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LETTER

The role of direct air capture and negative emissions technologies in the shared socioeconomic pathways towards +1.5 °C and +2 °C futures

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Abstract

The development of the shared socioeconomic pathways (SSPs) and associated integrated assessment modeling 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 higher energy demands. Several forms of DACCS are in development, with different costs and energy inputs, as well as potential for future cost and performance improvements. Here, we use the Global Change Analysis Model 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 up to a tens of $GtCO_2\ yr^{-1}$ 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 smaller deployments of DACCS and other negative emissions owing to immediate climate policy onset, greater ease of emissions abatement, and tighter constraints on future negative emissions.

1. 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 hold warming to well-below +2 °C above pre-industrial levels, and to pursue efforts to limit warming to +1.5 °C above pre-industrial levels—were heavily informed by an ensemble of IAM scenarios that featured deep (that is, tens of $GtCO_2$-scale) negative CO_2 emissions (IPCC 2014, Gasser *et al* 2015, IPCC 2018, Warszawski *et al* 2021). Ongoing lack of on-the-ground mitigation policies consistent with meeting the +1.5 °C or +2 °C goals in the ensuing several years has further deepened this reliance on globally net-negative emissions to meet them in the future (United Nations Environment Programme 2020, Australian Research Council 2021, Climate Action Tracker 2021). Depending on the remaining 1.5 °C consistent carbon budget, temporary overshoot of a 1.5 °C temperature goal may now be unavoidable even with rapid ramp-up of CO_2 removal by mid-century (Kriegler *et al* 2018). There are many potential negative emissions technologies (NETs) that could be used to deliberately remove CO_2 from the atmosphere (NRC 2015, 2018, Fuss *et al* 2018, Minx *et al* 2018, Nemet *et al* 2018). IAM scenarios to date have relied almost universally on bioenergy with carbon capture and storage (BECCS) and afforestation/reforestation for negative emissions, largely because the structures for modeling these pathways already existed (Fuhrman *et al* 2019). But these land-intensive strategies could have large impacts on global agricultural and natural biological systems if deployed at the scales envisaged (Wise *et al* 2009, Calvin *et al* 2014, Fuss *et al* 2014, Smith *et al* 2016). Direct air capture with carbon storage (DACCS) is an engineered process for separating and geologically storing atmospheric CO_2 that is receiving increasing attention from policymakers and major corporations (Business Wire 2019, Reuters 2019, Bipartisan Policy Center 2020, Microsoft 2020, Orbuch 2020, Rucinski 2020, Shopify 2020, Crowley and Rathi 2021). A small number of recent IAM studies—including our recent work (Fuhrman *et al* 2020)—have shown that DACCS could increase global capacity for negative emissions, reduce mitigation costs, and soften the sharpest tradeoffs of land-intensive negative emissions due to its much smaller physical footprint relative to bioenergy crop cultivation (Chen and Tavoni 2013, Marcucci *et al* 2017, Stler *et al* 2018, Realmonte *et al* 2019). But DACCS itself could require large amounts of energy and water, especially if it is mainly used to offset high levels of residual emissions (Fuhrman *et al* 2020). 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 (Realmonte *et al* 2019). Near-term incentives for DACCS deployment could reduce the risks of extreme-scale emergency deployments later in the century (Hanna *et al* 2021, McQueen *et al* 2021). Due to the emerging role of DACCS in the deep-negative emissions scenario ensemble, it is critical to more fully understand the factors that influence 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.

The shared socioeconomic pathway (SSP) framework defines five storylines that differ in the challenges for mitigation and adaptation, resulting in different levels of long-term warming in the absence of global climate policies (O'Neill *et al* 2014). 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 for internal consistency across integrated modeling scenarios and has been widely used across research communities over the past decade (O'Neill *et al* 2017, 2020). 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 (van Vuuren *et al* 2017). In contrast, SSP3 describes a scenario of 'regional rivalry' 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 (Fujimori *et al* 2017). 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 (Kriegler *et al* 2017). 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 (Fricko *et al* 2017). 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 (Calvin *et al* 2017). 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, +8.5 W m^{-2}) in 2100 (van Vuuren *et al* 2014). Finally, the shared climate policy assumptions 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 (Kriegler *et al* 2014). This SSP-RCP scenario matrix was featured in emissions trajectories that informed the Working Group I contribution the IPCC's Sixth Assessment Report (IPCC 2021).

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 °C target, but not fully eliminate it (van Vuuren *et al* 2018). But assessing the need for negative emissions as well as the relative contributions of different forms such as direct air capture and other forms of CO_2 removal 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 SSPs and 2 end-of-century radiative forcing targets (for a total of 10 main 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 might 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.

2. Methods

We used GCAM version 5.4, which is now available with the capability to model DACCS and features updated assumptions for renewables and transport electrification—both of which can reduce residual CO_2 emissions that drive some of the projected need for negative emissions (Fuhrman *et al* 2020, 2021, Iyer *et al* 2021). This latest version also features updated historical emissions inventories and updated marginal abatement cost curves for non-CO_2 greenhouse gas emissions (JGCRI 2021). GCAM is uniquely-suited for this analysis because it dynamically represents the energy, water, and land systems, competition for resources within and between these systems, and the resulting greenhouse gas emissions, in a computational environment coupled in code. This allows exploration of uncertainty of future socioeconomic conditions and technological developments, both of which are core to the SSP scenario exercises.

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} (below 1.5 °C in 2100) (Calvin *et al* 2009, van Vuuren *et al* 2011, Rogelj *et al* 2018). The radiative forcing anomaly from pre-industrial levels was 2.72 W m^{-2} as of 2019, and the decadal average surface temperature between 2011 and 2020 was 1.09 °C higher than it was between 1850 and 1900 (IPCC 2018, Environment European Agency 2019, Bellouin *et al* 2020, IPCC 2021, NOAA 2021). It is 'more likely than not' that the +1.5 °C temperature goal will be exceeded between 2021 and 2040, with future net-negative emissions making it possible for global mean temperature to subsequently decline back to below this level after intermediary overshoot (Australian Research Council 2021, IPCC 2021).

