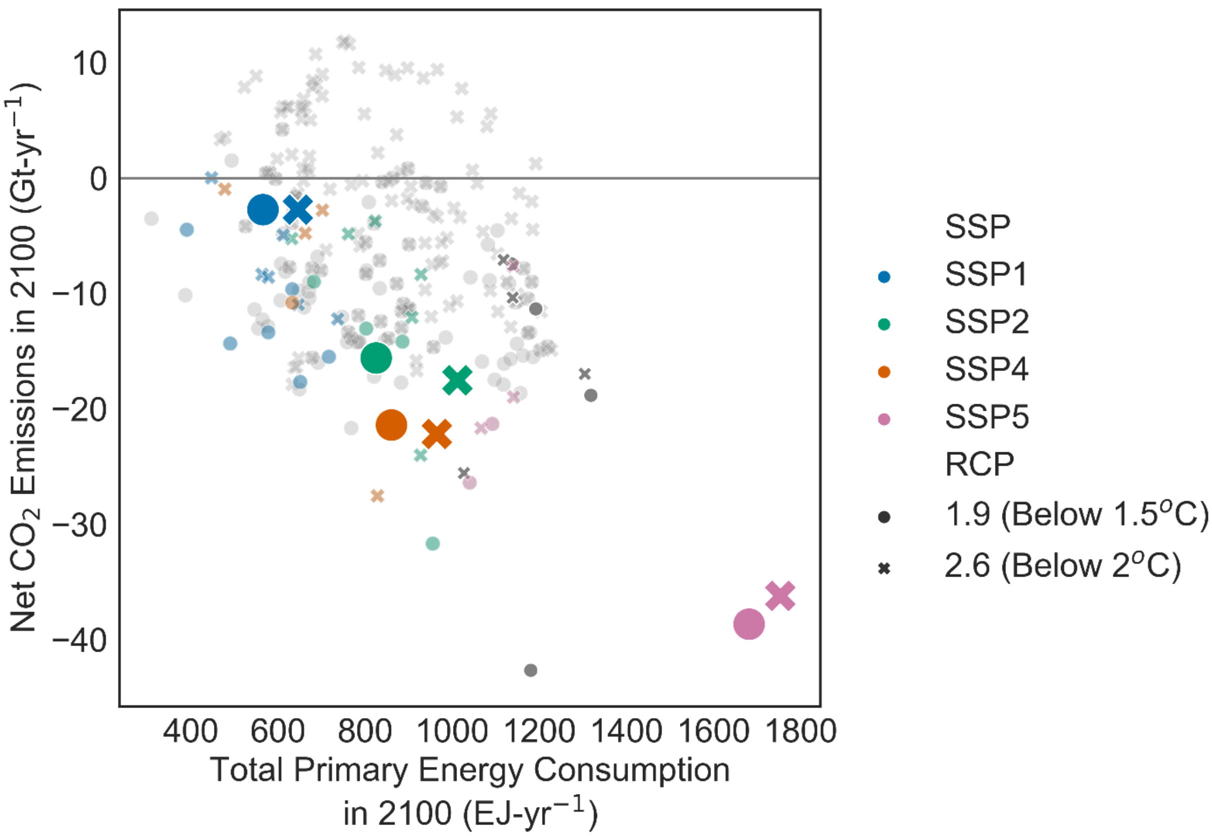

Figure D-5: Net CO_2 emissions vs. Primary Energy Consumption in 2100 for ambitious mitigation scenarios

Figure 5 reports trajectories for radiative forcing, and Figure 6 reports trajectories for global mean temperature anomaly, CO_2 concentration, and net CO_2 emissions for GCAM SSP scenarios with and without DACCS available. Scenarios without DACCS available are indicated by lighter shading. In all but the SSP1 scenarios where preference for DACCS was reduced and the total negative emissions constraint tightened, DACCS availability allows delayed mitigation and higher overshoot of the long-term climate target. Figures 7-9 report global water withdrawals, electricity generation, and electricity consumption for the GCAM-SSP-DACCS scenarios.

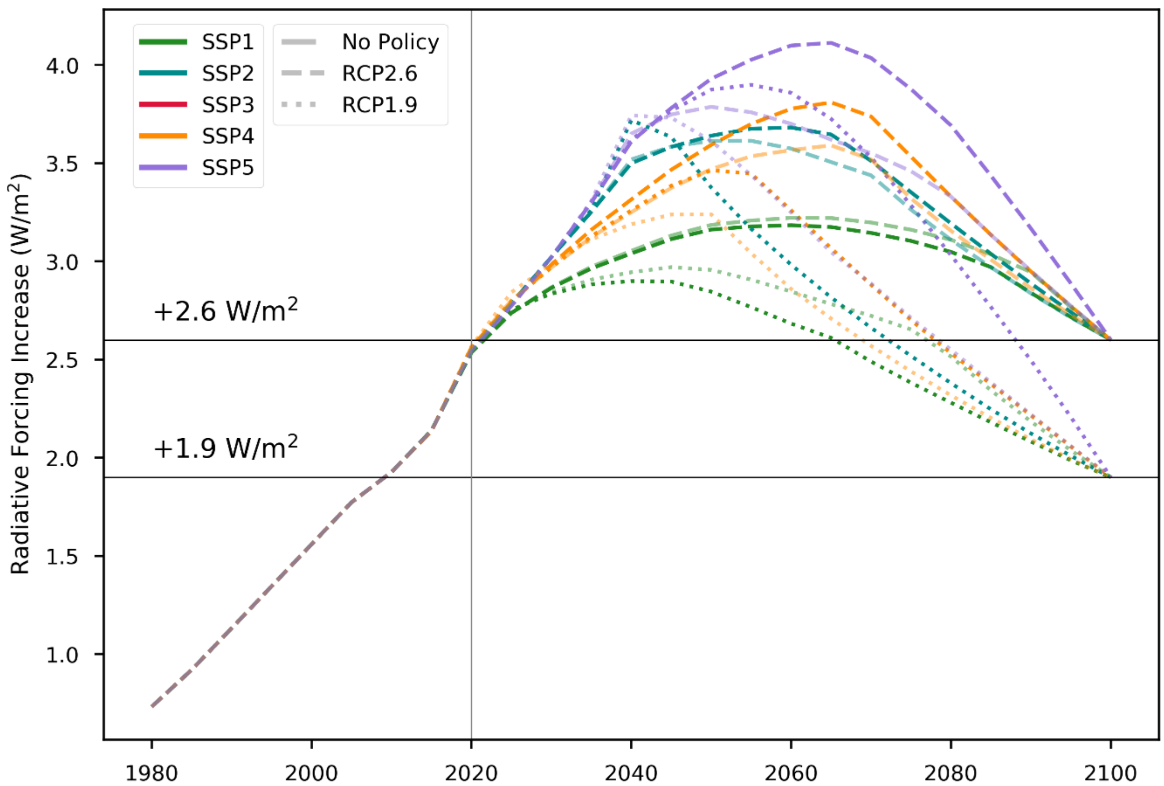

Figure D-6: Radiative forcing trajectories for GCAM SSP mitigation scenarios.

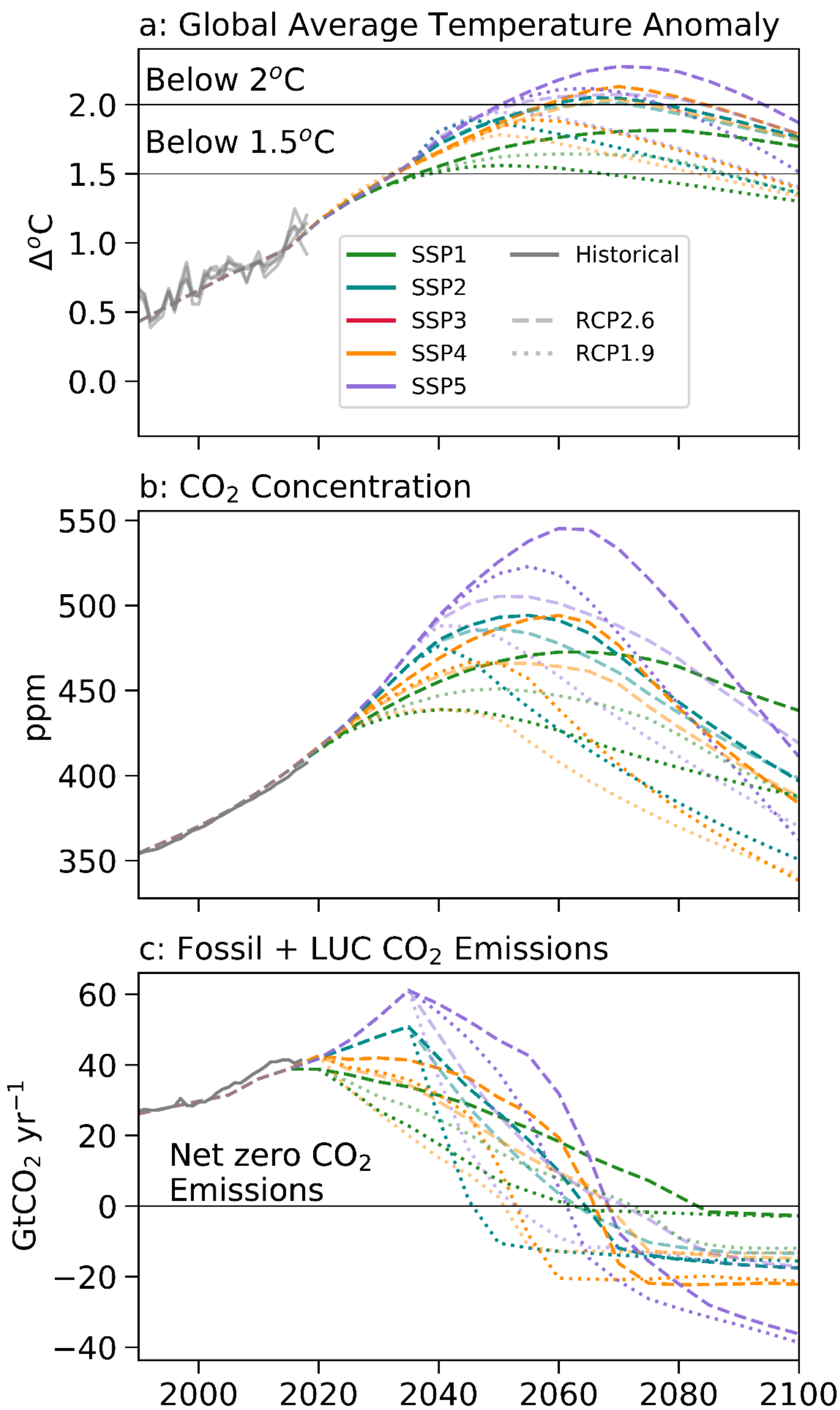

Figure D-7: Mitigation trajectories for global average temperature anomaly (a), CO2 concentrations (b), and CO2 emissions (c) with and without DACCS available.

