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Review article

A review of influencing factors for policy interventions in the deployment of bioenergy with carbon capture and storage

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A R T I C L E I N F O

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A B S T R A C T

Bioenergy with Carbon Capture and Storage (BECCS) is a key negative emission technology considered by many integrated assessment models (IAMs) to achieve the 2℃ or 1.5℃ goals in the Paris Agreement. However, the technical feasibility and economic costs of BECCS in these IAMs have been widely debated, which increases the uncertainty in the projection of climate change in the 21st century. Therefore, this paper reviews the latest understanding of BECCS. The key findings reveal the limitations of current models in projecting the capacity and costs of bioenergy with carbon capture and storage (BECCS), mainly due to insufficient consideration of ecological consequences, including availabilities of biomass and difficulties in the transportation of biomass and CO_2. To reduce uncertainties in the capacity and costs of BECCS, it is urgently needed to apply spatially explicit method for estimating the life-cycle emissions and the complete cost items when deploying BECCS, optimize the network of biomass acquisition, power plants retrofitting and transportation of biomass and CO_2, and represent the changes in the availability of biomass (for different types of bioenergy plants) under the impacts of climate change. This paper emphasizes the gap between the potential capacity of BECCS and the demand for BECCS that is needed to achieve the climate goals. Suggestion on policy interventions is provided to accelerate the application of BECCS from the aspects of economic tools, regulatory tools, and information tools. Deployment of BECCS could be accelerated to halt the rapid rise of global annual average temperature and reduce the risk of carbon lock-in from fossil-fuel supply infrastructure. As BECCS could play a key role in achieving ambitious climate targets, it is important to maintain a balance between environmental, social, and economic considerations in the Earth system under a high sustainability of development.

1. Background

The massive consumption of fossil fuels under the rising energy demand driven by economic growth has led to a sharp increase in global emissions of greenhouse gases (GHGs), which dramatically disrupts the balance of the carbon cycle and alters the atmospheric radiation in the Earth system [105]. The concentration of GHGs in the atmosphere has increased continuously since 1850, leading to significant greenhouse effects and rapid climate change [6]. If global countries fail to take strong and timely action to mitigate GHGs emissions, climate change will threaten sustainable development by triggering a range of catastrophic events, including glacier melting, frequent wildfires, and

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expansion of areas suffering from floods and droughts, which can produce strong feedbacks to economic growth by increasing the burdens on the social equality, economic development, and human health [70]. According to a recent study [9], if the temperature rise exceeds 1.5℃, the Earth is likely to experience sudden, hazardous and irreversible changes by crossing several tipping points. However, in order to achieve the goal of limiting global warming below 2℃ or 1.5℃, large-scale deployment of negative emission technologies is almost indispensable [73,83]. Negative emissions technologies refer to the processes of removing GHGs from the atmosphere and storing GHGs in the biosphere or geosphere [112]. Negative emissions can be achieved by measures such as afforestation/reforestation (A/R) by increasing the amount of carbon dioxide (CO_2) absorbed and stored by forests, direct air carbon capture and storage (DACCS) by capturing CO_2 directly from the air using various technologies followed by geological injection and storage, enhanced weathering/mineral carbonation (EW/MC) by capturing and storing CO_2 from the atmosphere when accelerating the natural weathering of minerals, ocean fertilization by adding nutrients to the ocean to enhance the growth of phytoplankton and the rate of carbon sequestration in the photosynthesis, biochar production by converting organic matter into stable carbon through biomass pyrolysis to achieve atmospheric CO_2 removal, soil organic carbon sequestration (SOCS) by sequestrating CO_2 from the atmosphere and storing the carbon in soil as organic matter, and bioenergy with carbon capture and storage (BECCS) by storing CO_2 captured from biomass combustion in power generation at the geological sites [68,150,233]. Among these technologies, BECCS is postulated to make a significant contribution to global CO_2 emissions reduction in the short- to mid-term, which can provide large benefits beyond CO_2 emissions reduction by substituting fossil fuels to produce electricity, heat, and biofuel [134]. Therefore, retrofitting coal-fired power plants to BECCS is considered a cost-effective option to limit global warming within 2 °C or 1.5 °C in Integrated Assessment Models (IAMs) [267]. However, the technical, economic and ecological feasibility is widely debated [220].

1.1. What is BECCS?

The concept of BECCS was firstly proposed in 1996 by Robert H. Williams et al. Williams [259], who pointed out that combining biomass energy production with carbon capture and storage (CCS) can theoretically remove a large amount of CO_2 from the atmosphere. In 2001, BECCS was proposed as a backstop technology to reduce the climate risks [182]. In 2007, BECCS were considered in a small number of IAMs adopted by the Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report as a potential option for stabilizing GHGs emissions or a quick-response strategy in face of abrupt climate change [104]. In 2014, BECCS played a more prominent role in limiting global warming below 2 ℃ in the Representative Concentration Pathway 2.6 (RCP2.6) in the IPCC Fifth Assessment Report [106]. In the latest IPCC Sixth Climate Assessment Report, BECCS was adopted as a major measure to offset industrial CO_2 emissions since 1850 by removing CO_2 from the atmosphere in all 213 scenarios, which aimed at limiting global warming below 1.5 ℃ [107,222].

We illustrate the processes when achieving negative emissions by deploying BECCS (Fig. 1). The growth of biomass sequestrates CO_2 from the atmosphere through photosynthesis. When the harvested biomass is transported to a plant to produce electricity, heat or biofuel, CO_2 emitted during the production process can be captured by CCS. Negative emissions can be achieved to offset CO_2 emissions from fossil fuels when the captured CO_2 is compressed, liquefied, and transported to an appropriate geological site for permanent storage [24,26,233]. In the projects of BECCS, the sources of biomass can be divided into three types: first-generation biofuels including food crops such as corn, wheat and sugarcane [20,84,168], second-generation biofuels including lignocellulosic biomass feedstocks such as agricultural residues, firewood and dedicated energy crops [20,84,158,168], and third-generation biofuels including microbiota biomass such as algae [20,34,47,176]. To achieve negative emissions, biomass can be converted into electricity [6,27,87,224], bio-ethanol or bio-methanol [126,132,165,224], bio-gasoline or bio-diesel [74,216,228], bio-gas [6,120,138,224], and bio-hydrogen [27,140,204,254]. Three approaches can be used to capture the emitted CO_2, including the pre-combustion CCS (e.g. absorption by chemical/physical solvents) [6,11,135,152], the post-combustion CCS (e.g. membrane/cryogenic separation) [6,11,135,277], and the oxy-fuel combustion CCS (e.g. chemical looping, combustion in pure oxygen) [6,149,175] (Table S1). Among these carbon capture technologies, adsorption is emerging as an alternative to current technologies due to its strong adaptability, good safety, and high cost-effectiveness [167].

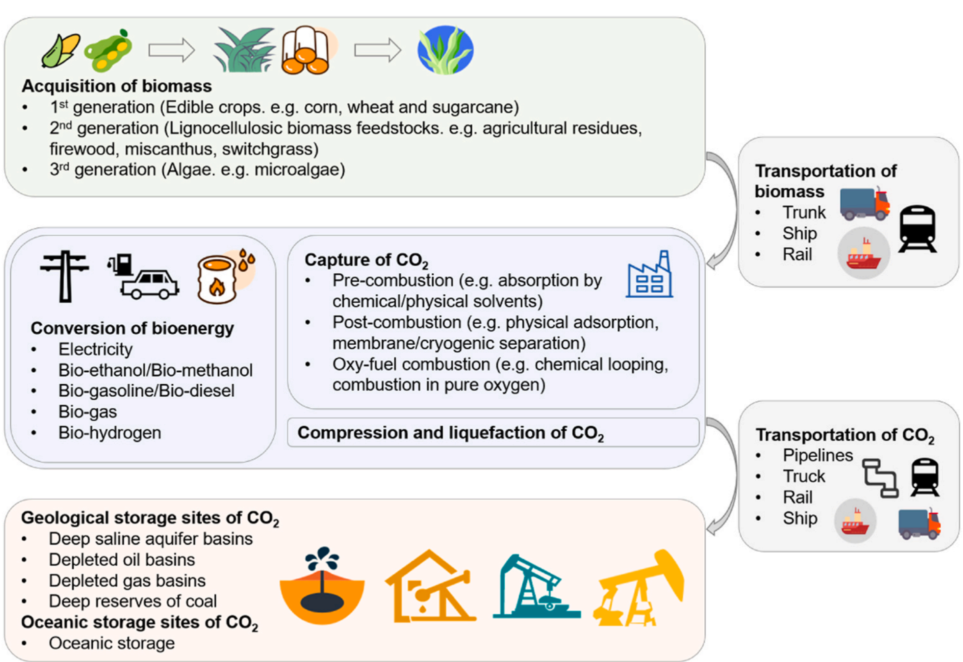

Fig. 1. Physical and chemical processes involved in the generation of bioenergy and sequestration of carbon when deploying BECCS.

The captured CO_2 needs to be compressed and liquefied, and then transported to the geological sites for storage using pipelines [11,12,48,235], trucks [39,78,119,183], railways [61,71,183,225], or ships [61,178,183,209]. There are at least five types of geological sites that are suitable for CO_2 storage, including the deep-saline aquifer basins [58,214,235], the depleted-oil basins [131,214,235,256], the depleted-gas basins [10,165,214], the deep reserves of coal mines [6,86,214], and the oceanic sites for injection into the basins [163,200].

BECCS was postulated not only to offset CO_2 emissions from fossil fuels, but also to generate co-benefits by increasing residential income in rural areas, creating new employment opportunities, and avoiding air pollution caused by unorganized burning of biomass in the field [99,187]. However, BECCS might have adverse impacts on food security, groundwater quality, and biodiversity due to cropland expansion when meeting the large demand for lands to provide the feedstock of biomass [84,266]. The large consumption of biomass in BECCS implies that land use implications should be evaluated against other land-based technologies of negative emissions (such as afforestation and reforestation, soil carbon sequestration, etc.) [68]. BECCS is widely assumed to play a key role when achieve ambitious climate goals in IAMs, but there are some limitations in current IAMs when considering BECCS. IAMs are the main tool for assessing climate change and developing climate action adaptation scenarios, as they merge quantitative knowledge from various fields such as physics, chemistry, biology, economics, and sociology [127]. By simulating the interactions and feed-back processes between human and natural systems, IAMs are widely employed to predict the future evolution of human activities and their impacts on climate change [123]. We emphasize the insufficient consideration of ecological consequences when obtaining biomass from the field (Table 1), impacts of climate change on the availability of biomass (Table 2), and challenges in the transportation of biomass and CO_2 (Table 3) in IAMs.

