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Title

The role of bioenergy for global deep decarbonisation: CO₂ removal or low-carbon energy?

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Global bioenergy in deep decarbonisation scenarios

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Abstract

Bioenergy is expected to have a prominent role in limiting global greenhouse emissions to meet the climate change target of the Paris Agreement. Many studies identify negative emissions from bioenergy with carbon capture and storage (BECCS) as its key contribution, but assume that no other CO₂ removal technologies are available. We use a global integrated assessment model,

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TIAM-UCL, to investigate the role of bioenergy within the global energy system when direct air capture and afforestation are available as cost-competitive alternatives to BECCS. We find that the presence of other CO₂ removal technologies does not reduce the pressure on biomass resources but changes the use of bioenergy for climate mitigation. While we confirm that when available BECCS offers cheaper decarbonisation pathways, we also find that its use delays the phase-out of unabated fossil fuels in industry and transport. Further, it displaces renewable electricity generation, potentially increasing the likelihood of missing the Paris Agreement target. We found that the most cost-effective solution is to invest in a basket of CO₂ removal technologies. However, if these technologies rely on CCS, then urgent action is required to ramp up the necessary infrastructure. We conclude that a sustainable biomass supply is critical for decarbonising the global energy system. Since only a few world regions carry the burden of producing the biomass resource and store CO₂ in geological storage, adequate international collaboration, policies, and standards will be needed to realise this resource while avoiding undesired land-use change.

Keywords

Bioenergy, BECCS, climate change mitigation, integrated assessment, scenario analysis, carbon dioxide removal

Introduction

Biomass has many potential applications across the energy system, including power generation or the production of heat and transport fuels (IEA 2017). Fitting bioenergy generation with carbon capture and storage (BECCS) could potentially deliver “negative emissions” (Smith *et al* 2016), which many studies have found to be critical for achieving net zero global CO₂ emissions later this century (IPCC 2014, 2018a). In a review of scientific literature on Carbon Dioxide Removal (CDR) technologies, Fuss *et al* (2018) conclude that, subject to biomass cultivation sustainability constraints and adequate supply chain governance, BECCS could remove up to 5 GtCO₂/yr by 2050.

Under limited global biomass resource potential, bioenergy could make an important contribution to reducing emissions in the transport sector in which low-carbon alternatives are expensive or impractical (Creutzig *et al* 2015, Pavlenko *et al* 2016). Others strongly advocate the role of large-scale deployment of BECCS in all sectors to meet the Paris Agreement (Dessens *et al* 2016, Fuss *et al* 2018). Crucially, and assuming that the primary input can be sourced sustainably, the effectiveness of carbon reduction from using bioenergy is determined by what it substitutes. The carbon savings are significant when substituting coal and oil, but small or non-existent when replacing renewable generation. These factors introduce considerable uncertainty around the role biomass could play in decarbonizing global energy systems.

Based on a life-cycle assessment (LCA) approach, Pavlenko *et al* (2016) suggest that transport biofuels could enable deeper decarbonisation of aviation, shipping, and heavy-duty transport, as these are likely to remain reliant on liquid carbon-based fuels in the longer term. They also consider a role for baseload biomass electricity generation to complement renewables in the short-term, but warn that long-term displacement of coal with biomass could hinder further renewable deployment. Using similar LCA methods, Staples *et al* (2017) conclude that using biomass to replace fossil electricity and heat is 1.6–3.9 times more effective for emissions mitigation than replacing liquid fuels, over their full life cycles. In other words, using biomass for electricity and heat would lead to a greater GHG emissions reductions as compared to using the same biomass for transport liquid fuels. However, due to the decarbonisation of the electricity mix over time they note that the GHG savings from bio-electricity decrease, therefore using between 18%–49% of the total biomass supply in 2050 for liquid transport fuels would lead to the greatest GHG emission savings.

Using IMAGE, an Integrated Assessment Model (IAM) that includes a simulation of the global energy system, Daioglou *et al* (2015) analyse competing uses of biomass for producing fuels and chemicals. Although incremental carbon tax scenarios divert increasing amounts of bioenergy towards electricity generation with CCS, they only consider BECCS plants for electricity generation and call for studies with a wider range of BECCS technologies to examine their results. Comparing 15 IAMs to understand the role of bioenergy in climate management, Rose *et al* (2014) conclude that it has a very high value for global energy systems, particularly under stringent climate targets, but call for more evidence around drivers of bioenergy use in IAMs. They also highlight the need to understand the role that climate constraints, biomass availability and model setup play in determining what bioenergy substitutes in the system. Reviewing scenarios from 22 IAMs for a 2 °C target, Dessens *et al* (2016) conclude that BECCS would be critical for achieving negative emissions in the second half of the century. They warn that delay or absence of BECCS from the technology portfolio make mitigation both harder and costlier to achieve.

More recent publications have however taken a step back and suggested that the role of biomass in delivering negative emissions through BECCS may not be as critical as expected. By comparing scenario results from 11 IAMs, Bauer *et al* (2018) highlight that bioenergy use is driven by levels of supply, but also by the availability and cost of biotechnologies (including BECCS), and the level of carbon budgets. Low budgets tend to see bioenergy allocated between electricity and liquid fuels in ratios that depended on fuel substitutability and low-carbon technologies modelled in each sector. The additional bioenergy which some models use for BECCS primarily increases the supply of low-carbon fuels without affecting net CO₂ removal. This highlights that the provision of carbon removal is not the only driver of BECCS deployment in energy systems. Looking at model structure, the IPCC (2018a) find a reduced role for BECCS in recent literature covering improved demand-side modelling, better consideration of behavioural change, the inclusion of other negative emission technologies, and a larger emphasis on the sustainability trade-offs between food and energy systems that reduce the potential for BECCS.

In practice, only one BECCS plant is operational. Located in Decatur, Illinois, USA, the \$208m plant captures 1 MtCO₂/yr from corn bioethanol production (Global CCS Institute 2017).

Achieving the negative emissions identified by Fuss *et al* (2018) for a 2 °C scenario would require 4000–6000 equivalent plants by 2050.

In view of the currently limited production of biomass for energy and lack of BECCS demonstration plants globally, it remains uncertain whether BECCS could be deployed at the rates required in IAM scenarios produced to date. Previous studies had only BECCS as a CDR option, and it is not clear if including alternatives would lead to similar conclusions as to biomass use within the energy system. We therefore complement the existing literature by answering a key question: what is the role of biomass for global climate change mitigation if CDRs other than BECCS are available? Specifically:

1. Does the availability of other CDR options reduce the need for BECCS?
2. Does the role of biomass for decarbonising the global energy system change if other CDRs are available?
3. Does the availability of other CDRs reduce the pressure on global biomass supply and trade?

We investigate these questions using long-term scenario analyses in TIAM-UCL (the TIMES Integrated Assessment Model). TIAM-UCL identifies global cost-optimal energy system investments that meet emissions targets. We investigate the role of bioenergy in climate change mitigation for scenarios in which the global temperature increase does not exceed 2 °C compared to pre-industrial levels. In line with Creutzig *et al* (2015) and the IPCC (2018a), we investigate these questions under scenarios of limited biomass availability, i.e. 100 EJ/yr, justified by the difficulty of achieving large-scale production of consistently sustainable biomass. In contrast to previous studies, we analyse bioenergy deployment in the presence of two other CDRs: direct air capture and storage (DACs) and afforestation/reforestation (AR). To understand the regional challenges of implementing bioenergy pathways under a global 2 °C target, we dig into regional specificities of trade and Carbon Capture and Storage (CCS) development. We then discuss these insights within the broader context of regional resource and storage availability, sustainability of supply and regional decarbonisation plans.

Materials and methods

We design and run scenarios using TIAM-UCL, a partial equilibrium model of the global energy system that identifies cost-optimal energy pathways subject to constraints, including global climate targets (Loulou and Labriet 2008). National economies are aggregated into 16 regions,

representing either single nations or groups of multiple countries, for which energy service demands are defined and met throughout the modelling period (Anandarajah *et al* 2011). Demand projections are based on future trends of drivers including GDP, population, household size, and sectoral outputs. In this study, these trends are consistent with a Shared Socioeconomic Pathway 2 (SSP2) future, that is, a middle-of-the-road scenario (Riahi *et al* 2017). Numerous energy supply technologies are defined for future deployment in each region to meet these demands. TIAM-UCL represents energy system transitions using five-year time steps to 2050 followed by ten-year steps to 2100.

Four features of the model are critical to this analysis and make it possible to advance upon previous work done in this field:

- i. bioenergy resources and technologies are available in each region, both with and without CCS, to produce electricity, hydrogen, transport fuels and/or heat;
- ii. global trade of biomass resource, bioenergy commodities and carbon permits is allowed between regions;
- iii. DACS and AR are available as alternative CDRs to BECCS in each region; and,
- iv. a climate module dynamically links cumulative global emissions to radiative forcing and global temperature.