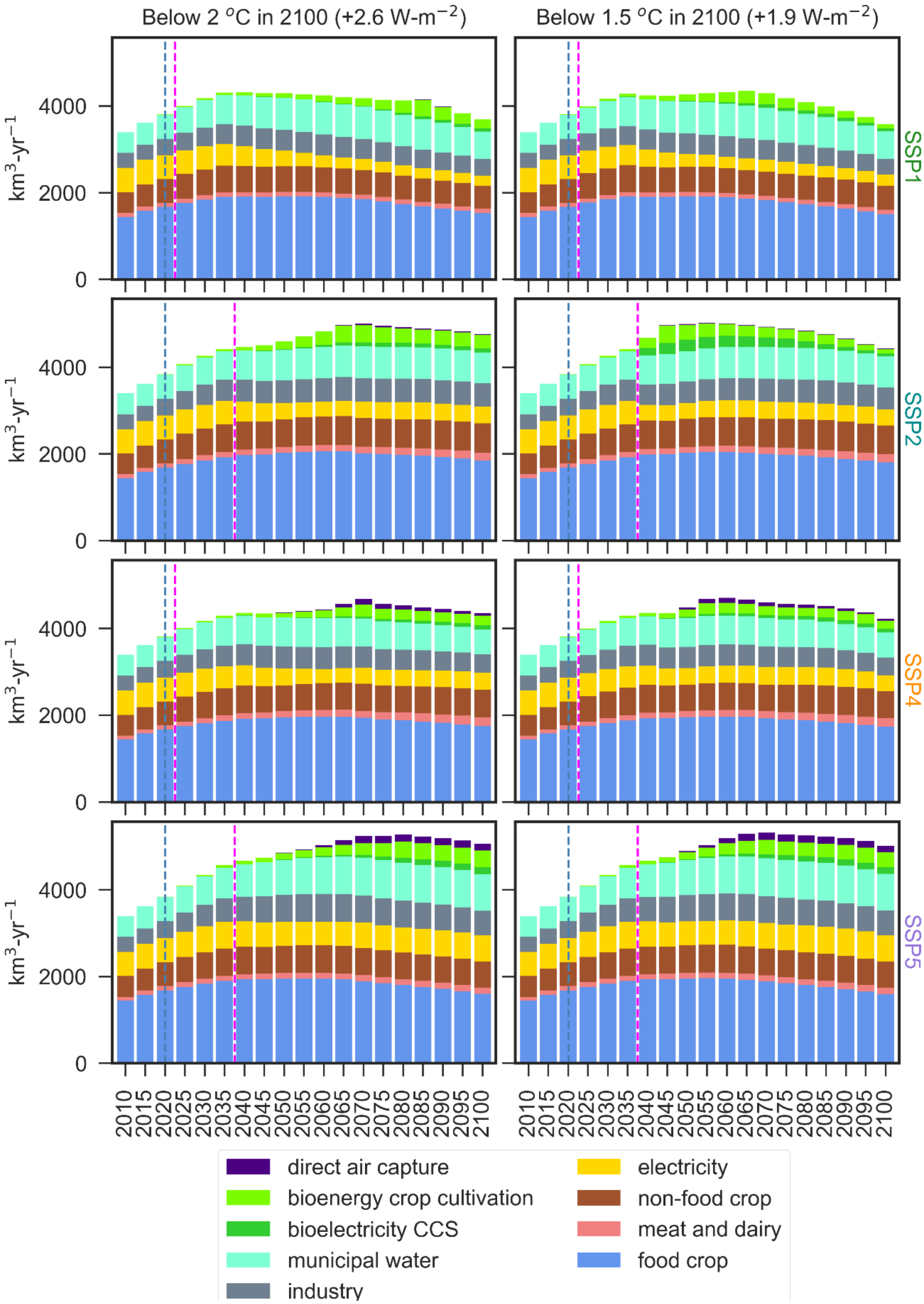

Figure D-8: Water withdrawals by sector for the SSP-DACCS scenarios

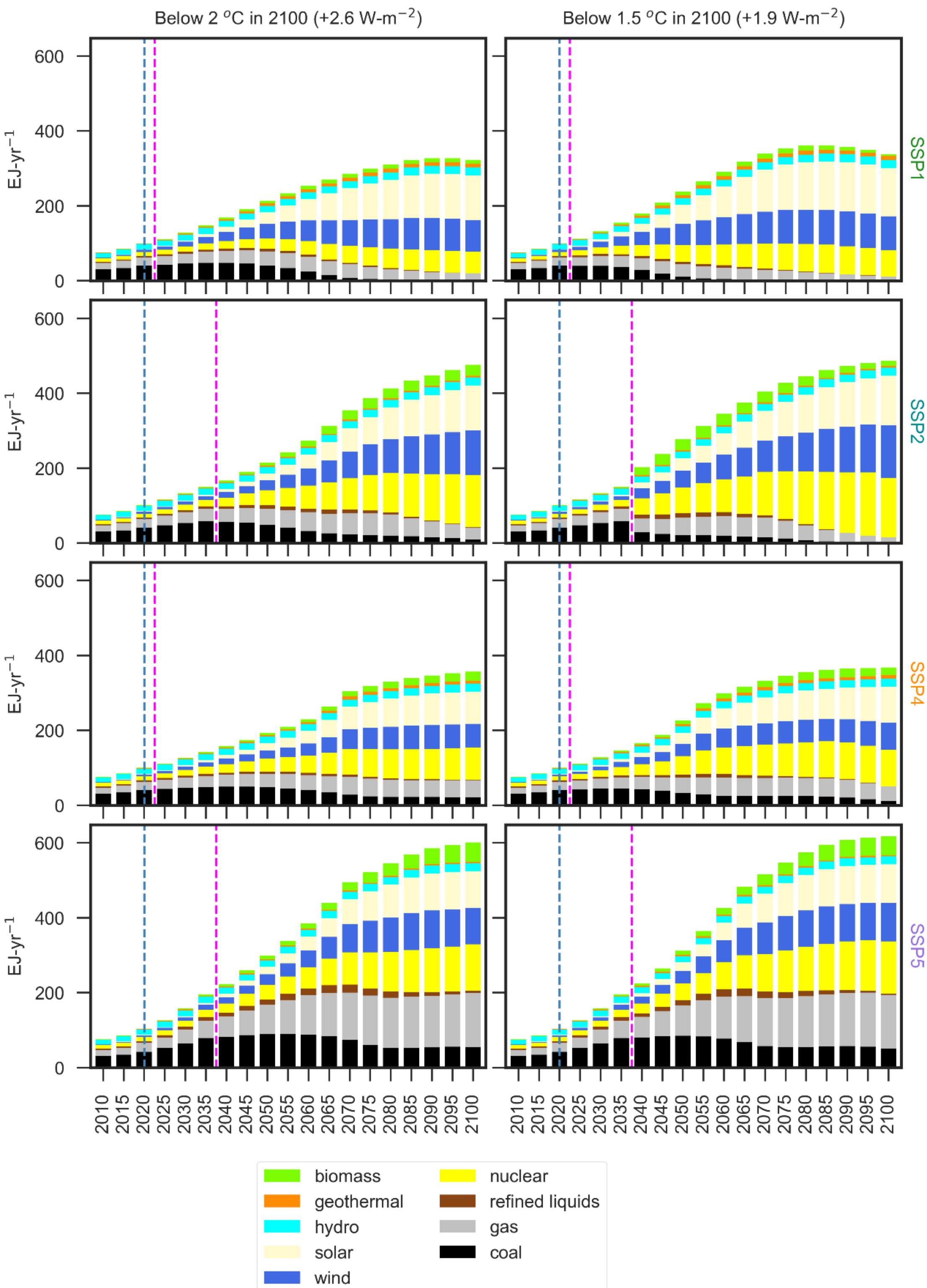

Figure D-9: Global electricity generation for the GCAM-SSP-DACCS scenarios by fuel

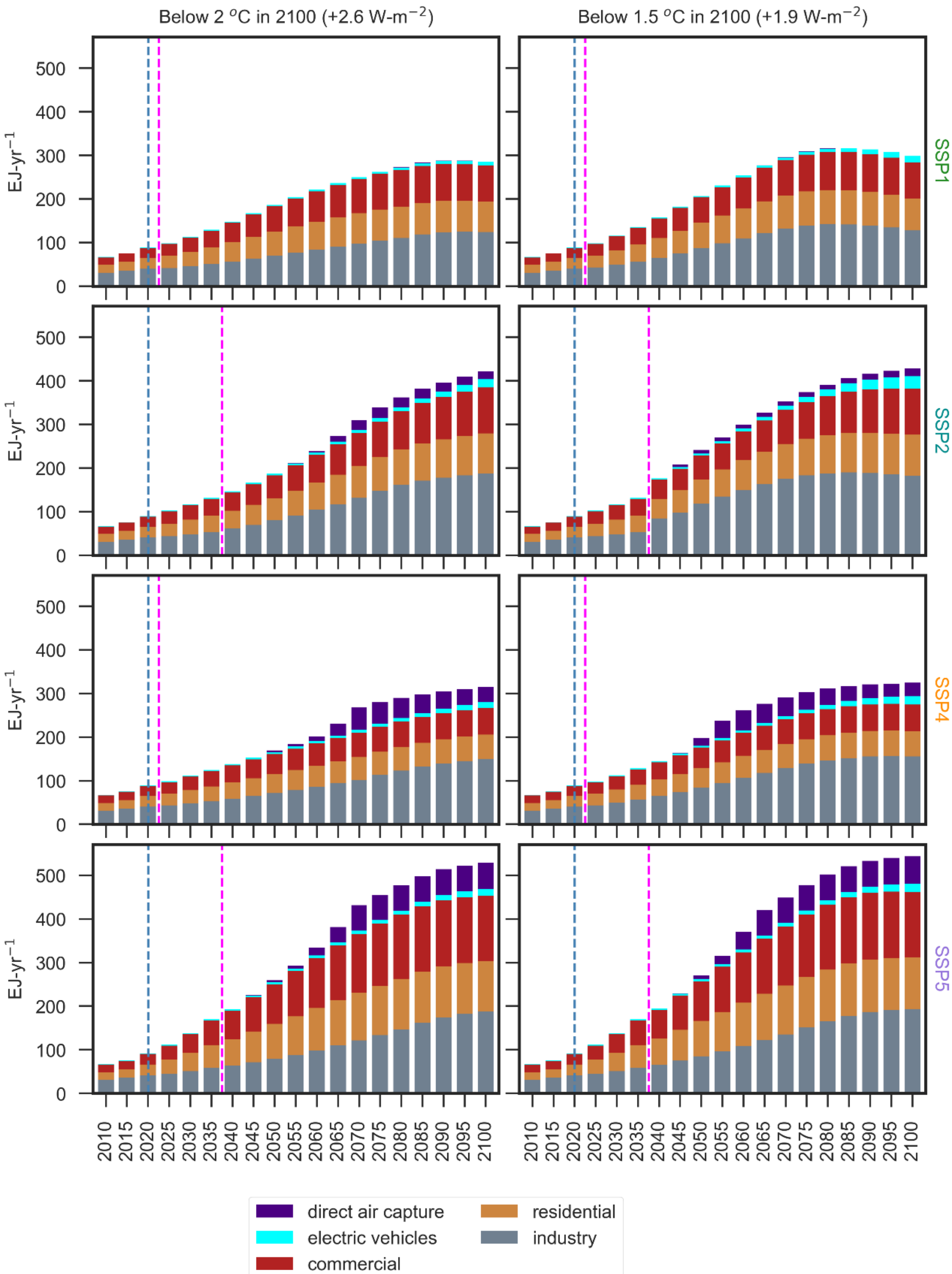

Figure D-10: Global electricity consumption for GCAM SSP-DACCS scenarios

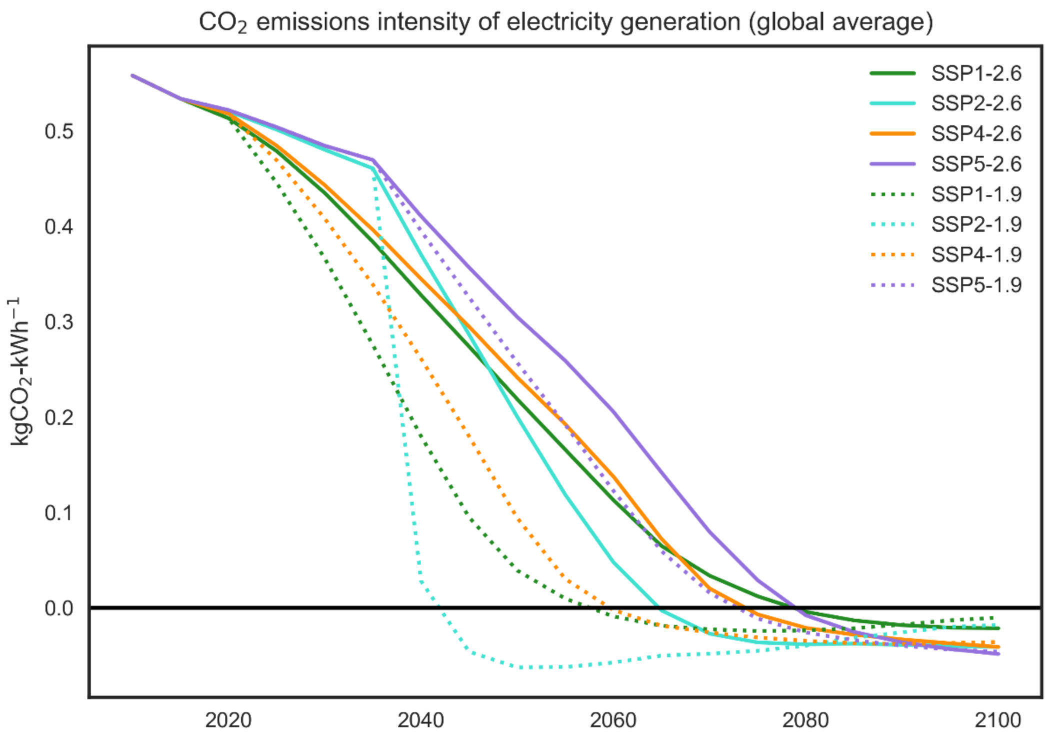

Figure D-11: Average CO_2 emissions intensity of global electricity generation for GCAM-SSP-DACCS scenarios

D3.5 GCAM-SSP results with no DACCS available

Figures D11-17 report results for emissions, geologic carbon sequestration, water withdrawals and consumption, primary energy consumption, electricity generation and consumption, and land use for the GCAM-SSP scenarios without DACCS available. The dashed teal lines indicate present-day levels (that is, 2020). The dashed magenta lines indicate the assumed start of global CO_2 emissions pricing. The SSP2-1.9 scenario was infeasible without DACCS due to delayed onset of mitigation policy and lesser capacity for negative emissions than in SSP5 owing to lower GDP growth assumptions.