1.2. Uncertainty factors in the prediction of capacity, costs and impacts of BECCS in IAMs

It has been recognized that IAMs' assumptions on the deployment of BECCS could be over-optimistic [243]. We emphasized a number of uncertainty factors, the consideration of which should be improved by current IAMs in the prediction of the capacity of CO_2 emissions abatement by BECCS, the economic costs of deploying BECCS and the socio-economic impacts of deploying BECCS at a large scale (Table 4).

When estimating the capacity of BECCS in CO_2 emissions abatement, IAMs should be improved by considering the ecological constraints, the feedback mechanism between climate change and BECCS, the actual rate of CO_2 injection and the regional differences in the capacity of CO_2 storage, the way of bioenergy, and the lifecycle emissions of GHGs. When estimating the economic costs of BECCS, IAMs should be improved by including a comprehensive consideration of the costs in biomass acquisition, estimating the costs of CO_2 and biomass transportation as a function of the distance of transportation in a spatially explicit method, and accounting for the effects of technological improvements on the cost reduction of deploying BECCS. In addition, the implementation of BECCS also faces some social and political barriers, which requires IAMs to consider the impacts of political priority, social acceptance, the safety of CCS, the issues of poverty and hunger [63].

1.3. Role of BECCS in climate mitigation considered by IAMs

Since the late 2000 s, BECCS has been widely considered by IAMs as a negative emissions technology for CO_2 removal and sequestration [241]. Fig. 2 compares the capacity of carbon sequestration by BECCS, total CO_2 emissions, and the ratio of carbon sequestration by BECCS to total CO_2 emissions from 2000 to 2100 in the predictions by different models under various temperature control scenarios, which are compiled from the database hosted by International Institute for Applied Systems Analysis (IIASA) [31]. In the scenarios limiting global warming

Table 1
Consideration of the ecological consequences when acquiring biomass for BECCS in IAMs.

IAMs	Methods	References
AIM/CGE	Soil conditions including soil type, salinity, and moisture content, climate conditions including temperature and rainfall are taken into account when considering the suitability of agricultural land in crop models. Agricultural technology development was considered in AIM/CGE by incorporating the variable of technological progress to study its impact on agricultural production.	[91]
AIM/CGE	Moderate and strengthened scenarios of biodiversity protection and soil protection were taken into consideration to estimate the global potential of bioenergy.	[262]
AIM/CGE, BET, DNE21+, FARM3.1, GCAM, GRAPE, IMACLIM-NLU, IMAGE, MESSAGE-GLOBIOM, POLES, and REMIND-MAGPIE	All EMF-33 models but two (IMAGE, POLES) accounted for the competition of bioenergy for lands against crops, forests, and pasture. IMAGE limits bioenergy expansion to non-commercial lands (such as the marginal land).	[13]
GCAM	The prediction of biomass availability for BECCS accounted for the implications from changing energy systems, and the limitations, trade-offs and synergies between different natural systems. This model considered the influences of applying BECCS at a large scale on water consumption, land use, and the carbon cycle.	[258]
TIAM-UCL	The amounts of woody agricultural and forest residues were predicted by the IMAGE model under the SSP2 scenario by accounting for the impact of biomass acquisition on soil quality. The amounts of dedicated energy crops were predicted by the Ricardo-EE model based on the regional projections of abandoned agricultural land by assuming no limitation in the lands when growing energy crops.	[198]
IMAGE, MESSAGE-GLOBIOM, GCAM, REMIND/MAgPIE, AIM, and TIAM-UCL	The models of IMAGE, MESSAGE-GLOBIOM, REMIND/MAgPIE and AIM had explicitly accounted for the water scarcity, soil and biodiversity concerns, while the models of GCAM and TIAM-UCL did not accounted for their limitations. Alothough the models of IMAGE, MESSAGE-GLOBIOM, REMIND/MAgPIE and AIM accounted for that the ecological constraints reduce the yields and land suitability in the production of dedicated energy crops, these models did not explicitly quantified the impacts of ecological constraints on the amounts of biomass potential.	[30]

Table 2
Consideration of the impacts of climate change on the amounts of biomass in IAMs.

IAMs	Methods	References
AIM/CGE	The mean crop yields of the irrigated or rain-fed area were calculated from the Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model. The crop yield depends on the effect of CO_2 fertilization. The base-year carbon stock density and energy-crop yields were estimated from the Vegetation Integrative SImulator for Trace gases model.	[91]
MESSAGE-GLOBIOM	The crop yield depends on GDP.	[192]
IMAGE	The crop yield depends on GDP.	[45,192]
AIM/CGE	The crop yield depends on the area of irrigation.	[192]
GCAM	The crop yield is predicted as a function of data compiled from the Food and Agriculture Organization database on crop yield.	[192]
IMAGE/GCAM	The crop yield depends on the effect of CO_2 fertilization.	[270]
TIAM-UCL	The model assumed an annual growth rate by 1.3% in crop yields based on the trend in crop yields between 2010 and 2017.	[198]
Multiple IAMs	The crop yield depends on the area of irrigation and the application of fertilizers.	[151]

Table 3
Consideration of challenges in the transportation of biomass and CO_2 in IAMs.

IAMs	Methods	References
AIM/CGE	The costs in the transportation of biomass and CO_2 were not included.	[91]
AIM/CGE	The costs in the international trade of biomass were considered.	[66]
GCAM	The costs in the domestic transportation of biomass were assumed to be constant.	[30,148]
IMAGE	The costs in the domestic transportation of biomass were assumed to be constant.	[30,242]
MESSAGE-GLOBIOM	The costs in the domestic transportation of biomass were calculated endogenously based on the distance and the type of transportation.	[30,238]
GCAM	The costs in the transportation of CO_2 were considered by region.	[169]
Remind/MAgPIE and TIAM-UCL	The costs in the transportation of CO_2 were assumed to be constant.	[30]
Message/Globiom	The costs in the transportation of CO_2 were assumed to be constant.	[30,124]

below 1.5 or 2 ℃, the average ratio of the carbon sequestration by BECCS to total CO_2 emissions is 24±11% (s.t.d.) or 15±6%, compared to a ratio of 2±2% or 0.1±0.5% when the target of temperature control is 3 or 4 ℃, respectively.

2. Capacity of CO_2 emissions abatement by BECCS

The capacity of CO_2 emissions abatement by BECCS depends on the feedstock of biomass, the capacity of carbon storage, and the amount of fossil fuels that can be replaced by bioenergy [12,90,244]. In addition, this capacity will be offset by the lifecycle emissions of GHGs when deploying BECCS (Fig. 3).

2.1. Biomass feedstocks

In general, generating 1 EJ of energy from biomass combined with CCS technology is approximately equivalent to abating 0.02–0.05 Gt of CO_2 emissions [68]. After improving the efficiency in energy production and CO_2 capture, the capacity of CO_2 emissions abatement by BECCS depends on the amount of biomass feedstocks and the fraction of biomass wasted in the processes of harvesting, preprocessing, and transportation [3,174]. For example, an assumption that 10% of the

Table 4
Factors contributing to uncertainties in the capacity, costs and impacts of BECCS in IAMs.

Factors	Descriptions
Land availability for bioenergy production	When the competition of lands in bioenergy production for BECCS against food production and forest protection has been considered in IAMs, there is a large difference in the area of lands required for energy crop cultivation among different IAMs, ranging from 200 to 1100 Mha [93,192]. Ecological constraints on the area of lands suitability for energy crop cultivation by biodiversity conservation, soil quality maintenance, and water resource protection had been considered in few IAMs [30,91].
Feedback of climate change to the feedstock of biomass	When large-scale global climate action is delayed, the rise of global temperature can reduce crop yields as a feedback of climate change to the feedstock of biomass. To compensate for the loss of crop yields, addition expansion of agricultural lands is probably needed to meet the rising demand for food crops under population growth. Changes in biological carbon sequestration and carbon emission associated with land use change could in turn accelerate the climate warming [267]. The biophysical effects of growing bioenergy crops affect the climate by biogeochemical cooling of net CO_2 removal from the atmosphere and biophysical warming of cooling of changes in the local energy balance [250,251]. There is potentially a strong interaction and feedback between climate change and biomass feedstock, which has been represented by few IAMs.
Capacity of carbon storage	Many IAMs estimated the capacity of carbon storage by assuming a static capacity of storage, but the actual capacity of storage in a reservoir might be limited by the injection rate, which declines over time as the pressure accumulates [81]. Some IAMs do not considered the regional variation in the capacity of CO_2 storage and only focus on the total global capacity of CO_2 storage [122,124].
Different ways of using bioenergy	Few IAMs have accounted for the difference in the efficiencies of using bioenergy with different technologies such as bio-ethanol with CCS, bio-electricity with CCS [69].
Life-cycle emissions of GHGs	Few IAMs have accounted for the life-cycle emissions of GHGs from the transportation of biomass [30,244].
Costs of biomass acquisition	Few IAMs had accounted for the costs of biomass acquisition, such as the cost of land rent and conversion, biomass storage and biomass pretreatment for combustion [30]. Some IAMs accounted for the costs of biomass transportation, but failed to account for the impact of the distance of biomass transportation on the costs of biomass transportation [42,148].
CO_2 transportation cost	Some IAMs accounted for the costs of CO_2 transportation, but failed to account for the impact of the distance of CO_2 transportation on the costs of CO_2 transportation [94,124].
Technological innovation	Existing IAMs cannot capture the rapid progress of other clean technologies. For example, with the development of technology, solar and wind energy as land-saving energy solutions [190] have experienced significant cost reductions [38,89]. The decrease in the cost of clean energy and the addition of new low-carbon technologies in the future may reduce the deployment of BECCS in IAMs [123]. Besides, the technological upgrading challenge of co-dependency such as waste sharing and CO_2 transport and storage infrastructure sharing to reduce carbon emissions costs is also overlooked in IAMs [210].

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Table 4 (*continued*)

Factors	Descriptions
Policy incentives	Few IAMs have accounted for the impacts of carbon pricing, policy priority, and governmental investments in research and development on the cost reduction for BECCS [62].
Social acceptation	Few IAMs have accounted for the safety of CCS due to leakage or overpressure in the layer of CO_2 storage [213].
Climate justice	Few IAMs have accounted for the impacts of poverty and hunger issues on the deployment of BECCS [96].

harvested biomass will be wasted before it can be used for BECCS [90] is consistent with the fraction of biomass loss (6% - 10%) when harvesting wood and miscanthus [113,146].