GCAM solves for the lowest-cost, exponentially increasing CO_2 price-path to limit or return to each end-of-century radiative forcing limit. The atmospheric carbon budget consistent with a given level of radiative forcing increase is treated as an exhaustible resource to be depleted (Hotelling 1931, Nordhaus 1982, 1992). The Hotelling rate (i.e. the annual rate of CO_2 price increase after policy initiation, equivalent to the discount rate) is set to 5% by default in the GCAM release. However, a lower discount rate may be more appropriate for modeling deep mitigation scenarios given the risks of large overshoot of the warming goal requiring even larger-scale negative emissions deployment in late-century to reverse it (Emmerling *et al* 2019). For the scenarios shown here, we reduced the discount rate in our main scenarios to 3%, which has strong empirical justification in recent estimates of real interest rates based on riskless return to capital investment (Bauer *et al* 2021, Carleton and Greenstone 2021). This 3% value is used by the US government to assess the social cost of carbon (EPA 2016). Discount rates are higher for developing countries that have higher rates of economic growth (Moore *et al* 2020). Such higher rates, if applied globally, would tend to increase temperature overshoot by reducing near-term mitigation and increasing future carbon removal (Emmerling *et al* 2019). To illustrate the effect of the discount rate on temperature overshoot, we perform sensitivity analysis using the higher 5% rate and report the results in the supplementary information (available online at stacks.iop.org/ERL/16/114012/mmedia). We note that the discount rate here is applied to mitigation costs only, and not to the risk of damages from future climate impacts. GCAM and most other IAMs contributing results to the SSP-RCP scenario framework do not capture climate damages. Endogenizing climate damage risks and other bidirectional feedbacks between the earth and human socioeconomic systems into GCAM and other IAMs is an important area of cutting-edge, ongoing research that is beyond the scope of this study (e.g. Snyder *et al* 2019). Studies that explicitly analyze the structure of the correlation between climate damages and future levels of income could result in discount rates lower or higher than the non-risk-adjusted value used here. The addition of this financial risk analysis is again beyond the scope of this study.

By default, GCAM imposes a constraint on financial transfers for negative emissions equivalent to 1% of Gross Domestic Product (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 half, to 0.5% of GDP to further limit reliance on future negative emissions but remain consistent with the SSP-RCP scenario framework (Anderson *et al* 2016, Bednar *et al* 2019, Rogelj *et al* 2019, Johansson *et al* 2020). 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 (Calvin *et al* 2019). 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

Table 1. Parametrizations for DACCS Technologies. Values are assumed to remain constant after 2030.

		Natural gas (GJ/tCO_2)		Electricity (GJ/tCO_2)		Non-energy cost (2015 $/$tCO_2$)		Water (m^3/tCO_2)	
Technology	Scenario	2020	2030	2020	2030	2020	2030	2020	2030
High temp. DACCS (natural gas)	SSP1—sustainable development	8.1	5.3	1.8	1.3	$296	$185	4.7	
	SSP2—middle of the road		5.3		1.3		$185		
	SSP3—regional rivalry		8.1		1.8		$296		
	SSP4—inequality		5.3		1.3		$78		
	SSP5—fossil fueled development		5.3		1.3		$78		
High temp. DACCS (fully electric)	SSP1—sustainable development	—		6	5	$384	$186	4.7	
	SSP2—middle of the road				5		$186		
	SSP3—regional rivalry				6		$384		
	SSP4—inequality				5		$101		
	SSP5—fossil fueled development				5		$101		
Low temp. DACCS (electric heat pump)	SSP1—sustainable development	—		5.5	2.5	$402	$235	—	
	SSP2—middle of the road				2.5		$235		
	SSP3—regional rivalry				3.8		$402		
	SSP4—inequality				2.5		$137		
	SSP5—fossil fueled development				2.5		$137		

radiative forcing constraints were permuted across the 5 SSPs, 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 (Mazzotti *et al* 2013, Keith *et al* 2018, Fuhrman *et al* 2020). There are several additional DACCS processes which have also been demonstrated at commercial or pilot scale (Carbon Engineering 2021, Climeworks 2021, Global Thermostat 2021). 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 (Fasihi *et al* 2019). The removal efficiency of DACCS is influenced in part by the carbon intensity of its electricity supply (Deutz and Bardow 2021, Terlouw *et al* 2021). 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 (Zeman 2007, Stolaroff *et al* 2008, Keith *et al* 2018). The low-temperature DACCS process is assumed to use solid sorbents and not require water input (Smith *et al* 2016).

Table 1 reports the parametrizations used for DACCS technologies. In developing our parametrizations, we generally followed the detailed methodology of Fasihi *et al* (2019) 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. To better inform the near-term deployment potential for DACCS, cost and energy efficiency improvements were assumed to take place over the next decade (i.e. by 2030) and remain constant thereafter. The rate of non-energy cost reductions for DACCS (between 1.6 and four fold over the next 10 years) is in part due to our conservative initial cost estimates but is within the range of historical

10 years cost improvement rates of mitigation technologies such as solar Photovoltaics (PV) and batteries (Shiraki and Sugiyama 2020). 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 (Fasihi *et al* 2019, Breyer *et al* 2020). Full details of our derivation of high, intermediate, and low-cost estimates are reported in the supplementary information. In addition, the results of a second sensitivity analysis with respect to DACCS cost and performance improvements for SSP1 and SSP4 are also reported in the supplementary information.

