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This report is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn,
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The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5°C or 2°C world

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Abstract: Bioenergy with carbon capture and storage (BECCS) and afforestation are key negative emission technologies suggested in many studies under 2°C or 1.5°C scenarios. However, these large-scale land-based approaches have raised concerns about their economic impacts, particularly their impact on food prices, as well as their environmental impacts. Here we focus on quantifying the potential scale of BECCS and its impact on the economy, taking into account technology and economic considerations, but excluding sustainability and political aspects. To do so, we represent all major components of BECCS technology in the MIT Economic Projection and Policy Analysis model. We find that BECCS could make a substantial contribution to emissions reductions in the second half of the century under 1.5 and 2°C climate stabilization goals, with its deployment driven by revenues from carbon dioxide permits. Results show that global economic costs and the carbon prices needed to hit the stabilization targets are substantially lower with the technology available, and BECCS acts as a true backstop technology at carbon prices around $240 per ton of carbon dioxide. If driven by economics alone, BECCS deployment increases the use of productive land for bioenergy production, causing substantial land use changes. However, the projected impact on commodity prices is limited, with global commodity price indices increasing by less than 5% on average, and up to 15% in selected regions. While BECCS deployment is likely to be constrained for environmental and/or political reasons, this study shows that the large-scale deployment of BECCS is not detrimental to agricultural commodity prices and could reduce the costs of meeting stabilization targets. Still, it is crucial that policies consider carbon dioxide removal as a complement to drastic carbon dioxide emissions reductions, while establishing a credible accounting system and sustainable limits on BECCS.

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1. Introduction

Negative emissions technologies (NETs) are valuable in scenarios leading to global warming of 2°C, and indispensable in meeting the more stringent target of 1.5°C (de Coninck and Revi, 2018). As a result, the majority of scenarios consistent with these targets feature some form of negative emissions technologies, mainly in the form of afforestation and land use management (AFOLU) and bioenergy with carbon capture and storage (BECCS) while other NETs, like direct air capture or enhanced weathering of materials, can also be considered (Rogelj *et al.*, 2018). The type of NET deployed, and the scale to which they are deployed, depends on the assumptions made in the models, including, but not limited to, demand-response, level of behavioral change, timing and intensity of climate mitigation action, and NET technology availability and cost. In the most recent IPCC report on global warming of 1.5°C, BECCS and AFOLU are the main NETs, and the level of annual negative emissions varies from a couple of gigatone of CO_2 per year 100% met by AFOLU in a low energy demand scenario, to up to 23 $GtCO_2$/yr 90% met by BECCS in a fossil-fuel intensive scenario (Huppmann *et al.*, 2018; Rogelj *et al.*, 2018).

However, the large-scale deployment of these land-based NETs have raised concerns about their environmental (Smith *et al.*, 2016; Fajardy and Mac Dowell, 2017; Fajardy *et al.*, 2018; Harper *et al.*, 2018; Heck *et al.*, 2018) and economic (Kreidenweis *et al.*, 2016; Muratori *et al.*, 2016) implications. From an environmental perspective, there are concerns related to sustainable biomass, land use change, biodiversity loss and water use, among others. While bioenergy can be sourced from wastes at a low scale (Pour *et al.*, 2018), large-scale deployment of BECCS usually relies on second-generation energy crops and wood from managed forestry (Winchester and Reilly, 2015; Heck *et al.*, 2018). Assessing how much such bioenergy could be sustainably produced without trespassing on planetary boundaries, or contradicting Sustainable Development Goals (SDGs), has been subject to scrutiny, but remains uncertain (Bauen *et al.*, 2010; Beringer *et al.*, 2011; Slade *et al.*, 2014; Creutzig *et al.*, 2015). Ranges of technical bioenergy potential as wide as 100-900 EJ/yr by 2050 can be found in the literature, but there tends to be an agreement towards the lower bound of the ranges, around 100 EJ/yr (Creutzig *et al.*, 2015), when it comes to sustainable potential. Disagreements and uncertainty around sustainable removal rate of residues, area of sustainable forestry, land available for bioenergy production and present and future bioenergy yields explain this wide range. Estimating future crop yields is particularly challenging, since most second-generation crops considered by models, such as perennial grasses or woody crops, have only been deployed at the local/experimental level. Based on historical trends in crop yield increase, regular and bioenergy crop yield improvement rates between 0.6% and 3.5% have been considered in the literature (Fisher *et al.*, 2002; FAO, 2009; Paltsev *et al.*, 2009; Smith *et al.*, 2013; Winchester and Reilly, 2015), assuming a combination of technical change and land management.

Land availability and productivity for bioenergy production have direct impacts on land use change *i.e.* bioenergy production replaces or displaces other land uses, such as crop or pasture land or natural forests or grassland. There are carbon emissions associated with these direct and indirect land use changes (Harper *et al.*, 2018). With higher yields, less land is needed for bioenergy crops, and therefore less land use changes need to occur, resulting in less land use change emissions.

From an economic perspective, there is concern that land-based NETs such as BECCS could cause increases in food and agricultural commodity prices through competition for land (Lotze-Campen *et al.*, 2013; Rulli *et al.*, 2016; IPCC, 2019). Several studies suggest that the large scale deployment of land-based mitigation strategies, such as bioenergy, BECCS and afforestation, could have a substantial effect on food prices (Kreidenweis *et al.*, 2016; Muratori *et al.*, 2016; Wiltshire, 2016; Popp *et al.*, 2017; Hasegawa *et al.*, 2018). Hasegawa *et al.* (2018) showed that land-based climate change mitigation strategies would have a more negative effect on food security than climate change itself. Reviewing all Shared Socio-Economic Pathways (SSP) Popp *et al.* (2017) quantified that climate mitigation policies could lead to an increase in food prices by 110% by 2100. The impact of increased AFOLU on food prices was also investigated, with a study showing that deploying AFOLU to the scale of 2,850 million hectares (Mha) of forested area to meet a 2°C target, could lead to a fourfold increase of the food index by 2100 (Kreidenweis *et al.*, 2016).

There are, however, complex interactions to consider between all technologies within the mitigation portfolio, and it can be useful to decouple climate change mitigation strategies in order to isolate the individual impact of each technology on the economy. For example, Muratori *et al.* (2016) looked at the particular impact of BECCS and CCS on carbon prices, energy trade, commodity trade and commodity prices, by comparing a 2°C scenario with and without CCS in any form. They found that, while the deployment of bioenergy led to an increase in food prices when CCS was not available, the deployment of BECCS however, allowed for a more efficient use of the biomass by providing the additional service of negative emissions, thereby decreasing the carbon price and relieving pressure on land. Adding CCS to both fossil and biogenic emissions in the mitigation portfolio therefore decreased food prices as compared with a 2°C scenario without CCS. However, this study could not decouple the effects of BECCS and fossil-based CCS, and therefore could not conclude as to the impact of negative emissions on the economy. The model setting in Muratori *et al.* (2016) did not include the feedback of policies on GDP levels and food prices on food consumption.

This paper extends the literature by integrating several components which are crucial for a comprehensive representation of BECCS technology, including land availability, endogenous land use change, direct and indirect land use change emissions, bio-crop production and transport, biomass conversion to electricity with CO_2 capture, transport and underground storage of CO_2 and the competition of BECCS with other low-carbon technologies. We then compare climate mitigation scenarios leading to 2°C and 1.5°C with and without BECCS.

2. Material and methods

2.1 The EPPA framework

The EPPA model is a multi-region, multi-sector dynamic model of the global economy, capturing the linkages between sectors and regions of the global economy, with a particular focus on energy (Paltsev *et al.*, 2005; Chen *et al.*, 2017). We represent a BECCS technology, explicitly accounting for the energy, land and other costs of producing and transporting the biomass, converting it to electricity, and capturing and storing the emissions. The version of the model used for this paper includes endogenous land use decisions and tracks land availability and both direct and indirect land use emissions (Gurgel *et al.*, 2016). While land use change emissions are not priced under the climate policy, they are included in meeting the 2°C and 1.5°C targets. The impact of BECCS on the economy is assessed by key metrics including total GHG emissions, primary energy production, electricity generation, carbon price, cost of meeting the policies and agricultural commodity prices, including livestock, crops and food. For additional information on the model, see Appendix A.

BECCS deployment in EPPA is entirely subject to economic drivers, and no exogenous political or sustainability constraints (*e.g.*, water use or biodiversity loss) are considered in the model. For this reason, the levels of BECCS deployment presented in this study may well be higher than what could be sustainably achieved. This study should therefore not be read as a future projection of the BECCS scale of deployment, but as a thought experiment providing insights into the economic impacts of meeting strong climate policies with or without BECCS.

2.2 Scenarios

In this study, we assess the impact of BECCS technology under two climate policy scenarios: achieving 2°C and 1.5°C targets with (scenarios "2°C BECCS" and "1.5°C BECCS") and without BECCS (scenarios "2°C" and "1.5°C"). The 2°C and 1.5°C scenarios are constructed with global economy-wide carbon pricing starting in 2020 and covering all GHGs. The scenarios utilize a greenhouse gas (GHG) emissions profile consistent with the stabilization of the global average atmospheric temperature at either 2°C above pre-industrial levels with a probability of 66% or 1.5°C above pre-industrial levels with a probability of 50%[1]. The carbon price is chosen endogenously in each scenario to meet these targets. "BAU" is the reference case with no climate mitigation policy. Technology costs are based on Morris *et al.* (2017). An annual yield increase of 1% is considered for bioenergy crops in all policy scenarios.

3. Results

3.1 BECCS within the energy system

First, we explore how the availability or otherwise of BECCS influences the evolution of global energy consumption and supply on a trajectory compatible with 1.5/2°C scenarios. **Figure 1** presents the primary energy use in the five different scenarios (with the 2°C scenarios shown as non-transparent and the 1.5°C scenarios as transparent). In the BAU, global energy consumption grows from approximately 550 EJ in 2005 to up to 1200 EJ in 2100, with a predominance of fossil fuels, accounting for 83% of the primary energy mix in 2100. Under both climate policies, and without BECCS available, the total primary energy use sharply decreases down to 33-38% of the BAU energy demand by 2100, when it is comprised of 36-43% fossil fuels, 15-17% intermittent renewables (wind and solar) and 26-30% nuclear. Bioenergy only contributes 22 EJ of primary energy in 2100, as fossil-based CCS, nuclear and renewables prove to be more economic options. With BECCS available, total primary energy use increases back to near the BAU level, but with fossil fuels comprising 51-56% by 2100 and bioenergy 30-36%, 90-92% of which is deployed with CCS. Total bioenergy deployment reaches 30-140 EJ in 2050, and 320-390 EJ in 2100. This is somewhat higher than most global *sustainable* bioenergy potential assessments, as deployment is driven by economics alone without consideration of sustainability or political concerns that may limit the expansion of biomass. Overall, when BECCS is available, fossil fuel use is three times higher than the corresponding case without BECCS available. In the 1.5°C and 2°C cases with BECCS, most of the coal and gas is used in combination with CCS, while emissions from oil use are offset by BECCS.