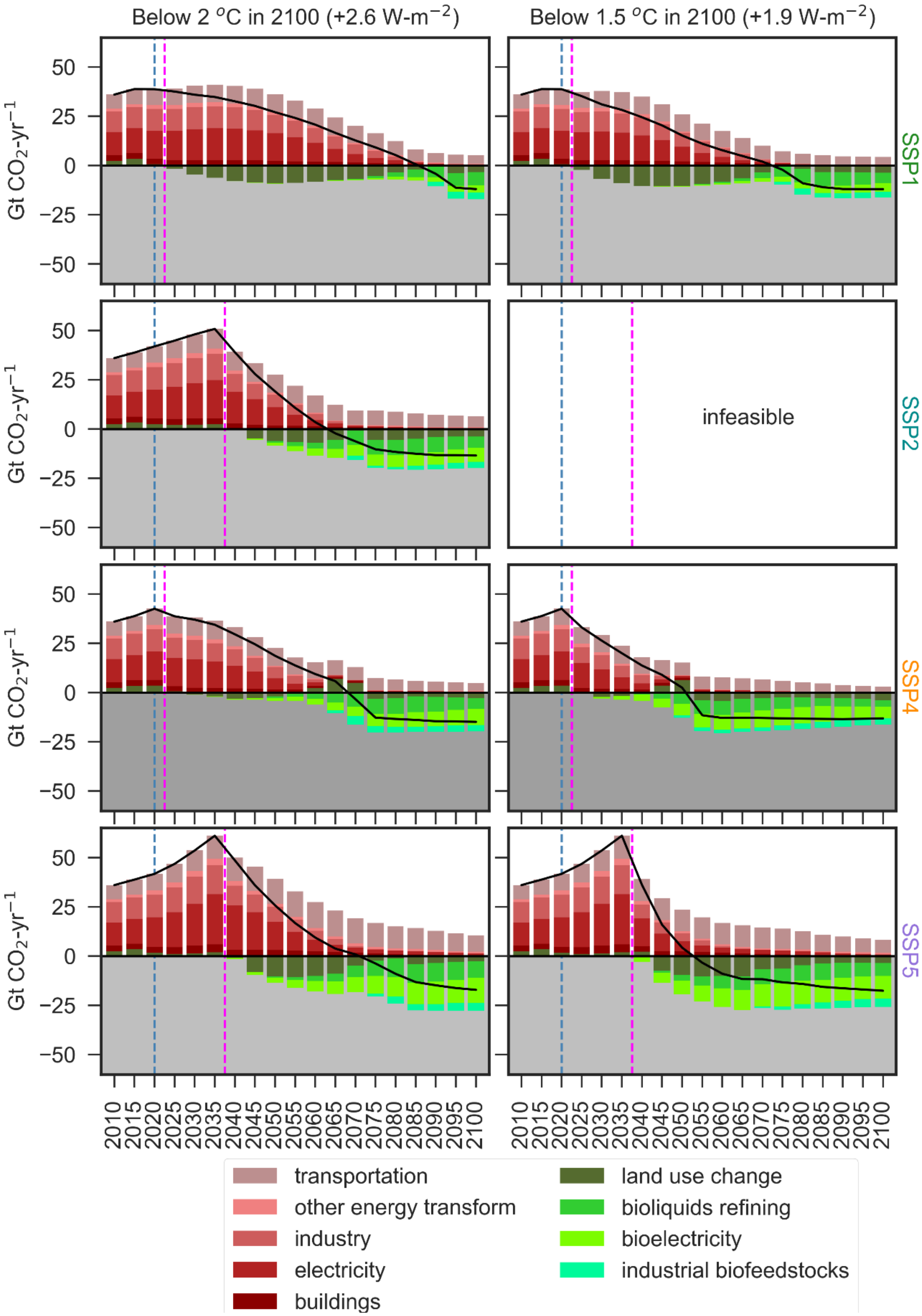

Figure D-12: CO2 emissions by sector for GCAM SSP scenarios with no DACCS available

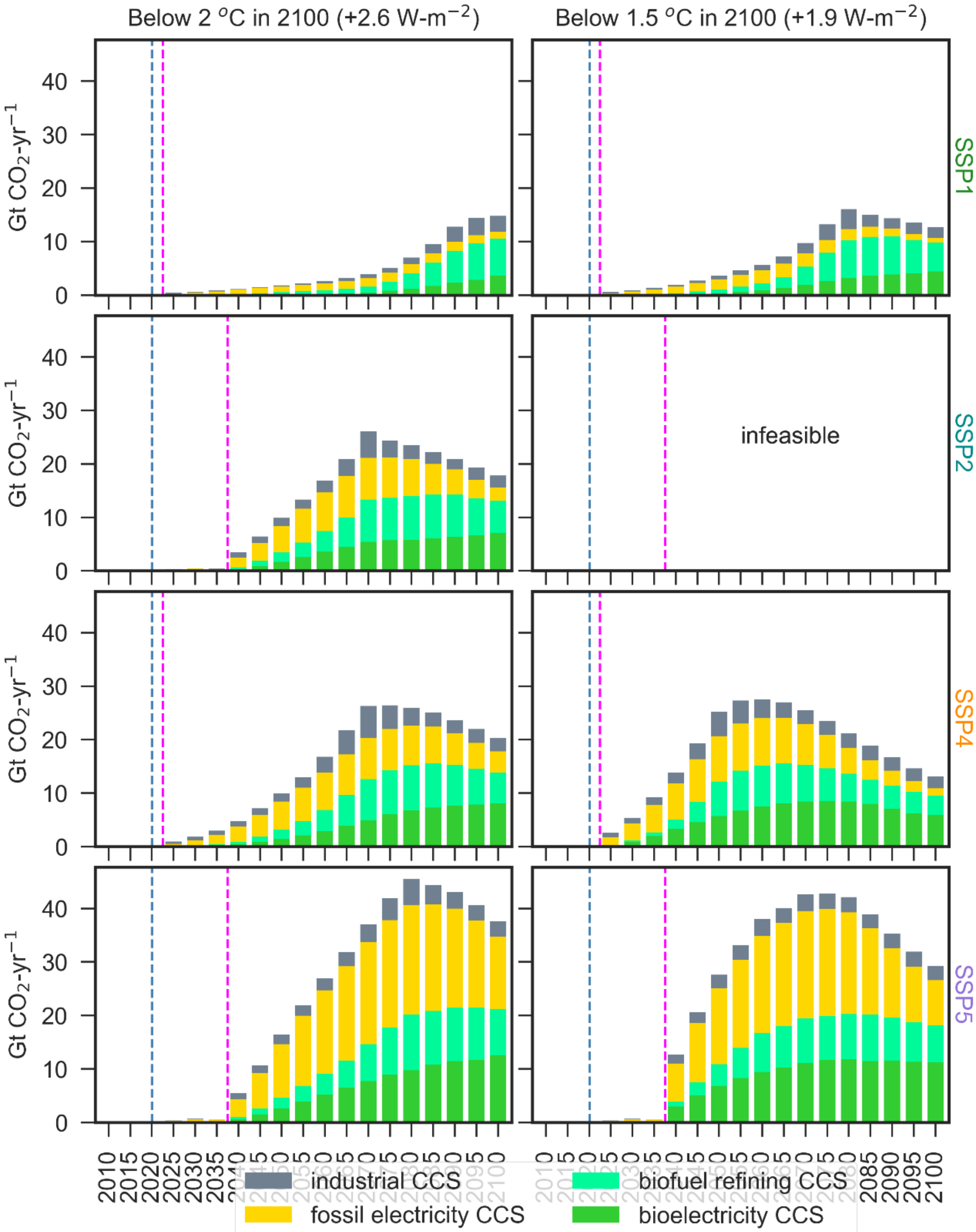

Figure D-13: CCS by sector for GCAM SSP scenarios with no DACCS available

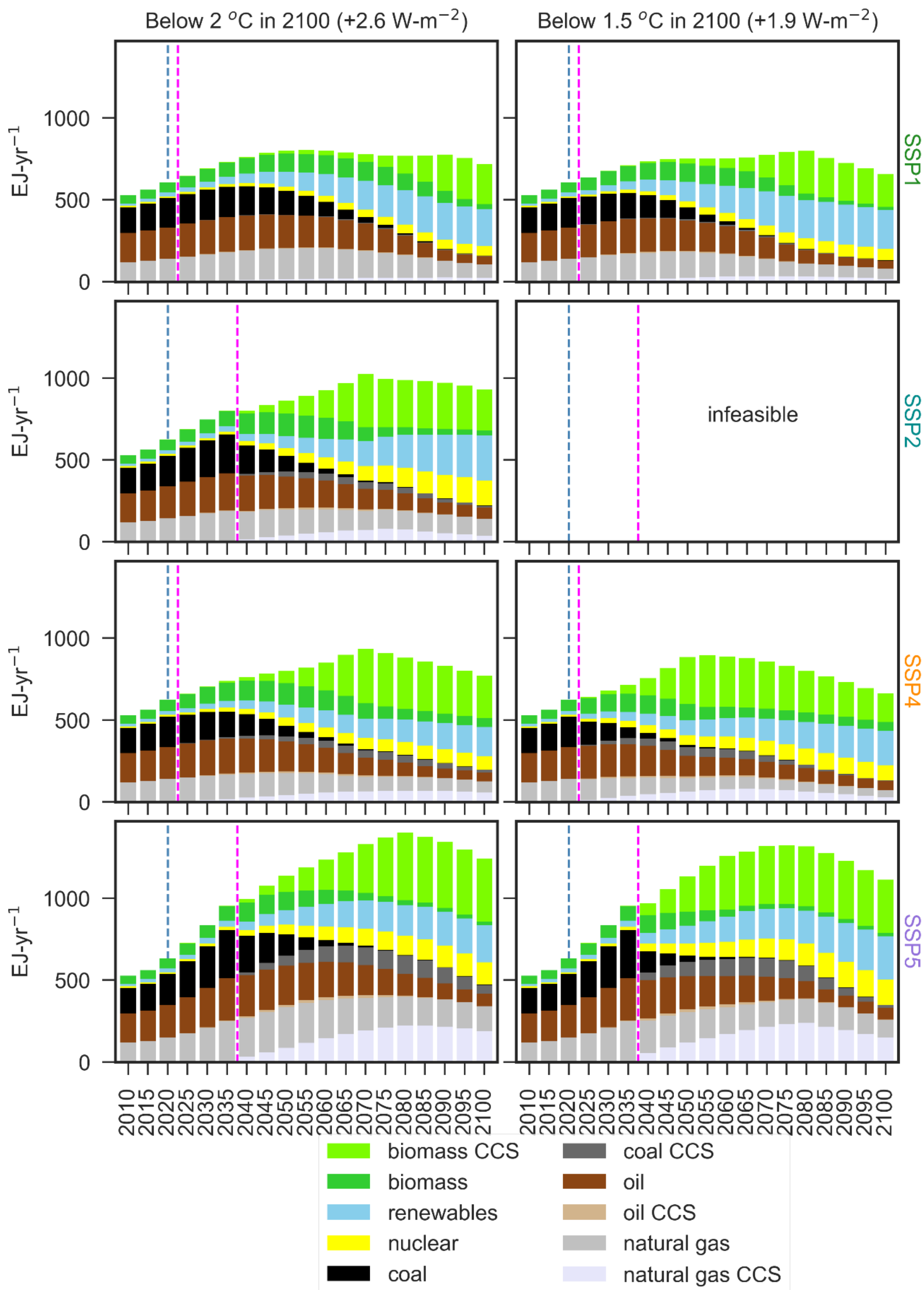

Figure D-14: Primary energy consumption for GCAM SSP scenarios with no DACCS available