For this work we have updated TIAM-UCL biomass resource assumptions and have revised carbon accounting for biomass to include GHG emissions from land-use change (LUC) as well as carbon sequestration by AR. First generation fuels are represented through the inclusion of bioliquids (bioethanol and biodiesel from food crops) and biomethane (gas captured from industrial and municipal waste treatment options, and from controlled landfill sites). Primary feedstocks for second generation technologies are represented as four fractions: (i) energy crops, cultivated for energy purposes only, (ii) solid biomass, comprising agricultural and forest residues, (iii) municipal solid waste, which includes waste produced by households, industry, hospitals and the tertiary sector that are collected by local authorities; and (iv) industrial waste, with both solid and liquid products (e.g. tyres, sulphite lyes (black liquor)), usually combusted directly in specialised plants to produce heat and/or power (Anandarajah *et al* 2011). Regional availability of solid biomass is based on (Daioglou *et al* 2016) while energy crops values rely on (van Vuuren *et al* 2017, Ricardo-AEA 2017). Final assumptions used in TIAM-UCL for this work are shown in Figure 1. Biomass costs in 2050 vary between 4 and 16 \$/GJ for solid biomass, and between 6 and

15 \$/GJ for energy crops depending on the region. These costs do not include a potential increase of land costs due to increased bioenergy demand. Note that all costs are considered in 2005 USD. The waste fraction costs are included in TIAM using an import cost, ranging between 6 and 8 \$/GJ, for bringing the commodity into the energy system. The costs of processing these waste streams into energy feedstock are included as operational costs of the different processing technologies that deal with that waste on the upstream side of the subsequent energy chains.

These assumptions consider that energy crops are cultivated only on degraded agricultural land and pastures which cover 207 Mha in 2050 (Ricardo-AEA 2017). This area remains constant to 2100 and we do not allow competition with food production or other uses of land. Available land and energy crop yields are detailed on a regional basis and determine the maximum amount which can be produced by energy crop production technologies in each region. In addition, the energy crops produced in our scenarios cause emissions which vary from 15–25 kgCO₂/GJ between regions. These represent the impact of bringing degraded land into cultivation in terms of land-use (LU) and land-use change (LUC). The first is linked to planting, growing and harvesting the biomass; the second, to switching land from its current use to the production of energy crops (Daioglou *et al* 2017). The resulting emission factors are attached to the technologies which produce the energy crops: each unit of crops produced is linked to a corresponding level of CO₂ emission. We do not consider indirect LUC potentially caused by energy crops expansion and LUC emissions for other biomass fractions.

Non-waste biomass resources as well as biofuel commodities (bio-diesel, bio-kerosene, bio-jet kerosene, bio-naphtha) and their fossil counterparts can be traded between the 16 regions of the model. Waste fractions can only be used within each region. Assumptions on the regional distribution of biomass fractions are represented in Figure 2.

A range of commodities can be produced from biomass in TIAM-UCL: (i) electricity generated by combustion or gasification of biomass with and without (w and w/o) CCS; (ii) heat from biomass in combined heat and power w/o CCS and in large-scale plants w CCS; (iii) hydrogen from small-, medium- and large-scale biomass plants; and (iv) transport fuels produced through Fischer Tropsch (FT) processes available w and w/o CCS. Bioenergy technologies w/o CCS can use any biomass fraction, but BECCS relies only on energy crops and solid biomass. A schematic representation of bioenergy pathways in TIAM-UCL is given in Figure 3. The techno-economic

assumptions used to describe these technologies are listed in the Supporting Information, together with assumptions on fossil CCS, AR and DACS.

The model also has a backstop mechanism. This technology is deployed if the model does not have sufficient mitigation options to remain within a given temperature limit or carbon budget. This is only done as a last resort: the option is costed well above the most expensive technological option in the model, at \$5000/tCO₂.

The TIAM-UCL climate module is used to constrain global temperature increase to a maximum of 2 °C above preindustrial levels. We model a greater than 66% likelihood of staying below 2 °C by limiting the cumulative global carbon budget to 1,180 GtCO₂ over 2018-2100 (IPCC 2018c).

To answer our research questions, we analyse bioenergy pathways across four scenarios: Reference, with no climate target and no AR; and three no-overshooting 2 °C scenarios, differentiated by the inclusion and exclusion of BECCS and DACS technologies (Table 1). The scenarios excluding BECCS and DACS assume that they would not be economically-viable technologies. In all scenarios, we assume the same sustainable biomass resource availability.

Results

We examine the results in three time periods that address short- (up to 2030), mid- (2030-2050) and long-term (2050-2100) system changes.

BECCS as one of multiple CDR options

The availability of different CDR options in the system leads to similar decarbonisation pathways under the assumption of no overshooting 2 °C, as reflected in the trajectory of global net CO₂ emissions presented in Figure 4. In all 2 °C the global net emissions drop considerably in the short and medium term to ensure that warming peaks by 2060. When DACS is not available (scenario 2C_noDACS) the CO₂ emission removal by BECCS and AR is not sufficient and the system has to resort to backstop technologies in the last decade of the century to keep global temperature increase under 2 °C. When BECCS is not available (2C_noBECCS), the system is able to find an optimal solution due to the high CO₂ emission removal by DACS.

Net CO₂ output is shown as a combination of emissions and removals in Figure 5. In the short-term, CO₂ emissions are mitigated across all sectors and all 2 °C scenarios as compared to the

Reference. The fastest emission reduction occurs in electricity generation by combining increased renewable generation, including biomass, and the deployment of fossil CCS. By 2030, CCS installed on fossil power plants captures between 60 MtCO₂/yr in 2C_full and 76 MtCO₂/yr in 2C_noBECCS. Industry also shows strong decarbonisation in the short-term. Due to limited low-carbon options, the principal decarbonisation option in industry is installing CCS on industrial facilities which, by 2030, captures around 310 MtCO₂/yr in all 2 °C scenarios.

These trends continue in the mid-term with all scenarios seeing the power sector reach virtually net zero emissions by 2040, when BECCS for electricity generation is available, vs 2050 in the scenario without BECCS. This has knock-on effects in lowering emissions from buildings and transport, which are both strongly electrified by mid-century. In industry, fossil CCS is ramped up to capture around 2.3 GtCO₂/yr by 2050. An even faster ramp up occurs for BECCS and DACS, which remove respectively up to 3.7 GtCO₂/yr, and 60 to 112 MtCO₂/yr by 2050. Note that when allowed in our scenarios, BECCS starts in 2030 and DACS in 2040.

When BECCS is not allowed in the system, in the 2C_noBECCS, high heat and electricity requirements from DACS lead to significant increase in power sector emissions, by 0.4 GtCO₂/yr in 2050 and 0.6 GtCO₂/yr in 2080. This is due to energy requirements for DACS being met using gas and coal fitted with CCS, technology options with net positive CO₂ outputs that increase total emissions to be removed. Conversely, the unavailability of DACS leads to infeasibility, i.e. backstop technologies are required in the last decade of the century to remove approximately 2 GtCO₂. This means that the system is not able to supply the required energy demand and decarbonise fast enough to keep the temperature increase under 2 °C by the end of the century.

Overall, both 2 °C feasible scenarios show high levels of CO₂ removal and sequestration in geological storage. The highest levels of CO₂ capture climb to 7 Gt CO₂/yr in 2080 in the 2C_full, when fossil CCS captures 4.5 Gt CO₂/yr, BECCS 2.3 and DACS 0.1 Gt CO₂/yr. Cumulatively, between 2030 and 2100 the total CO₂ capture and storage requires a geological storage between 490 GtCO₂ (2C_noBECCS) and 540 GtCO₂ (2C_full).

Role of biomass for decarbonising the global energy system

As shown in Figure 6, the role of biomass for decarbonising the global energy system is critical, i.e. both feasible 2 °C scenarios use higher levels of biomass than the Reference, and maximise global reliance on biomass by 2050. Most importantly, DACS availability allows a scenario w/o

BECCS to solve, while its unavailability leads to infeasibility due to the low availability of biomass (and therefore low removal by BECCS) considered in this study. Depending on the availability of BECCS, biomass has different uses within the system. In the short-term, the 2 °C scenarios rely on modern bioenergy to decarbonise power and industry by replacing coal in electricity generation and industrial heat production. When available, BECCS is built as fast as possible and diverts biomass from heat and power w/o CCS towards electricity generation w CCS. This trend continues through the 2050s with the capacity of BECCS for electricity increasing from 70 GW in 2030 to 400 GW in 2050. By 2050, traditional use of biomass is phased out in the majority of regions, except for Africa, South-Eastern Asia and India. This frees up to 6 EJ biomass resource per year that are used instead for large-scale heat and FT fuels production w CCS. When BECCS is not available, biomass is used for decarbonising industry and transport (bio FT fuels w/o CCS). In the long-term, as electricity decarbonises using renewable energy, biomass is diverted from electricity generation to heat and FT fuels w CCS (when BECCS is available) and to FT fuels and residential use w/o CCS (when BECCS is not available).