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In GCAM, the cost (excluding emissions prices or removal subsidies) and performance trajectories of all technologies including DACCS are parametrized based upon the storylines of each SSP, and thus are assumed to progress independently of any policies incentivizing their deployment. This exogenous treatment allows sensitivity analysis of cost or efficiency targets for different technologies. Other IAMs (e.g. WITCH, MERGE-ETL) endogenize these changes in cost and performance in an attempt to capture technological development in response to economic incentives (Fuhrman *et al* 2019). 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 (Kriegler *et al* 2014) and their implementation protocols and are summarized qualitatively in the supplementary information (Riahi *et al* 2015). The numerical assumptions external to DACCS are documented in detail in publications accompanying the release of the most recent major update to GCAM and its contribution to the SSP scenarios (Calvin *et al* 2017, 2019). Cost and performance assumptions for key BECCS and renewables technologies that influence the requirement for DACCS and other forms of negative emissions are provided in the supplementary information. The full numerical assumptions and source code may be accessed on the GCAM Github site (JGCRI 2021).

3. Results

3.1. CO_2 emissions

Figure 1 reports positive and negative CO_2 emissions by sector for below +2 °C (+2.6 W m^{-2}) in 2100 scenarios and below +1.5 °C (+1.9 W m^{-2}) in 2100 scenarios. Hereafter, the scenarios are denoted by their SSP, end-of-century radiative forcing limit, and availability or lack thereof of DACCS technology. No model in previous studies of the SSPs found feasible solutions to limit warming to below +2 °C in the SSP3 'regional rivalry' scenario (Bauer *et al* 2017). Here, we find that even the prospective availability of DACCS does not enable meeting a below +2 °C target in 2100 in this fragmented and economically poor world. In the SSP1-1.9-DACCS scenario, DACCS deployment reaches 14 $MtCO_2$ yr^{-1} globally (several reference plants) by 2030, scales at a maximum annual rate of 25%, and peaks at 3.4 $GtCO_2$ yr^{-1} in 2075. Gross CO_2 removals reach nearly 13 $GtCO_2$ yr^{-1}, dominated by uptake from land use change, which peaks at over 11 $GtCO_2$ yr^{-1} in 2040. This is opposite in sign and over two times the magnitude of present-day land-use change emission rates (Le Quéré *et al* 2018). Global CO_2 emissions reach net-zero around 2050 in this scenario. In the SSP1-2.6-DACCS scenario, DACCS reaches 3 $MtCO_2$ yr^{-1} scale by 2030 and peaks at 4.6 $GtCO_2$ yr^{-1} in 2095.

In the SSP2-DACCS-2.6 scenario, DACCS deployment reaches 10 $GtCO_2$ yr^{-1}. DACCS, BECCS, and land use change all contribute negative emissions in a relatively balanced manner with no one technology dominating, with gross CO_2 removal rates reaching over 25 $GtCO_2$ yr^{-1}. Both SSP2-1.9 scenarios were infeasible with both a 3% and 5% Hotelling rate assumption.

In both the SSP4-1.9-DACCS and SSP4-2.6-DACCS scenarios, DACCS availability increases CO_2 removal capacity by approximately 55% relative to their respective no-DACCS scenarios. The role of Land Use Change (LUC) negative emissions is drastically reduced in SSP4, leading to greater emphasis on technological CO_2 removal from both BECCS and DACCS. By 2030, global DACCS deployment reaches 90 $MtCO_2$ yr^{-1} in the SSP4-DACCS-2.6 scenario and nearly doubles to 180 $MtCO_2$ yr^{-1} (hundreds of reference plants) in the SSP4-DACCS-1.9 scenario. Year-over-year growth rates for DACCS are over 200% between 2025 and 2030 to first reach these scales, with more modest annual growth rates (8%–18%) thereafter. For context, the compound annual growth rate of natural gas extraction via hydraulic fracturing in the US was approximately 43% per year between 2007 and 2011 EIA (2021). DACCS deployment reaches over 20 $GtCO_2$ yr^{-1} in both SSP4 scenarios.