Figure 2 shows total global electricity generation under each of the scenarios (see Figure B1 in Appendix B for the generation technology mix under each scenario). Under the BAU scenario, global electricity increases to about 57,100 TWh by 2100. Generation is comprised of mostly natural gas (29%) and coal (31%), as well as wind and solar (22%). Under the 2°C and 1.5°C scenarios without BECCS, electricity increases

1 Uncertainty quantification for the temperature increase is based on a 400-member ensemble of IGSM (Sokolov *et al.*, 2017). In comparison to median scenarios reported in the IPCC 1.5 Report (IPCC, 2018), our scenarios allow for a larger carbon budget, which is within the range of the reported estimates (Rogelj *et al.*, 2019)

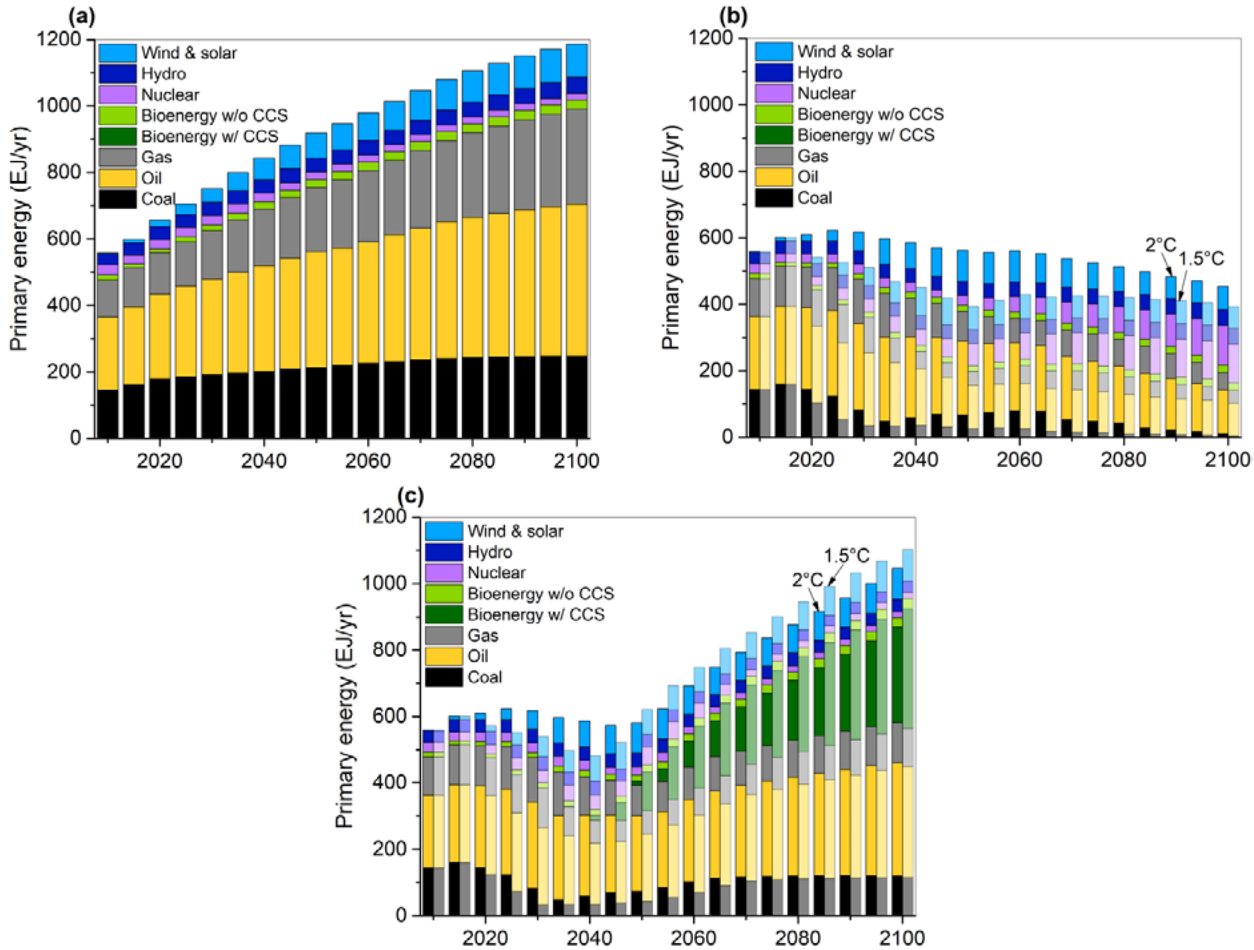

Figure 1. Total primary energy in the BAU scenario (a), in the 2°C and 1.5°C scenarios without BECCS (b), and in the 2°C and 1.5°C scenarios with BECCS (c). Meeting a 2°C target without BECCS leads to a drastic decrease in total primary energy use, down to 33-38% of the world primary energy demand in the BAU. With BECCS available in both the 1.5°C and 2°C scenarios, primary energy increases back to just below that in the BAU scenario.

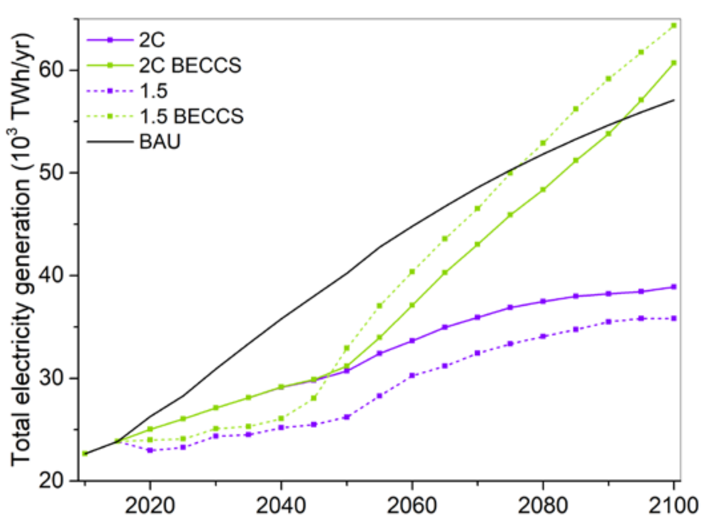

Figure 2. Total electricity generation in the BAU scenario (black), and with (green) or without (purple) BECCS under the 2°C and 1.5°C scenarios.

much more modestly, reaching about 35,800-38,900 TWh by 2100. In those cases, nuclear power is the key technology by the end of the century (41-44%), but CCS (both gas and coal) also plays an important role (12-16%), along with wind and solar (22-23%). Allowing BECCS under the climate policy scenarios results in electricity increasing to 60,700-64,300 TWh by 2100, surpassing even the BAU generation level at the end of the century. In these cases, BECCS comprises 34-40% of the generation mix by 2100, displacing nuclear power and allowing for more coal CCS. The negative emissions produced by BECCS lower the cost of electricity generation via BECCS. With sufficiently high carbon prices (in this scenario \$240/tCO_2, see section 3.2), BECCS becomes the cheapest generation option, lowering the overall electricity price and encouraging more electricity use.

Representing CO_2 equivalent emissions over time further demonstrates the different roles of fossil fuels under climate policy with and without BECCS. **Figure 3** shows the total net CO_2 equivalent emissions and the amount of gross negative emissions via BECCS deployed in the various scenarios.

Without BECCS available, a CO_2eq budget consistent with 1.5°C or 2°C can be achieved by removing between 0.8 and 1.8 GtCO_2/yr by 2100 with afforestation, and decreasing fossil CO_2 emissions by 86%-90%, industrial process CO_2 emissions by 79-82%, and non-CO_2 GHG emissions by 64%-70%, as compared to the BAU scenario. Under the 2°C, with BECCS available, however, gross negative emissions via BECCS reach 21 GtCO_2/yr by the end of the century, allowing for annual GHG emissions to increase by 57%, and industrial CO_2 emissions by 42%, and CO_2 fossil emissions threefold, relative to the 2°C scenario without BECCS available. The system does not become net CO_2 negative by the end of the century. Similar trends are obtained under the 1.5°C with BECCS available, with the difference that gross negative emissions reach 26 GtCO_2/yr by 2100, and the system becomes net CO_2 negative by 2090. The cumulative global negative CO_2 emissions from BECCS between 2020 and 2100 is 620 Gt under the 2°C policy with BECCS and 1060 Gt under the 1.5°C policy with BECCS.

3.2 The cost of mitigation: carbon price and global welfare

The flexibility provided by negative emissions in the mitigation portfolio results in reduced policy costs. **Figure 4** shows the CO_2eq price profiles (left) as well as policy costs

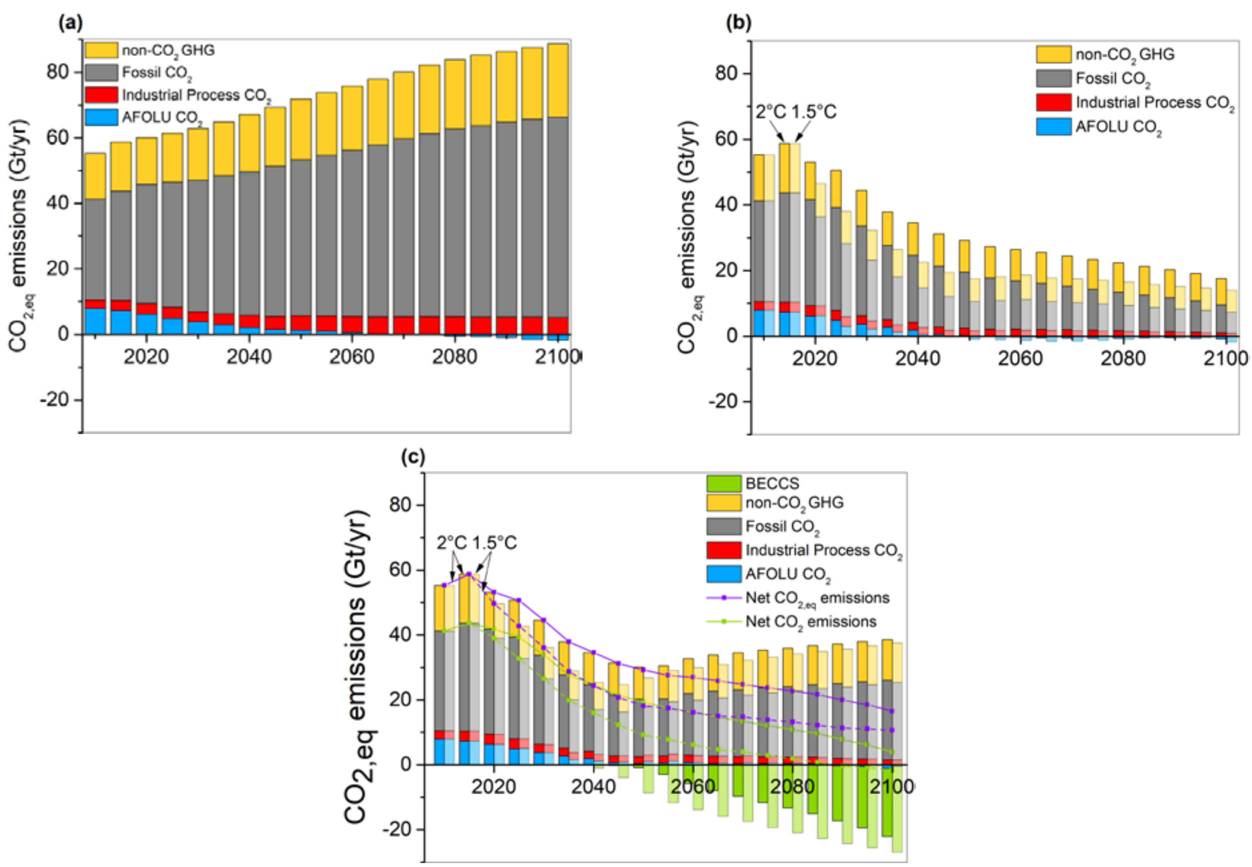

Figure 3. Total net CO_2 equivalent emission trajectory and amount of negative emissions via BECCS in the BAU scenario (a), in the 2 and 1.5°C scenarios without BECCS (b), and in the 2 and 1.5°C scenarios with BECCS (c). Gross negative emissions via BECCS reach 21-26 GtCO_2 by 2100, allowing for more GHG emissions and fossil CO_2 emissions. With BECCS available, net CO_2 emissions are never negative in the 2°C scenario, and reach negativity by 2090 in the 1.5°C scenario.