Across the scenarios analysed here, in the period to 2030, modern biomass w/o CCS is used to reduce emissions from electricity generation and industry. These findings mirror real world developments; for example, the Drax power plant in the UK converted 2,400 MW coal generation to biomass (Drax power, 2018). After 2030, the most cost-effective use of biomass depends on the availability of BECCS. If BECCS is not available, then new bioenergy installations after 2030 produce advanced transport fuels and heat w/o CCS. Electricity generation from biomass gradually reduces as bio-power plants come to the end of their lives, with increasing electricity demands met by other renewable generation. Bio-heat generation increases to 2050, led by an increased deployment of DACS. Alternatively, in scenarios in which BECCS is available, bioenergy is used w CCS for electricity and heat generation as they capture a greater proportion of biomass carbon than transport biofuel plants, suggesting that BECCS is deployed for its CDR potential, rather than low-carbon fuels supply.

The use of BECCS for producing electricity has the potential to affect the amount of installed renewable capacity. Figure 7 compares the installed capacity for electricity generation in the 2C_full vs 2C_noBECCS in the short-, mid- and long-term. The renewable capacity in the 2 °C with full technology base (2C_full) is consistently lower than in the case 2C_noBECCS in the three periods analysed. The biggest difference is seen in 2050, when the global installed renewable

capacity in 2C_full is 1,300 GW lower than in 2C_noBECCS. Putting this into context, the global renewable capacity in 2018 was of 2,351 GW. This suggests that BECCS used for electricity generation may displace renewable electricity generation. To avoid this happening, earlier investments in renewables are required, at the same time as investments in CDR. We tested this finding in our sensitivity analyses, in which we halved the costs of solar PV from 2020.

In terms of the cost effectiveness of using biomass for global mitigation, Figure 8 illustrates the efficiency of biomass use for reducing CO₂ emissions against the global mitigation costs across the mitigation scenarios analysed here. Efficiency is measured using cumulative biomass use over the period 2015 – 2100 divided by cumulative CO₂ emission reduction in each scenario as compared to the Reference. Similarly, the mitigation cost is taken as the difference in total system cost between each scenario and the Reference, respectively. Note that our measure of biomass efficiency for climate mitigation reflects the overall climate mitigation in the energy system, including but not limited to different uses of biomass for climate mitigation across different sectors. For example, in the scenario 2C_full, the overall emission reduction are due to a combination of energy efficiency measures across all sectors, biomass used as low-carbon fuel to replace fossil fuel supply chains, and BECCS acting as CDR besides AR and DACS. In the 2C_noBECCS scenario, the system loses one CDR option (BECCS) but still counts on low-carbon bioenergy across all sectors, and available AR and DACS for CO₂ removal. By using this aggregated measure of biomass efficiency, we aim to understand system configurations that lead to the highest emission reduction with the lowest use of (scarce) biomass.

In terms of costs, our results confirm that the unavailability of BECCS in the system results in higher system costs, in line with previous studies (e.g. Rose *et al* 2014, Daioglou *et al* 2015, IEA 2017). Furthermore, our results suggest that allowing for a combination of CDRs across the energy system (2C_full) is cheaper than limiting the type of CDR technologies (i.e. no BECCS). To put this in context, the difference between the total cost of the global energy system over the full time horizon in the 2C_full and the 2C_noBECCS scenario is around 17 % of 2018 global GDP. While this cost difference seems relatively small, it is subject to high uncertainties as all CDR technologies considered in this study are currently in their infancy and are still to be developed and built at scale.

The no DACS scenario is infeasible, as there is insufficient CO₂ removal capacity available to the system with the inflexible energy demands of the SSP2 pathway. Converging towards a feasible

solution in this scenario would require either mitigating energy demand or building more CDR technologies into the system (e.g. increasing global AR or BECCS capacity), or developing other CDR technologies, (e.g. soil carbon management), which are not explored here. The energy demand reduction case is investigated in the sensitivity analyses below, and the increased BECCS and AR is considered in the discussion section.

In terms of biomass efficiency for climate mitigation, the 2C_noBECCS scenario uses the least amount of biomass per unit of CO₂ emission removal. In this scenario biomass displaces unabated fossil fuels, providing low-carbon options for decarbonising industry and transportation. Lower emission reductions per unit of biomass used in the system are observed in the 2C_full. In this case, several CDRs are available in the system. These allow for higher levels of fossil fuel use in the short-term, compensated by stronger CO₂ removal in the second half of the century. These results suggest that CDRs are not mitigation technologies, but they are complementary to the extended use of fossil fuels in the first half of the century.

Biomass supply and geological storage

The results presented in Figures 4 to 8 show an aggregated picture of global biomass for climate mitigation w and w/o CCS. Looking more closely at the regional picture, we now focus on the production and trade of primary biomass, and the global deployment of geological storage.

Production and trade of primary biomass

As illustrated in Figure 9, the production and trade of primary biomass is not influenced by the availability of BECCS. In 2030, the year BECCS starts being deployed when available, both energy crops and solid biomass are exploited to their full potential. At this point in time, Africa, South-Eastern Asia, China and India produce around two thirds of the total global biomass in 2 °C scenarios. The total biomass that enters into global trade represents between 15 and 25 % of the global biomass supply. In both scenarios China is the main importer of solid biomass, from Africa and Canada in the 2C_full, and from Africa, Canada, Western Europe and Central and South America, in the 2C_noBECCS. In both scenarios this biomass is used for industry and power decarbonisation w/o CCS.

By 2050, in both scenarios, energy crop production expands in the majority of regions, providing between 35 and 40% of global tradable biomass. As compared to the 2030s, global biomass trade increases to account to up to half of total produced biomass in 2C_full vs 35% in 2C_noBECCS.

Similar to the 2030s, solid biomass is the main contributor to trade. When BECCS is not available, the main importers are the USA (28%) and the UK (25%), while the main exporters are Canada, South Eastern Asia. As DACS delivers large-scale CO₂ emission removal by 2050, energy crops are brought in to fuel large-scale bio-heat production. This is more visible in the case of smaller players in the international biomass trade; for example, the United Kingdom becomes a big importer of biomass, fuelling bio-heat production w/o CCS for a strong DACS deployment in the country. When BECCS is available, the USA and China are the biggest importers of solid biomass with the main exporters including Canada, Central and South America, and South-Eastern Asia.

By 2080, biomass trade drops again under 20 % of production. When BECCS is available, the main importers are Africa and South-Eastern Asia. Both regions rely on biomass mainly for industrial uses. In the absence of BECCS, the only importer is Africa for which biomass is a critical low-carbon energy feedstock.

Global deployment of geological storage

A limited number of regions account for most carbon sequestration in the 2 °C compliant scenarios. Figure 10 shows that just three regions (China, South-Eastern Asia and India) consistently carry the burden of investing in and deploying more than 50% of the global geological storage required in 2060, the time of the peak warming in our 2 °C scenarios. Western Europe and the USA play a secondary role but are still expected to ramp deployment up significantly in cases when DACS is deployed at large scale. While the USA already has a third of all large scale CCS projects in the world (Global CCS Institute 2017), and China has demonstrated tremendous large-scale infrastructure ramp up (e.g. its wind power capacity increased from 1.3 GW in 2005 to 184 GW in 2017 (Dai *et al* 2018)), other regions might be less prepared for such a quick and large-scale deployment of geological storage. In particular, this ramp up will require the development of extensive CO₂ transport infrastructure linking capture locations to the geological storage. This study assumes that CO₂ transport is available in all regions at an average cost of 10 \$/tCO₂. Using the similar TIAM-FR model, and assuming similar geological storage capacity, (Selosse and Ricci 2017) found that doubling the CO₂ transport price does not reduce the deployment of CCS, but favours the utilisation of onshore storage (closer to the capture site). In our scenarios, onshore storage accounts for 40% of total geological storage. More research is needed to understand the implications of developing such a large-scale CO₂ transport and storage infrastructure. Understanding financing, particularly in developing economies, and public opinion

is important. Also, it is necessary to consider competition for land with food production, urbanisation and protected natural areas that are consistent with meeting the Paris Agreement (IPCC 2018b).