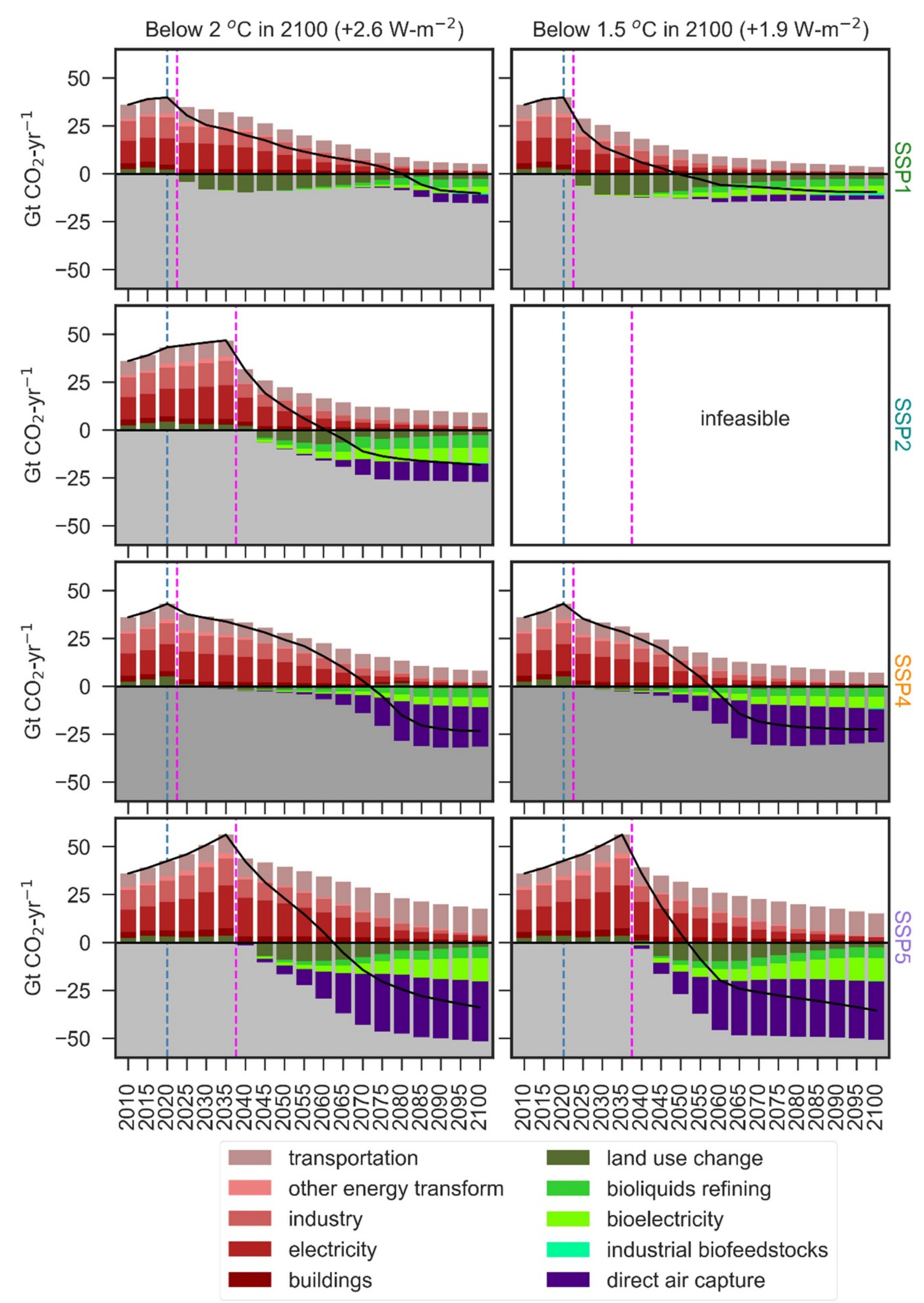

Figure 1. Positive and negative CO_2 emissions by sector for deep mitigation scenarios with DACCS available. Gray shading indicates net CO_2 removal. The dashed teal lines indicate the year 2020. The dashed magenta lines indicate the start of global CO_2 emissions pricing.

In SSP5-2.6, DACCS availability doubles peak negative emissions capacity relative to its respective no-DACCS scenario, from 29 to 51 $GtCO_2$ yr^{-1} and as in SSP4 enables meeting the end-of-century warming goal after higher overshoot. In 2040, the first assumed year of global climate policy, DACCS deployment scales rapidly to 0.7 $GtCO_2$ yr^{-1} in the SSP5-2.6-DACCS scenario, and to 2 $GtCO_2$ yr^{-1} (thousands of reference plants) in the SSP5-1.9-DACCS scenario. The SSP5-1.9 scenario was

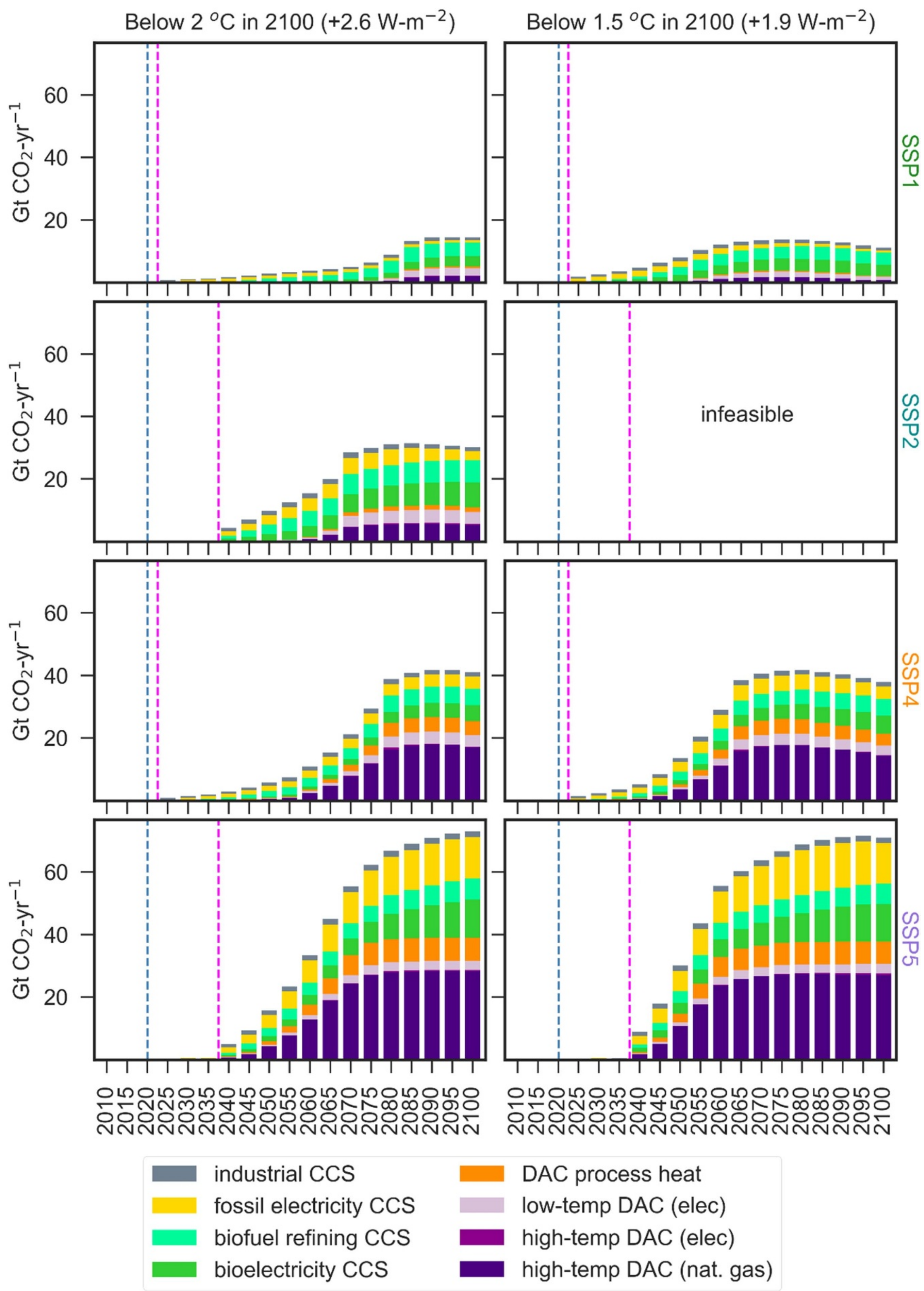

Figure 2. Global geologic carbon storage by sector for deep mitigation scenarios with DACCS available. The dashed teal lines indicate the year 2020. The dashed magenta lines indicate the start of global CO_2 emissions pricing.

infeasible without DACCS available with both a 3% and 5% Hotelling rate assumption.