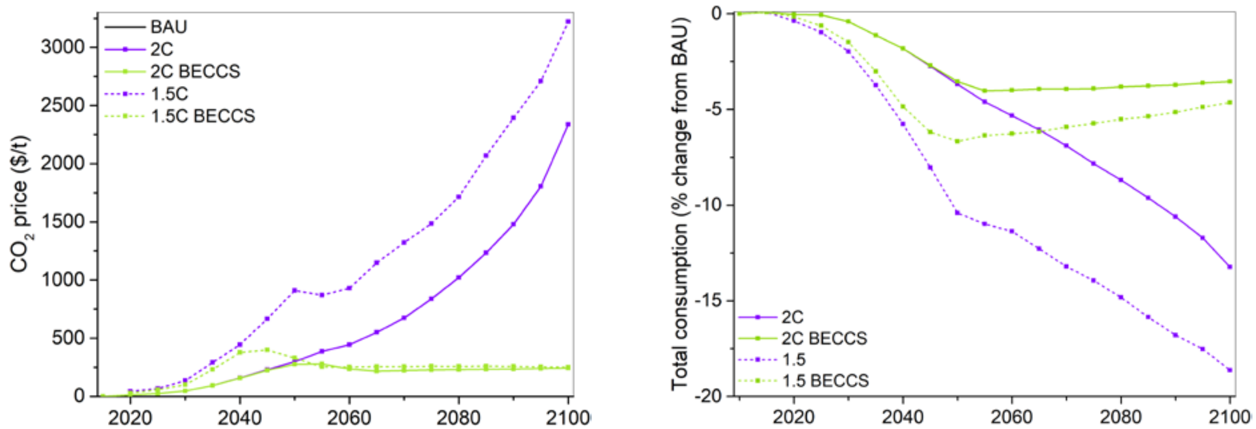

Figure 4. Price on carbon dioxide (left) and total consumption (right) relative to the BAU scenario with (green) or without (purple) BECCS. The introduction of BECCS lowers the carbon price required to meet the 1.5-2°C targets by an order of magnitude at the end of the century. BECCS also enables a 11-17% increase in global welfare under stringent climate policies, as compared to when BECCS is not available.

(right) associated with achieving the 2°C and 1.5°C targets with and without BECCS.

CO_2eq prices significantly decrease with the inclusion of BECCS in the mitigation portfolio. While the price is close to \$160/tCO_2eq in both 2°C scenarios in 2040, it increases sharply to \$2340/tCO_2eq in 2100 without BECCS, but with BECCS stays at about \$240/tCO_2eq for the rest of the century. Both 1.5°C scenarios have a price around \$400/tCO_2eq in 2040, but the case without BECCS rises to \$3220/tCO_2eq by 2100, while the case with BECCS falls to about \$250/tCO_2eq by 2060 and remains flat for the rest of the century. BECCS effectively caps the CO_2eq prices at about \$240/tCO_2eq. By creating negative emissions, the technology relieves pressure from the emissions cap and therefore lowers the price of emissions permits. This also boosts technologies such as coal or gas with CCS, which under higher carbon prices are less competitive due to the carbon penalty on their uncaptured emissions.

A CO_2 price of \$240/tCO_2eq constitutes a substantial revenue stream for the BECCS plant. As a BECCS plant receives revenue from both electricity generation and CO_2 removal, it is interesting to identify which of those constitutes the largest revenue stream for the BECCS plant. Four experiments were performed to elucidate this question: 1) a 2°C BECCS scenario with no CO_2 permits for BECCS, 2) a 2°C BECCS scenario with twice as high BECCS cost, 3) a 2°C BAC scenario where BECCS no longer provides electricity to the system, *i.e.* is only considered as a CO_2 removal technology: "Biological Air Capture", or BAC, and 4) a 2°C BAC scenario where the capital cost of BAC is 22% cheaper than that of BECCS to account for the cost savings from not generating electricity.

When the BECCS cost is twice as high, the BECCS plant is still deployed, though less than for the base case cost scenario. BECCS in 2100 decreases from 21 to 13 GtCO_2/yr, and the CO_2eq price increases to \$470/tCO_2eq. The fact that BECCS still get deployed even though it is not at all competitive with other technologies in terms of cost of electricity generated, highlights the predominance of CO_2 permits as a revenue stream over electricity generation. This is confirmed in the second experiment, where CO_2 permits no longer exist for BECCS. In the absence of CO_2 permits, BECCS plants do not get deployed at all. This demonstrates that the deployment of BECCS is driven by revenue from CO_2 permits, not electricity generation. This is in line with previous studies, which showed that the value of the service of carbon dioxide removal delivered by BECCS (provided it is appropriately remunerated, for example through a negative emissions credit) was higher than that of electricity production (Bui, Fajardy and Mac Dowell, 2017; Mac Dowell and Fajardy, 2017; Daggash, Heuberger and Mac Dowell, 2019). In the third experiment, BECCS is operated as a CO_2 removal technology—"BAC"—without dispatching any electricity to the grid, but operating at the same overall cost as BECCS. The absence of electricity from BAC results in a higher CO_2eq price to meet the 2°C target, increasing from \$240/tCO_2eq to \$275/tCO_2eq by 2100, but BAC still gets deployed at the scale of 19 GtCO_2/yr in 2100. This shows that BECCS is primarily deployed for the purpose of CO_2 removal. In the final experiment, where the capital cost of BAC is made to be 22% lower than that of BECCS to account for the cost savings from not generating electricity, the CO_2eq price returns to \$240/tCO_2eq and BAC deployment is 21 GtCO_2/yr in 2100, the same level as the original 2°C BECCS case. This suggests that the revenue from the electricity generation covers the additional capital costs associated with generating electricity along with carbon dioxide removal. So while the electricity generation component of BECCS is not needed for deployment (*i.e.*, BAC can be significantly deployed), it essentially pays for itself, so the economic prospects for BAC and BECCS are basically the same.

CO_2eq price is not a true measure of the full cost of policy to the economy. For that, we look at the change in total economy-wide consumption (or welfare) under policy relative to consumption under the BAU scenario. Figure \ref{Fig:CO_2price} (right) presents policy costs under the 2°C and 1.5°C scenarios. Without BECCS available, meeting the mitigation targets leads to a 13% decrease in consumption by 2100 in the 2°C scenario, and a 19% decrease in the 1.5°C scenario, relative to BAU. With BECCS available, this drop is reduced to 4% by 2100 in the 2°C scenario and 5% in the 1.5°C scenario. Allowing BECCS to be deployed decreases the cost of policy born by the global economy. Negative emissions from BECCS make it easier to meet the climate targets, allowing for less drastic changes from the BAU in terms of consumption of primary energy, electricity, fossil fuels, and output from various sectors. With BECCS, behavior more similar to that under the BAU can continue because the emissions associated with such behavior are offset by the negative emissions. It should be noted if additional decarbonization options (*e.g.*, hydrogen, industrial CCS, etc.) were represented in the model, the gap in policy costs with and without BECCS would decrease.

3.3 Land use change and implications for food prices

3.3.1 Global impacts

In this section, we investigate the impact of BECCS deployment on land use change and agricultural commodity prices. The high level of BECCS deployment observed translates into substantial land use change as compared with meeting the 2°C or 1.5°C targets without BECCS. **Figure 5** shows the land use change between scenarios where BECCS is not available and scenarios where BECCS is, under a 2°C policy and 1.5°C policy. Bioenergy crop land represents the land used for growing feedstocks to BECCS and other bio-based energy technologies.

When BECCS is available in the 2°C case, the amount of land needed for bioenergy production reaches 540 Mha in 2100, which corresponds to an increase of 490 Mha in land for bioenergy relative to the 2°C scenario without BECCS. For context, there are currently about 1500 Mha of total cropland worldwide. This expansion of bioenergy crop tends to displace managed land such as cropland and pasture land, and to a smaller extent natural grassland and forest. Tightening the target from 2°C to 1.5°C with BECCS available leads to an additional land use change of 170-400 Mha, with the largest additional impacts occurring around mid-century. This is because the 1.5°C case deploys more BECCS and begins deploying it earlier in the century when crop yields are lower (due to annual crop yield improvements, a given kWh of BECCS requires more land at mid-century than at the end of the century). The 1.5°C BECCS case also displaces far more natural grassland and forest than the 2°C BECCS case, relative to policy scenarios when BECCS is not available, with up to 470 Mha displaced at mid-century and 430 Mha at the end of the century, compared to 30 Mha and 120 Mha, respectively, under 2°C with BECCS.

Global food price indices are presented on the right axis of Figure 5, with the price in 2015 normalized to 1. Under the BAU, food prices change very little over time, rising by about 6% between 2015 and 2050 and then declining to end up in 2100 at only about 3% higher than in 2015. This is due to the fact that the increase in demand, driven by population and GDP growth, is compensated by an increase in supply, facilitated by agricultural land expansion and intensification. Under the 2°C and 1.5°C policy, however, lower end-of-the-century values for food prices are reached when meeting the targets without BECCS (with prices in 2100 2-5% lower than in 2015), while higher values are reached when BECCS is available (with prices in 2100 4-5% higher than in 2015). This can be explained

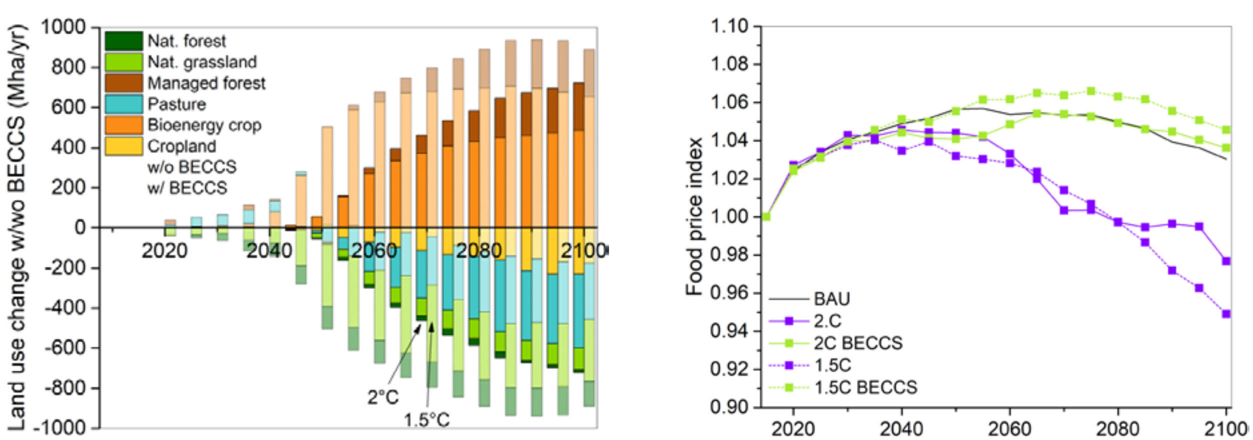

Figure 5. Land use change between a 2°C or 1.5°C world (left), and global food index in the BAU, 2°C and 1.5°C scenarios (right), with and without BECCS. By 2100, 450-650 additional Mha is used for bioenergy when BECCS is available, primarily displacing cropland and pasture lands under 2°C, but also displacing significant amounts of natural grassland and forest under 1.5°C. Global food index with BECCS is up to 6% higher than 2015 levels, but remains within 2% of that of the BAU scenario.

by a combination of two factors: 1) a lower overall demand under 2°C or 1.5°C policies than in the BAU and 2) a higher competition for land with BECCS available than without. First, achieving the 1.5°C or 2°C target without BECCS leads to a decrease in total consumption compared to the BAU, leading to lower demand for primary goods, such as energy, food, and crop and livestock products. This explains why the food price indices in the policy cases without BECCS are lower than in the BAU scenario. However, total consumption in the policy cases with BECCS is also lower than that in the BAU scenario (though to a lesser extent than in the policy cases without BECCS, see Figure \ref{Fig:CO_2eq}), but the food prices are not very different from the BAU, and actually end up somewhat higher by the end of the century. This is because meeting the 2°C or 1.5°C target with BECCS increases the pressure on land, displacing cropland and pasture land for bioenergy production. The downward price pressure from less demand for agricultural goods is offset by upward price pressure from increased land competition and thus land prices. As a result, food price increases of between 0.6 and 1.5% relative to the BAU are observed by 2100 when BECCS is available. Given the level of BECCS deployment, the impact on global food prices is quite limited.