Sensitivity analyses

In energy systems optimisation models such as TIAM-UCL, technology capital costs are key determinants of the final (optimal) energy supply. These costs are affected by assumptions on: (i) technology learning (i.e. technologies become cheaper over time due to increased deployment); (ii) technology hurdle rates, which reflect the risk of investment in certain technologies (similar to weighted cost of capital); and, (iii) system discount rate, which determine how the costs devalue in the future as compared to today. To test the robustness of our results to some of our cost assumptions on bioenergy w and w/o CCS, we run sensitivity analyses on the value of some technology hurdle rates. Synthetic Fischer Tropsch (FT) fuels are still in early stages of development and are being tested at prototype to pilot scale (IRENA 2016). Current challenges include finding cost-effective selective catalysts and upscaling them, so they are risky investments at the moment. In a sensitivity study, we represented this investment risk by increasing their hurdle rate from 10% to 35% in non-OECD countries, and to 25% in OECD countries. This resulted into an almost complete drop of biomass for FT fuels production in 2C_full, as compared to a 25-45 % drop in 2C_noBECCS (Figure S2 in the Supporting Information). Note that this lower impact will, in part, be due to structural effects of TIAM-UCL; while the risk in using FT fuels is higher, the need for it in a world w/o BECCS remains high. Notwithstanding, this suggests more research is needed to better understand the risks associated with the upscale of such incipient technologies.

All the 2 °C scenarios presented above were run with inelastic energy service demands (i.e. demands were fixed to an exogenous trajectory in line with the SSP2 narrative, and were insensitive to increases in energy prices). To test the uses of biomass when final demand could decrease due to increased energy prices, we ran all the 2 °C scenarios with elastic energy service demands, in which TIAM-UCL maximises producer and consumer surplus instead of minimising total system costs. We found that the use of biomass is not affected by a reduction in energy demand, even when this reduction is considerable (i.e. 50% in the transport sector in the 2C_noBECCS run in elastic demand – see Figures S2 and S3 in the Supporting Information). Reduced energy demand means that less CO₂ removal is required. However, with a limited

biomass supply of 100 EJ/yr, a noDACS scenario still does not deliver a 2 °C target. While BECCS were deployed at the same rate as in the scenario with inflexible demand (it removes around 200 GtCO₂ over the period 2030-2100), the relatively inflexible energy demand from industry (less than 10% drop) and buildings (less than 20% drop) lead to the use of backstop technologies. We found the highest reduction in CO₂ removal in the scenario 2C_noBECCS, in which DACS removes 60% less CO₂ as compared to the scenario without elastic demand. However, this was possible by significant deployment of renewable electricity production and drop in the energy demand from the transport sectors, which by 2050 dropped by 50% (Figure S3 in the Supporting Information). The sensitivity analysis also confirms that the most efficient use of biomass within the energy system is w/o CCS (Figure S5 in the Supporting Information) and that BECCS may displace renewable energy generation (Figure S6 in the Supporting Information).

In the light of new research showing that the cost of solar PV is already much lower than typically represented in IAMs (see (Vartiainen *et al* 2019)), we also run a sensitivity analysis halving the capital costs of solar PV. Although our results show that this does not affect the uses of bioenergy for climate mitigation (Figure S7), and BECCS still displaces renewable power including solar PV (Figure S8), lower capital costs for solar PV induced a faster mitigation of transport emissions through a mix of faster electrification and increased use of bio-hydrogen w CCS. This resulted into a cumulative “avoided” emission from transport of 2 Gt over the period 2015 – 2100. If more storage options would be enabled in TIAM-UCL, e.g. using EVs, this could potentially lead to solving a noDACS scenario even in conditions of reduced biomass resource and BECCS, as investigated here. More research would be needed to dig into the consequences of faster and bigger deployment of renewables onto the need for CDRs, including BECCS.

Discussion

Under the Paris Agreement, 196 countries committed to mitigation of, and adaptation to, climate change so that together they can limit the global average temperature increase to “well below 2 °C” above pre-industrial levels. In preparation for the agreement, 160 parties submitted their Intended Nationally Determined Contributions (INDCs), which described plans for climate mitigation and adaptation. While the biomass utilisation for electricity and heat generation is mentioned in 40% of the INDCs (UNFCCC 2013), BECCS and other CDR technologies are completely absent (Fuss *et al* 2016). The latest IPCC report highlights an important role for

BECCS in scenarios that overshoot 1.5 °C, but little or no BECCS in scenarios with reduced demand and lots of AR (Rogelj *et al* 2018). Crucially though, in-depth INDC analysis has shown that the current level of international pledges will still fall 12–14 GtCO₂ short of the 2 °C limit, let alone the more ambitious 1.5 °C aspirational one (Hsu *et al* 2019). As each country prepares to submit new or updated NDCs in 2020, it is important to review again the role biomass could play in deep decarbonisation scenarios. To this end our study re-assesses the role bioenergy could play in decarbonising the global energy system when AR and DACS are available.

We find the availability of other CDR technologies reduces the need for BECCS. If other large-scale CO₂ removal technologies are available (e.g. DACS), then BECCS is not required for meeting a 2 °C target even in cases of high and inflexible energy demand. Notwithstanding, if BECCS is available then it will be used at its maximum potential to provide electricity and heat for running DACS. Indeed, running DACS at the scales required for a 2 °C target requires a substantial increase of energy production, also noted by other recent studies (Realmonte *et al* 2019). For instance, in our 2C_noBECCS scenario, at the peak of removal in 2050, DACS alone consumes between 7 and 8 EJ heat/yr. By 2100 this increases to 30-39 EJ/yr. This heat is supplied approximately half by bioenergy w/o CCS and half by gas and coal w CCS. Note that currently TIAM-UCL does not consider the use of industrial waste heat for DACS, but this has been evidenced as more cost-effective than producing dedicated heat for running the capture process (Realmonte *et al* 2019). More sustainable alternatives for powering DACS are solar and wind for the electricity input, and heat pumps powered by geothermal or other renewables for the heat input (Creutzig *et al* 2019), options currently not included in our model. Wherever it is sourced from, this heat would represent more than a third of the current global heat consumption of 22 EJ/yr (IEA, 2018). If DACS is to be deployed at the scales envisaged in this study, i.e. removing up to 7 GtCO₂/yr in 2100, more research is required both into alternative sources of decarbonised heat and more energy efficient variations of DACS.

A second concern with deploying any “DACS type” CDR at scale is that it stands to double the size of the corresponding CO₂ transport and storage infrastructure which will be required. This, in practice, represents an unprecedented challenge. The current global CO₂ capture and storage infrastructure (including fossil CCS) includes 21 facilities able to capture 37 MtCO₂/yr, with another 16 facilities to capture 18 MtCO₂/yr currently under development (Global CCS Institute 2017). This study suggests that capture rates would need to be scaled up from 55 MtCO₂/yr in

2020 to 340 - 1200 MtCO₂/yr by 2030 and up to 17 GtCO₂/yr by 2090. This represents an increase in CO₂ throughput of two orders of magnitude over seventy years and will involve overcoming substantial technological and political challenges. As well as retrofitting fossil facilities with CCS by 2050, and building new BECCS and DACS, it will also imply building the infrastructure for transporting CO₂ to storage, and engaging all the stakeholders along the value chain of CCS. The latter has proved challenging for many existing projects, making financing difficult (Global CCS Institute 2017). Note that this study does not account for fugitive emissions from either the transport or storage of CO₂. Such leakages would affect the overall efficiency of carbon sequestration and would probably lead to higher levels of installed capacity of DACS. Considering global restrictions on biomass availability, unless a fast decarbonisation of the electric grid with solar and wind happens before the scale up of CDRs, the additional heat for DACS would most likely come from natural gas w CCS.

Public opinions and consumer preferences are a potential issue. Our results suggest that 40% of the CO₂ storage would rely on onshore reservoirs. Along with CO₂ transport, this has received stronger public opposition than capture itself in communities that were previously educated in relation to the components and function of CCS (Wallquist *et al* 2012). Changing this public perception by increasing community awareness on the importance of CCS is a critical element of any policy on CCS (Global CCS Institute 2017). Another solution is to consider lower final energy demands so as to reduce the need for carbon sequestration. This, however, relies on changes in public perceptions of their energy needs that are just as complex as those involved in improving CCS acceptance.

Large infrastructure projects require consistent and long-term policy support. The example of the UK government's withdrawal of funding support for a large pilot CCS deployment in 2016 has shown that this can be difficult to guarantee (UK NAO 2017). An option not investigated here, but potentially reducing the need for CO₂ transport and storage, is using captured CO₂ for other applications or processes, for example the production of chemicals such as formic acid (Aldaco *et al* 2019), or of less carbon intensive transport fuels (Davis *et al* 2018). These options would need to be investigated on a case-by-case basis to ensure that their implementation would lead to a meaningful reduction in global GHG emissions (MacDowell *et al* 2017).