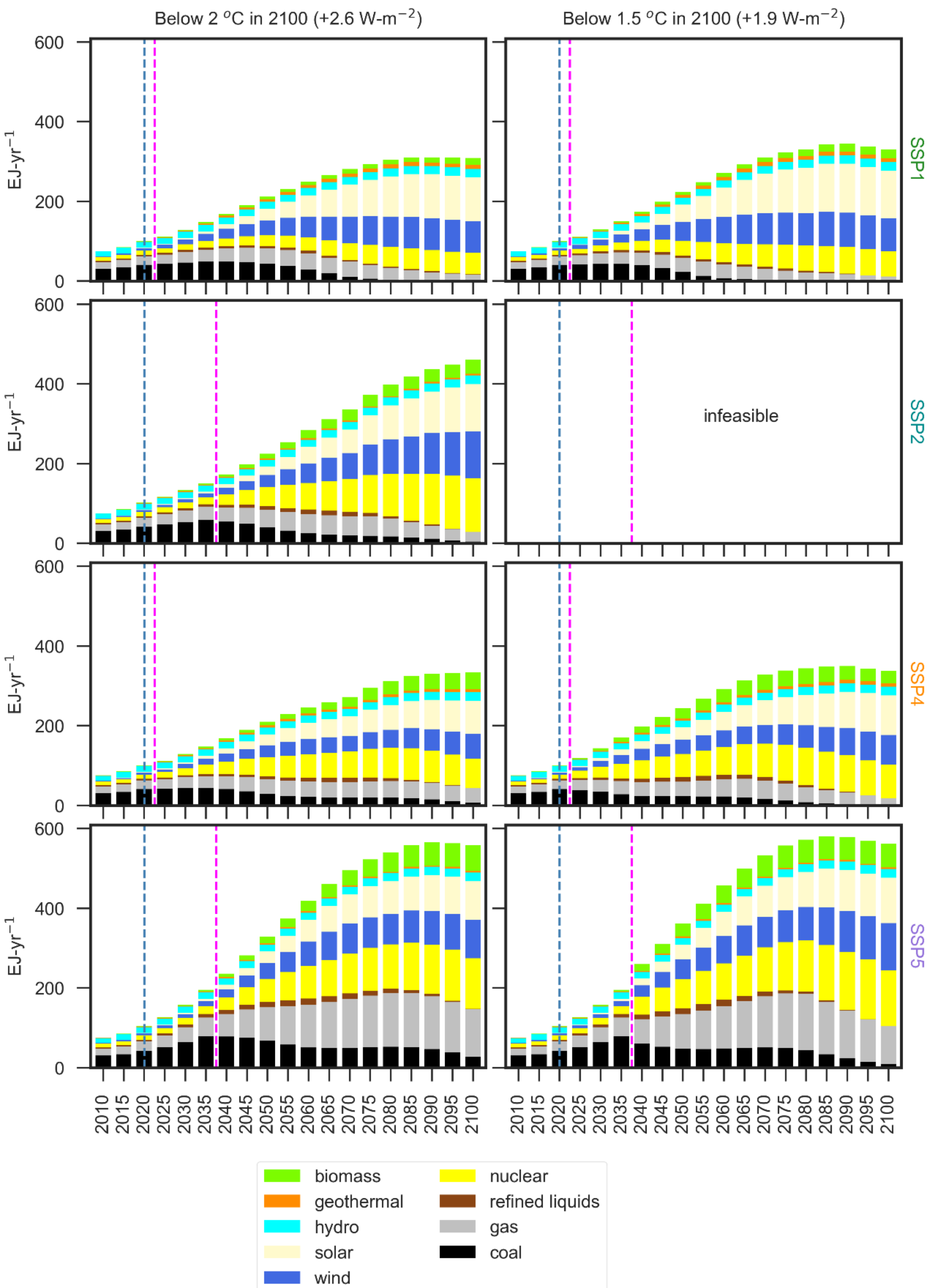

Figure D-15: Global electricity generation for GCAM-SSP scenarios with no DACCS available by fuel

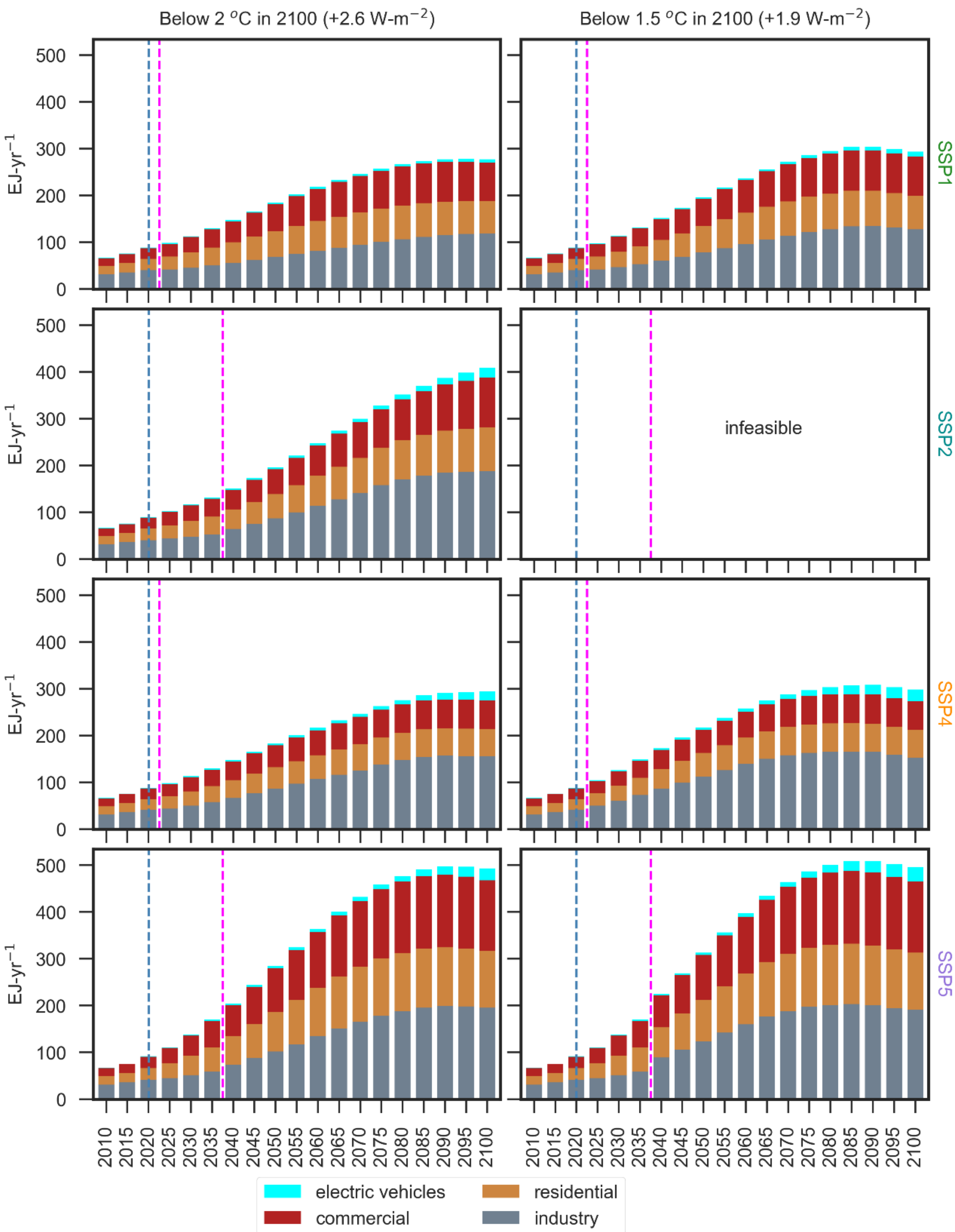

Figure D-16: Global electricity consumption for GCAM-SSP scenarios with no DACCS available

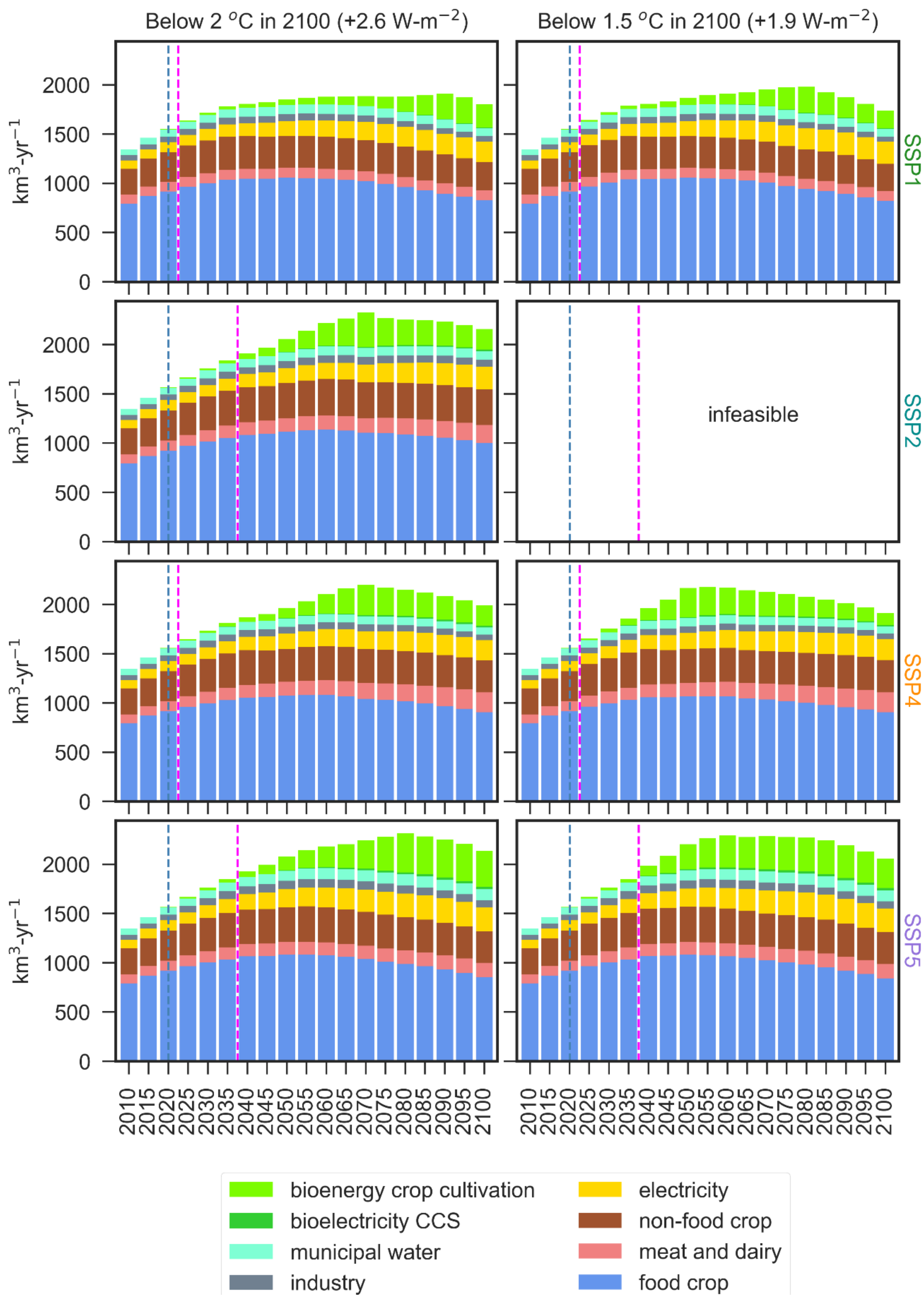

Figure D-17: Water consumption by sector GCAM SSP scenarios with no DACCS available

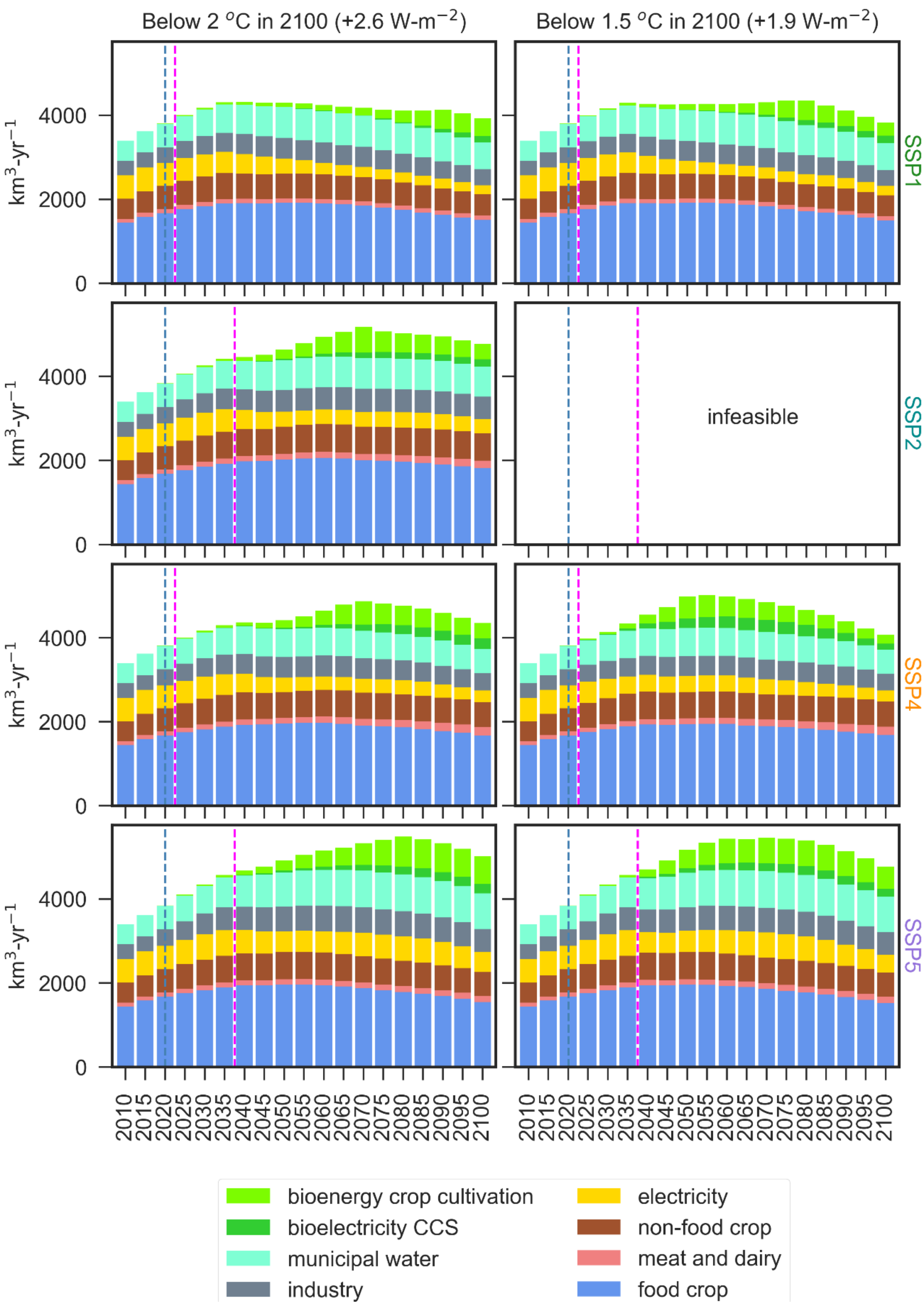

Figure D-18: Water withdrawals by sector for GCAM SSP scenarios with no DACCS available