The sensitivity of these results to the productivity of the land was assessed by considering a low productivity scenario ("LowProd") with 0.8% annual productivity increase, and a high productivity scenario ("HighProd") with a 1.25% annual productivity increase. Although food prices and land use change are impacted by the productivity of land, for the range of productivity assumptions tested, the impact remains small (see Figure B2 in Appendix B). For example, meeting a 1.5°C policy with BECCS results in a 2100 food price that is 8% higher than the 2015 price under a low productivity assumption and relatively stable under a high productivity assumption (compared to 5% higher under the base productivity assumption).

Other agricultural commodity prices, such as crop and livestock, have similar results, with the prices under policy with BECCS ending up in 2100 less than 5% higher than BAU prices (see figure \ref{Fig:sensindex15} in Appendix B). Under a 1.5°C scenario with BECCS, by 2100 the livestock products price index rises threefold compared to 2015 (which is about 1.1-2.8% higher than under BAU), and the crop price index rises by a factor of 1.7 (which is 3.0-4.6% higher than under BAU). Without BECCS, these indices increase by factors of 2.6 (livestock) and by 1.2 (crop) respectively (which translates to the 2100 prices being 3-23% and 16-29% lower than under BAU). Crop and livestock commodity prices rise by more than the food prices because commodity prices actually have a limited weight on food prices, since a large portion of food prices is value-added (*e.g.*, food processing, transportation and other services). In developing regions where there might be less value added in the overall chain, higher crop and livestock indices might have a higher overall impact on the food index. This is further elucidated in the next section, which explores the regional impacts of BECCS deployment. Still, globally, the increase in commodity prices under policy with the inclusion of BECCS is limited to 0-5% above the prices under the BAU scenario.

3.3.2 Regional impacts

Figures 6, 7 and 8 show the BECCS' level of deployment in selected regions, and its impact, under the 1.5°C policy scenario with BECCS. The map presents regional cumulative CO_2 removal via BECCS, and the graphs show land use change (relative to meeting the same climate policy without BECCS) as a fraction of the region's total land area,

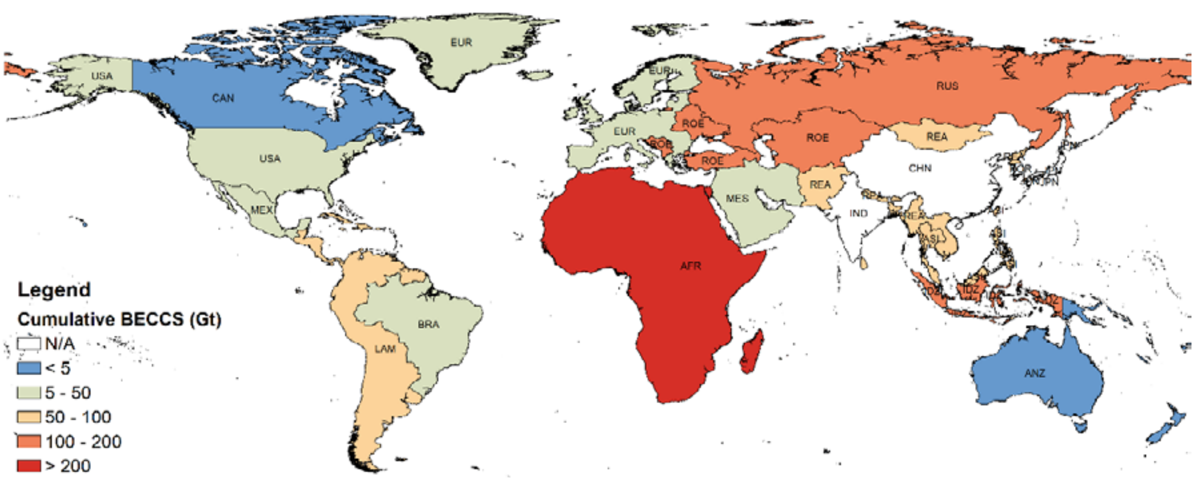

Figure 6. Cumulative CO_2 removal from BECCS under 1.5°C policy with BECCS. 84% of BECCS deployment occurs in developing nations, with 26% alone in Africa.

as well as the food price index in the BAU and under the 1.5°C policy with and without BECCS.

BECCS gets primarily deployed in Africa (AFR), Eastern Europe and Central Asia (ROE), Russia (RUS), Latin America (LAM) and Indonesia (IDZ). The main drivers for this deployment are land availability (LAM, AFR and RUS, ROE) and/or high land productivity (IDZ, LAM). In ROE, Russia and Indonesia, bioenergy cropland expansion represents 10 to 25% of the region's total land area. Overall, the trend of food prices with BECCS tends to follow loss of cropland and pasture land. This translates to increases

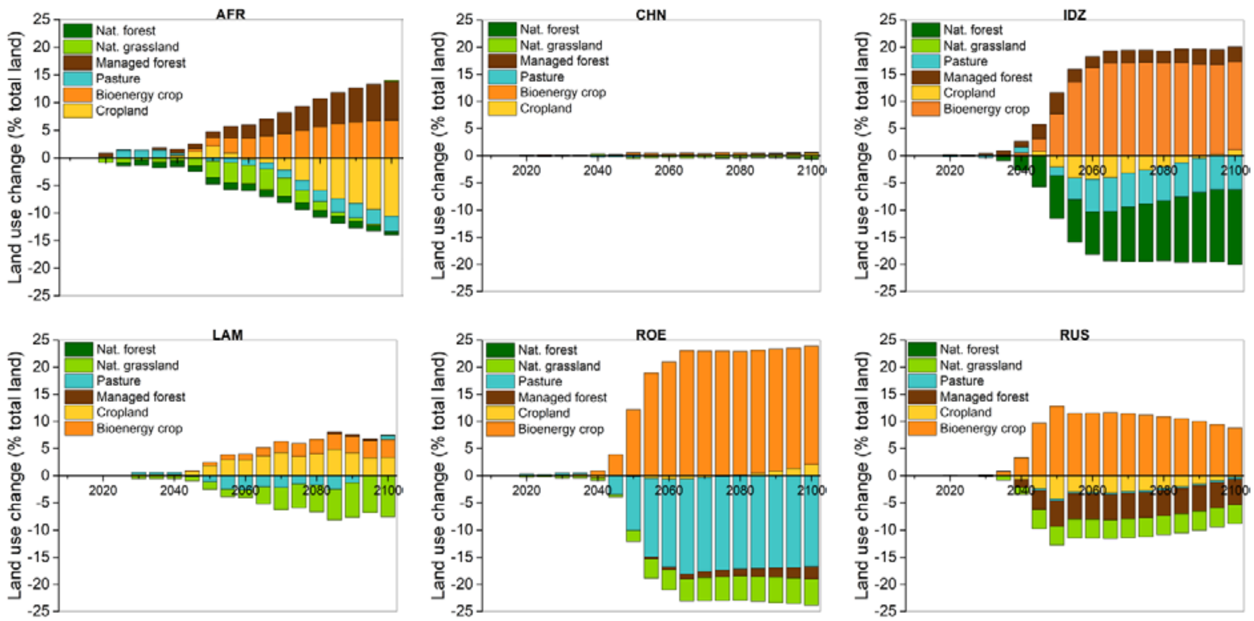

Figure 7. Land use change relative to the BAU scenario in selected regions under 1.5°C policy with and without BECCS. Bioenergy crop expansion cause significant displacement of cropland and pasture land at mid-century (e.g., Russia and Indonesia).

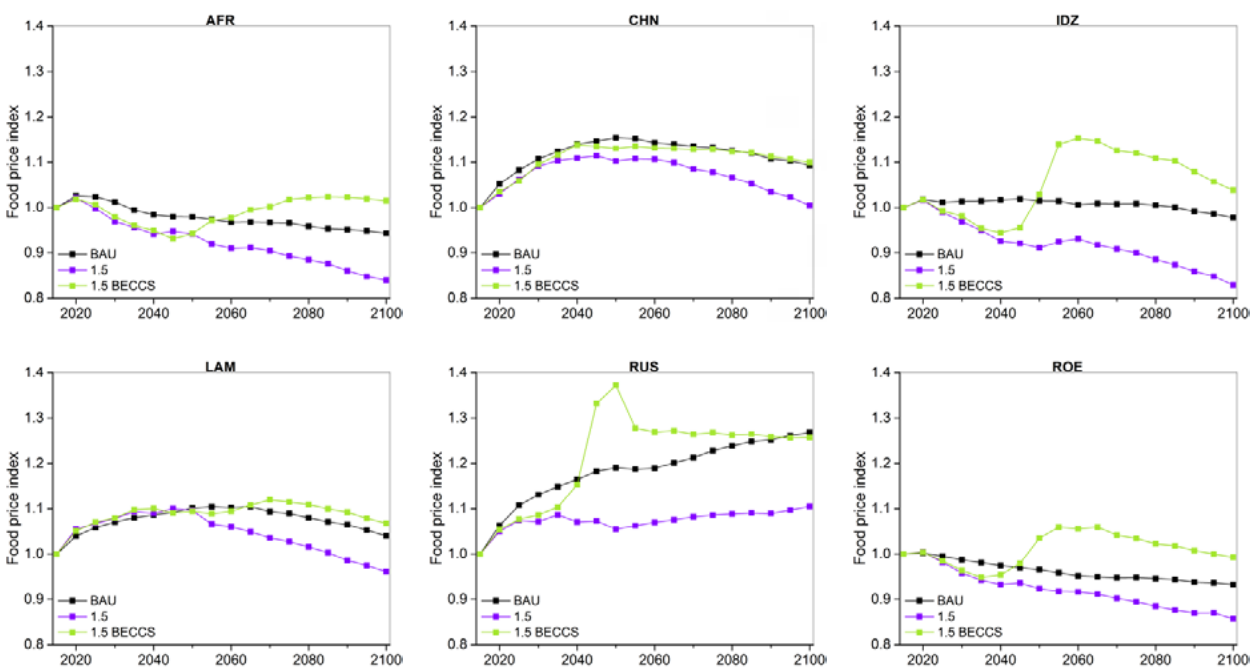

Figure 8. Food price index in selected regions under BAU and 1.5°C policy with and without BECCS. In 2100, in regions where BECCS is primarily deployed, food price index increase by as much as 30% from 2015 levels, but remain within 5-7% of the BAU level. At mid-century, however, they peak at 15% relative to BAU levels, which means a 18% to 38% increase from 2015 levels, where there is significant displacement of cropland and pasture land (e.g., Russia and Indonesia).

in the food price index of between 5 and 7% by the end of the century relative to BAU, with a spike at 15% in Russia and Indonesia at mid-century. As a counter example, in China where no BECCS is deployed and no cropland and pasture land is displaced, the food price index remains stable when BECCS is available, and drops when BECCS is not available (due to the drop in overall consumption). Careful monitoring of these local effects will be required. Another observation is that 84% of BECCS deployment occurs in developing nations, with 26% alone in Africa. Whilst the CDR literature abounds in OECD countries, which highlights an interest in deploying these technologies, the expertise and budget to deploy these technologies may be lacking in other regions with lower levels of development. International cooperation under climate equity principles, in the form of technology transfer and/or international financial incentives, will be required to enable BECCS deployment in these regions and ensure such deployment benefits both the environment and population.