We find the role of biomass for decarbonising the global energy system changes rather than diminishes if other CDR options are available. Using bioenergy w/o CCS becomes compatible

with a 2 °C target as the other CDR technologies can compensate for residual CO₂ emissions. Our results suggest that the most efficient use of bioenergy is in industry, and in the production of synthetic transport fuels w/o CCS. In these cases, bioenergy replaces fossil fuels, in particular coal and oil, and makes the most difference when meeting increased energy demand without adding fossil CO₂ emissions to the atmosphere. These results are in line with recent recommendations from the Committee for Climate Change (CCC) for the UK Government for a transition to net zero by 2050 (UK CCC 2019), who suggest using biomass to decarbonise industry. Furthermore, the CCC recommends prioritising the industrial cases where there is potential for BECCS in the long term. We did not consider this option in TIAM-UCL as technology development is at an early stage and credible cost data are not available. The no BECCS scenario requires a quick ramp up of renewable energy and an early and rapid phase out of fossil fuels, which are compensated by increased electrification and use of biomass in sectors in which less mitigation options are available (i.e. transport and industry). Delivering these changes would require strong policies that promote early investment in DACS or other CDR technologies. To be effective, these policies would need to transcend the electoral cycles, and continue in place in the long-term (Global CCS Institute 2017).

When BECCS is available, it is most cost effective to delay the phase-out of fossil fuels in industry and transport and to deploy the most efficient BECCS for CO₂ removal (i.e. for electricity and heat production). These results suggest that rather than substituting fossil fuels, BECCS complement a continued use of unabated fossil fuels. This insight is consistent with other IAM scenario studies (e.g. Klein *et al* 2014, Bauer *et al* 2018). This trajectory does however introduce significant risk of overshooting global emission targets if progress towards the sustainable scale-up of BECCS is slow or otherwise delayed. In addition, our results also suggest that BECCS utilised for electricity generation may reduce renewable energy generation. These results are not communicated by other IAM studies, but they confirm warnings coming from LCA studies, (e.g. Pavlenko *et al* 2016). These results call for a careful planning of the power sector transition to avoid bioenergy displacing renewable energy generation. This could mean, for example, a transitional short-term role for BECCS to accelerate building the CO₂ infrastructure capacity, which can be used later by fossil CCS and DACS. However, BECCS power plants tend to be located near the biomass resource, if they are deployed at small scale, or near maritime ports, if they need large amounts of biomass (Albanito *et al* 2019). This spatial arrangement might not be

best suited for DACS, which require large amounts of heat. If industrial waste heat is to be used, as suggested by (Realmonte *et al* 2019), then DACS should be located closer to the industrial clusters, which may not match BECCS locations. More research is required to understand different options of locating BECCS and other CDR to rationalise distances to the geological storage sites.

We find that the availability of other CDR options does not reduce the pressure on global biomass supply and trade. Bioenergy deployment is critical in all 2 °C scenarios analysed here, independently of it being fitted or not w CCS. By 2050, biomass is used to its availability limit across all scenarios (i.e. approximately 100 EJ/yr). We set this limit in line with what is widely considered to be a feasible sustainable supply (Creutzig *et al* 2015). In particular, we constrained the cultivation of energy crops to marginal lands only to avoid competition for land. This implicitly assumes that any expansion or new establishment of energy crop plantations are regulated by consistent policies across the globe that would, for example, avoid direct and indirect deforestation. This is important as these adverse practices could lead to loss of carbon from soil (not considered here) and from the change in over ground vegetation which could easily offset the carbon removed by BECCS (Harper *et al* 2018), and reduce the mitigation potential of bioenergy replacing fossil fuels. Notwithstanding, consistent global and national regulations around biomass sustainability do not exist yet and would imply difficult monitoring, reporting and verification on a global scale to ensure sustainability at point of use. Land-use change would also cause other environmental impacts that are not considered here, including water consumption and pollution, soil nutrient depletion or albedo changes (Smith *et al* 2016). These could affect the productivity of all agricultural systems, including energy crops. Related to the latter, we assumed that energy crops yield between 5 and 12 o.d.t/ha depending on the region. While these yields are consistent with other studies (Pavlenko and Searle 2018), they are about double the yields assumed by (Harper *et al* 2018). In addition, we assume that each region cultivates the best yielding energy crop for its specific location and that climate change does not influence their yields or growing conditions. However, targeting the cultivation of highest yielding energy crops in each location might results into mono-cropping over large areas of land. This raises the question of whether using marginal land for bioenergy is indeed preferable to letting it revert to its native state, which could lead to significant ecological benefits that we do not currently account for (Stephenson and MacKay 2014).

Central and South America, China and South-Eastern Asia are the main producers and exporters of energy crops in our 2 °C scenarios. With no clear sustainability criteria established for traded biomass, these regions could undergo considerable land-use change to accommodate the increased demand, reducing or even cancelling out the mitigation potential of bioenergy. Domestically, bioenergy is also seen as critical contributor to decarbonising the power and transport system in non-OECD countries (Rose *et al* 2014, IEA 2017). This suggests that, even in the absence of international demand for energy crops, increased domestic consumption could promote the expansion of cultivated land, again causing land-use change, and potentially counteracting the mitigation potential of bioenergy. To ensure that the supply of fresh biomass is sustainable, more evidence is needed on the characteristics of regional supply and consumption of biomass. We also need consistent sustainability criteria across all countries, preventing the emission spillages from one region to another that render global action inefficient.

Overall, we found that using bioenergy w/o CCS for replacing fossil fuels use in the industry and transport sectors is the most effective use of biomass for climate mitigation. This is possible when other large-scale CDR technologies are available. More research is needed to investigate the uses of bioenergy in 2 °C scenarios with very low energy demand, e.g. SSP1 type trajectories, when key changes in the demand structure reduce considerably the global GHG emissions. Also more research is needed to understand how a step increase in storage to support a vast deployment of intermittent renewable electricity generation could affect the need for CDR, including BECCS.

We also found that only a few regions in the world could supply most of both biomass and geological storage required for a 2 °C scenario, i.e. China, South East Asia and Central South America. Both results rely heavily on frictionless and timely collaboration, particularly in terms of policy and standards, between regions that are allowed to trade both biomass and carbon credits freely. Such a situation has thus far not been readily observed in history. TIAM-UCL uses a global planner approach, in which all regions collaborate towards reaching the global target as described in the Paris Agreement. This approach needs to be checked and balanced against individual country interests and targets, including those that could conflict with climate and energy goals (e.g. food security), which might diverge from such an optimal energy system path. As we come to the end of the first five-year phase of the Paris Agreement, signatory nations will be expected to submit extensions and incremental reviews of their climate ambitions. Our results

provide evidence about bioenergy to assist countries around the world to revisit the ambition of their NDCs and plan a careful transition of their energy systems.

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Data availability statement

Any data that support the findings of this study are included within the article and the Supporting Information.