Biomass feedstocks for BECCS can come from first-generation biofuels that can be used for food, second-generation biofuels include lignocellulosic biomass feedstocks, and third-generation biofuels represented by algae. Compared to the first-generation biofuels, the second-generation biofuels can reduce the impact of BECCS on food supply by expanding new lands [50,97]. The yield of lignocellulosic biomass feedstocks by growing dedicated energy crops has been predicted by bioenergy crop models [142,171] or statistical models [143]. The global amount of biomass that can be used for BECCS was projected to reach 0–1272 EJ y^{-1} by 2050 and 105–380 EJ y^{-1} by 2100 based on the production of biomass and the fraction of biomass that can be used for bioenergy (see Fig. 4 for a comparison of different estimates and Table S2 for the sources of data). When achieving the targets of limiting global radiative forcing below 2.6 and 4.5 W m^{-2} by 2100, the demand for bioenergy would be 100–200 EJ y^{-1} by 2050 and 200–300 EJ y^{-1} by 2100 [92,262]. It indicates that achievements of the maximal capacity of biomass supply makes it possible to meet the demand when achieving the ambitious climate targets. However, the potential contribution of biomass to the global supply of energy is controversial, with sources of debate including concerns about the interconnections between bioenergy and food supply, water use and biodiversity conservation [95,218]. Crop residues and biowaste could be the promising sources of biomass for bioenergy production, owing to the large amounts of crop production, low lifecycle emissions of biowaste, and the weak impacts of using crop residues on food production [36,53,201,257]. The global energy potential is estimated to be 3–75 EJ y^{-1} for crop residues and

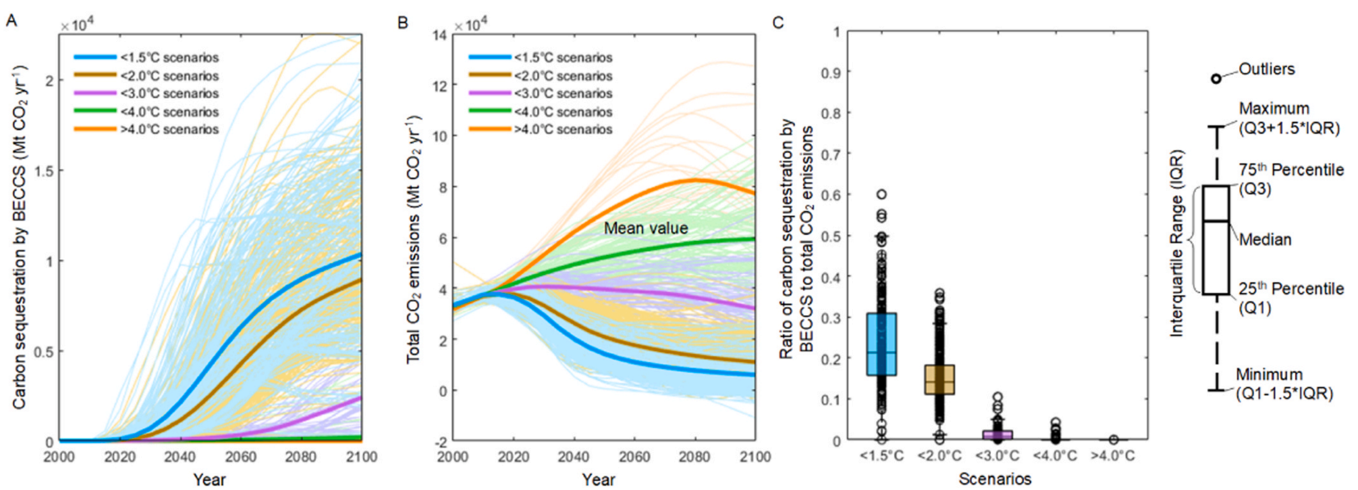

Fig. 2. The contribution of carbon sequestration by BECCS to total CO_2 emissions in the Integrated Assessment Models (IAMs) considered by the Sixth Assessment Report of Intergovernmental Panel on Climate Change [31]. (A, B) Prediction of carbon sequestration by BECCS (A) and total CO_2 emissions (B) from 2000 to 2100 in IAMs. (C) The contribution of cumulative carbon sequestration by BECCS to cumulative total CO_2 emissions from 2000 to 2100. The bold line represents the average contribution predicted by different IAMs in a group of temperature control scenarios.

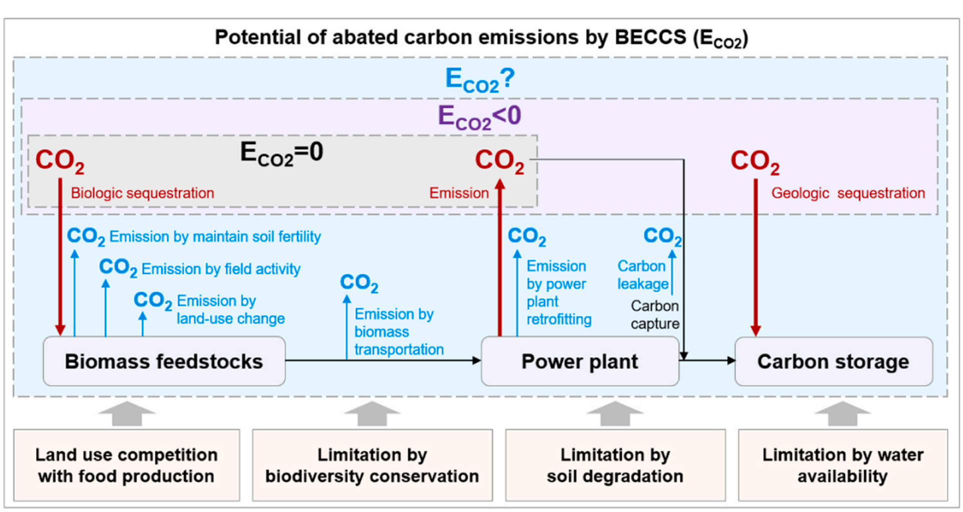

Fig. 3. The budget of CO_2 emissions abatement by BECCS.

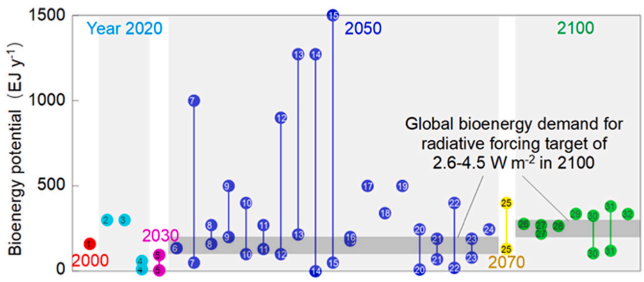

Fig. 4. Comparison between the global supply of bioenergy and the demand for bioenergy when meeting the climate targets. The circle denotes the supply of bioenergy, while the black shading denotes the demand for bioenergy in the scenarios, which limit global total radiative forcing below 2.6 and 4.5 W m^{-2} by 2100. The number in each circle denotes the number of a reference, which has been listed in Table S2.

3–120 EJ y^{-1} for biowaste, which are approximately 5.9–13.6% and 9.4–13.6% of the global energy potential of energy crops (22–1272 EJ y^{-1}), respectively [36,54,211,218].

The feedstocks of biomass depend on the levels of climate change, due to the impacts of temperature and precipitation on the yield of crops [223]. In response to a rising ambient temperature in the growing seasons, the crop yields decrease after reaching a peak at the optimal temperature [267]. The yields of C3 crops such as wheat and rice increase under the rising atmospheric CO_2 concentration due to acceleration of photosynthetic, but this effect would saturate when atmospheric CO_2 concentration exceeds a threshold of ~700 ppm [143,267]. Some measures are useful to prevent the reduction of crop yields caused by climate change by regulating the phenology of crops, enhancing the tolerance of crops under extreme temperatures, and providing sufficient water and nutritional resources in the field [1]. Li et al. suggested that 9–19% of biomass production in the 21st century can be increased by improving agricultural technologies [141]. Nevertheless, the impacts of climate change and adaptive agricultural strategies to offset the decline in the feedstocks of biomass due to the detrimental effects of global warming on crop yields should be considered in IAMs when evaluating the effectiveness of mitigation measures relying on BECCS.

2.2. Capacity of carbon storage

As the supply of biomass meets the demand, the capacity of CO_2 emissions abatement by BECCS is constrained by the capacity of carbon storage. Currently, rock formation is the most feasible option for large-scale and long-term storages of high-pressure liquefied CO_2 [32,144]. The regional capacity of carbon storage has been investigated at different types of storage locations (Fig. 5). The highest capacity of carbon storage has been identified in the former Soviet Union (1938 Gt CO_2), the United States (1788 Gt CO_2), and Central and South America (1293 Gt CO_2), contributing almost half of global capacity of carbon storage. The capacity of carbon storage is relatively low in South Korea, Japan, and the Middle East, with the identified capacity of 4.5, 17, and 192 Gt CO_2, respectively. The ratio of onshore CO_2 storage capacity (60%) is higher than that for offshore CO_2 storage capacity (40%) with spatial differences, and onshore CO_2 storage is mainly distributed in China and Middle East [46,81,94,117,215]. And 90% of CO_2 storage is dominated by deep saline aquifer basins [46,81,94,215].