4. Discussion and conclusions

The results of this study are a quantification of the potential scale of BECCS deployment and its impact on the economy when considering technology and economics, but excluding sustainability/environmental, political and societal aspects. A key takeaway is that BECCS has the economic potential to be a significant climate mitigation technology. The model accounts for all major components of the BECCS process, including land availability, crop production and transport, biomass conversion to electricity with CO_2 Capture, and the transport and underground storage of the CO_2. The modelling shows that BECCS deployment results in a reduced cost of meeting 1.5 and 2°C targets. Meeting these targets without BECCS is feasible, but would incur a dramatic drop in global welfare. In the 1.5°C scenario, global consumption decreases by almost 20% by 2100 when BECCS is not available, but only by 5% when BECCS is available. BECCS deployment also allows CO_2 prices to be an order of magnitude lower than when BECCS is not available. The scenarios modelled suggest that BECCS acts as a backstop technology at a carbon price of about \$240/tCO_2.

Significant land use change is associated with the deployment of BECCS to meet the climate policies, with additional land used for bioenergy by 2100 reaching 490-650 Mha, or about 33-43% the size of total global cropland as of 2015. The model accounts for this land use change, as well as the direct and indirect greenhouse gas emissions associated with this change. Land for bioenergy crops mostly replaces cropland and pasture land under 2°C, but under 1.5°C BECCS also causes significant reductions in natural grassland and forest. While certain areas (*e.g.*, national parks) were excluded from biomass production, in general the ecosystem impacts and social acceptability of reductions of natural land were not considered and may limit the overall deployment of BECCS. It is worth noting, however, that alternative sources of feedstock such as marine biomass (Beal *et al.*, 2018), which could drastically reduce BECCS' pressure on land use, were not considered in this study.

We find the impact on agricultural commodity prices from the land use impacts of BECCS, which has been the largest concern about BECCS, to in fact be quite limited. Compared to the BAU scenario, meeting a 2°C or 1.5°C policy with BECCS only increases global food, livestock and crop prices by less than 5% by 2100. The global food price increase in particular is limited to just 1.5% compared to BAU. A caution is warranted to interpretation of these numbers: While aggregate regional changes may seem small, there might be substantial distributional impacts within a region. In some regions where BECCS is heavily deployed, such as Indonesia and Russia, the regional food price index increases up to 15% at mid-century before stabilizing at a 5% increase at the end of the century. These results suggest that BECCS deployment is likely to be more beneficial than harmful to the global economy, though local policies, with the help of international financing and offsets, will be required to safeguard BECCS deployment in regions with potential high deployment and lower levels of development.

These model results are not predictions; they are scenarios that show the potential of BECCS. Among the main uncertainties impacting BECCS deployment are availability of sustainable biomass, availability of geological storage of CO_2, policy incentives, development of a credible accounting and valuation system for negative emissions, and social acceptance. The scenarios show results for 1.5 and 2°C stabilization levels. However, it is important to note that BECCS can also play a significant role under higher stabilization targets or any policy that results in a carbon price above about \$240/tCO_2.

While there is no large-scale BECCS facility (*i.e.*, negative emissions greater than 1 MtCO_2/yr) operating today, all technical components currently exist. Large biomass-fired power plants operate today, the largest being the DRAX power station North Yorkshire, England, capable of producing 2.6 GW of electricity from biomass. CCS has been demonstrated on the Mt scale at two coal-fired power plants: Boundary Dam in Saskatchewan, Canada and Petra-Nova outside of Houston, TX. Applying CCS to a biomass-fired power plant is very similar to operations at a coal-fired power plant. Currently, a pilot CCS unit at the DRAX biomass-fired power plant captures one tonne of CO_2 per day.

From the standpoint of the electricity system, BECCS has a major advantage over fossil-fired CCS in terms of dispatch. Fossil-fired power plants have high marginal operating costs compared to renewables and nuclear generation. As renewables increase their market share, fossil-fired power plants (with or without CCS) are dis patching less, which hurts their profitability. On the other hand, negative emissions generated by a BECCS plant lowers its marginal operating cost. At a high enough carbon price, the marginal operating cost for BECCS will be lower than both renewables and nuclear, theoretically allowing BECCS plants to operate at a 100% capacity factor (Mac Dowell and Fajardy, 2017). This also helps lower overall electricity prices, which is a key reason why more electricity is used in the BECCS scenarios than in BAU.

A critical component of BECCS is to have a sufficient supply of *sustainable* biomass. Large-scale biomass solutions to reduce CO_2 concentrations in the atmosphere is a highly controversial topic. Providing the right choices are made in the feedstock—forestry and agricultural residues, wastes, energy crops on degraded land, and along the whole BECCS value chain, BECCS can however lead to sustainable negative emissions (Fajardy and Mac Dowell, 2017). As far as BECCS's impact on ecosystems are concerned, and forests in particular, forests can successfully be maintained for multiple purposes, including direct CO_2 removal, bioenergy production (with potential synergies with BECCS), ecosystem preservation, and recreation. When a forest is producing value and providing jobs, there is less likelihood that it will be targeted for development compared to a forest that is left untouched.

Direct air capture (DAC) has been attracting much interest lately. DAC is the capture of CO_2 directly from the air by chemical processes, which, when combined with long-term geological CO_2 storage, leads to CO_2 removal from the atmosphere. Whilst BECCS can be a net energy provider, DAC is a net energy consumer, which needs to be considered when planning the structure of the future energy system (Daggash and Mac Dowell, 2019). In terms of cost, this paper estimates costs for BECCS at around \$240/tCO_2 avoided. While similar costs for DAC have been reported in the literature (Keith *et al.*, 2018), we do not find these estimates credible. Other studies evaluate DAC cost to be much higher (APS 2011; House *et al.* 2011) . However, the role of biomass is critical for the advantages of BECCS over DAC. The biomass concentrates the CO_2 from the atmosphere and provides the energy required to drive the CCS process, with excess energy available to produce carbon-free electricity. There is a cost in the production and handling of the biomass, and the cost of BECCS could increase in regions where resources are constrained for sustainability reasons, but our modeling suggests that the benefits of BECCS far outweigh the costs.

Finally, another concern about BECCS has been that reliance on it could delay carbon mitigation action. Our modeling does show that BECCS enables less drastic changes from the BAU in terms of consumption of primary energy, electricity, fossil fuels, and output from various sectors. However, the emissions mitigation and climate stabilization targets are achieved, which is the ultimate goal. Ultimately, it is crucial that policies consider CO_2 removal as a complement to deep CO_2 emissions reductions, while establishing sustainability protocols for BECCS and creating a credible accounting system for negative emissions.

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5. References

American Physical Society (APS) (2011): *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).

Bauen, A.W. *et al.* (2010): Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. *Bioresource Technology* 101(21): 8132–8143. doi:10.1016/j.biortech.2010.05.002.

Beal, C.M. *et al.* (2018): Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability. *Earth's Future*, 6. doi:10.1002/2017EF000704.

Beringer, T., W. Lucht and S. Schaphoff (2011): Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, 3(4): 299–312. doi:10.1111/j.1757-1707.2010.01088.x.

Bui, M., M. Fajardy and N. Mac Dowell (2017): Bio-Energy with CCS (BECCS) performance evaluation: Efficiency enhancement and emissions reduction. *Applied Energy*, 195(June): 289–302. doi:10.1016/j.apenergy.2017.03.063.

Chen, Y.-H. *et al.* (2016): Long-term Economic Modeling for Climate Change Assessment. *Economic Modeling*, (52): 867–883. doi:10.1016/j.econmod.2015.10.023.

Chen, Y.-H.H. *et al.* (2017) *The MIT Economic Projection and Policy Analysis (EPPA) Model: Version 5*, *Joint Program Report Series Report*. Cambridge, MA. (https://globalchange.mit.edu/publication/16620).

de Coninck, H. and A. Revi (2018) *Chapter 4. Strengthening and implementing the global response. IPCC special report on global warming of 1.5°C, 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*. Edited by V. Masson-Delmotte. Geneva, Switzerland. (http://report.ipcc.ch/sr15/pdf/sr15_chapter4.pdf).

Creutzig, F. *et al.* (2015): Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, 7(5): 916–944. doi: 10.1111/gcbb.12205.

Cuellar, D.A. and H. Herzog (2015) : A Path Forward for Low Carbon Power from Biomass. *Energies*. doi:10.3390/en8031701.

Daggash, H.A. and N. Mac Dowell (2019): Higher Carbon Prices on Emissions Alone Will Not Deliver the Paris Agreement. *Joule*, 3(May): 1239–1251. doi:10.1016/j.joule.2019.08.008.

Daggash, H.A., C.F. Heuberger and N. Mac Dowell (2019) The role and value of negative emissions technologies in decarbonising the UK energy system. *International Journal of Greenhouse Gas Control*, 81: 181–198. doi:10.1016/j.ijggc.2018.12.019.

Duffy, M. (2008): Estimated Costs for Production, Storage and Transportation of Switchgrass. *Iowa State University Extension*, (February): 1–8. (https://www.extension.iastate.edu/agdm/crops/pdf/a1-22.pdf).

Fajardy, M., S. Chiquier and N. Mac Dowell (2018): Investigating the BECCS resource nexus: delivering sustainable negative emissions. *Energy & Environmental Science*, 11(12): 3408–3430. doi:10.1039/C8EE01676C.

Fajardy, M. and N. Mac Dowell (2017): Can BECCS deliver sustainable and resource efficient negative emissions?. *Energy & Environmental Science*, 10(6): 1389–1426. doi: 10.1039/C7EE00465F.

FAO (2009) *Global agriculture towards 2050, How to feed the world 2050, High-level expert forum*. (http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf).

Felzer, B.S. *et al.* (2009): Importance of carbon-nitrogen interactions and ozone on ecosystem hydrology during the 21st century. *Journal of Geophysical Research*, 114: G01020. doi:10.1029/2008JG000826.

Fisher, G. *et al.* (2002) *Global agro-ecological assessment for agriculture in the twenty-first century: Methodology and Results*. (http://www.fao.org/landandwater/lwdms.stm#cd21).

Gurgel, A. *et al.* (2016): CGE Models: Linking natural resources to the CGE framework. in T. Bryant and A. Dinar (eds) *The WSPC Reference on Natural Resources and Environmental Policy in the Era of Global Change: Volume 3: Computable General Equilibirum*. World Scie. doi:10.1142/9789813208179_0003.

Hamilton, M.R., H.J. Herzog and J.E. Parsons (2009): Cost and U.S. public policy for new coal power plants with carbon capture and sequestration. *Energy Procedia*, 1(1): 4487–4494. doi:10.1016/j.egypro.2009.02.266.

Harper, A.B. *et al.* (2018): Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications*, 9(1): 2938. doi:10.1038/s41467-018-05340-z.