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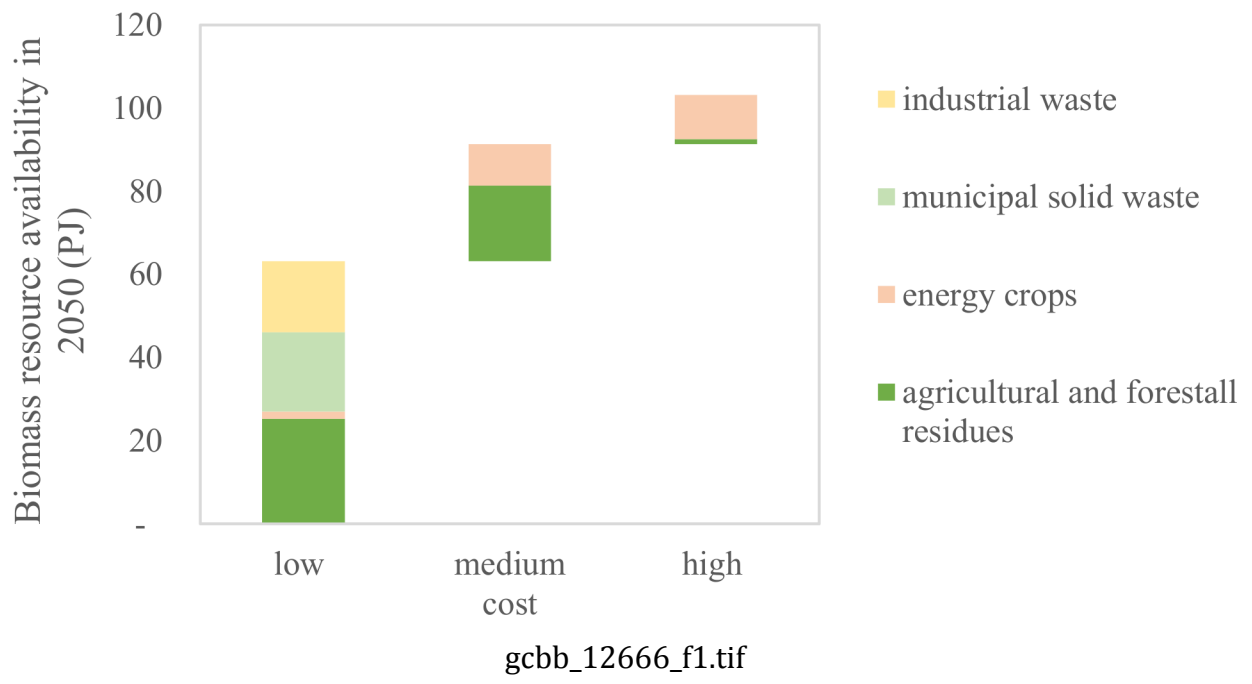
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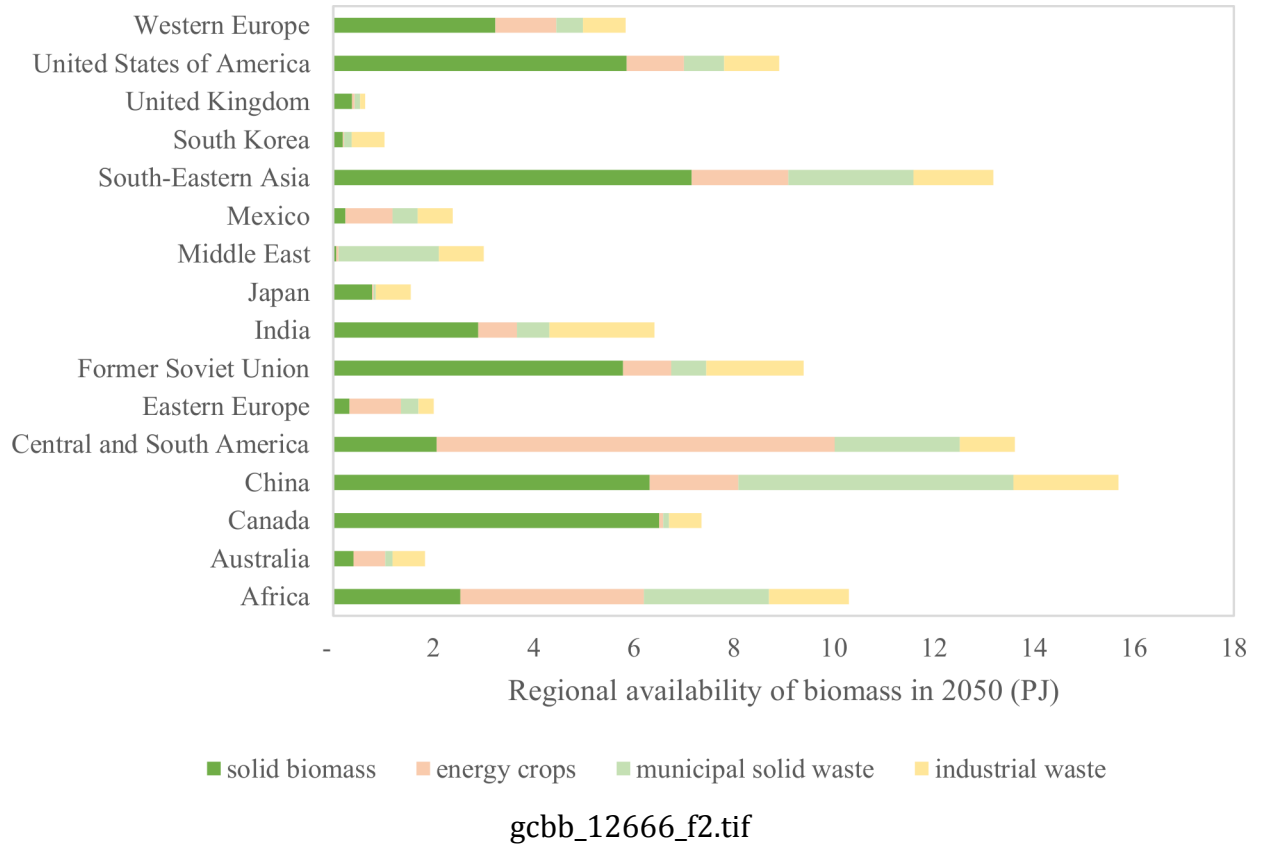
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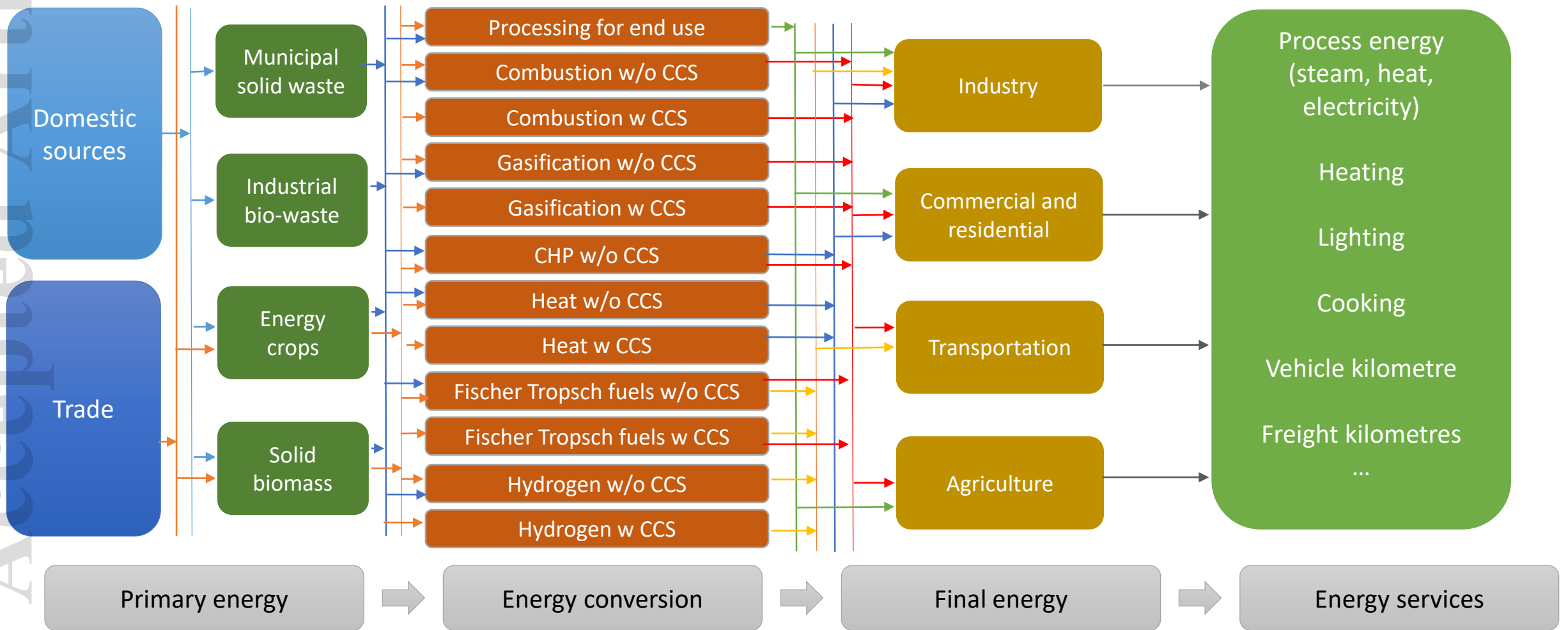
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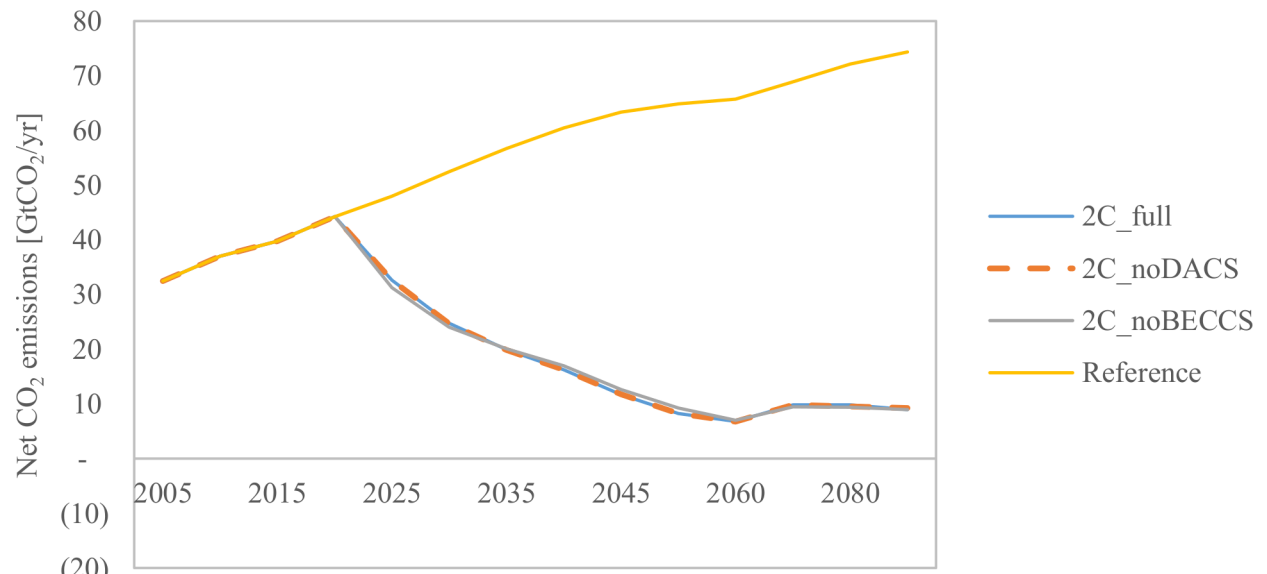
Table 1. Overview of the scenarios considered in this paper.