3.2. Geologic carbon storage

In addition to understanding sources of positive and negative CO_2 emissions, it is also critical to understand how the use of NETs, and geologic carbon storage more generally, might vary depending on socioeconomic developments. Figure 2 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. 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 $GtCO_2$-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 $GtCO_2$ yr^{-1} in 2020 (Page *et al* 2020).

In the SSP1 scenarios, emphasis on renewable energy and carbon removal from land-use change result in the lowest geologic carbon storage requirements relative to the other SSPs. Total CCS scales up relatively gradually in the SSP1-2.6-DACCS (maximum of 9% y/y growth) and SSP1-1.9-DACCS (maximum of 7% y/y growth) scenarios. Sequestration from fossil electricity (i.e. emissions avoidance) dominates early in the century along with sequestration from biofuels refining (i.e. negative emissions). Storage rates from DACCS reach $GtCO_2$ scales after mid-century, with fully-electric and natural gas based processes having roughly equal shares of total deployment. In SSP2, the assumed delay in mitigation requires CCS to reach $GtCO_2$ scales immediately after the climate policy begins in 2040 in the SSP2-2.6-DACCS scenario. In the SSP2-2.6-DACCS scenario, DACCS, BECCS, and fossil CCS are relatively well-balanced, with no one technology dominating. In the SSP4-2.6-DACCS and SSP4-1.9-DACCS scenarios, peak CCS deployment is nearly doubled relative to their respective no-DACCS scenarios. Scale-up of CCS is smooth but rapid, with peak scaling rates of 11% in both scenarios. DACCS makes small relative contributions initially before growing to dominate total CCS later in the century due to large negative emissions requirements to compensate for the initial carbon budget overshoot. As in SSP2, CCS must scale rapidly in SSP5 at the onset of the assumed climate policy in 2040, peaking at over 70 $GtCO_2$ yr^{-1} in both scenarios. In both SSP4 and SSP5, natural gas-based DACCS process dominate due to the higher carbon intensity of electricity generation in these scenarios.

3.3. Primary energy consumption

Figure 3 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 the supplementary information.

DACCS does not have large impacts on global energy consumption in either of the SSP1 scenarios due to the gradual phase-down of fossil fuels and early mitigation efforts leading to less requirement for its deployment in the future. This is in contrast with the SSP4 and SSP5 scenarios, where peak process heat requirement for natural gas-based DACCS comprises between 15% and 25% of 2019 total global primary energy consumption (BP 2020). In these scenarios, DACCS availability increases peak primary energy consumption by between 17% and 24% relative to their no-DACCS counterparts due to its direct energy consumption for process heat and electricity input as well as income and price elasticity effects resulting from the lower carbon emissions prices. In the SSP2-DACCS-2.6 scenario, DACCS has relatively lower but still-large primary energy impacts, with peak natural gas process heat requirements for DACCS reaching 4% 2019 primary energy consumption.

3.4. Water use

Figure 4 reports water consumption (that is, water that is lost to evaporation or otherwise consumed by humans or livestock) (Vickers 2001) 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 the supplementary information. In all scenarios, irrigation for agriculture dominates global water consumption, with irrigation for bioenergy crop cultivation constituting a substantial additional water demand. 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 the supplementary information.

The availability of DACCS did not substantially impact overall global water consumption in any scenario relative to its no-DACCS counterpart. DACCS availability reduces peak direct water consumption for negative emissions activities (i.e. DACCS and BECCS) by up to 37% due to its lower water intensity, as well its displacement of the most irrigation-intensive bioenergy crop cultivation. As we and others have reported previously, the water intensity of DACCS is over one order of magnitude lower than total bioenergy crop evapotranspiration and roughly a factor of 3 lower than evaporative losses for bioenergy crop irrigation (Smith *et al* 2016, Fuhrman *et al* 2020). The reductions in water