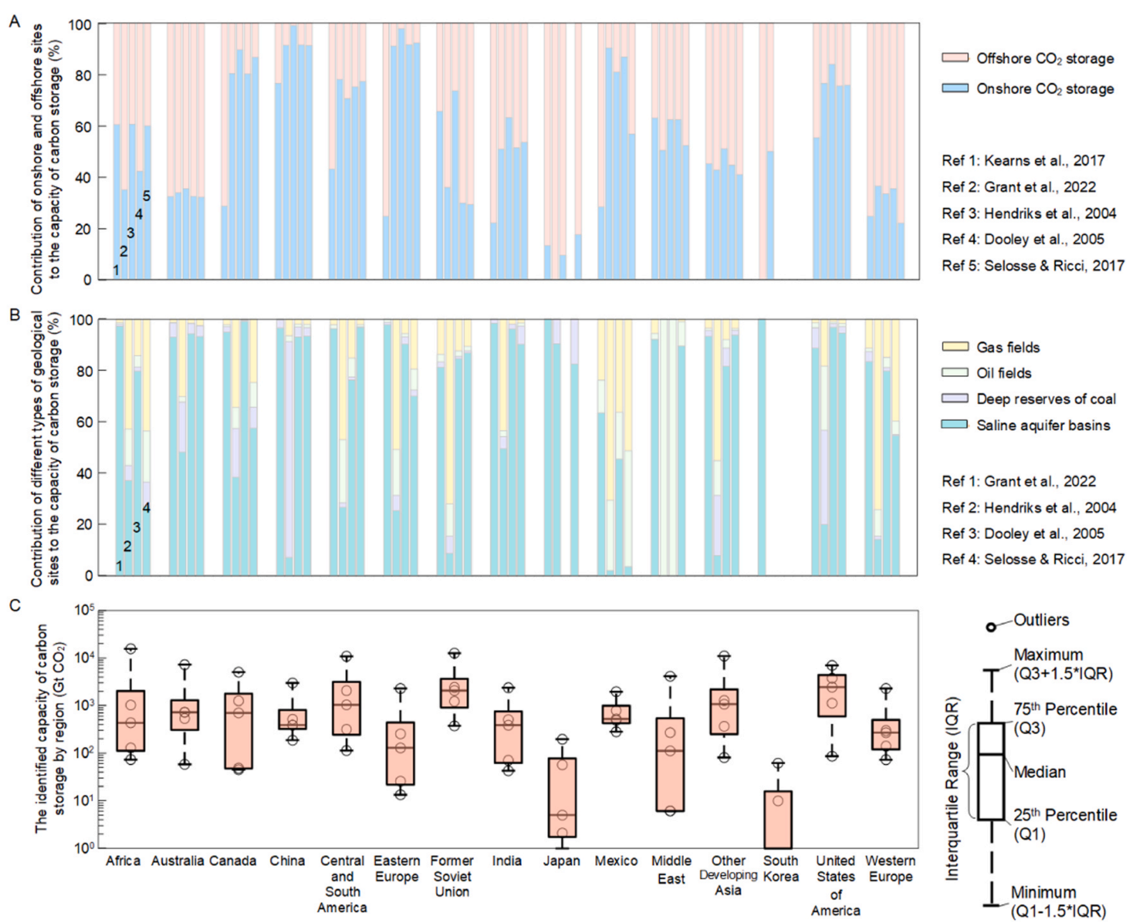

Fig. 5. Capacity of carbon storage. (A) Contribution of onshore and offshore sites to the capacity of carbon storage. (B) Contribution of different types of geological sites to the capacity of carbon storage. (C) The identified capacity of carbon storage by region.

The Special Report on Carbon Dioxide Capture and Storage of IPCC [43] recommended a capacity to store 2000 Gt CO_2 worldwide. The International Energy Agency suggested that the global capacity of basin-based carbon storage is 8000–15000 Gt CO_2 [179]. By reviewing the estimates from different sources of data, Fuss et al. suggested that the global capacity of carbon storage is 320–50000 Gt CO_2 [68]. Kelemen et al. suggested that the global capacity of carbon storage in sedimentary basins is probably 8200–35000 Gt CO_2 [118]. Despite the large capacity of carbon storage, the areas suitable for cultivating energy crops are mainly distributed in tropical or temperate regions [143], but the geological sites identified for CO_2 sequestration are mostly located in the former Soviet Union, the United States, and Central and South America (Fig. 5). This mismatch between the area of biomass feedstocks and the sites of carbon storage represents a limitation to the current deployment of BECCS, thereby requiring the long-range transportation of biomass or CO_2 by developing a global network to achieve the ambitious targets of CO_2 sequestration.

There are some factors that can influence the total capacity of carbon storage. The high capacity of carbon storage at suitable geological sites relies on an assumption that there is enough porosity structure in the geological layers. This assumption, however, does not fully account for limitations to the actual rate of CO_2 injection. In commercial projects for CO_2 storage, the rate of injection depends on the rate of CO_2 capture in power plants, which is the main factor affecting the quantity of CO_2 storage [129]. For example, the ZeroGen project failed because the injection rate of CO_2 cannot meet the requirements to guarantee stability of the porosity structure in the geological layers [72]. Therefore, given the constraints in the pre-investment costs in reducing the instability of the injection rate, the contractual costs to reduce the cross-departmental risks due to inconsistency between CO_2 sources and sink, and the institutional costs to gather the critical expertise from industry and the regulator, Grant et al. suggested that the feasibility is high only for carbon storage in the oil and gas basins with core technologies and expertise that is capable of providing the stable CO_2 injection rate [81]. In addition, the injection rate decreases as reservoir pressure increases, which affects the ultimate capacity of carbon storage achieved in geologic formations [81]. Based on the production of oil and gas, the global maximum capacity of carbon storage is 8.6 Gt CO_2 per year [81], which will take up only 10% of the global total capacity (9390 Gt CO_2) by the end of the next century [81]. Considering the public resistance to onshore carbon storage and the restrictions on the costs of CO_2 transportation, offshore carbon storage could be more plausible than onshore carbon storage, which reduces the global capacity of carbon storage from 10142 to 4461 Gt CO_2 [215], this capacity could be lower by considering the constraints of water depths, distance to the coastline, and non-polar regions [117]. Considering the safety of geological storage, storing CO_2 in deep saline aquifer basins and depleted oil basins provides the capacity of 1914 and 168 Gt CO_2, respectively [256]. At last, the demand for CO_2 sequestration in this century is 614–2330 Gt CO_2 in different IAMs [179], which is generally lower than the global total capacity of carbon storage.

2.3. *Capacity of power plants that can be retrofitted from fossil fuels to BECCS*

In addition to the amount of biomass feedstocks and the capacity of carbon storage, the capacity of CO_2 emissions abatement by BECCS depend on the capacity of power plants that can be retrofitted from fossil fuels to biomass in the scenarios with high penetration of renewables such as photovoltaic and wind power, geothermal, hydro, nuclear and tidal [114,230]. The consumption of fossil fuels in the power sector depends on the total demand for electricity and the penetration of renewable energy (Fig. 6). The average power capacity in 2050 is projected to be 540±570 (s.t.d.) GW by coal, 2340±1460 GW by gas and 100±120 GW by oil in the scenarios of limiting temperature below 2 ℃, compared to 2130±880, 3560±1480 and 140±170 GW in the scenarios with global warming exceeding 4 ℃, respectively. However, there are some economic and technical constraints when retrofitted the power plants from fossil fuels to BECCS. The retrofitting of power plants from fossil fuels to BECCS faces significant costs, as substantial capital investments are required to construct new equipment and technological components [11,245]. In addition, the spatial distribution of coal, oil, and gas power plants around the world in 2018 is shown in Figure S1. Due to the mismatch between power plants, biomass sources and CO_2 storage sites, retrofitting from fossil fuels to BECCS power plants involves significant changes to existing infrastructure, such as pipelines, which pose challenges in the commercialization of technology and require significant time and effort [80].

2.4. *Lifecycle emissions of GHGs*

The net GHGs emissions abated by BECCS will be equivalent to the

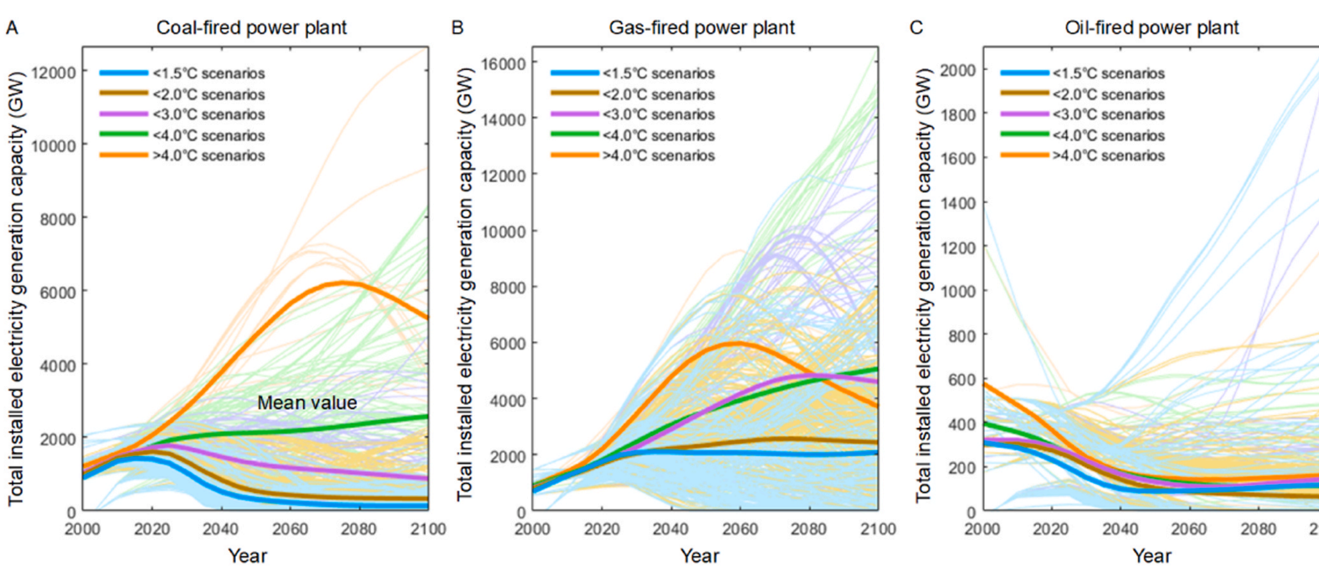

Fig. 6. Installed capacity of fossil-fuel power plants. The capacity of coal (A), gas (B) and oil (C)-fired power plants that can retrofitted for biomass burning are predicted in the scenarios, which meet different temperature targets [31]. The bold line denotes the average capacity predicted by different models in a group of temperature targets.