Scenario name	Global climate target	AR	BECCS	DACS
Reference	-	-	✓ endogenous	✓ endogenous
2C_full	2 ⁰ C, 66%	✓ exogenous	✓ endogenous	✓ endogenous
2C_noBECCS	2 ⁰ C, 66%	✓ exogenous	-	✓ endogenous
2C_noDACS	2 ⁰ C, 66%	✓ exogenous	✓ endogenous	-

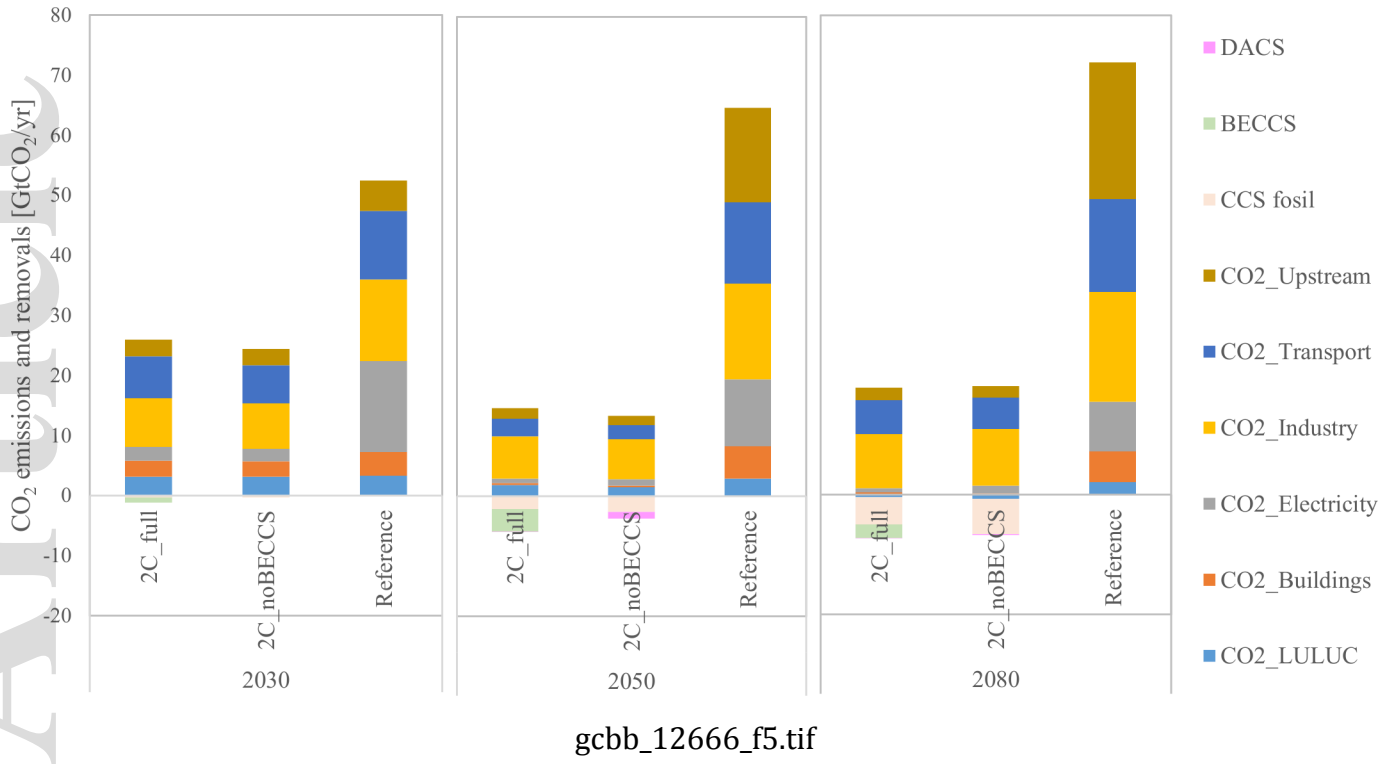