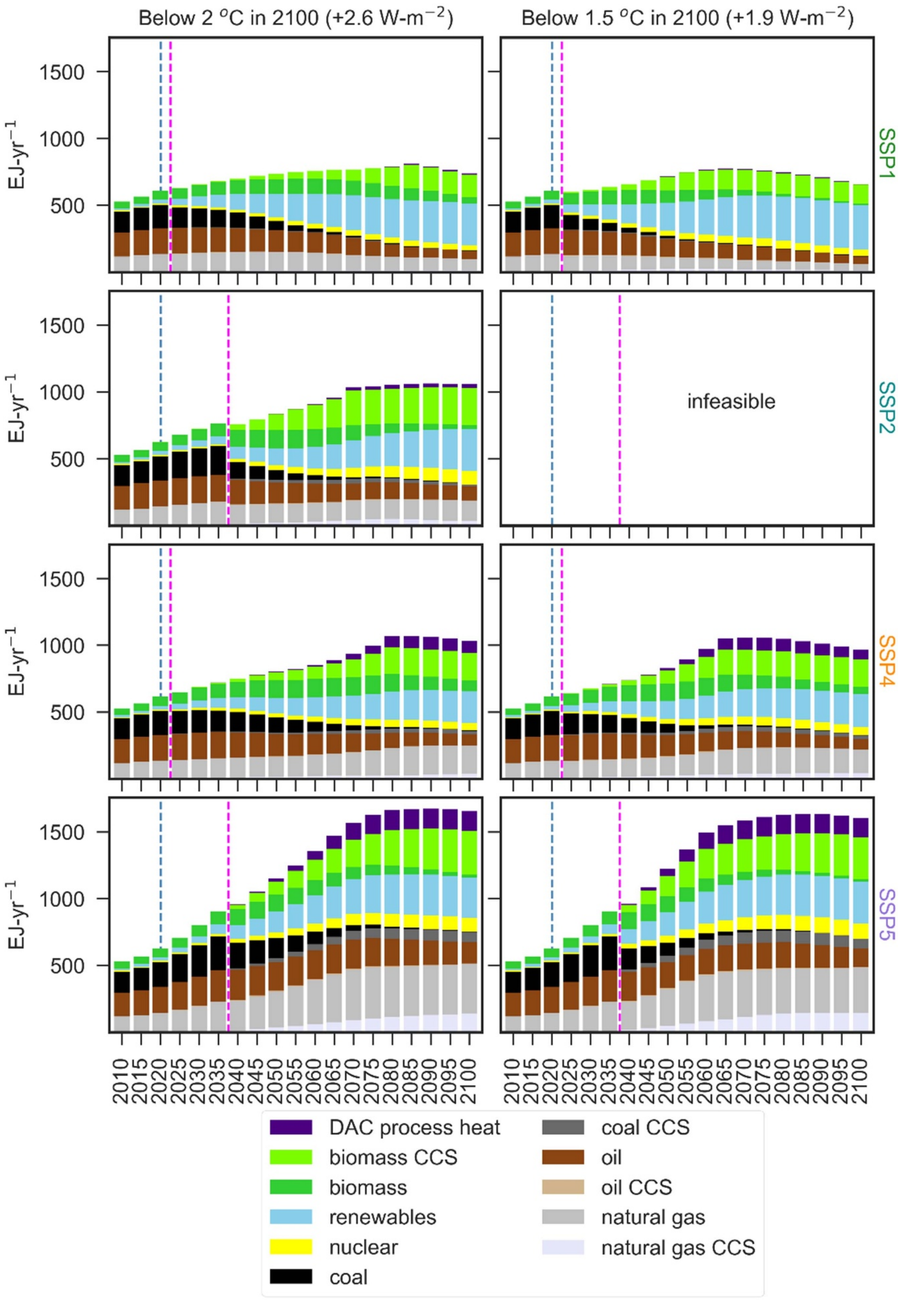

Figure 3. Global primary energy consumption by source for deep mitigation scenarios with DACCS available. Primary energy is reported here as a direct equivalent; that is 1 EJ of renewable or nuclear electricity generation is reported as 1 EJ of primary energy consumption. Natural gas process heat for high-temperature DACCS is shown in purple and subtracted from other natural gas with CCS (light gray) to avoid double counting. The dashed teal lines indicate the year 2020. The magenta dashed lines indicate the assumed initiation of global CO_2 emissions pricing.