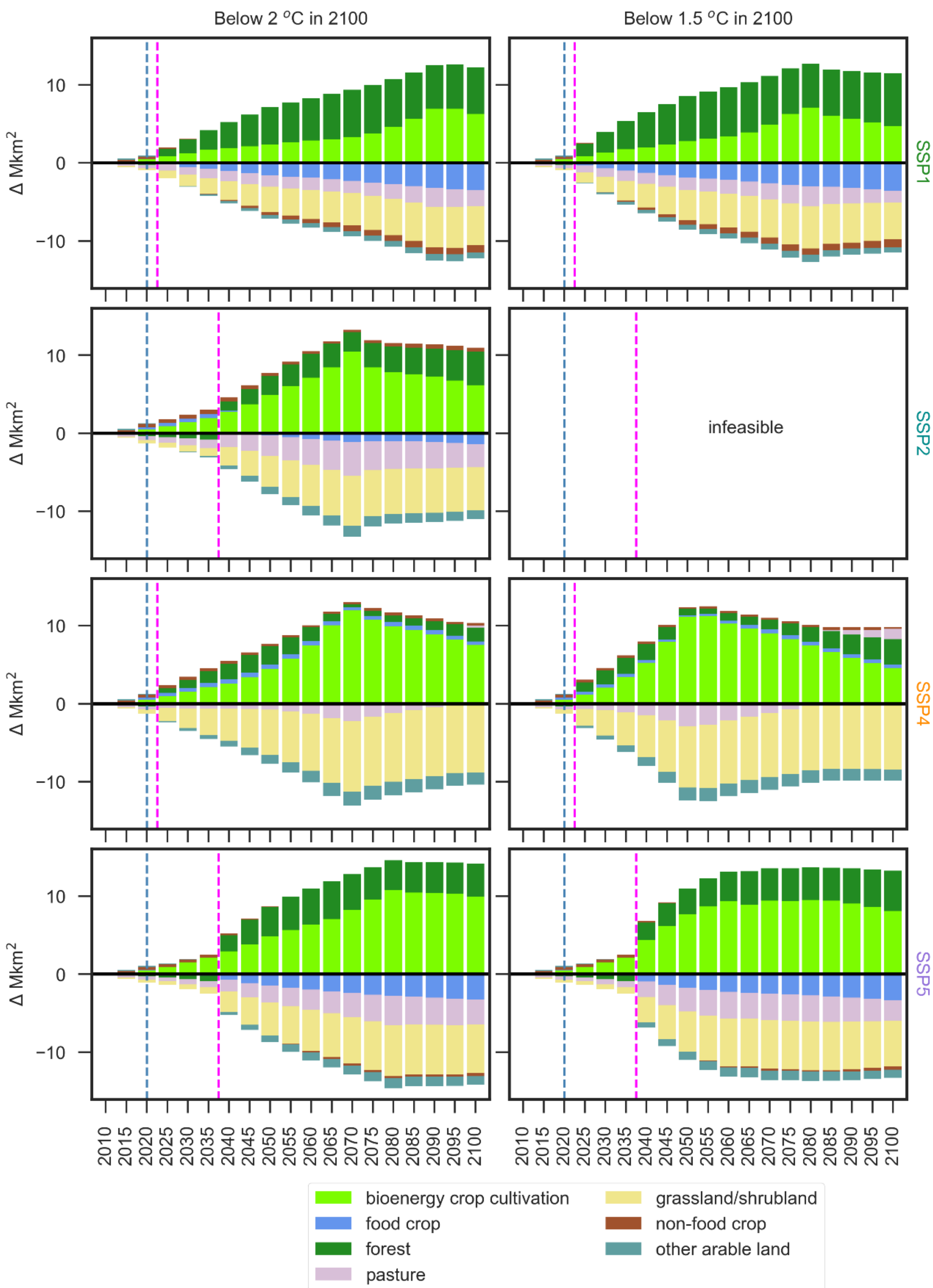

Figure D-19: Land use change from 2010 for GCAM SSP scenarios with no DACCS available.

The lack of availability of DACCS leads to greater reliance on bioenergy for both mitigation and CO_2 removal, reducing forest expansion relative to the DACCS scenarios.

References

1. Organization, W. M. *State of the Global Climate 2020 PROVISIONAL REPORT*. https://gcos.wmo.int/en/global-climate-indicators.
2. U.S. Global Change Research Program. Fourth National Climate Assessment. **II**, 1–470 (2018).
3. *Attribution of Extreme Weather Events in the Context of Climate Change*. *Attribution of Extreme Weather Events in the Context of Climate Change* (National Academies Press, 2016). doi:10.17226/21852.
4. IPCC. *CLIMATE CHANGE 2013 The Physical Science Basis Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel On Climate Change*. (2013).
5. Geden, O. An actionable climate target. *Nature Geoscience* vol. 9 340–342 (2016).
6. Rogelj, J. *et al.* Zero emission targets as long-term global goals for climate protection. *Environ. Res. Lett.* **10**, 105007 (2015).
7. Le Quéré, C. *et al.* Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nat. Clim. Chang.* **10**, 647–653 (2020).
8. Le Quéré, C. *et al.* Fossil CO2 emissions in the post-COVID-19 era. *Nat. Clim. Chang.* **11**, 197–199 (2021).
9. UNFCCC. Conference of the Parties (COP). *Paris Climate Change Conference-November 2015, COP 21. Adoption of the Paris Agreement. Proposal by the President.* vol. 21932 (2015).
10. Secretariat, U. N. F. C. on C. C. *Synthesis report on the aggregate effect of the intended nationally determined contributions*. http://unfccc.int/focus/indc_portal/items/9240.php (2015).
11. Secretariat, U. N. F. C. on C. C. *Nationally determined contributions under the Paris Agreement*.
12. Rogelj, J. *et al.* Paris Agreement climate proposals need a boost to keep warming well below 2 °c. *Nature* vol. 534 631–639 (2016).
13. IPCC. *Climate Change: The IPCC 1990 and 1992 Assessments*. https://www.ipcc.ch/site/assets/uploads/2018/05/ipcc_90_92_assessments_far_cover.pdf (1992).
14. IPCC. *Climate Change 1995: Second Assessment Report*.
15. Albritton, D. L. *et al. Climate Change 2001: Third Assessment Report*. http://www.cambridge.org (2001).
16. Bernstein, L. *et al. Climate Change 2007: Fourth Assessment Report*. vol. 104.
17. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC, 2014).
18. 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,*. https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf (2018).
19. Huppmann, D., Rogelj, J., Krey, V., Kriegler, E. & Riahi, K. A new scenario resource for integrated 1.5 °C research. *Nat. Clim. Chang.* (2018) doi:10.1038/s41558-018-0317-4.
20. Lawrence, B. M. G. Promises and perils of the Paris Agreement. *Science (80-.).* **364**, (2019).
21. Anderson, Kevin; Peters, G. The Trouble With Negative Emissions. *Science (80-.).* **354**, 182–184 (2016).
22. Peters, G. P. *et al.* The challenge to keep global warming below 2 °C. *Nat. Clim. Chang.* **3**, 4–6 (2013).
23. Holz, C., Siegel, L. S., Johnston, E., Jones, A. P. & Sterman, J. Ratcheting ambition to limit warming to 1.5 °c-trade-offs between emission reductions and carbon dioxide removal. *Environ. Res. Lett.* **13**, 64028 (2018).
24. Muratori, M., Calvin, K., Wise, M., Kyle, P. & Edmonds, J. Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environ. Res. Lett.* **11**, 095004

(2016).
25. Wise, M. *et al.* Implications of Limiting CO2 Concentrations for Land Use and Energy. *Science (80-.).* **324**, 1183–1186 (2009).
26. Calvin, K. *et al.* Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Clim. Change* **123**, 691–704 (2014).
27. Wilcox, J., Psarras, P. C. & Liguori, S. Assessment of reasonable opportunities for direct air capture. *Environ. Res. Lett.* **12**, 065001 (2017).
28. Smith, P. *et al.* Biophysical and economic limits to negative CO2emissions. *Nat. Clim. Chang.* **6**, 42–50 (2016).
29. NRC. Negative Emissions Technologies and Reliable Sequestration. *Natl. Acad. Press* (2018) doi:10.17226/25259.
30. Keith, D. W., Holmes, G., St Angelo, D. & Heidel, K. A Process for Capturing CO 2 from the Atmosphere. (2018) doi:10.1016/j.joule.2018.05.006.
31. American Physical Society. *Direct Air Capture of CO 2 with Chemicals Direct Air Capture of CO 2 with Chemicals A Technology Assessment for the APS Panel on Public Affairs.* https://www.aps.org/policy/reports/assessments/upload/dac2011.pdf (2011).
32. Beuttler, C., Charles, L. & Wurzbacher, J. The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. *Front. Clim.* **1**, (2019).
33. Chevron, Occidental invest in CO2 removal technology - Reuters. https://www.reuters.com/article/us-carbonengineering-investment/chevron-occidental-invest-in-co2-removal-technology-idUSKCN1P312R.
34. Engineering, C. Carbon Engineering's Large-scale Direct Air Capture Breakthrough. *Carbonbrief* https://carbonengineering.com/news-updates/climate-change-breakthrough/ (2018).
35. Climeworks – Capturing CO2 from Air. https://www.climeworks.com/.
36. Ping, E. & Sakwa-Novak, M., Eisenberger, P. Global thermostat low cost direct air capture technology. in *International Conference on Negative CO2 Emissions, Gothenburg* 22–24 (2018).
37. ExxonMobil and Global Thermostat to Advance Breakthrough Atmospheric Carbon Capture Technology | Business Wire. https://www.businesswire.com/news/home/20190627005137/en/ExxonMobil-Global-Thermostat-Advance-Breakthrough-Atmospheric-Carbon.
38. Carbon Engineering inks Shopify as its first partner for carbon removal as a service | TechCrunch. https://techcrunch.com/2021/03/09/carbon-engineering-inks-shopify-as-its-first-partner-for-carbon-removal-as-a-service/.
39. Microsoft. Progress on our goal to be carbon negative by 2030. https://blogs.microsoft.com/on-the-issues/2020/07/21/carbon-negative-transform-to-net-zero/ (2020).
40. Edenhofer, O. *et al.* Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett.* **13**, 044015 (2018).
41. Realmonte, G. *et al.* An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun.* **10**, (2019).
42. Chen, C. & Tavoni, M. Direct air capture of CO2 and climate stabilization: A model based assessment. *Clim. Change* **118**, 59–72 (2013).
43. Marcucci, A., Kypreos, S. & Panos, E. The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. *Clim. Change* **144**, 181–193 (2017).
44. Buck, H. J., Furhman, J., Morrow, D. R., Sanchez, D. L. & Wang, F. M. Adaptation and Carbon Removal. *One Earth* **3**, 425–435 (2020).
45. Von Stechow, C. *et al.* 2°C and SDGs: United they stand, divided they fall? *Environ. Res. Lett.* **11**, (2016).