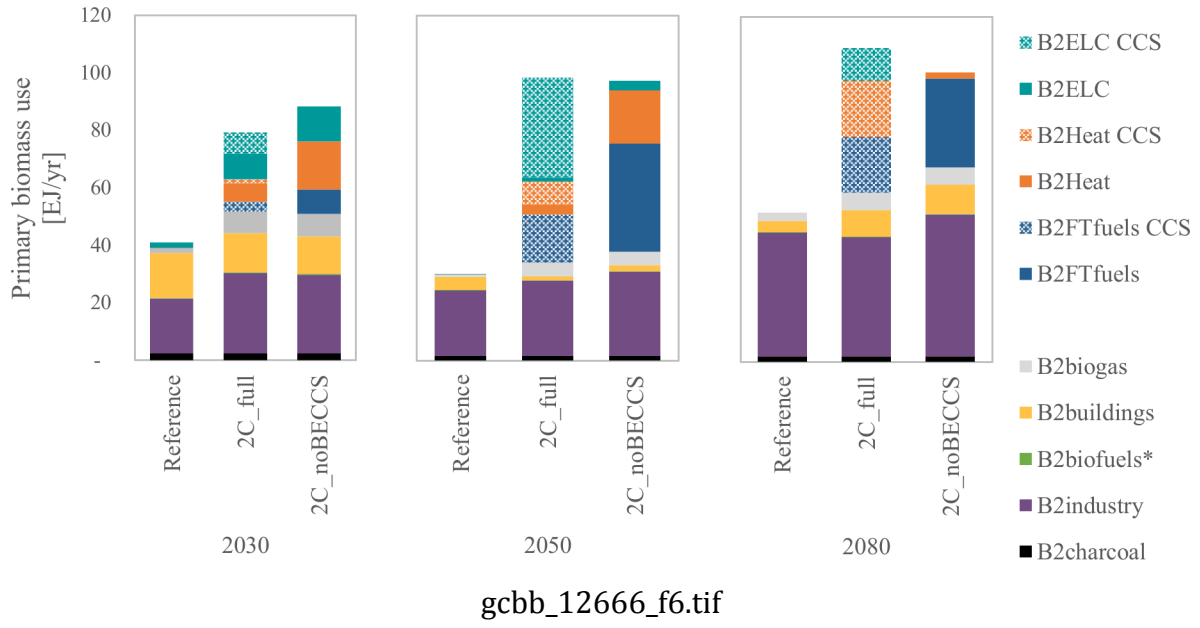


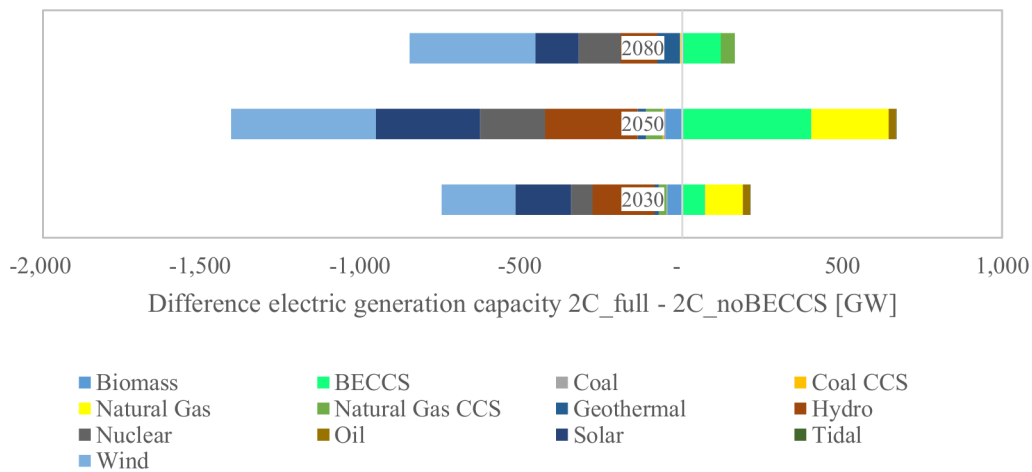




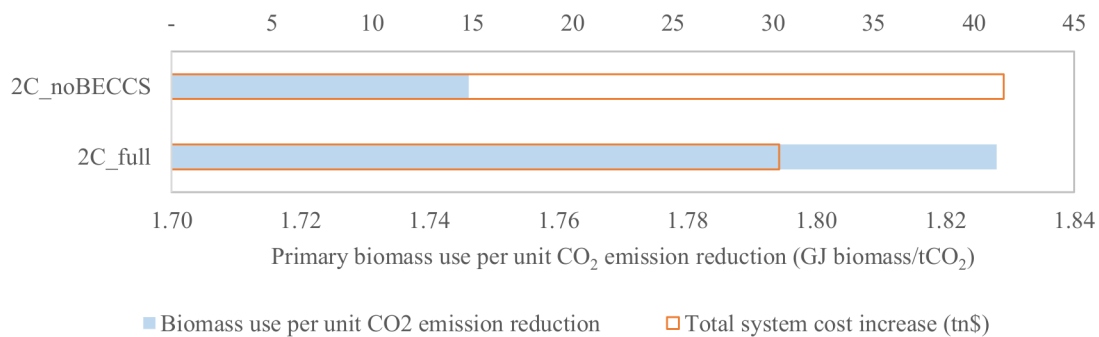
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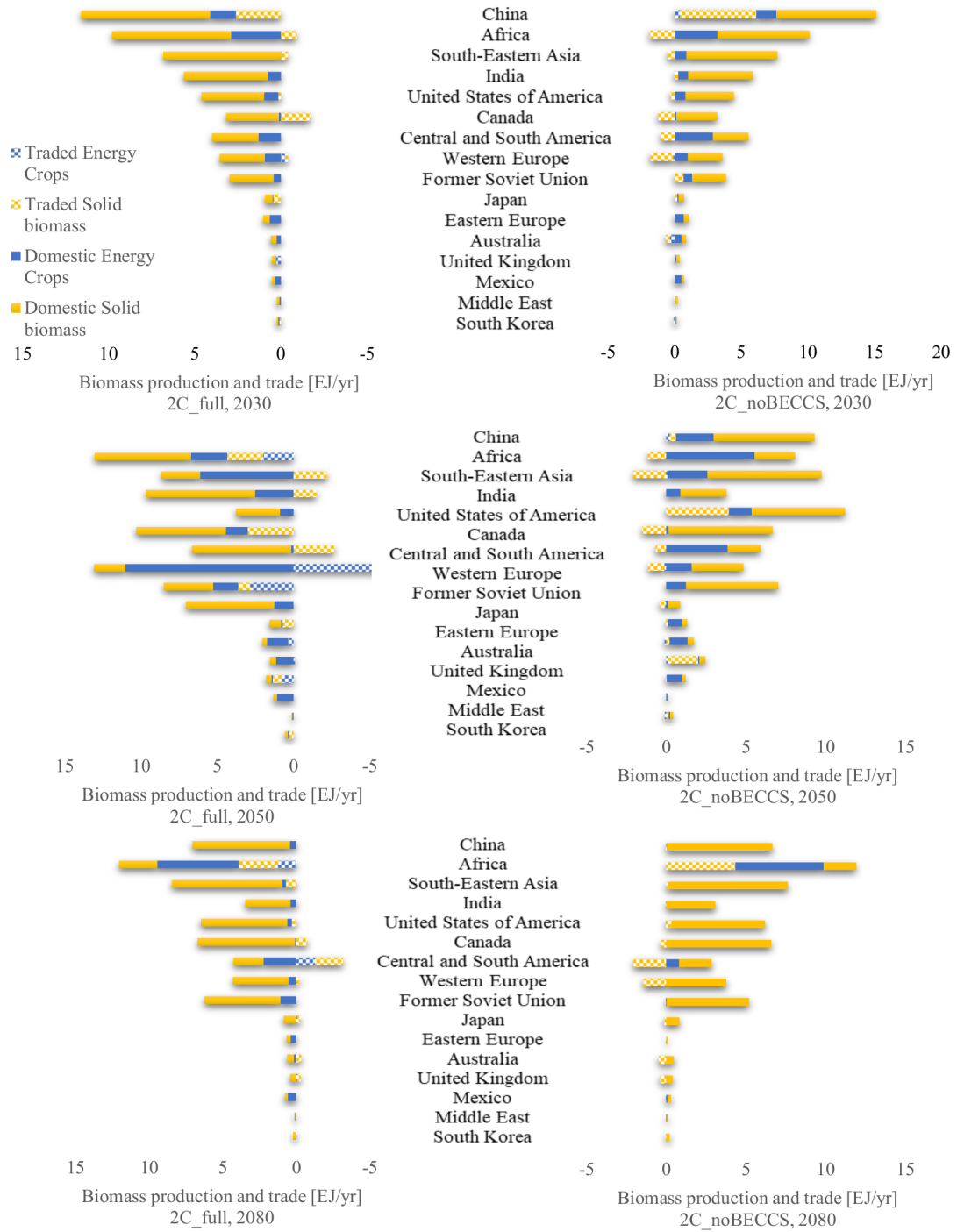




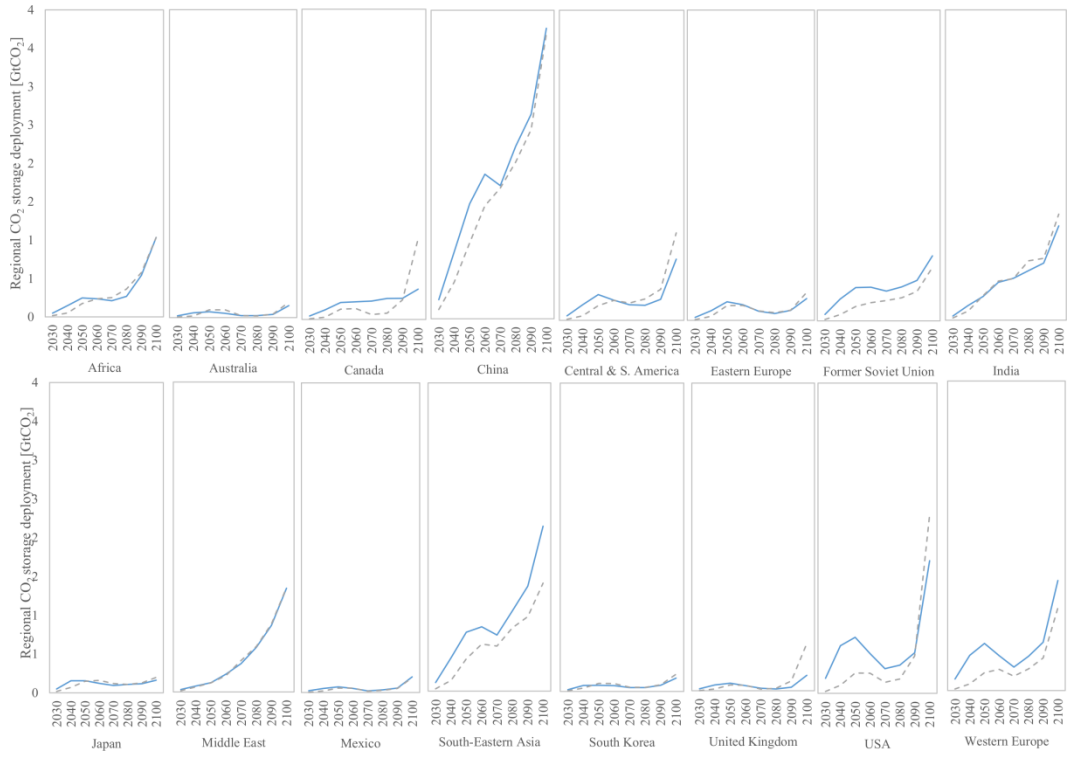
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