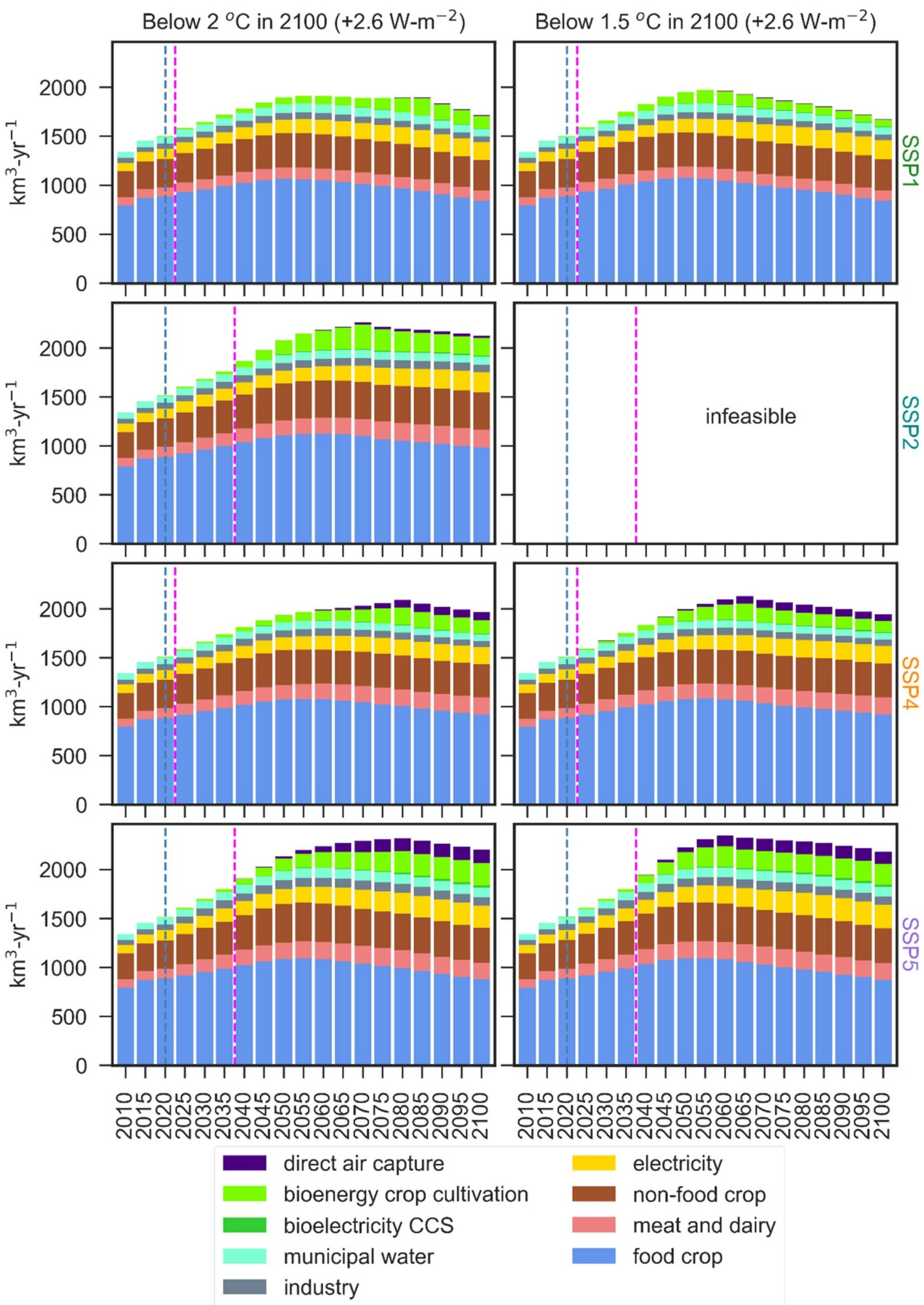

Figure 4. Water consumption by sector for deep mitigation scenarios with DACCS available. The dashed teal lines indicate the year 2020. The dashed magenta lines indicate the assumed start of global CO_2 emissions pricing.

consumption found here—while substantial—are lower than these factors due to interactions between irrigated and rainfed agriculture that are treated endogenously by GCAM, as well as the displacement by DACCS of emissions avoidance as well as BECCS.

3.5. Land use change

Figure 5 reports changes in global land use from 2010 for each of the feasible SSP-DACCS scenarios. Land use change projections for scenarios without DACCS available are reported in the supplementary information. The balance and timing of forest vs bioenergy

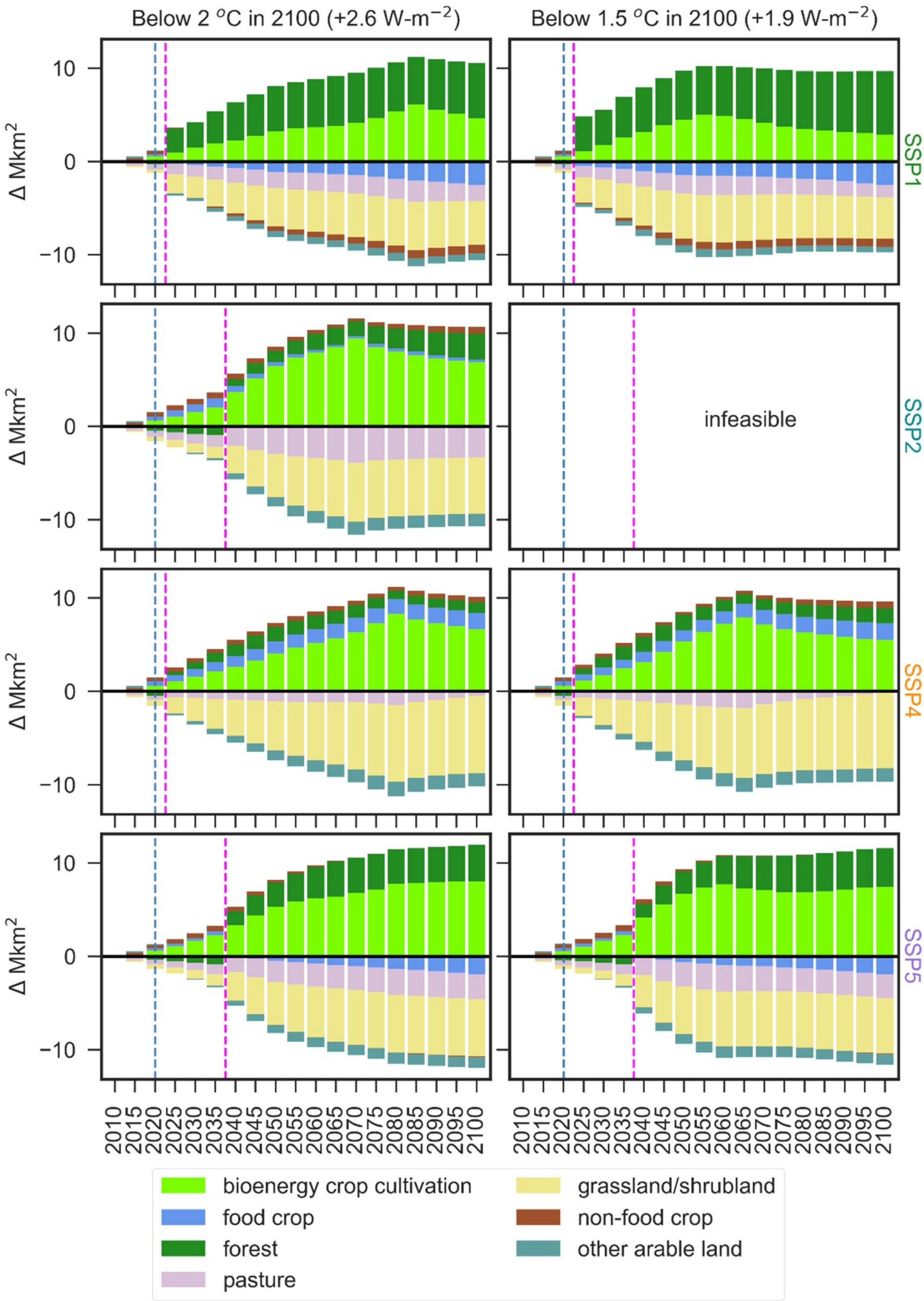

Figure 5. Cumulative change in global land use, relative to 2010 for deep mitigation scenarios with DACCS available. The dashed teal lines indicate the year 2020. The dashed magenta lines indicate the assumed start of global CO_2 emissions pricing.

expansion, as well as which land types are displaced to make room for them, varies by SSP and long-term climate target. Land use plays an enormous role in mitigation even with large-scale DACCS deployment, consistent with previous studies (for example, Roe *et al* 2019). In all scenarios, over 10 Mkm^2 of land are projected to be devoted to climate mitigation in the form of forests and bioenergy crop cultivation, even with DACCS available. DACCS availability enables reductions in peak land area dedicated to bioenergy crop cultivation of between 18% and 31% relative to scenarios in which DACCS is not available,

Table 2. Comparative summary of DACCS and no-DACCS scenarios.