46. Iyer, G. *et al.* Implications of sustainable development considerations for comparability across nationally determined contributions. *Nat. Clim. Chang.* **8**, 124–129 (2018).
47. Bednar, J., Obersteiner, M. & Wagner, F. On the financial viability of negative emissions. *Nat. Commun.* **10**, 1783 (2019).
48. Rogelj, J. *et al.* A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357–363 (2019).
49. Morrow, D. R. & Thompson, M. S. *Reduce, Remove, Recycle: Clarifying the Overlap between Carbon Removal and CCUS*. (2020).
50. NRC. *Climate Intervention. Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* (2015). doi:10.17226/18805.
51. NRC. *Climate Intervention: Reflecting Sunlight to Cool Earth*. (2015).
52. Luderer, G. *et al.* Residual fossil CO2 emissions in 1.5–2 °C pathways. *Nat. Clim. Chang.* **8**, 626–633 (2018).
53. Honegger, M. & Reiner, D. The political economy of negative emissions technologies: consequences for international policy design. *Clim. Policy* **18**, 306–321 (2018).
54. UNEP. Emissions Gap Report 2019. (2019).
55. UNFCCC. *Paris Agreement. Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015* vol. 26 (2015).
56. The Rt Hon Chris Skidmore MP. UK becomes first major economy to pass net zero emissions law - GOV.UK. *Department for Business, Energy & Industrial Strategy* https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law (2019).
57. Statement attributable to the Spokesperson for the Secretary-General – on Japanese Prime Minister Suga's net-zero announcement | United Nations Secretary-General. https://www.un.org/sg/en/content/sg/statement/2020-10-26/statement-attributable-the-spokesperson-for-the-secretary-general-–-japanese-prime-minister-suga's-net-zero-announcement.
58. Statement by H.E. Xi Jinping President of the People's Republic of China At the General Debate of the 75th Session of The United Nations General Assembly. https://www.fmprc.gov.cn/mfa_eng/zxxx_662805/t1817098.shtml.
59. Haley, N. R. *C.N.464.2017.TREATIES-XXVII.7.d (Depositary Notification)*. (2017).
60. Blinken, A. J. The United States Officially Rejoins the Paris Agreement - United States Department of State. https://www.state.gov/the-united-states-officially-rejoins-the-paris-agreement/ (2021).
61. Miller, S. Executive Order Establishing the One Trillion Trees Interagency Council. *Fed. Regist.* (2020).
62. Reister, D. B. & Edmonds, J. . *A general equilibrium two-sector energy demand model. Modeling Energy-Economy Interac-tions: Five Approaches*. (1977).
63. O'Neill, B. C. *et al.* The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.* **42**, 169–180 (2017).
64. Gasser, T., Guivarch, C., Tachiiri, K., Jones, C. D. & Ciais, P. Negative emissions physically needed to keep global warming below 2 °C. *Nat. Commun.* **6**, 7958 (2015).
65. van Vuuren, D. P. *et al.* The role of negative CO2 emissions for reaching 2 °C—insights from integrated assessment modelling. *Clim. Change* **118**, 15–27 (2013).
66. Huppmann, D. *et al.* IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. (2018) doi:10.22022/SR15/08-2018.15429.
67. IIASA. *SSP Model Description*. (2015).

68. Van Vuuren, D. P. *et al.* A comprehensive view on climate change: Coupling of earth system and integrated assessment models. *Environ. Res. Lett.* **7**, (2012).
69. Snyder, A., Calvin, K., Phillips, M. & Ruane, A. *A crop yield change emulator for use in GCAM and similar models: Persephone v1.0. Geoscientific Model Development* vol. 12 (2019).
70. Schinko, T. *et al.* Economy-wide effects of coastal flooding due to sea level rise: a multi-model simultaneous treatment of mitigation, adaptation, and residual impacts. *Environ. Res. Commun.* **2**, 015002 (2020).
71. Daniel, K. D., Litterman, R. B. & Wagner, G. Declining CO2 price paths. *Proc. Natl. Acad. Sci.* **116**, (2019).
72. Wilson, C. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy* **50**, 81–94 (2012).
73. van Sluisveld, M. A. E. *et al.* Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change. *Glob. Environ. Chang.* **35**, 436–449 (2015).
74. Wilson, C., Grubler, A., Bauer, N., Krey, V. & Riahi, K. Future capacity growth of energy technologies: Are scenarios consistent with historical evidence? *Clim. Change* **118**, 381–395 (2013).
75. Di Vittorio, A. V. *et al.* From land use to land cover: restoring the afforestation signal in a coupled integrated assessment–earth system model and the implications for CMIP5 RCP simulations. *Biogeosciences* **11**, 6435–6450 (2014).
76. He, S. & Mo, Z. Reforestation Projects at Pearl River Basin of Guangxi in China. in *Forest Carbon Practices and Low Carbon Development in China* 91–127 (Springer Singapore, 2019). doi:10.1007/978-981-13-7364-0_4.
77. California Department of Forestry and Fire Protection, California Natural Resources Agency & California Environmental Protection Agency. *California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate.* http://resources.ca.gov/wp-content/uploads/2018/05/California-Forest-Carbon-Plan-Final-Draft-for-Public-Release-May-2018.pdf (2018).
78. Vaughan, N. E. & Gough, C. Expert assessment concludes negative emissions scenarios may not deliver. *Environ. Res. Lett.* **11**, 095003 (2016).
79. Haszeldine, R. S., Flude, S., Johnson, G. & Scott, V. Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **376**, 20160447 (2018).
80. Matter, J. M. *et al.* Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science (80-.).* **352**, 1312–1314 (2016).
81. Gattuso, J.-P. *et al.* Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. *Front. Mar. Sci.* **5**, 337 (2018).
82. Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).
83. United Nations Environment Programme. Emissions Gap Report 2018. (2018).
84. Climate Action Tracker. *Warming Projections Global Update.* https://climateactiontracker.org/documents/644/CAT_2019-09-19_BriefingUNSG_WarmingProjectionsGlobalUpdate_Sept2019.pdf (2019).
85. Tollefson, J. Can the world kick its fossil-fuel addiction fast enough? *Nature* **556**, 422–425 (2018).
86. Clarke, L. *et al. Assessing Transformation Pathways Coordinating Lead Authors: Chapter Science Assistant. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter6.pdf (2014).
87. Rogelj, J. *et al.* Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. *Glob. Warm. 1.5°C. An IPCC Spec. Rep. impacts Glob. Warm. 1.5°C above pre-industrial levels Relat. Glob. Greenh. gas Emiss. pathways, Context Strength. Glob. response to Threat Clim. Chang.* (2018).
88. Minx, J. C. *et al.* Negative emissions—Part 1: Research landscape and synthesis. *Environ. Res. Lett.* **13**, 063001 (2018).
89. Fuss, S. *et al.* Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).
90. Nemet, G. F. *et al.* Negative emissions - Part 3: Innovation and upscaling. *Environmental Research Letters* vol. 13 063003 (2018).
91. Kato, E. & Yamagata, Y. BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions. *Earth's Futur.* **2**, 421–439 (2014).
92. van Vuuren, D. P. *et al.* Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim. Chang.* **8**, 391–397 (2018).
93. Sanderman, J., Hengl, T. & Fiske, G. J. Soil carbon debt of 12,000 years of human land use. *Proc. Natl. Acad. Sci.* **114**, 9575–9580 (2017).
94. Creutzig, F. *et al.* The mutual dependence of negative emission technologies and energy systems. *Energy Environ. Sci.* (2019) doi:10.1039/C8EE03682A.
95. Rau, G. H. The race to remove CO2 needs more contestants. *Nat. Clim. Chang.* (2018) doi:10.1038/s41558-019-0445-5.
96. Realmonte, G. *et al.* An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun.* **10**, 3277 (2019).
97. Chen, C. & Tavoni, M. Direct air capture of CO2 and climate stabilization: A model based assessment. *Clim. Change* **118**, 59–72 (2013).
98. Marcucci, A., Kypreos, S. & Panos, E. The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. *Clim. Change* **144**, 181–193 (2017).
99. Strefler, J. *et al.* Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett.* **13**, (2018).
100. Rogelj, J. *et al.* Mitigation pathways compatible with 1.5 C in the context of sustainable development. (2018).
101. Keller, D. P. *et al.* The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): Rationale and experimental protocol for CMIP6. *Geosci. Model Dev.* (2018) doi:10.5194/gmd-11-1133-2018.
102. Bastin, J.-F. *et al.* The global tree restoration potential. *Science (80-.).* **365**, 76 LP – 79 (2019).
103. Abotalib, M., Zhao, F. & Clarens, A. Deployment of a Geographical Information System Life Cycle Assessment Integrated Framework for Exploring the Opportunities and Challenges of Enhanced Oil Recovery Using Industrial CO<inf>2</inf> Supply in the United States. *ACS Sustain. Chem. Eng.* **4**, (2016).
104. Middleton, R. S., Clarens, A. F., Liu, X., Bielicki, J. M. & Levine, J. S. CO_2 Deserts: Implications of Existing CO_2 Supply Limitations for Carbon Management. *Environ. Sci. {&} Technol.* **48**, 11713–11720 (2014).
105. Huijgen, W. J. J., Witkamp, G. J. & Comans, R. N. J. Mineral CO2 sequestration by steel slag carbonation. *Environ. Sci. Technol.* **39**, 9676–9682 (2005).
106. Strefler, J., Amann, T., Bauer, N., Kriegler, E. & Hartmann, J. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* **13**, (2018).
107. Beerling, D. J. *et al.* Farming with crops and rocks to address global climate, food and soil

security. *Nat. Plants* **4**, (2018).
108. Taylor, L. L. *et al.* Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nat. Clim. Chang.* **6**, 402–406 (2016).
109. Kohler, P., Hartmann, J. & Wolf-Gladrow, D. A. Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proc. Natl. Acad. Sci.* **107**, 20228–20233 (2010).
110. Griscom, B. W. *et al.* Natural climate solutions. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 11645–11650 (2017).
111. Boyd, P. *et al.* High level review of a wide range of proposed marine geoengineering techniques. (2019).
112. Macreadie, P. I. *et al.* Can we manage coastal ecosystems to sequester more blue carbon? *Front. Ecol. Environ.* (2017) doi:10.1002/fee.1484.
113. McLeod, E. *et al.* A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Frontiers in Ecology and the Environment* (2011) doi:10.1890/110004.
114. Macreadie, P. I. *et al.* Can we manage coastal ecosystems to sequester more blue carbon? *Front. Ecol. Environ.* **15**, 206–213 (2017).
115. Calvin, K. *et al.* GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model Dev.* **12**, 677–698 (2019).
116. Rogelj, J. *et al.* A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357–363 (2019).
117. Lemoine, D. & Traeger, C. P. Economics of tipping the climate dominoes. *Nat. Clim. Chang.* (2016) doi:10.1038/nclimate2902.
118. Tavoni, M. & Socolow, R. Modeling meets science and technology: an introduction to a special issue on negative emissions. *Clim. Change* **118**, 1–14 (2013).
119. Steffen, W. *et al.* Trajectories of the Earth System in the Anthropocene. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 8252–8259 (2018).
120. Zickfeld, K., MacDougall, A. H. & Matthews, H. D. On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions. *Environ. Res. Lett.* **11**, 055006 (2016).
121. Gambhir, A. *et al.* A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS. *Energies* **12**, 1747 (2019).
122. Schleussner, C.-F. *et al.* Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Chang.* **6**, 827–835 (2016).
123. Obersteiner, M. *et al.* How to spend a dwindling greenhouse gas budget. *Nat. Clim. Chang.* **8**, 7–10 (2018).
124. BP. *BP Statistical Review of World Energy.* https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf (2019).
125. Le Quéré, C. *et al.* Global Carbon Budget 2018. *Earth Syst. Sci. Data* **10**, 2141–2194 (2018).
126. Sen, I. S. & Peucker-Ehrenbrink, B. Anthropogenic Disturbance of Element Cycles at the Earth's Surface. *Environ. Sci. Technol.* **46**, 8601–8609 (2012).
127. Coady, D., Parry, I., Le, N. P. & Shang, B. Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates. *IMF Working Paper* https://www.imf.org/en/Publications/WP/Issues/2019/05/02/Global-Fossil-Fuel-Subsidies-Remain-Large-An-Update-Based-on-Country-Level-Estimates-46509 (2019).
128. Acemoglu, D., Aghion, P., Bursztyn, L. & Hemous, D. The Environment and Directed Technical Change. **V**, 1–23 (2011).
129. Acemoglu, D., Akcigit, U., Hanley, D. & Kerr, W. R. Transition to Clean Technology. *J. Polit.*

Econ. **124**, (2014).
130. Wilson, C. *et al.* Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Clim. Change* **118**, 381–395 (2013).
131. Rogelj, J. *et al.* Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Chang.* **8**, 325–332 (2018).
132. Luderer, G. *et al.* Residual fossil CO2 emissions in 1.5–2 °C pathways. *Nat. Clim. Chang.* **8**, 626–633 (2018).
133. McCollum, D. L. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nat. Energy* **3**, 589–599 (2018).
134. Moreira, J. R., Romeiro, V., Fuss, S., Kraxner, F. & Pacca, S. A. BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues. *Appl. Energy* (2016) doi:10.1016/j.apenergy.2016.06.044.
135. Iyer, G. *et al.* Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technol. Forecast. Soc. Change* **90**, 103–118 (2015).
136. Wilson, C. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy* **50**, 81–94 (2012).
137. Broehm, M., Strefler, J. & Bauer, N. Techno-Economic Review of Direct Air Capture Systems for Large Scale Mitigation of Atmospheric CO2. *SSRN Electron. J.* (2015) doi:10.2139/ssrn.2665702.
138. von Stechow, C. *et al.* 2 °C and SDGs: united they stand, divided they fall? *Environ. Res. Lett.* **11**, 034022 (2016).
139. Iyer, G. *et al.* Implications of sustainable development considerations for comparability across nationally determined contributions. *Nat. Clim. Chang.* **8**, 124–129 (2018).
140. Canadell, J. G. & Schulze, E. D. Global potential of biospheric carbon management for climate mitigation. *Nat. Commun.* **5**, 5282 (2014).
141. Calvin, K. *et al.* GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model Dev* **12**, 677–698 (2019).
142. Hurtt, G., Chini, L., Sahajpal, R., Frolking, S. & et al. Harmonization of global land-use change and management for the period 850-2100. *Geosci. Model Dev. (In prep)* (2018).
143. Teluguntla, P. *et al.* Global Cropland Area Database (GCAD) derived from Remote Sensing in Support of Food Security in the Twenty-first Century: Current Achievements and Future Possibilities. in *Chapter 7, Vol. II. Land Resources: Monitoring, Modelling, and Mapping, Remote Sensing Handbook edited by Prasad S. Thenkabail.* (2014).
144. Thenkabail, P. S. *et al.* Assessing future risks to agricultural productivity, water resources and food security: how can remote sensing help? *Photogramm. Eng. Remote Sensing* **78**, 773–782 (2012).
145. Wise, M. *et al.* Implications of limiting CO2 concentrations for land use and energy. *Science (80-.).* **324**, 1183–6 (2009).
146. Tokarska, K. B. & Gillett, N. P. Cumulative carbon emissions budgets consistent with 1.5 °C global warming. *Nat. Clim. Chang.* **8**, 296–299 (2018).
147. Fawcett, A. A. *et al.* Can Paris pledges avert severe climate change? *Science (80-.).* **350**, 1168–1169 (2015).
148. Le Quéré, C. *et al.* Global Carbon Budget 2018. *Earth Syst. Sci. Data* **10**, 2141–2194 (2018).
149. NRC. Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. *Natl. Acad. Press* (2015) doi:10.17226/18988.
150. Roe, S. *et al.* Contribution of the land sector to a 1.5 °C world. *Nature Climate Change* vol. 9 817–828 (2019).
151. Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W. & Clarens, A. F. From Zero to Hero?: Why