amount of CO_2 that is absorbed through photosynthesis in the growth of biomass and ultimately stored in geological storage sites, which could be partly offset by lifecycle emissions of GHGs in the various processes [4, 37]. These lifecycle emissions of GHGs could come from energy consumption in the activities such as planting, cultivation, harvesting, and biomass processing. For example, harrowing and baling processes of miscanthus consumes 2.39 and 1.33 l of diesel to produce one tonne of biomass [71], which leads to emissions of 6.5 and 3.6 kg CO_2 [147], respectively. To maintain the soil fertility required for the sustainable growth of biomass, the amount of fertilizers required by dedicated energy crops to achieve the 2 ℃ target will increase the consumption of agricultural fertilizers by almost 57% [141]. The increase in nitrogen fertilizer demand will lead to the conversion of excess soil nitrogen into nitrous oxide (N_2O), the global warming potential with a time horizon of 100 years (GWP100) of which is 273 times that of CO_2 equivalent [107]. In addition to fertilizer application, GHGs emissions are increased in the production of fertilizers [249]. Cumulative CO_2 emissions from the production and application of fertilizers for energy crops during 2012–2099 can offset 5% of the cumulative GHGs emissions abatement by BECCS in the RCP2.6 scenarios [141]. Due to the spatial mismatch between biomass production and power generation, the transportation of biomass from the harvesting sites to the power plants for combustion can lead to substantial CO_2 emissions if the transportation consumes fossil fuels. For example, transportation by truck, rail and ship consumes diesel by 0.7, 0.009, and 0.003 l km^{-1}, respectively [71], which leads to emissions by 1.9, 0.02 and 0.008 kg CO_2 [147], respectively. Additional CO_2 emissions will be generated when retrofitting current fossil-fuel power plants consumes energy in form of fossil fuels. Converting an integrated gasification combined cycle power plant to an integrated gasification combined cycle power plant equipped with CCS increases the construction emission by 0.55–0.88 g equivalent CO_2 when generating 1 kWh of electricity [145,147]. In addition, growing dedicated energy crops for BECCS requires direct land-use change from grassland or forest to energy crops or indirect land-use change from grassland or forest into agricultural land as compensation for planting energy crops on existing agricultural land [24], which increase GHGs emissions by releasing the carbon stocks in the soils to the atmosphere [157]. Emissions of GHGs from land-use changes depends on carbon stocks in the soils, which could exceed the CO_2 emissions abated by BECCS in the long term [60]. The indirect GHG emissions from land-use change depends on spatial ecology, macroeconomics and biomass feedstock types, which varies from −12–285 g CO_2-eq when producing 1 MJ of bioenergy [112]. At last, the efficiency of carbon capture cannot reach 100% under current technologies of CCS, which depends on the leakage of carbon in the processes of capture [162].

The lifecycle emissions of GHGs offset the climate benefits of BECCS [25,112,229], which have been considered in few IAMs. The total emissions of GHGs from direct and indirect land-use changes, the supply chain of biomass, and the processes of carbon capture were suggested to offset 54% of the total CO_2 emissions abatements by BECCS [56]. When generating one MWh of power, the amount of CO_2 captured by biological sequestration was 1277–1474 kg equivalent CO_2, but the lifecycle GHGs emissions will be 123–361 kg from the supply chain of biomass, 275–348 kg from the energy conversion processes, and 20–22 kg from the operation of CCS infrastructure [5]. Therefore, a full lifecycle analysis needs to be performed when estimating the capacity of CO_2 emissions abatement by BECCS in global climate action or the local projects of mitigation.

2.5. Competition of land by BECCS against food production

In addition to the factors mentioned above, the capacity of BECCS to abate CO_2 emissions by growing dedicated energy crops will be constrained by the availability of land. When deploying BECCS to limit global warming below 1.5 °C, 380–700 Mha of land could be needed to cultivate dedicated energy crops by 2100 [23,221,260], which is equivalent to taking up 25–46% of global total arable lands [84,221]. Given the projected increase in crop production driven by population growth by 2050 [59,153], requirements of additional lands for cultivating the dedicated energy crop will threaten the availability of arable lands that is needed for food production [57,193,221]. Growing dedicated energy crops motivated by carbon prices will directly compete with food production for land, leading to a worldwide increase in the prices of crops by at least 60% [166] or 110% in the Shared Socioeconomic Pathway 2 (SSP2) scenario [192]. Relative to the baseline scenario without BECCS, a large-scale land-based climate mitigation would lead to an increase by 11% in the price of food and an increase in the population with a risk of hunger by 230 million by 2050 [44]. An increase in global demand for bioenergy from 200 to 300 EJ y^{-1} can lead to an increase in the prices of crops by up to 40% and a decrease in the daily per capita food supply by up to 45 kcal by 2100 [92]. The shortage of food caused by the competition for lands mainly occurs in developing countries, which can deteriorate the levels of malnutrition and social unrest [206]. In the regions with food shortage such as Asia and Africa, the demand for food may become a dominant factor limiting the amount of biomass feedstocks and thus the capacity of BECCS.

2.6. Constraint by the protection of biodiversity

The feedstocks of biomass for BECCS can be constrained by the demand for protecting biodiversity for two reasons. First, expansion of croplands for cultivating dedicated energy crops will significantly reduce the biodiversity [98,177], mainly by reducing the area of habitats for mammals and birds [133,226]. Application of BECCS to sequestrate 0.5–5 Gt CO_2 y^{-1} based on lignocellulosic crops requires occupation of lands by more than 100 Mha, which will cause more than ten vertebrate species to face the risk of extinction [88]. If the application of BECCS lasts for 30 years, the negative effects of land-use change on the richness of vertebrate species could exceed the benefits from climate change mitigation [88]. Second, the large amount of water consumption in the irrigation when cultivating dedicated energy crops will accelerate the freshwater biological degradation and loss of aquatic biodiversity [184]. The constraints by protecting biodiversity should be considered when determining the feasibility of BECCS in the regions with high risks of species extinction. In a global assessment, the total amount of bioenergy for BECCS in 2050 and 2100 will decrease from 245 and 335 EJ y^{-1} to 172 and 230 EJ y^{-1} by considering the impact of moderate biodiversity protection, and further to 160 and 202 EJ y^{-1} by considering the impact of enhanced biodiversity protection, respectively [262].

2.7. Constraint by the prevention of soil degradation

The effect of deploying BECCS on climate change mitigation depends not only on the maximal amount of biomass, but also on the temporal variation in the amount of biomass, which depends on the rate of soil degradation. The impact of soil degradation should be considered when evaluating the effectiveness of deploying BECCS for three reasons. First, the removal of biomass from the field may lead to a reduction in soil nutrients relative to the case without the removal. BECCS requires using large amounts of agricultural residues and dedicated energy crops as biomass feedstocks, whereas returning agricultural residues back to soils plays an important role in reducing soil erosion and maintaining the content of organic carbon in the soils [170]. When these agricultural residues are removed from the field for energy production in the power plants, nutrient elements such as nitrogen, phosphorus and potassium in the soils are synchronously removed [221]. Dedicated energy crops absorb nutrients from the soil during their growth, leading to soil degradation by depleting nutrients in the soils. Address this issue requires controlling the proportion of agricultural residues removal or increasing the application of fertilizers. At most 70% of the total collectable agricultural residues can be removed from the croplands to prevent wind or water erosion [234], while retaining 30% of the agricultural residues in the field can prevent the soils from degradation and nutrient scarcity [194]. Second, expansion of croplands could significantly accelerate soil erosion by increasing rainfall and runoff. In the past 8000 years, anthropogenic croplands expansion is responsible for the removal of 783±243 Pg of organic carbon from the soils, which is a major reason for a decline in the fertility of soils [172,232,253]. Third, there is a feedback of climate change to soil erosion and degradation, which might lead to a lower capacity of BECCS if the deployment has been delayed. Under a warming climate, extreme weather events such as heavy rainfall will increase the loss of nutrients at the layer of topsoil and accelerate soil erosion and degradation, the effect of which will be strengthened if the natural land is shifted to croplands [17]. Soil degradation reduces the availability of biomass. The amount of biomass feedstocks in 2050 and 2100 will decrease from 245 and 335 EJ y^{-1} to 244 and 229 EJ y^{-1} by considering the impact of moderate soil protection, and further to 333 and 317 EJ y^{-1} by considering the impact of enhanced soil protection, respectively [262].

2.8. Constraint by the availability of water

The large-scale deployment of BECCS increases the consumption of water in the agricultural and power sectors, which can become a major limiting factor in the regions with water scarcity [212]. Agriculture and power generation account for 70% [247] and 15% [101] of the world's total freshwater consumption, respectively. The production of dedicated energy crops when meeting the demand for bioenergy of 300 EJ y^{-1} will double agricultural water consumption [22]. Second, the BECCS power plants increases the consumption of water for cooling the condenser tower [56,156,272] and capturing CO_2 using either chemical or physical measures [51,273]. The large-scale application of CCS in power plants will likely double the human water footprint and exacerbate water shortage in many regions of the world [205]. Deploying BECCS to offset fossil-fuel emissions of 3.3 Gt C y^{-1} by 2100 will increase water consumption in agricultural irrigation and power generation by up to 720 km^3 y^{-1}, which is equivalent to 3% of the currently available freshwater resources for human use [221]. About 1.2 billion people are currently living in the regions of absolute water scarcity, while 1.6 billion people are going to face water scarcity [82]. Due to population growth and climate change, these numbers may increase in the future [278]. Therefore, the availability of freshwater resources will constrain the capacity of BECCS in the future, which has not been considered in current IAMs.

3. Economic costs of deploying BECCS

3.1. Cost of biomass acquisition

When estimating the cost of BECCS, it is essential to consider the cost of biomass acquisition, which includes purchasing biomass, pretreatment of biomass for transportation and combustion, and transportation of biomass from the field to power plants [265,268]. The cost of purchasing biomass is generated when supplying raw materials such as seeds and pesticides, consuming energy or machinery for planting, cultivation, and harvesting, and paying for the acquisition of land, soil remediation and labors [35,121,128,265]. The purchasing cost depends on the type of biomass feedstock, which is generally lower for the second-generation of biofuels than others (Fig. 7). The purchasing cost is 70–620 $ t^{-1} for the first-generation biofuels, 10–242 $ t^{-1} for the second-generation biofuels, and 546–1639 $ t^{-1} for the third-generation biofuels. The supply of the first-generation biofuels relies on grains, so their purchasing cost is determined by the price of grains, which is 316, 325, 307, and 70 $ t^{-1} for corn, wheat, sorghum, and sugar beet, respectively [79]. The purchasing cost of the second-generation biofuels depends on the type of biofuel, which varies from 13 $ t^{-1} for municipal solid waste to 61, 52, 76, 84 and 60 $ t^{-1} for agricultural residues, woody biomass, managed forest woods, grass energy crops and woody energy crops. The purchasing cost of the third-generation biofuels is currently the highest, which exceeds 1000 $ t^{-1}. However, algae can grow in lakes without the need for fertile land, while the large-scale application is feasible due to the high photosynthetic productivity [11].