Hasegawa, T. *et al.* (2018): Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, 8(August): 699–703. doi:10.1038/s41558-018-0230-x.

Heck, V. *et al.* (2018): Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, 8(2): 151–155. doi:10.1038/s41558-017-0064-y.

House, K.Z. *et al.* (2011): Economic and energetic analysis of capturing CO_2 from ambient air. *Proceedings of the National Academy of Sciences*, 108(51): 20428–20433. doi:10.1073/pnas.1012253108.

Huppmann, D., J. Rogelj, *et al.* (2018): A new scenario resource for integrated 1.5 °C research. *Nature Climate Change*. doi:10.1038/s41558-018-0317-4.

Huppmann, D., E. Kriegler, *et al.* (2018): IAMC 1.5°C Scenario Explorer and Data hosted by IIASA'. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis. doi:10.22022/SR15/08-2018.15429.

IEA (no date) *Projected costs of generating electricity*. (https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf).

IPCC (2018): *Special report: Global Warming of 1.5C*. (https://www.ipcc.ch/sr15).

IPCC (2019) *Special report: Climate Change and Land*. (https://www.ipcc.ch/srccl).

Kearns, J. *et al.* (2017): Developing a Consistent Database for Regional Geologic CO_2Storage Capacity Worldwide. *Energy Procedia*. ExxonMobil Upstream Research Company, 114(November 2016): 4697–4709. doi:10.1016/j.egypro.2017.03.1603.

Keith, D.W. *et al.* (2018): A Process for Capturing CO_2 from the Atmosphere. *Joule*, 2(8): 1573–1594. doi:10.1016/j.joule.2018.05.006.

Kreidenweis, U. *et al.* (2016): Afforestation to mitigate climate change: Impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, 11(8): 085001. doi:10.1088/1748-9326/11/8/085001.

Lotze-Campen, H. *et al.* (2013): Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agricultural Economics*, 45(1): 103–116. doi:10.1111/agec.12092.

Mac Dowell, N. and M. Fajardy (2017): Inefficient power generation as an optimal route to negative emissions via BECCS?. *Environmental Research Letters*, 12(4): 045004. doi:10.1088/1748-9326/aa67a5.

Morris, J. *et al.* (2017): Representing the Costs of Low-Carbon Power Generation in Energy-Economic Models. *International Journal of Greenhouse Gas Control*. doi:10.1016/j.ijggc.2019.05.016.

Morris, J.F., J.M. Reilly and Y.-H.H. Chen (2019): Advanced technologies in energy-economy models for climate change assessment. *Energy Economics*, 80, pp. 476–490. doi:10.1016/j.eneco.2019.01.034.

Muratori, M. *et al.* (2016): Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters* 11: 095004. doi:10.1088/1748-9326/11/9/095004.

Muratori, M. *et al.* (2017): Carbon capture and storage across fuels and sectors in energy system transformation pathways. *International Journal of Greenhouse Gas Control* 57: 34–41. doi:10.1016/j.ijggc.2016.11.026.

NETL (2013) *Carbon storage: Technology Program Plan*. (https://www.netl.doe.gov/sites/default/files/netl-file/Program-Plan-Carbon-Storage_0.pdf).

Paltsev, S. *et al.* (2005) *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, Joint Program Report Series Report*. Cambridge, MA.

Paltsev, S., J. Reilly and A. Gurgel (2009) *Commercial Viability of Second Generation Biofuel Technology, The Biofuels Market: Current Situation and Alternative Scenarios*. Geneva and New York. (http://www.unctad.org/Templates/webflyer.asp?docid=12454&intItemID=1397&lang=1).

Popp, A. *et al.* (2017): Land-use futures in the shared socio-economic pathways. *Global Environmental Change* 42: 331–345. doi:10.1016/j.gloenvcha.2016.10.002.

Pour, N., P.A. Webley and P.J. Cook (2018): Potential for using municipal solid waste as a resource for bioenergy with carbon capture and storage (BECCS). *International Journal of Greenhouse Gas Control*, 68(November 2017): 1–15. doi:10.1016/j.ijggc.2017.11.007.

Rogelj, J. *et al.* (2018): Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, 8(April): 1–8. doi:10.1038/s41558-018-0091-3.

Rogelj, J. *et al.* (2019): Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, 571: 335–342. doi:10.1038/s41586-019-1368-z.

Rubin, E.S., J.E. Davison and H.J. Herzog (2015): The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*, 40: 378–400. doi:10.1016/j.ijggc.2015.05.018.

Rulli, M.C. *et al.* (2016): The water-land-food nexus of first-generation biofuels. *Scientific Reports*, 6(Fe): 22521. doi:10.1038/srep22521.

Slade, R., A. Bauen and R. Gross (2014): Global bioenergy resources. *Nature Climate Change*, 4(2): 99–105. doi:10.1038/nclimate2097.

Smith, P. *et al.* (2016): Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, 6(1): 42–50. doi:10.1038/nclimate2870ormation.

Smith, S.L., K.D. Thelen and MacDonald, S.J. (2013): Yield and quality analyses of bioenergy crops grown on a regulatory brownfield. *Biomass and Bioenergy* 49: 123–130. doi:10.1016/j.biombioe.2012.12.017.

Sokolov, A. *et al.* (2017): Climate Stabilization at 2°C and Net Zero Carbon Emissions. (https://dspace.mit.edu/bitstream/handle/1721.1/111809/MITJPSPGC_Rpt309.pdf?sequence=1).

Wiltshire, A. (2016) *Implications for food security of large scale BECCS deployment*. (http://www.avoid.uk.net/2016/06/implications-for-food-security-of-large-scale-beccs-deployment-d2c).

Winchester, N. and J.M. Reilly (2015): The feasibility, costs, and environmental implications of large-scale biomass energy. *Energy Economics* 51: 188–203. doi:10.1016/j.eneco.2015.06.016.

Appendix A. Supplementary Methods

The EPPA framework

The Economic Projection and Policy Analysis (EPPA) model is the part of the MIT Integrated Global Systems Model (IGSM) that represents the human systems (Paltsev, Reilly and Gurgel, 2009; Chen *et al.*, 2016). The EPPA model is a recursive-dynamic, multi-region, multi-sector, dynamic general equilibrium model of the world economy, which is built on the GTAP dataset and additional data for GHG and urban gas emissions, taxes and details of selected economic sectors. Provision is made for analysis of uncertainty in key human influences, such as the growth of population and economic activity and the pace and direction of technical advances. It is designed to develop projections of economic growth, energy transitions and anthropogenic emissions of greenhouse gas and air pollutants.

The model projects economic variables (GDP, energy use, sectoral output, consumption, etc.) and emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and other air pollutants (CO, VOC, NO_x, SO_2, NH_3, black carbon, and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling, agricultural activities and land use change. Different versions of the model have also been formulated for targeted studies (see (Chen *et al.*, 2017) for a discussion of different versions of the EPPA model).

Endogenous land use representation (Gurgel *et al.*, 2016)

Land is an input for five sectors in EPPA, including Crops, Forestry, Livestock, biomass to electricity, and biomass to fuel. To account for land use by each of these sectors, five land classes are considered: three managed land (cropland, pastureland and managed forest), and two natural land (natural grasslands and natural forests). The transition from one land category to another is determined by profitability. Cropland, pastureland, managed forests and natural forests are attributed a region-specific unit price obtained from various sources. For lack of data on natural grassland, the same price ratio of natural to managed forest is applied to grassland to determine the unit price of natural grasslands (see (Gurgel *et al.*, 2016) for the full methodology). Direct and indirect CO_2,eq emissions—both CO_2 and N_2O—from land use change are also accounted for and a function of the soil and vegetation carbon pool which characterizes each land type. The emissions associated with each transition in each region were calculated in the TEM model (Felzer *et al.*, 2009).

Bioenergy production

In the EPPA model, production technologies are described using nested constant-elasticity of substitution (CES) functions (see Paltsev *et al.*, (2005; Chen *et al.*, (2016)) for a detailed structures of production and consumption sectors of the EPPA model). Some technologies produce perfect substitutes for existing products (*e.g.*, electricity), and their penetration is driven by a technology specific factor (Morris *et al.*, 2019).

In this study, we introduce a dedicated bioenergy crop representation for the use in bioelectricity (with and without CCS). While BECCS is likely to be deployed via both bioelectricity and liquid biofuels (Muratori *et al.*, 2017; Huppmann *et al.*, 2018), we chose to focus exclusively on bioelectricity and exclude liquid biofuels (with and without CCS) from the mitigation portfolio. Our parametrization of feedstock costs assumes that a representative energy crop is grown in each region and follows (Winchester and Reilly, 2015). Based on a literature review of switchgrass and Miscanthus yields in the US, these authors assign a base energy grass yield of 16.8 oven dry tons per hectare (ODT/ha) in this region. Base yields for other regions are calculated by multiplying the US yield by net primary productivity for C3-C4 grasslands estimated by the Terrestrial Ecosystem Model (Felzer *et al.*, 2009) divided by net primary productivity for the same grasslands in the US.

For each case, base yields are combined with cropland rents to estimate land costs per ton of biomass produced. Production cost for other inputs required for delivered biomass—including growing, storage and transportation—are assigned using estimates from (Duffy, 2008). The production structure for the representative energy crop is shown in **Figure A1**. The nesting structure facilitates endogenous yield responses to

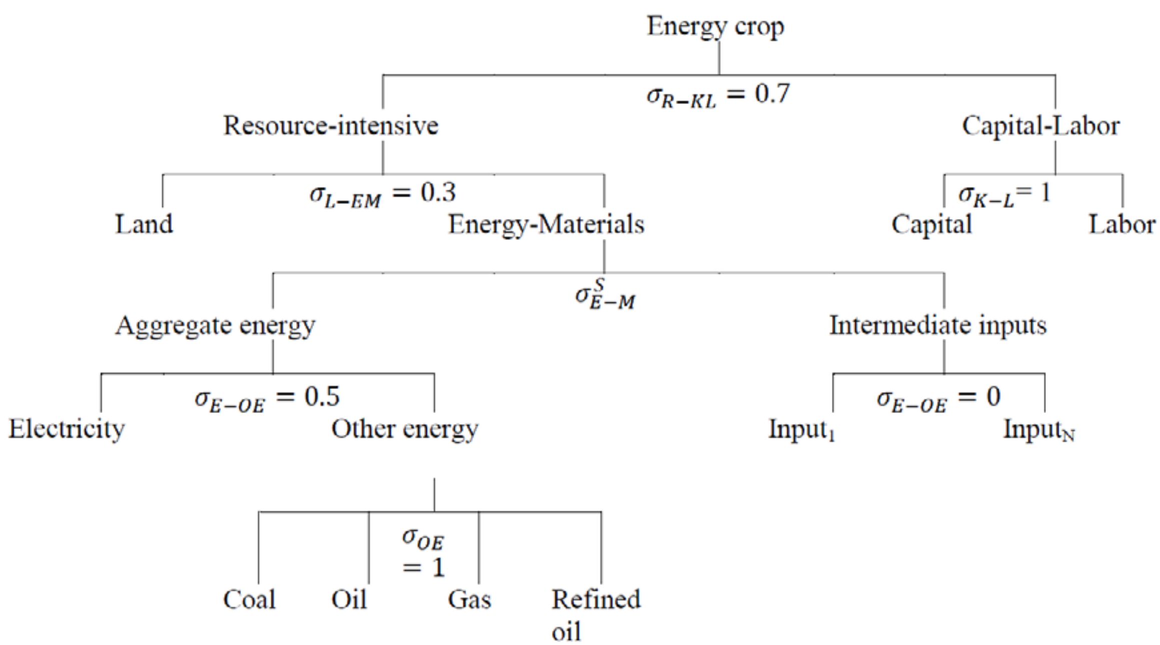

Figure A1. Nesting structure for production of energy crop in the EPPA model.

changes in land prices by allowing substitution between land and the energy materials composite (*e.g.*, fertilizer) and between the resource-intensive bundle and the capital-labor aggregate. The model also includes compounding exogenous yield improvements of 1% per year for all crops (including food crops), which is applied to the base yields in each case.