Integrated Assessment Modeling of Negative Emissions Technologies Is Hard and How We Can Do Better. *Front. Clim.* **1**, (2019).
152. Wise, M. *et al.* Implications of limiting CO2 concentrations for land use and energy. *Science (80- .).* (2009) doi:10.1126/science.1168475.
153. Calvin, K. *et al.* Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Clim. Change* **123**, 691–704 (2014).
154. Fuss, S. *et al.* Betting on negative emissions. *Nat. Clim. Chang.* (2014) doi:10.1038/nclimate2392.
155. Carbon Engineering - Pioneering Direct Air Capture of CO2. https://carbonengineering.com/our-technology/ (2021).
156. Global Thermostat. https://globalthermostat.com/.
157. Keith, D. W., Ha-Duong, M. & Stolaroff, J. K. Climate strategy with CO2 capture from the air. *Clim. Change* **74**, 17–45 (2006).
158. Haddeland, I. *et al.* Global water resources affected by human interventions and climate change. *Proc. Natl. Acad. Sci.* **111**, 3251–3256 (2013).
159. Fricko, O. *et al.* Energy sector water use implications of a 2 °C climate policy. *Environ. Res. Lett* **11**, (2016).
160. Peters, G. P. *et al.* Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. *Nature Climate Change* vol. 10 3–6 (2020).
161. US Department of Commerce, NOAA, E. S. R. L. ESRL Global Monitoring Division - Global Greenhouse Gas Reference Network. *NOAA Res.* (2019).
162. Environment European Agency. Global average near surface temperatures relative to the pre-industrial period. https://www.eea.europa.eu/data-and-maps/daviz/global-average-air-temperature-anomalies-5#tab-dashboard-02 (2019).
163. Wise, M. *et al.* Implications of limiting CO2 concentrations for land use and energy. *Science* **324**, 1183–6 (2009).
164. Calvin, K. *et al.* The SSP4: A world of deepening inequality. *Glob. Environ. Chang.* **42**, 284–296 (2017).
165. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).
166. Popp, A. *et al.* Land-use futures in the shared socio-economic pathways. *Glob. Environ. Chang.* **42**, 331–345 (2017).
167. Zeman, F. Energy and Material Balance of CO2 Capture from Ambient Air. (2007) doi:10.1021/ES070874M.
168. Stolaroff, J. K., Keith, D. W. & Lowry, G. V. Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray. *Environ. Sci. Technol.* **42**, 2728–2735 (2008).
169. Fasihi, M., Efimova, O. & Breyer, C. Techno-economic assessment of CO 2 direct air capture plants. *J. Clean. Prod.* **224**, 957–980 (2019).
170. Committee on Climate Change. Net Zero Technical Report. 282 Figure 10.2 (2019).
171. Mazzotti, M., Baciocchi, R., Desmond, M. J. & Socolow, R. H. Direct air capture of CO2 with chemicals: Optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor. *Clim. Change* **118**, 119–135 (2013).
172. Institute, J. G. C. R. GCAM v5.2 Documentation: Table of Contents. *2019* https://jgcri.github.io/gcam-doc/toc.html.
173. USGS. New Map of Worldwide Croplands Supports Food and Water Security. *Global Food Security-Support Analysis Data at 30 m* https://www.usgs.gov/news/new-map-worldwide-croplands-supports-food-and-water-security (2017).
174. Hoff, H. *et al.* Greening the global water system. *J. Hydrol.* **384**, 177–186 (2010).
175. Fajardy, M. & Mac Dowell, N. Can BECCS deliver sustainable and resource efficient negative

emissions? *Energy Environ. Sci.* **10**, 1389–1426 (2017).
176. Ng, T. L., Eheart, J. W., Cai, X. & Miguez, F. Modeling miscanthus in the Soil and Water Assessment Tool (SWAT) to simulate its water quality effects as a bioenergy crop. *Environ. Sci. Technol.* **44**, 7138–7144 (2010).
177. Canadell, J. G. & Schulze, E. D. Global potential of biospheric carbon management for climate mitigation. *Nat. Commun.* **5**, (2014).
178. Arnell, N. W., Lowe, J. A., Challinor, A. J. & Osborn, T. J. Global and regional impacts of climate change at different levels of global temperature increase 1 Introduction and context. *Clim. Change* **155**, 377–391 (2019).
179. Calvin, K. *et al.* Global Market and Economic Welfare Implications of Changes in Agricultural Yields Due to Climate Change. *Clim. Chang. Econ.* **11**, (2020).
180. Nelson, G. C. *et al.* Climate change effects on agriculture: Economic responses to biophysical shocks. *Proc. Natl. Acad. Sci. U. S. A.* **111**, 3274–3279 (2014).
181. McLaren, D. & Markusson, N. The co-evolution of technological promises, modelling, policies and climate change targets. *Nat. Clim. Chang.* **10**, 392–397 (2020).
182. Alvarez, R. A. *et al.* Assessment of methane emissions from the U.S. oil and gas supply chain. *Science (80-.).* **361**, 186–188 (2018).
183. Chu, E., Anguelovski, I. & Carmin, J. A. Inclusive approaches to urban climate adaptation planning and implementation in the Global South. *Clim. Policy* **16**, 372–392 (2016).
184. Füssel, H. M. How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: A comprehensive indicator-based assessment. *Glob. Environ. Chang.* **20**, 597–611 (2010).
185. Fuhrman, J. *et al.* Food-Energy-Water Implications of Negative Emissions Technologies in a +1.5°C Future. *Nature Climate Change* In Press https://github.com/jayfuhrman/No-Safety-NET-DAC-Modeling (2020).
186. NDRC. Enhanced actions on climate change: China's intended nationally determined contributions. (2015).
187. Chen, W., Yin, X. & Zhang, H. Towards low carbon development in China: a comparison of national and global models. *Clim. Change* **136**, 95–108 (2016).
188. Zhou, N. *et al.* China's energy and emissions outlook to 2050: Perspectives from bottom-up energy end-use model. *Energy Policy* **53**, 51–62 (2013).
189. Chai, Q.-M. & Xu, H.-Q. Modeling an emissions peak in China around 2030: Synergies or trade-offs between economy, energy and climate security. *Adv. Clim. Chang. Res.* **5**, 169–180 (2014).
190. Qi, Y. *Annual Review of Low-Carbon Development in China: 2010*. (WORLD SCIENTIFIC, 2013). doi:10.1142/8301.
191. Zhou, S. *et al.* Energy use and CO2 emissions of China's industrial sector from a global perspective. *Energy Policy* **58**, 284–294 (2013).
192. Pan, X. *et al.* Implications of near-term mitigation on China's long-term energy transitions for aligning with the Paris goals. *Energy Econ.* **90**, 104865 (2020).
193. Fuhrman, J. *et al.* Food–energy–water implications of negative emissions technologies in a +1.5 °C future. *Nat. Clim. Chang.* **10**, 920–927 (2020).
194. Climate Action Tracker. Countries with submitted or proposed NDC updates. (2020).
195. UK net zero target | The Institute for Government. https://www.instituteforgovernment.org.uk/explainers/net-zero-target (2020).
196. Peters, G. P., Davis, S. J. & Andrew, R. A synthesis of carbon in international trade. *Biogeosciences* **9**, 3247–3276 (2012).
197. Meng, J. *et al.* The rise of South-South trade and its effect on global CO2 emissions. *Nat.*

Commun. **9**, 1–7 (2018).
198. Mi, Z., Meng, J., Green, F., Coffman, D. M. & Guan, D. China's "Exported Carbon" Peak: Patterns, Drivers, and Implications. *Geophys. Res. Lett.* **45**, 4309–4318 (2018).
199. Liu, Z. *et al.* Embodied carbon emissions in China-US trade. *Sci. China Earth Sci.* **63**, 1577–1586 (2020).
200. Zhang, Z. *et al.* Embodied carbon emissions in the supply chains of multinational enterprises. *Nat. Clim. Chang.* **10**, (2020).
201. CDIAC. Carbon Dioxide Information Analysis Center. (2017).
202. IEA. Global CO2 emissions in 2019 – Analysis. (2020).
203. Wang, H. *et al.* Modeling of power sector decarbonization in China: comparisons of early and delayed mitigation towards 2-degree target. *Clim. Change* (2019) doi:10.1007/s10584-019-02485-8.
204. Stanway, D. China's new coal power plant capacity in 2020 more than three times rest of world's: study | Reuters. https://www.reuters.com/article/us-china-coal/chinas-new-coal-power-plant-capacity-in-2020-more-than-three-times-rest-of-worlds-study-idUSKBN2A308U (2021).
205. Myllyvirta, L., Zhang, S. & Shen, X. Analysis: Will China build hundreds of new coal plants in the 2020s? *Carbon Brief* https://www.carbonbrief.org/analysis-will-china-build-hundreds-of-new-coal-plants-in-the-2020s (2020).
206. Monitor, G. E. & Air, C. for R. on E. and C. *China Dominates 2020 Coal Plant Development*. (2021).
207. Wang, H. & Chen, W. Modelling deep decarbonization of industrial energy consumption under 2-degree target: Comparing China, India and Western Europe. *Appl. Energy* **238**, 1563–1572 (2019).
208. Yin, X. *et al.* China's transportation energy consumption and CO2 emissions from a global perspective. *Energy Policy* **82**, 233–248 (2015).
209. Zhang, H., Chen, W. & Huang, W. TIMES modelling of transport sector in China and USA: Comparisons from a decarbonization perspective. *Appl. Energy* **162**, 1505–1514 (2016).
210. Pietzcker, R. C. *et al.* Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy* **64**, 95–108 (2014).
211. Yu, S. *et al. Five strategies to achieve china's 2060 carbon neutrality goal*. (2020).
212. Zheng, X. *et al.* Drivers of change in China's energy-related CO2 emissions. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 29–36 (2020).
213. Fuss, S. *et al.* Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).
214. Cao, S. Why large-scale afforestation efforts have failed to solve the desertification problem. *Environ. Sci. Technol.* 1826–1831 (2008).
215. Cao, S. *et al.* Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration. *Earth-Science Reviews* vol. 104 240–245 (2011).
216. Jia, X., Shao, M., Zhu, Y. & Luo, Y. Soil moisture decline due to afforestation across the Loess Plateau, China. *J. Hydrol.* **546**, 113–122 (2017).
217. Wang, J. *et al.* Large Chinese land carbon sink estimated from atmospheric carbon dioxide data. *Nature* **586**, 720–723 (2020).
218. Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W. & Clarens, A. F. From Zero to Hero?: Why Integrated Assessment Modeling of Negative Emissions Technologies Is Hard and How We Can Do Better. *Front. Clim.* **1**, 11 (2019).
219. Zastrow, M. China's tree-planting drive could falter in a warming world. *Nature* vol. 573 474–475 (2019).
220. Muratori, M., Calvin, K., Wise, M., Kyle, P. & Edmonds, J. Global economic consequences of