The cost of biomass pretreatments is generated in the procedures of bulk dehydration, shredding, grinding and pelletizing, which mainly aims at reducing the volume of biomass to make it suitable for long-distance transportation [71]. These pretreatments improve the efficiency of biofuel combustion by mechanical, thermal, chemical, or biological processes to reduce slagging/fouling [26]. The pretreatment cost is estimated to be $5.5 t^{-1} for agricultural residues and $23 t^{-1} for the pelletized switchgrass [274]. The cost of biomass transportation depends on the weight of biomass and the mode of transportation, which increases from $0.004 t^{-1} km^{-1} for the shipping transportation [55] to $0.09–0.61 t^{-1} km^{-1} for road transportation [55,225,274] and $0.04–0.22 t^{-1} km^{-1} for railway transportation [225,274].

3.2. Cost of retrofitting the existing fossil-fuel power plants

When achieving the ambitious mitigation targets, retrofitting the existing fossil-fuel power plants to new biomass co-firing plants equipped with CCS accelerates the decommissioning of fossil fuels [188], so the retrofitting cost should be counted in the cost of decarbonization. The cost of retrofitting a fossil-fuel power plant to a biomass cofiring

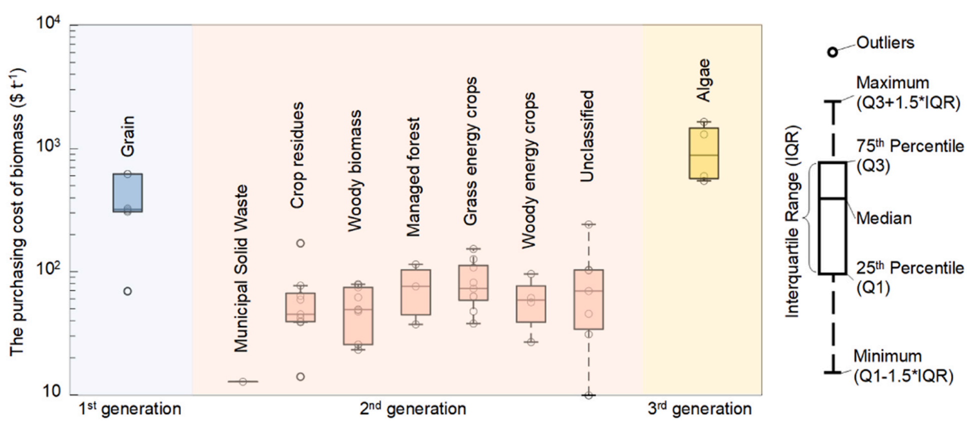

Fig. 7. The purchasing costs of different types of biomass. Each circle behind the whisker box is coming from a previous estimate, the data sources of which are listed in Table S3.

plant with CCS depends on the ratio of biomass cofiring and plant types. Due to the high moisture and ash content of biomass, a higher ratio of biomass co-firing requires more equipment retrofitting and technology to adapt to the properties of the mixed fuel and the CO_2 emissions [52], resulting in higher retrofitting costs (Fig. 8A). For power plant types, integrated gasification combined cycle power plants are already equipped with gas treatment units to handle the waste gas produced during combustion and syngas provided by gasification, these gas treatment units can be used for CO_2 capture [237]. Therefore, regardless of whether it is for coal-fired power plants or biomass-fired power plants, the cost of retrofitting integrated gasification combined cycle power plants with CCS is lower than the retrofitting cost of steam power plants (Fig. 8B).

3.3. Cost of capturing CO_2 in power plants

The cost of capturing CO_2 emitted from power plants ranges from \$9 to \$157 $(t\ CO_2)^{-1}$ with a median of \$49 $(t\ CO_2)^{-1}$ (Fig. 9A). The cost of capturing CO_2 is generally higher when adopting a higher ratio of biomass co-firing, which is \$34.8, \$40.3, \$48.7, \$54.9 and \$82.2 $(t\ CO_2)^{-1}$ when the ratio of biomass co-firing is 0%, 10%, 20%, 40%, and 100%, respectively [268] (Fig. 9B). In two extreme cases, the cost of capturing CO_2 increased from \$60 $(t\ CO_2)^{-1}$ for a coal-fired power plant to \$101 $(t\ CO_2)^{-1}$ for a biomass-fired power plant [245] (Fig. 9B). The reason for this trend is that the higher the ratio of biomass co-firing, the lower the concentration of carbon dioxide in the flue gas, resulting in higher capital and operating costs for carbon capture. The cost of capturing CO_2 also depends on the type of power plant and the technology of CO_2 capture (Fig. 9C). The cost of capturing CO_2 decreased from \$40–42 $(t\ CO_2)^{-1}$ in supercritical-pulverized-coal (SCPC) power plants and \$60–65 $(t\ CO_2)^{-1}$ in natural-gas-combined-cycle (NGCC) power plants using post-combustion CO_2 capture to \$28–30 $(t\ CO_2)^{-1}$ for coal-based integrated gasification combined cycle power plants using pre-combustion CO_2 capture, and close to \$46 $(t\ CO_2)^{-1}$ for SCPC power plants using oxy-fuel combustion CO_2 capture [207]. The cost of capturing CO_2 with post-combustion capture is close to that with oxy-fuel combustion, but generally higher than that with pre-combustion capture due to the higher purity of CO_2 in post-combustion capture facilities [115]. In addition, the efficiency of post-combustion CO_2 capture is higher than that of pre-combustion or oxy-fuel combustion capture technology, which can reduce the net emissions of CO_2 in BECCS [84].

3.4. Cost of CO_2 transportation

The cost of CO_2 transportation depends on the type of transportation and likely on the distance of transportation, which is relatively cheaper for pipeline and shipping transportation than railway and truck transportation (Fig. 10). Pipeline transportation is considered as the most feasible method in the long-distance onshore transportation of large quantities of CO_2 [135,227]. The cost of pipeline transportation depends on the lifespan of the pipeline, which could exceed 23 years [180]. In addition, an increase in the flow rate of CO_2 and a decrease in the length of CO_2 pipeline can reduce the unit cost of pipeline transportation from \$105.2 to \$2.3 $(t\ CO_2)^{-1}$ [154]. The unit cost of CO_2 transportation increases from \$1.1–2.0 to \$3.6–7.4 $(t\ CO_2)^{-1}$ as the capacity of CO_2 transportation decreases from 30 to 3 Mt $CO_2\ y^{-1}$ [43], while another study suggests that the unit cost of CO_2 transportation increases from \$2.9 to \$16.7 $(t\ CO_2)^{-1}$ as the capacity of CO_2 transportation decreases from 35 to 1.5 Mt $CO_2\ y^{-1}$ [111]. In addition, the unit cost of CO_2 transportation by the offshore pipeline at \$4.2–7.4 $(t\ CO_2)^{-1}$ is higher than that by onshore pipeline at \$2.6–4.9 $(t\ CO_2)^{-1}$ [173,189].

3.5. Cost of CO_2 storage

The cost of CO_2 storage is mainly dominated by the cost of drilling and operations, owing to the profit in the sale of incremental fuels when applying BECCS in the enhanced coalbed methane or enhanced oil recovery [217], the carbon storage costs could be even negative [246], which varies from -\$14.2 to \$163.9 $(t\ CO_2)^{-1}$ (Table 5). The cost of CO_2 storage depends on the location of injection, which is -\$14.2–20.0 $(t\ CO_2)^{-1}$ in the depleted oil fields or \$0.5–163.9 $(t\ CO_2)^{-1}$ in saline aquifers, or -\$7.6–21.4 $(t\ CO_2)^{-1}$ in the gas fields [102,199,217,239,269]. The cost of offshore CO_2 storage ranges from \$2.9–28.6 $(t\ CO_2)^{-1}$, while the cost of onshore CO_2 storage is \$1.4–17.1 $(t\ CO_2)^{-1}$ [102]. An increase in the injection rate of CO_2 from 1 Mt to 15 Mt $CO_2\ y^{-1}$ leads to a decline in the cost of CO_2 storage from \$16.6–23.4 to \$6.3–8.5 $(t\ CO_2)^{-1}$ [219].

3.6. Cost of measures to maintain the fertility of soils

To prevent the depletion of nutrients in the soil, additional fertilizers are needed to maintain the fertility of soils when using biomass in the field for power generation in power plants. Addition of 76.0 and 47.8 kg nitrogen ha^{-1} by increasing the application of urea ammonium nitrate

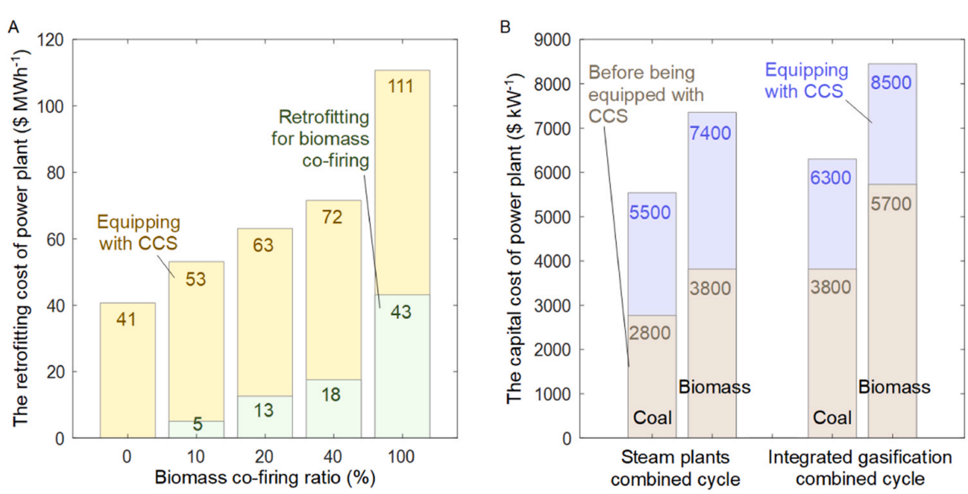

Fig. 8. Cost of retrofitting the existing fossil-fuel power plants. (A) Dependence of the cost of retrofitting a fossil-fuel power plant to a biomass cofiring plant with CCS on the ratio of biomass cofiring. The cost of equipping CCS is show by the yellow column, while the cost of retrofitting for biomass co-firing is show by the green column. Data in this plot are compiled from a previous study [268]. (B) Dependence of the capital cost of retrofitting a fossil-fuel/biomass power plant to a plant with CCS on the plant types. The capital cost before equipping CCS is show by the grey column, while the capital cost after equipping CCS is show by the purple column. Data in this plot are compiled from a previous study [169].