The fuel costs for the bioenergy technologies are based on the base year feedstock costs in the EPPA model. These feedstock costs vary by region as the biomass crop yields vary by regions. The base year fuel costs for EPPA regions are given in **Table A1**.

Technology cost structure in the EPPA model (Morris *et al.*, 2019)

As described in (Morris, Reilly and Chen, 2019), the relative costs of all technologies in the base year of the EPPA model need to be defined. This is done by using "markups", which represent the cost of a technology relative to the price received for electricity generation. A markup of 1.5 therefore means that the technology is 50% more expensive in the base year than the price received for electricity in that year. Over time, the relative costs will change endogenously as the costs of inputs change and substitution of inputs occurs. The base year markups are determined based on a levelized cost of electricity (LCOE) approach, which is calculated using equation (1):

$$LCOE = \frac{TCR \times CRC}{OH} + \frac{FOM}{OH} + VOM + FC + CTS \qquad (1)$$

$$CRC = \frac{r}{1-(1+r)^{-n}} \qquad (2)$$

Table A1. Base year biomass fuel costs in the EPPA model (in 2007$)

Region	$/MMBTU	Region	$/MMBTU
AFR	2.85	**JPN**	10.86
ANZ	2.91	**KOR**	3.25
ASI	3.25	**LAM**	2.85
BRA	2.67	**MES**	4.62
CAN	2.87	**MEX**	2.74
CHN	3.99	**REA**	3.73
EUR	3.19	**ROE**	3.43
IDZ	3.25	**RUS**	2.83
IND	6.07	**USA**	3.22

In equation (1), TCR is total capital requirement (overnight capital costs + construction schedule cost), CRC is capital recovery charge, calculated from equation (2); r is the discount rate, n is the project life (20 years); OH is operating hours (capacity factor x hours in year); FOM is the cost of the inputs that do not depend on the level of production (fixed operation and maintenance or O&M); VOM is variable O&M per kWh; FC is fuel cost in $/BTU multiplied by the heat Rate (BTU/kWh); CTS is the cost of transportation and storage of captured CO_2 per kWh (for CCS technologies).

The LCOE and markups used in the study are shown for the U.S. in **Tables A2 and A3**. Markups for other regions in the EPPA model are provided in (Morris *et al.*, 2019). The data sources used for the bioenergy generation technologies include (IEA, 2015; Cuellar and Herzog, 2015;

Table A2. Markup Calculation for USA for established power generation technologies (in 2015$).

	Units	Coal	Gas	Biomass	Wind	Solar	Nuclear
"Overnight" Capital Cost	$/kW	2148	1031	4181	1845	1581	4286
Scaled Overnight Capital Cost	$/kW	2365	1135	4602	2031	1740	4718
Total Capital Requirement	$/kW	2743	1226	5339	2194	1879	6133
Capital Recovery Charge Rate	%	10.6	10.6	10.6	10.6	10.6	10.6
Fixed O&M	$/kW/year	39	30	109	50	26	71
Variable O&M	$/kWh	0.0035	0.0028	0.0054	0.0147	0.0168	0.0035
Project Life	years	20	20	20	20	20	20
Capacity Factor	%	85	85	80	35	20	85
Capital Recovery Required	$/kWh	0.0389	0.0174	0.0805	0.0756	0.1133	0.0870
Fixed O&M Recovery Required	$/kWh	0.0052	0.0041	0.0155	0.0165	0.0146	0.0095
Efficiency (HHV)	%	42	53	30			33
Fuel cost	$/GJ	2.08	4.16	3.14	0	0	0.0096
Levelised Cost of Electricity	$/kWh	0.0656	0.0523	0.1391	0.1068	0.1447	0.1097
Transmission and Distribution (T&D)	$/kWh	0.03	0.03	0.03	0.03	0.03	0.03
Levelised Cost of Electricity *incl.* T&D	$/kWh	0.0956	0.0823	0.1691	0.1368	0.1747	0.1397
EPPA Base Year Electricity Price	$/kWh	0.09	0.09	0.09	0.09	0.09	0.09
Markup Over Base Electricity Price		1.03	0.89	1.83	1.48	1.89	1.51

Table A3. Markup Calculation for USA for advanced power generation technologies (in 2015$).

Parameter	Units	Coal w/ CCS	Gas w/ CCS	BECCS	Coal+ Bio CCS	Gas w/ Adv CCS	Wind Gas	Wind Bio
"Overnight" Capital Cost	$/kW	4100		8867			2536	6026
Scaled Overnight Capital Cost	$/kW	4514		9762			2792	6634
Total Capital Requirement	$/kW	5417	2236	11714	563	1431	3015	7165
Capital Recovery Charge Rate	%	10.6	10.6	10.6	10.6	10.6	10.6	10.6
Fixed O&M	$/kW/year	62	59	169	78	35	58	159
Variable O&M	$/kWh	0.0057	0.0065	0.0087	0.0057	0.0028	0.0141	0.0132
Project Life	years	20	20	20	20	20	20	20
Capacity Factor	%	85	85	80	85	85	42	42
(Capacity Factor Wind)	%						35	35
(Capacity Factor Biomass/NGCC)	%						7	7
Capital Recovery Required	$/kWh	0.0769	0.0332	0.1766	0.0799	0.0203	0.0866	0.2058
Fixed O&M Recovery Required	$/kWh	0.0084	0.0079	0.0242	0.0104	0.0048	0.0157	0.0433
Efficiency (Higher Heating Value)	%	33	45	21	32	53	40	30
Fuel cost	$/GJ	2.08	4.16	3.14	2.08	4.16	4.16	3.14
Levelised Cost of Electricity	$/kWh	0.1230	0.0845	0.2783	0.1298	0.0594	0.1194	0.2655
Transmission and Distribution (T&D)	$/kWh	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Levelised Cost of Electricity *incl.* T&D	$/kWh	0.15	0.11	0.31	0.16	0.09	0.16	0.31
EPPA Base Year Electricity Price	$/kWh	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Markup Over Base Electricity Price		1.66	1.24	3.34	1.73	0.97	1.73	3.31
For CCS								
Carbon content	kgC/GJ	24.686	13.700	24.975	24.686	13.7		
Capture efficiency	%	95	90	90	95	10		
Cost of CO_2 Transport & Storage (T&S)	$/tCO_2$	10	10	10	10	10		
CO_2 T&S cost	$/kWh	0.0094	0.0036	0.0143	0.0096	0.0034		

Rubin *et al.*, 2015). For the overnight capital for BECCS, we take the overnight capital cost for Biomass and add the difference in capital cost between Coal with CCS and Coal, and then we adjust that value for the decrease in efficiency from adding CCS, which we assume drops from 30% (based on Cuellar and Herzog, (2015)) to 21% (which is the same difference in efficiency as between Coal and Coal with CCS). Efficiencies are converted to heat rates by dividing the number of BTUs in one kWh of electricity (3412) by the efficiency. Fixed O&M costs for BECCS come from (Cuellar and Herzog, 2015). Variable O&M costs for BECCS are calculated by scaling the variable O&M for Biomass by the ratio of variable O&M between Coal and Coal with CCS.

The cost of transportation and storage of captured CO_2 is assumed to be \$10/tCO_2, consistent with (Hamilton *et al.*, 2009; NETL, 2013; Rubin *et al.*, 2015). The CO_2 transportation and storage cost per kWh is added to the LCOE. The base fuel cost for biomass comes from GTAP. The LCOE for BECCS in each region is compared to the base year electricity price in that region to calculate that region's markup for BECCS. The markups for BECCS for the 18 regions in the EPPA model are given in **Table A4**.

Electricity from biomass

Electricity from biomass, with and without CCS, produces a perfect substitute for other generation technologies that do not have additional requirements for integration to the grid. We assume that it can be used for baseload and peaking generation. The rate of penetration of the bioelectric technology is determined by the technology specific factor that is described in Morris *et al.*, (2019). **Figure A2** illustrates the nesting structure for the production of bioelectricity. The technology represents electricity production using the energy crop, capital and labor inputs. The input shares are parameterized based on Table A4 for the USA, and corresponding tables for other regions. BECCS generates emissions permits as a co-product of the electricity generation. BECCS generates emissions allowances (which is a source of revenue) by storing CO_2 released in the process of biomass combustion, therefore creating negative emissions (since those emissions were absorbed by the biomass while growing). The amount of negative CO_2 created is calculated based on the fuel input amount.

Table A4. BECCS Markups by EPPA Region

Region	BECCS Markup	Region	BECCS Markup
AFR	3.25	**JPN**	3.00
ANZ	3.02	**KOR**	2.76
ASI	2.47	**LAM**	3.19
BRA	2.68	**MES**	2.26
CAN	4.68	**MEX**	2.12
CHN	3.76	**REA**	2.53
EUR	2.46	**ROE**	2.53
IDZ	2.45	**RUS**	2.68
IND	3.30	**USA**	3.34

CO_2 storage capacity

Assessments of the geologic storage capacity of carbon dioxide in the current literature are incomplete and inconsistent, complicating efforts to assess the worldwide potential for CCS. Kearns *et al.*, (2017) developed a method for generating first-order estimates of storage capacity requiring minimal data to characterize a geologic formation. Their simplified method accounts for the majority of the variance in storage capacity found in more detailed studies conducted in the United States. They estimate that globally there are between 8,000 and 55,000 gigatonnes (Gt) of practically accessible geologic storage capacity for carbon dioxide storage. **Table A5** provides a summary of the results for the regions of the EPPA model.

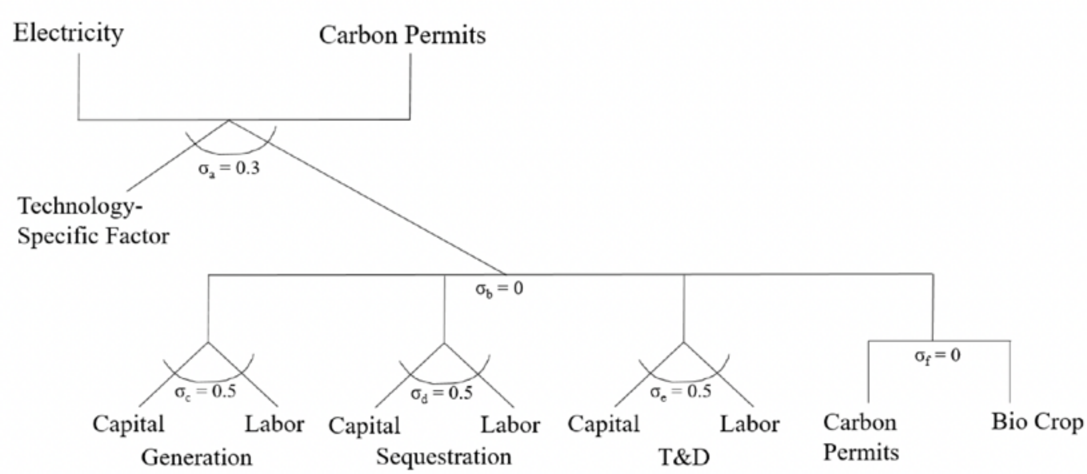

Figure A2. Nesting structure of bioenergy generation with CCS (BECCS).