deploying bioenergy with carbon capture and storage (BECCS). *Environ. Res. Lett.* **11**, (2016).
221. US Department of Commerce, N. G. M. L. Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases.
222. United Airlines invests in carbon-capture project to be 100% green by 2050 | Reuters. https://www.reuters.com/article/united-arlns-climate-occidental/united-airlines-invests-in-carbon-capture-project-to-be-100-green-by-2050-idUSKBN28K1NE.
223. Yu, S. *et al.* CCUS in China's mitigation strategy: insights from integrated assessment modeling. *Int. J. Greenh. Gas Control* **84**, 204–218 (2019).
224. Rogelj, J. *et al.* Mitigation pathways compatible with 1.5°C in the context of sustainable development. *Spec. Report, Intergov. Panel Clim. Chang.* (2018).
225. IPCC. *IPCC Special Report on 1.5 C, Chapter 2.* http://report.ipcc.ch/sr15/pdf/sr15_chapter2.pdf (2018).
226. Realmonte, G. *et al.* An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun.* **10**, 3277 (2019).
227. JGCRI. GCAM v5.3 documentation: Global Change Analysis Model (GCAM). (2020).
228. Kaufman, N., Barron, A. R., Krawczyk, W., Marsters, P. & McJeon, H. A near-term to net zero alternative to the social cost of carbon for setting carbon prices. *Nat. Clim. Chang.* (2020) doi:10.1038/s41558-020-0880-3.
229. Daniel, K. D., Litterman, R. B. & Wagner, G. Declining CO 2 price paths . *Proc. Natl. Acad. Sci.* 201817444 (2019) doi:10.1073/pnas.1817444116.
230. Keith, D. W., Holmes, G., St. Angelo, D. & Heidel, K. A process for capturing CO2 from the atmosphere. *Joule* **2**, 1573–1594 (2018).
231. Zeman, F. Energy and material balance of CO2 capture from ambient air. *Environ. Sci. Technol.* **41**, 7558–7563 (2007).
232. Stolaroff, J. K., Keith, D. W. & Lowry, G. V. Carbon dioxide capture from atmospheric air using sodium hydroxide spray. *Environ. Sci. Technol.* **42**, 2728–2735 (2008).
233. Fasihi, M., Efimova, O. & Breyer, C. Techno-economic assessment of CO2 direct air capture plants. *J. Clean. Prod.* **224**, 957–980 (2019).
234. Smith, P. *et al.* Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Chang.* **6**, 42–50 (2016).
235. Businessweek, B. Occidental to Strip Carbon From the Air and Use It to Pump Crude. 1–4 (2021).
236. Bipartisan Policy Center. Investing in Climate Innovation: The Environmental Case for Direct Air Capture of Carbon Dioxide. 18 (2020).
237. Stripe's first negative emissions purchases. https://stripe.com/blog/first-negative-emissions-purchases.
238. Fighting for the Future: Shopify Invests $5M in Breakthrough Sustainability Technologies. https://news.shopify.com/fighting-for-the-future-shopify-invests-5m-in-breakthrough-sustainability-technologies.
239. Hanna, R., Abdulla, A., Xu, Y. & Victor, D. G. Emergency deployment of direct air capture as a response to the climate crisis. *Nat. Commun.* 1–41 doi:10.1038/s41467-020-20437-0.
240. O'Neill, B. C. *et al.* A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Clim. Change* **122**, 387–400 (2014).
241. van Vuuren, D. P. *et al.* Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Glob. Environ. Chang.* (2017) doi:10.1016/j.gloenvcha.2016.05.008.
242. Kriegler, E. *et al.* Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Glob. Environ. Chang.* **42**, 297–315 (2017).
243. Smith, P. *et al.* The marker quantification of the Shared Socioeconomic Pathway 2: A middle-

of-the-road scenario for the 21st century. *Glob. Environ. Chang.* **42**, 251–267 (2017).
244. Fujimori, S. *et al.* SSP3: AIM implementation of Shared Socioeconomic Pathways. *Glob. Environ. Chang.* **42**, 268–283 (2017).
245. van Vuuren, D. P. *et al.* A new scenario framework for Climate Change Research: Scenario matrix architecture. *Clim. Change* **122**, 373–386 (2014).
246. Kriegler, E. *et al.* A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Clim. Change* **122**, 401–414 (2014).
247. van Vuuren, D. P. *et al.* The representative concentration pathways: An overview. *Clim. Change* **109**, 5–31 (2011).
248. Calvin, K. *et al.* 2.6: Limiting climate change to 450 ppm CO2 equivalent in the 21st century. *Energy Econ.* **31**, S107–S120 (2009).
249. Nordhaus, W. D. An Optimal Transition Path for Controlling Greenhouse Gases. *Science (80-.).* **258**, 1315–1319 (1992).
250. Nordhaus, W. How fast should we graze the global commons. *Am. Econ. Rev.* **72**, 242–246 (1982).
251. Deutz, S. & Bardow, A. Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nat. Energy* 1–11 (2021) doi:10.1038/s41560-020-00771-9.
252. Keith, D. W., Holmes, G., St. Angelo, D. & Heidel, K. A Process for Capturing CO2 from the Atmosphere. *Joule* (2018) doi:10.1016/j.joule.2018.05.006.
253. Breyer, C., Fasihi, M. & Aghahosseini, A. Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitig. Adapt. Strateg. Glob. Chang.* **25**, 43–65 (2020).
254. Riahi, K. *et al. Integrated Assessment Modeling of Shared Socio Economic Pathways-Study protocol for IAM runs*. (2015).
255. Friedlingstein, P. *et al.* Global carbon budget 2019. *Earth Syst. Sci. Data* **11**, 1783–1838 (2019).
256. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).
257. Bauer, N. *et al.* Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Glob. Environ. Chang.* **42**, 316–330 (2017).
258. Fujimori, S. *et al.* SSP3: AIM implementation of Shared Socioeconomic Pathways. *Glob. Environ. Chang.* **42**, 268–283 (2017).
259. Kriegler, E. *et al.* Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Glob. Environ. Chang.* **42**, 297–315 (2017).
260. EIA. U.S. Natural Gas Gross Withdrawals and Production. https://www.eia.gov/dnav/ng/ng_prod_sum_dc_NUS_mmcf_a.htm (2021).
261. Page, B. *et al. Global Status of CCS 2020. Global CCS Institute* (2020).
262. Vickers, A. *Handbook of Water Use and Conservation.* (WaterPlow Press, 2001).
263. Smith, P. *et al.* Impacts of Land-Based Greenhouse Gas Removal Options on Ecosystem Services and the United Nations Sustainable Development Goals. *Annu. Rev. Environ. Resour.* **44**, 1–32 (2019).
264. Nagelkerken, I. *et al.* The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquat. Bot.* **89**, 155–185 (2008).
265. Canadell, J. G. & Schulze, E. D. Global potential of biospheric carbon management for climate mitigation. *Nat. Commun.* **5**, 5282 (2014).
266. Furukawa, K., Wolanski, E. & Mueller, H. Currents and Sediment Transport in Mangrove Forests. *Estuar. Coast. Shelf Sci.* **44**, 301–310 (1997).
267. Gacia, E. & Duarte, C. M. Sediment Retention by a Mediterranean Posidonia oceanica

Meadow: The Balance between Deposition and Resuspension. *Estuar. Coast. Shelf Sci.* **52**, 505–514 (2001).
268. Barbier, E. B. *et al.* The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* **81**, 169–193 (2011).
269. Jobbágy, E. G. & Jackson, R. B. Groundwater use and salinization with grassland afforestration. *Glob. Chang. Biol.* **10**, 1299–1312 (2004).
270. Ornstein, L., Aleinov, I. & Rind, D. Irrigated afforestation of the Sahara and Australian Outback to end global warming. *Clim. Change* **97**, 409–437 (2009).
271. Mac Dowell, N. & Fajardy, M. Inefficient power generation as an optimal route to negative emissions via BECCS? *Environ. Res. Lett.* (2017) doi:10.1088/1748-9326/aa67a5.
272. Yang, S. L., Shi, B. W., Bouma, T. J., Ysebaert, T. & Luo, X. X. Wave Attenuation at a Salt Marsh Margin: A Case Study of an Exposed Coast on the Yangtze Estuary. *Estuaries and Coasts* **35**, 169–182 (2012).
273. Mendez, F. J. & Losada, I. J. An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. *Coast. Eng.* **51**, 103–118 (2004).
274. Howarth, R. W., Santoro, R. & Ingraffea, A. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change* vol. 106 679–690 (2011).
275. Griscom, B. W. *et al.* Natural climate solutions. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 11645–11650 (2017).
276. Resiliency, M. O. of R. and, Corporation, N. E. D. & Recovery, G. office of storm. *Lower Manhattan Climate Resiliance Study*. (2019).
277. Kantola, I. B., Masters, M. D., Beerling, D. J., Long, S. P. & DeLucia, E. H. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biology Letters* vol. 13 20160714 (2017).
278. Veldman, J. W. *et al.* Comment on "The global tree restoration potential". *Science* vol. 366 (2019).
279. Doelman, J. C. *et al.* Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Glob. Chang. Biol.* gcb.14887 (2019) doi:10.1111/gcb.14887.
280. Dooley, J. J., Kim, S. H., Edmonds, J. A., Friedman, S. J. & Wise, M. A. A first-order global geological CO2-storage potential supply curve and its application in a global integrated assessment model. *Greenh. Gas Control Technol.* 573–581 (2005) doi:10.1016/B978-008044704-9/50058-6.
281. Dooley, J. J. & Friedman, S. J. *A Global but Regionally Disaggregated Accounting of CO2 Storage Capacity: Data and Assumptions for Compiling Regional CO2 Storage Capacity Supply Curves for Incorporation within ObjECTS->MiniCAM.* http://www.osti.gov/energycitations/servlets/purl/15020437-1NPuqv/%5Cn10.2172/15020437 (2005).
282. Dahowski, R. T., Davidson, C. L. & Dooley, J. J. Comparing large scale CCS deployment potential in the USA and China: A detailed analysis based on country-specific CO2 transport & storage cost curves. *Energy Procedia* **4**, 2732–2739 (2011).
283. Decarre, S., Berthiaud, J., Butin, N. & Guillaume-Combecave, J. L. CO2 maritime transportation. *Int. J. Greenh. Gas Control* **4**, 857–864 (2010).
284. U.S Bureau of Economic Analysis. Gross Domestic Product: Implicit Price Deflator (GDPDEF) | FRED | St. Louis Fed. https://fred.stlouisfed.org/series/GDPDEF.
285. Mekonnen, M. M. & Hoekstra, A. Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **15**, 1577–1600 (2011).
286. Chaturvedi, V. *et al.* Climate mitigation policy implications for global irrigation water demand. *Mitig. Adapt. Strateg. Glob. Chang.* **20**, 389–407 (2013).

287. Hejazi, M. I. *et al.* Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. *Hydrol. Earth Syst. Sci.* **18**, 2859–2883 (2014).
288. Kyle, P. *et al.* Influence of climate change mitigation technology on global demands of water for electricity generation. *Int. J. Greenh. Gas Control* **13**, 112–123 (2013).
289. Davies, E. G. R., Kyle, P. & Edmonds, J. A. An integrated assessment of global and regional water demands for electricity generation to 2095. *Adv. Water Resour.* **52**, 296–313 (2013).
290. Hartin, C. A., Patel, P., Schwarber, A., Link, R. P. & Bond-Lamberty, B. . A simple object-oriented and open-source model for scientific and policy analyses of the global climate system – Hector v1.0. *Geosci. Model Dev.* **8**, 939–955 (2015).
291. EPA. *Inventory of Greenhouse Gas Emissions and Sinks 1990–2009. EPA Publication 430-R-11–005* (2011).
292. Venkatesh, A., Jaramillo, P., Griffin, W. M. & Matthews, H. S. Uncertainty in life cycle greenhouse gas emissions from United States natural gas end-uses and its effects on policy. *Environ. Sci. Technol.* **45**, 8182–8189 (2011).
293. Miller, S. M. *et al.* Anthropogenic emissions of methane in the United States. *Proc. Natl. Acad. Sci. U. S. A.* **110**, 20018–20022 (2013).
294. Brandt, A. R. *et al.* Methane leaks from North American natural gas systems. *Science* vol. 343 733–735 (2014).
295. McJeon, H. *et al.* Limited impact on decadal-scale climate change from increased use of natural gas. *Nature* **514**, 482–485 (2014).
296. Institute, J. G. C. R. Releases · JGCRI/gcam-core · GitHub. *2019*.
297. DEA. Technology Data for Individual Heating Plants | Energistyrelsen. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-individual-heating-plants (2016).
298. DEA. Technology Data for Generation of Electricity and District Heating | Energistyrelsen. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and (2016).
299. Holmes, G. & Keith, D. W. An air-liquid contactor for large-scale capture of CO2 from air. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **370**, 4380–4403 (2012).
300. van der Made, A. *et al. Design Study Report ANTECY solar fuels development*. (2015).
301. Ping, E. & Sakwa-Novak, M. Eisenberger, P. Lowering the cost of direct air capture: pilot to commercial deployment. in *Presentation at International Conference on Negative CO2 Emissions, Gothenburg* (2018).
302. Kintisch, E. Can Sucking CO2 Out of the Atmosphere Really Work? | MIT Technology Review. *MIT Technology Review* https://www.technologyreview.com/2014/10/07/171023/can-sucking-co2-out-of-the-atmosphere-really-work/ (2014).
303. Simon, E. The Swiss company hoping to capture 1% of global CO2 emissions by 2025 | Carbon Brief. https://www.carbonbrief.org/swiss-company-hoping-capture-1-global-co2-emissions-2025 (2017).
304. Train, K. *Discrete Choice Methods with Simulation*. (2003).
305. McFadden, D. Conditional Logit Analysis of Qualitative Choice Behavior. *Front. Econom.* (1973).