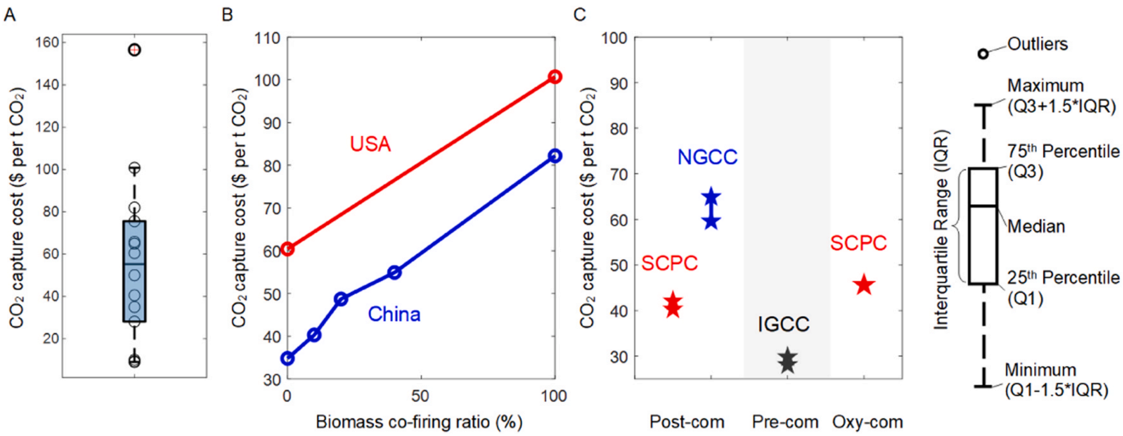

Fig. 9. Costs of capturing CO_2 in power plants. (A) A whisker plot of the cost of CO_2 capture. (B) Dependence of the cost of CO_2 capture on the ratio of biomass co-firing in a power plant. The blue line shows the cost of CO_2 capture for a coal-fired power plant in China [268], while the red line shows the cost of CO_2 capture for a coal-fired power plant in the USA [245]. (C) Dependence of the cost of CO_2 capture on the type of power plants and the technology of CO_2 capture. We compare the cost of CO_2 capture among the technologies of oxy-combustion (oxy-com), post-combustion (post-com), and pre-combustion (pre-com) applied in the power plants based on supercritical pulverized coal (SCPC), natural gas combined cycle plants (NGCC) and integrated coal gasification combined cycle (IGCC), respectively. Each pentagram shows an independent estimate, the data sources of which are listed in Table S4.

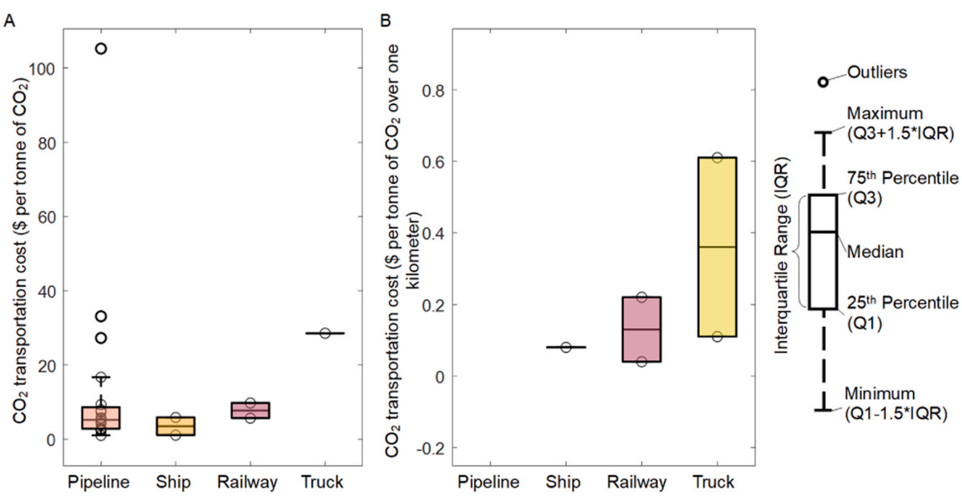

Fig. 10. Costs of CO_2 transportation. (A) The cost of transporting one tonne of CO_2 by different measures. (B) The unit cost of transporting one tonne of CO_2 over one kilometer by different measures. Each circle behind the whisker box is coming from a previous estimate, the data sources of which are listed in Table S5.

Table 5
Cost of CO_2 storage in the literature.

CO_2 storage cost ($ per t CO_2)							
Saline aquifer basins		Oil basins		Gas basins		Coal basins	Reference
Onshore	Offshore	Onshore	Offshore	Onshore	Offshore	-	
1.9–26.5		-14.2		-7.6		-	[217]
0.5–7.4		-		-		-	[269]
2.9–17.1	8.6–28.6	1.4–14.3	2.9–20.0	-		-	[102]
-		-		2.6	6.1	-	[239]
26.0–163.9		-		4.6	4.6–21.4	-	[199]
2.3–8.2							[49]
6.1–11.4							[8]
7.0–8.8							[40]
10.5–13.2							[41]
0.9–10.5							[159]
1.3–16.6							[125]
6.3–8.5 when CO_2 injection rate is 15 Mt CO_2 y^{-1}							[219]
6.8–9.2 when CO_2 injection rate is 6 Mt CO_2 y^{-1}							[219]
8.1–10.8 when CO_2 injection rate is 3.2 Mt CO_2 y^{-1}							[219]
16.6–23.4 when CO_2 injection rate is 1 Mt CO_2 y^{-1}							[219]

fertilizer is required for corn stover production in the soft and alkaline soils based on the N content of stover (1.3±0.1%) and the corn yield of 3.7 and 6.0 Mg ha^{-1} y^{-1}, respectively [75]. When cultivating the dedicated energy crops, addition of 18–128 kg ha^{-1} of N, 10–46 kg ha^{-1} of P_2O_5, and 100–218 kg ha^{-1} of K_2O is required to maintain the fertility of soils based on the contents of N (0.12–0.64%), P (0.05–0.23%) and K (0.50–1.09%) in the miscanthus and the yield of miscanthus (20 t ha^{-1}) [137]. The costs of fertilizers depend on the amount of fertilizers and the price of N, P, and K fertilizers, which is 0.58 \$ $(kg\ N)^{-1}$, 0.79 \$ $(kg\ P)^{-1}$, and 0.41 \$ $(kg\ K)^{-1}$, respectively [261].

3.7. Cost of water consumption

The cost of water consumption in the deployment of BECCS depends on the amount of water consumption and the prices of water [22,29]. Production of one tonne of switchgrass, miscanthus and wheat straw consumes 261, 585–645 and 1529 m^3 of water in irrigation, respectively [100,263]. We compare the footprint of blue water by consuming the freshwater available to humans when harvesting 17 types of crops (Table 6). The blue water footprint is smaller for the second-generation biofuels than the first-generation biofuels, which depends on the regional weather and soil characteristics [76,109]. Further, the operation of BECCS plants requires 76–780 m^3 MWh^{-1} of water for cooling in power generation [100] and 1.71–2.59 m^3 $(t\ CO_2)^{-1}$ of water for CCS in coal or gas-fired power plants retrofitted with post-combustion technologies for CO_2 capture [205]. The lifecycle consumption of water in BECCS is approximately 333–575 m^3 to sequestrate one tonne of CO_2, which is dominated by water consumption in the agricultural irrigation [205].

Relative to the consumption of water, the price of water is equally variable (Table 7). The price of irrigation water varies from \$4.36 to \$420 $(1000\ m^3)^{-1}$ due to differences in the sources of water among different countries [33,236,255]. The price of cooling water for power plants is about \$30 $(1000\ m^3)^{-1}$, which depends on the price of industrial water [160], which could increase by approximately 20%-30% by 2050 due to the increasing scarcity of water at a global scale [28]. The high cost of water consumption will reduce the competitiveness of BECCS against other types of renewables with a low requirement for water in the regions with water scarcity.

4. Policy instruments to accelerate the deployment of BECCS

Accelerating the deployment of BECCS is not only useful to halt the rapid rise of global annual average temperature, but also important to examine the feasibility of large-scale BECCS, which can reduce the risk of carbon lock-in from fossil fuel supply infrastructure. There is an implementation gap between the demand for CO_2 emissions abatement by BECCS in many scenarios with the ambitious targets for climate stabilization projected by IAMs and the current rate of BECCS deployment at both the global and regional scales. Strengthening policy support to accelerate the deployment of BECCS is needed to reduce the risk of climate change in the scenarios with over-optimistic reliance on negative emissions [19,64,67]. We reinforced the necessity of policy reform in incentivizing BECCS deployment based on economic, regulatory, and informational tools [64], which are illustrated in Fig. 11.

Table 6
Blue water footprint of crops.

Crops	Blue water footprint (m^3 of water to produce one tonne of crops)					
	[263]	[76]		[139]	[77]	[155]
Switchgrass	287	-	-	-	-	-
Barley	-	147	6510	-	-	-
Cassava	-	0	1437	-	65	0
Jatropha curcas	-	1170	14344	-	-	-
Maize	-	0	2267	52	850	-
Rapeseed	-	0	4130	-	-	231
Rice	-	19	4629	-	1139	341
Potato	-	0	922	-	-	-
Rye	-	245	1220	-	-	-
Sorghum	-	0	14117	35	-	81
Soybean	-	546	2583	-	1628	70
Beet	-	0	376	-	-	26
Sugarcane	-	8	217	-	28	57
Wheat	512	0	9989	-	-	342
Peanut	-	-	-	-	1559	-
Cotton	-	-	-	-	-	1306
Sunflower	-	-	-	-	-	148

Table 7
Prices of irrigation water and cooling water.

Price of water (\$ per 1000 m^3 of water)			
Irrigation water	UK	21	[236]
	Jordan	21	
	Australia	4.36	
	France	5.26	
	Morocco	19	
	Spain	128	
	Turkey	40	
	Israel	235	
	Netherlands	330	
	Tanzania	420	
	Canada and Romania	10	
	USA	60	
	China	8	[33,255]
Cooling water		33	[160]

4.1. Economic tools

Economic tools generally refer to the provision or reduction of material resources to achieve an environmental target [21], which can be combined with the deployment of BECCS (Table 8). Further studies are needed to compare the effects between the combination of multiple economic tools and the application of a single tool, which likely differ between countries.