Table A5. Storage capacity estimates for regions defined by the EPPA model. Note: Totals in the table may not add up due to rounding. Source: Kearns *et al.*, (2017)

EPPA 6	Regions	Estimated Storage capacity (Gt)							
		Lower Estimate[a]				Upper Estimate[b]			
		On-shore	Offshore		Total[c]	On-shore	Offshore		Total[c]
			Technical[d]	Practical[e]			Technical[d]	Practical[e]	
AFR	**Africa**	1344	880	220	1563	9444	6185	1543	10986
ANZ	**Australia & New Zealand**	334	699	261	595	2349	4912	1835	4184
ASI	**Asia**	36	115	83	119	251	806	593	834
BRA	**Brazil**	224	267	73	297	1572	1877	515	2087
CAN	**Canada**	206	514	112	318	1445	3610	790	2236
CHN	**China**	325	100	77	403	2286	704	544	2830
EUR	**Europe**	161	492	141	302	1129	3459	991	2120
IDZ	**Indonesia**	96	166	67	163	672	1163	472	1144
IND	**India**	75	264	25	99	525	1853	172	697
JPN	**Japan**	4	24	5	8	26	171	34	59
KOR	**Korea**	0	9	3	3	0	62	24	24
LAM	**Other Latin America**	443	614	163	606	3111	4317	1145	4257
MES	**Middle East**	370	218	121	492	2603	1530	851	3454
MEX	**Mexico**	79	200	58	138	556	1408	411	967
REA	**Other East Asia**	161	377	110	272	1135	2651	776	1911
ROE	**Other Eurasia**	415	202	70	485	2916	1422	494	3410
RUS	**Russia**	1180	621	54	1234	8291	4361	382	8673
USA	**United Sates**	551	445	261	812	3872	3130	1836	5708

a 0.037 Gt per thousand cubic kilometers sedimentary basin.
b 0.26 Gt per thousand cubic kilometers sedimentary basin.
c Onshore and practically accessible offshore.
d All offshore aeras for which data is available.
e Water depth less than 300 meters, within 200 miles of a major landmass, and outside of Arctic or Antartic regions.

Appendix B. Supplementary results

Results in **Figure B1** show that most of the fossil fuels deployed in the 2°C and 1.5°C scenarios are combined with CCS. Only the inclusion of bioenergy with CCS encourages the use of bioelectricity. As noted with Figure 1 of the main text, BECCS enables the prolonged use of fossil fuel without CCS such as gas, which only starts phasing out by 2080, as compared to 2050 in the 2°C scenario without BECCS.

Agricultural commodity price indices under different land productivity scenarios

Figure B2 presents the evolution of the food, crop and livestock products indexes in the BAU, 1.5°C and 1.5°C BECCS scenarios, for median, low ("LowProd") and high ("HighProd") annual land productivity increases. As expected, it is observed that the level of land productivity improvement over time impacts agricultural commodity prices. Under a 1.5°C BECCS and low land productivity scenario, food price index increases by 8% relative to the 2015 value, as compared to the 4% increase in the average land productivity scenario. In the high productivity, however, food price index increases by 4% by mid-century, but drops to its 2015 level by the end of the century.

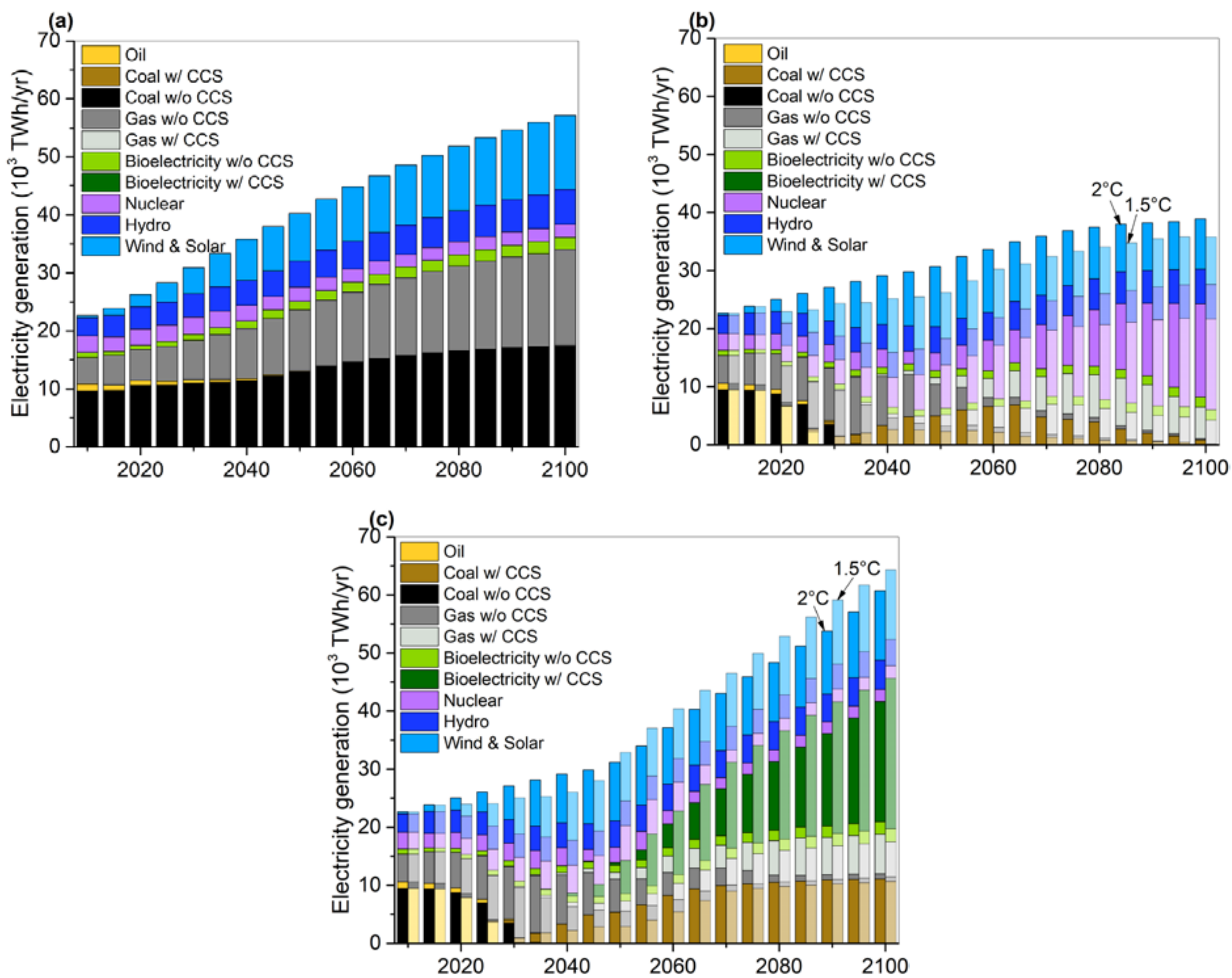

Figure B1. Total electricity generation mix in the BAU scenario (a), in the 2 and 1.5°C scenarios without BECCS (b), and in the 2 and 1.5°C scenarios with BECCS (c). Most fossil fuel deployed after 2050 use CCS in the 2°C scenario, whereas BECCS enables the prolonged use of gas without CCS until the last quarter of the century. Without BECCS, bioenergy barely contributes to the electricity system.

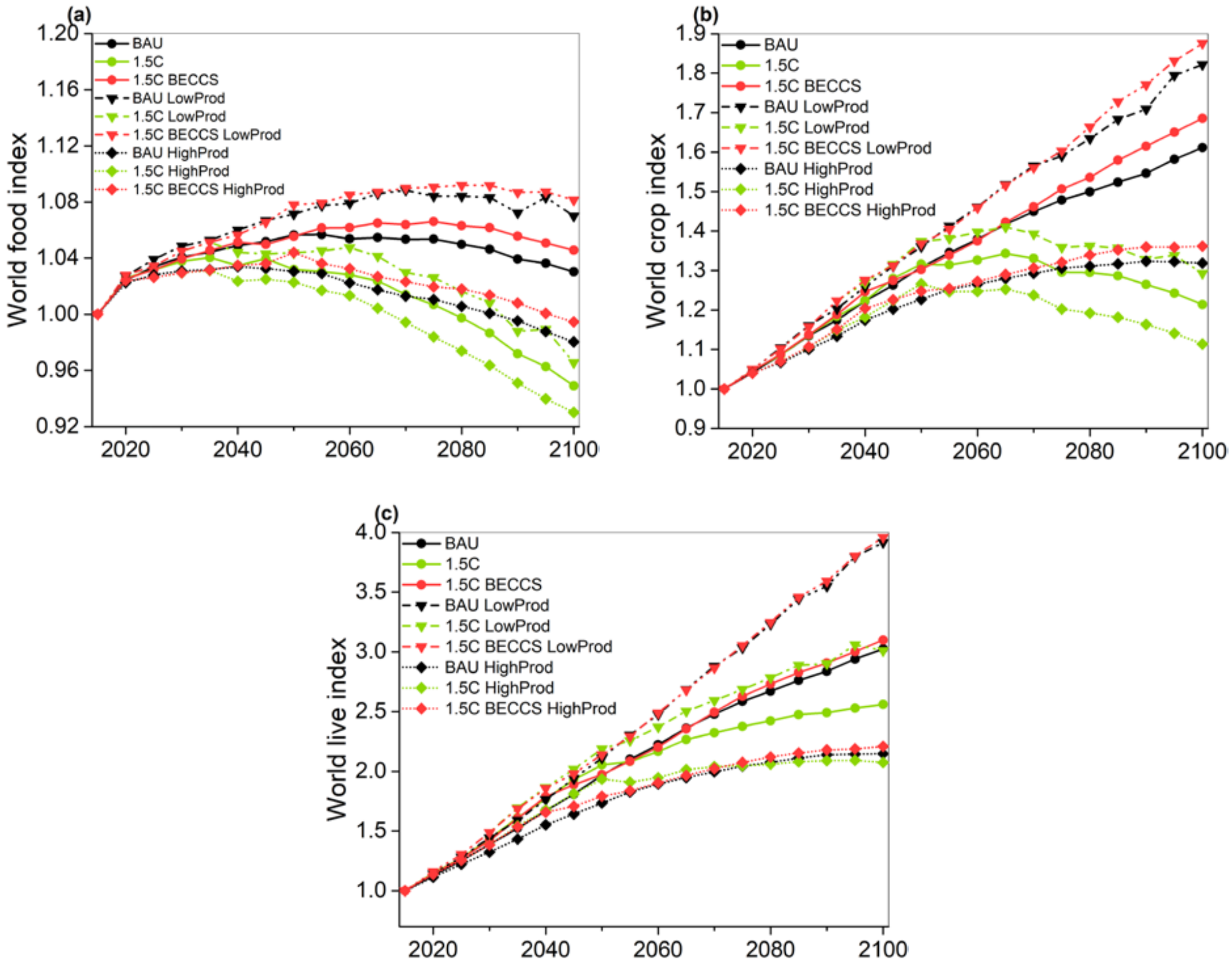

Figure B2. World index of food (a), crop (b) and livestock (c) products under the BAU, 1.5°C and 1.5°C BECCS policies, for a medium land productivity level (1%), a high land productivity level (1.25% or "HighProd") and a low land productivity level (0.8% or "LowProd"). Even at low land productivity, the increase in global food price index relative to 2015 remains below 8% in the 1.5 BECCS scenario.

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