		SSP1		SSP2	SSP4		SSP5	
	Scenario	2 °C	1.5 °C	2 °C	2 °C	1.5 °C	2 °C	1.5 °C
Peak temperature, °C (year of peak)	DACCS	1.89 (2075)	1.63 (2045)	2.07 (2060)	2.15 (2075)	1.96 (2060)	2.26 (2075)	2.12 (2055)
	No-DACCS	1.87 (2075)	1.65 (2045)	2.02 (2055)	2.03 (2070)	1.80 (2055)	2.07 (2055)	—
2050 gross CO_2 removal ($GtCO_2$ yr^{-1})	DACCS	9.1	13	10	3.6	8.5	17	27
	No-DACCS	8.7	11	12	4.2	8.9	21	—
2050 CCS deployment ($GtCO_2$ yr^{-1})	DACCS	5.6	8	9.8	5.7	14	15	30
	No-DACCS	2.9	6.5	12	7.9	17	21	—
2050 primary energy consumption (EJ yr^{-1})	DACCS	737	716	834	803	831	1150	1225
	No-DACCS	735	711	835	783	817	1088	—
2050 water consumption for bioenergy + DACCS (km^3 yr^{-1})	DACCS	70	121	151	78	127	144	225
	No-DACCS	71	107	182	104	202	236	—
2050 land use for bioenergy crop cultivation (Mkm^2)	DACCS	3.2	4.5	6.5	4.1	5.4	5.3	6.7
	No-DACCS	3.2	4.1	7.4	5.2	8.7	8.4	—
First year of global CO_2 pricing (exogenously assumed)		2025		2040	2025		2040	
Initial CO_2 emissions price (2020 $/$tCO_2$)	DACCS	51	110	118	36	58	87	118
	No-DACCS	53	98	98	56	101	160	—
DAC deployment in 2030 ($MtCO_2$ yr^{-1})	DACCS	3	14	—	90	180	—	—
DAC deployment in 2050 ($GtCO_2$ yr^{-1})	DACCS	0.01	0.4	0.24	0.68	4.2	4.7	12
Peak DAC y/y scaling rate after first reference plant	DACCS	24%	25%	97%	14%	20%	68%	102%

freeing up this land for food production or ecological conservation.

4. Summary comparison

Table 2 summarizes the peak emissions, energy, water, and land-use impacts reported in figures 1–5, and compares them to the no-DACCS scenarios. It also reports projections for maximum temperature anomalies, initial CO_2 prices, and scaling rates and deployments for DACCS for easier comparisons between the various SSP scenarios, as well as those with and without DACCS. The SSP1-1.9-DACCS scenario shows the least overshoot of the +1.5 °C goal, reaching a peak of +1.63 °C in 2045, before declining to +1.34 °C in 2100. This is lower than the maximum temperature anomaly reached in the SSP-1.9-noDACCS scenario (1.65 °C) due to the tightened constraint on financial transfers for all negative emissions detailed in the section 2. In all other scenarios, the option to deploy large-scale DACCS substantially reduces CO_2 prices and allows the 2100 temperature goals to be met after larger overshoot under our assumption of an exponentially-increasing CO_2 emissions price. A study published while this one was in review suggests that alternative formulations for emissions price trajectories could further reduce temperature overshoot (Stler *et al* 2021). By 2030, DACCS deployment reaches between 3 $MtCO_2$ yr^{-1} in SSP1 and up to 180 $MtCO_2$ yr^{-1} in the SSP4 scenarios, where global emissions pricing is assumed to begin after 2020. The lower bound is on the same order as the International Energy Agency's forecast for 2030 direct air capture deployment in its 'sustainable development' scenario (IEA 2020). The full results of the no-DACCS scenarios are reported in the supplementary information.

5. Discussion and 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 +1.5 °C in 2100 rapidly closing, IAM scenarios aiming to meet these targets in 2100 have been allowed to trade off near-term emissions reductions with a reliance on deep negative CO_2 emissions in the second half of the century. These scenarios relied almost solely on BECCS and afforestation for negative emissions 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 even under relatively conservative assumptions regarding its future cost and energy efficiency improvements, DACCS could play a large role in mitigation and reduce the sharpest tradeoffs of land and irrigation-intensive negative emissions deployments across a wide range of potential socioeconomic futures. Under the assumption of CO_2 emissions pricing that begins within the next 5 years and then rises over time to limit end-of-century warming to well-below 2 °C (as in the SSP1 and SSP4 scenarios), DACCS deployment could reach several to hundreds of $MtCO_2$-scales globally by the year 2030. DACCS availability could reduce initial CO_2 emissions prices by up to 60%, but its energy requirement for natural gas process heat alone could reach up to 25% of present-day global primary energy consumption later in the century. Of the scenarios we assessed, the SSP1-1.9-DACCS scenario had the lowest overshoot of the +1.5 °C goal, due in part to tightened constraints on negative emissions deployments that we imposed as part of the SSP1-DACCS scenario's design. In the SSP2 and SSP5 scenarios, the 1.5 °C long-term temperature goal is exceeded before climate policy is assumed to begin in 2040. This illustrates the risks of delaying mitigation policies and thus further deepening the reliance on large-scale negative emissions, or else failing to come anywhere close to meeting the goals of the Paris Agreement. Given the emerging emphasis on DACCS in deep negative emissions scenarios, we propose that the IAM community more fully integrate this technology into their models—including in scenario formulations that more explicitly constrain emissions declination trajectories and/or temperature overshoot—such that the risks and opportunities of its deployment can be better understood.

Data availability statement

GCAM is an open-source integrated assessment model available at: https://github.com/JGCRI/gcam-core. The additional data that support the findings of this article will be made openly available following publication.

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/jayfuhrman/gcam-core/tree/dac-ssp. Data will be available from 12 October 2021.

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