4.2. Regulatory tools

Regulatory tools refer to policies that influence human behaviors

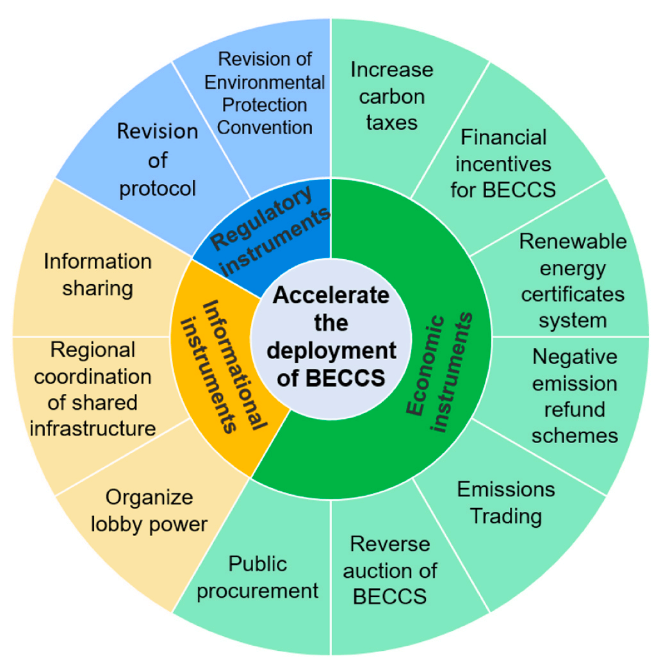

Fig. 11. Policy instruments to accelerate the deployment of BECCS.

Table 8
Economic tools to accelerate the deployment of BECCS.

Economic tools to incentivize BECCS	Approaches
Carbon taxes	Carbon taxes refer to taxation of carbon emissions from enterprises [85,275]. The taxes on carbon emissions should be higher than the capital and operational costs to stimulate investment in BECCS [18,136], by consideration of tax refunding on negative emissions [64].
Financial incentives	Financial incentives for BECCS refer to the provision of government fund on benefiting technological innovation to reduce the capital costs of BECCS [15,275], subsidizing the prices of electricity generated by BECCS, and increasing the enterprise cash flow to application of BECCS [85].
Renewable energy certification	Renewable energy certification system refer to production of one certificate for the renewable energy generated by BECCS, which can be sold in the market as the tradable emission rights to increase the profits of BECCS by rewarding the expansion of biofuel power [196,197].
Negative emission refund	Negative emissions can form a refund system by receiving refunds for CO_2 removed from the atmosphere in the projects of BECCS [195–197].
Emission trading system	Emissions trading system allows countries to sell the surplus emission rights to other countries, which can be used to incentivize countries to support the deployment of BECCS in other countries with rich resources of bioenergy [64,275].
Reverse auction	Reverse auction refer to the formation of a market with one buyer for carbon removal credit quotas and multiple sellers for negative emissions, which can be used to reduce the costs and promote the deployment of BECCS [67,271].
Public procurement	Public procurement uses the purchasing ability by the government or public institutions to promote the application of BECCS by prioritizing the selection of goods or services that meet the requirement of negative emissions [186].

when the decision makers are defining rules or directives that could be followed by individuals [21]. Regulatory tools include binding and enforceable agreements or environmental protection conventions, which could be relaxed to reduce the restriction on the deployment of BECCS. For example, the United Nations regulatory tools had banned the export and submarine storage of CO_2, whereas revisions to regulatory tools, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic and the London Protocol, have removed regulatory barriers related to carbon storage and promoted the storage and export of submarine CO_2 [103]. The regulatory documents at the international and supranational levels should be further reformed to coordinate the global, regional and national regulations, which could reduce the regulatory barriers for accelerating the deployment of BECCS [64].

4.3. Information tools

Information tools refer to actions that attempt to influence the promotion of new technologies through the transfer of knowledge and theoretical exchanges, which include the organizational lobbying, information sharing, and the shared equipment [21]. Organizational lobbying aims at changing the structure of network by obtaining the political support from a specific team of lobbying [181]. Information sharing refers to the integration and sharing of operational experience and the experience learning between countries when deploying BECCS [64,275]. At last, the shared equipment refers to the sharing of infrastructure between countries or regions [275]. Investigation and comparison of the effects of upgrading the economic, regulatory and information tools on the deployment and promotion of BECCS is needed to examine the feasibility of this new technology.

Carbon taxes, financial incentives, and reverse auction have been considered as appropriate options to support BECCS deployment, while a combination of policies might accelerate the deployment of BECCS [248]. Meantime, biowaste (e.g., fruit and vegetable waste) could provide another source of biomass for BECCS [2,164]. In addition, public-private partnerships are critical to advance the deployment of BECCS by combining public policy support with private innovation, efficiency improvements, and social capitals [191,208]. For example, trade of carbon credits has been used to ensure rentability of the capital investments in BECCS plants (https://sustainable-energy-week.ec.europa.eu/swedish-project-pioneering-bioenergy-carbon-capture-and-storage-technology-announced-finalist_en). Such collaboration could contribute to global efforts in climate change mitigation [108].

5. Conclusions

This review emphasizes the biophysical and economic limitations to large-scale deployment of BECCS, which aims at achieving the climate goals of the Paris Agreement. There are several limitations in current IAMs when predicting the capacity of CO_2 emissions abatement by BECCS. Few IAMs have accounted for the ecological factors limiting the production of dedicated energy crops, the impact of climate change on the production of bioenergy due to feedbacks of climate change to the yield of crops, and the impact of the injection rate of CO_2 on the capacity of carbon storage at geological sites. When predicting the costs of deploying BECCS, few IAMs have accounted for the costs of biomass production, the impact of the distance of CO_2 and biomass transportation on the cost of transportation, and the cost of water consumption and measures to maintain the fertility of soils. In additions, there is generally a lack of studies to investigate the effects of combined policy instruments in accelerating the deployment of BECCS. These limitations together increase uncertainties in the effects of deploying BECCS at different time points on slowing the rate of global warming.

6. What's next?

The following are the research focuses on BECCS, which can be addressed in the academic community, markets, and governments.

6.1. Development of spatially explicit models

To reduce the uncertainties in the capacity of CO_2 emissions abatement by BECCS in IAMs, we emphasize the importance of developing spatially explicit models, which should be driven by data of observations on the relationships between crop production and various climate and ecological factors such as land use competition, biodiversity conversion, soil degradation, and water availability [252,265]. Developing spatially explicit models should fully account for the impact of the injection rate of CO_2 on the capacity of CO_2 storage, the impact of deploying other types of renewables on the maximal capacity of CO_2 capture in the power plants, and the life-cycle emissions of GHGs from land-use changes and additional energy consumption. Developing these models should also account for costs of acquiring different types of biomass, costs of retrofitting thermal power plants for biomass co-firing and application of CCS, costs of CO_2 capture in power plants, costs of transportation and storage of CO_2 based on the most economical measures, costs of maintaining soil fertility using the advanced technology for soil remediation, and costs of water consumption in biomass cultivation by considering measures to improve the efficiency of irrigation.

6.2. Development of carbon-neutral agriculture with BECCS

Agricultural activities are a significant contributor to global GHGs emissions and climate change [276]. The future increase in food demand driven by the growth of the population and the increasing demand for calories will lead to further increases in emissions of GHGs from agriculture [240], making it challenging to achieve the target of carbon neutrality in the agricultural sector. The strategies of management such as reasonable irrigation, fertilization, and appropriate straw retention can reduce GHGs emissions from agricultural activities, but probably cannot meet the target of carbon neutrality [264]. It is interesting to investigate how to use agricultural residues efficiently in the application of BECCS to achieve carbon neutrality in the agricultural sector, the cost of which can be compared against measures abating GHGs emissions in the other sectors.

6.3. Feeding BECCS with the algae

Algae have a high CO_2 fixation efficiency and biomass productivity with a low requirement for arable lands [34]. Feeding BECCS with the algae can mitigate climate change by reducing atmospheric CO_2 concentration without compromising food security or increasing freshwater consumption [14]. Currently, both CCS plants and a combination of commercial microalgae with CCS plants are still under the pilot stage, and the high cost of algae makes its application less competitive than the projects which feeds BECCS with agricultural residues or the wasted woods in forests. Key technological breakthroughs are needed to maximize the lipid content and the growth rate of algae and improve the efficiency of electricity generation in power plants using algae as the sources of bioenergy [120].

6.4. Combination of BECCS with other negative emissions technologies

A single negative emissions technology probably cannot meet the pledged CO_2 emissions abatement to achieve the 1.5 ℃ or 2 ℃ target. A combination of multiple negative emissions technologies can increase the possibility to achieve the ambitious climate goals [24,161], which has significant benefits in the energy-water-land systems with substantial cost reduction in the mitigation [65]. Enhanced weathering captures CO_2, counteracts acidification, reduces soil acidity, improves soil fertility, and enhances plant productivity, which can be combined with BECCS [7,16,17,130,231]. Application of biochar in the field retains organic matter in the soils, increases the permeability and porosity of soils, and enhances the capacity of water-holding and nutrient retention, which is beneficial to promote the production of biomass for BECCS [110,116,185,203]. Afforestation can protect biodiversity and increase ecological resilience, which counteracts the effects of growing dedicated energy crops on biodiversity reduction [24], while the wasted woods in the forests can increase the bioenergy feedstock for BECCS [202]. When meeting the long-term targets in climate mitigation, it is more important to consider a combination of technologies such as enhanced weathering, biochar and reforestation with BECCS to compensate the drawbacks of BECCS and provide more sustainable and cost-effective mitigation measures than deploying BECCS alone.

CRediT authorship contribution statement

Rong Wang led the project, conceived the research and designed the study. Xiaofan Xing compiled data, performed the research, prepared graphs and wrote the first draft of the paper and supplementary materials. Yuankang Xiong, Yuan Gao and Siqing Xu compiled data. Rong Wang, Philippe Ciais, Thomas Gasser, Josep Penuelas, Jordi Sardans, Jianmin Chen, Tang Xu and Renhe Zhang provided review, editing, and supervision for this study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nxsust.2024.100040.

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