The impact of cost reductions in renewables on the value of carbon capture and storage

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SUMMARY

A growing school of thought argues that the falling cost of renewables could remove the need for carbon capture and storage (CCS) in mitigation pathways. This view contrasts with much integrated assessment modelling which has highlighted a critical role of CCS. Using a global integrated assessment model, we explore how the value of CCS is impacted by cost reductions in solar photovoltaics, onshore and offshore wind. Cost reductions in these renewables erode the value of CCS by 15-96% across different energy system sectors. Renewables directly compete with CCS in electricity/hydrogen production, drive near-term emissions reductions through faster power sector decarbonisation and enable greater electrification of end-use sectors. All three channels erode the value of CCS in decarbonising energy systems. CCS is most valuable, and most resilient to low-cost renewables, in sustainable bioenergy and industrial applications, while the value of CCS in hydrogen and electricity generation is limited. This suggests that targeted, rather than blanket, CCS deployment represents the best strategy for achieving the Paris Agreement goals.

INTRODUCTION

The goal of international climate policy is clear – to limit warming to ‘well-below 2 °C’ and pursue efforts to limit the temperature increase to 1.5 °C[1]. Despite this clarity, there remains widespread disagreement on the best means of achieving this goal. Many different technologies and strategies could be involved in reducing emissions, and most have their supporters and detractors. From hydrogen[2,3] to demand reduction[4,5], CO_2 removal[6,7] to bioenergy[8,9] – debate continues on the relative merits of different proposed solutions to achieve the Paris Agreement goals. There is an urgent need for continued research to help policymakers understand which technologies are truly essential for decarbonisation, and which represent potentially costly or dangerous distractions to the task at hand. This can help policymakers design investment strategies which prioritise the most valuable technologies and therefore help achieve cost-effective and successful decarbonisation.

The exemplar amongst current debates concerns renewable energy, and whether it might render other low-carbon technology options, such as nuclear or carbon capture and storage (CCS), obsolete. Low-carbon scenarios demonstrate that renewable electricity will be the backbone of climate action, with a rapid expansion of clean electricity essential to reduce emissions[10]. In the IEA’s roadmap for achieving net zero by 2050, electricity generation more than doubles by mid-century due to electrification of end-use sectors, while the share of renewable electricity triples to 90%[11]. This requires unprecedented deployment of variable renewable electricity in particular, with generation from wind and solar growing by 15- and 30-fold respectively by 2050.

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Historically, many low-carbon scenarios have suggested CCS will be a valuable complement to renewables in reducing emissions[12–16]. In the IPCC's 5th assessment report (AR5) scenario database, the cost of limiting warming to well-below 2 °C more than doubles if CCS is unavailable[17]. This substantial value arises in part from the perceived versatility of CCS, which can be deployed in a range of energy system sectors. CCS is an essential component of engineered CO_2 removal via BECCS[18], can capture emissions from heavy industry[19,20] (particularly CO_2 released by chemical processes, which cannot be avoided by fuel-switching), and has been proposed as a method for producing low-carbon hydrogen[21] and electricity[22]. Integrated Assessment Models (IAMs) in particular deploy large amounts of CCS – in scenarios which limit warming to 1.5 °C with no/limited overshoot in the SR1.5 database, median CCS deployment reaches 8.5GtCO$_2$/y in 2050, and over the century 790GtCO$_2$ is captured and stored[23], representing almost 20 years of current CO_2 emissions[24].

The value of CCS as a low-carbon technology has been challenged in recent years. A growing school of thought has suggested that renewables could provide all of the world's energy needs by mid-century[9,25–30], removing the need for CCS. The recent focus on net-zero emissions also presents challenges for CCS deployment. CCS applied to fossil fuels may be low-carbon, but is not zero-carbon due to upstream emissions and imperfect capture rates[31]. In a net-zero world, fossil CCS would therefore have to be paired with CO_2 removal, which is a contentious and risky strategy[6]. In the Race to Zero[32], CCS may therefore struggle to keep pace with zero-carbon competitors. Concerns have also been raised around the feasibility of large-scale CCS deployment[33–36], with CCS facing barriers such as limited CO_2 storage potential in some regions[37] and challenges of resource availability[33,38] (particularly in the case of BECCS).

Debate continues around the role of CCS in reducing emissions, and the extent to which renewables render CCS obsolete. Energy systems which rely entirely on renewables face challenges relating to the large-scale integration of variable renewables such as wind and solar[39–41]. While solutions to these challenges exist, concerns have been raised about the potential high cost of such systems. 100% renewable energy systems may be technically viable, but they may not be the most cost-effective mitigation strategy[41,42]. Equally, given the scale of decarbonisation required and challenges in deploying renewables at sufficient pace[43], CCS could provide a bridging role, helping reduce emissions from fossil fuels while renewables scale up and supporting market development for key fuels like hydrogen[44]. There are also certain sectors where CCS is the only option for reducing emissions, particularly capturing process emissions from industrial processes such as cement production[45]. Prematurely excluding CCS as a low-carbon technology could therefore prove counterproductive. While displaying lower deployment than comparable IAM scenarios, the IEA's Net Zero roadmap still sees a critical role for CCS, with 7.6GtCO$_2$/y captured by 2050 across all sectors[11].

The debate on the relationship between CCS and renewables needs to account for real-world context, where the fortunes of these technologies are markedly different. Renewables have experienced a decade of unprecedented cost reductions and rapid deployment. The cost of electricity from solar photovoltaics (PV) fell 85%, and the cost of onshore and offshore wind fell by 56% and 48% respectively over the last decade[46]. Installed capacity of solar, onshore and offshore wind has also grown rapidly, at 33%/y, 15%/y and 27%/y respectively over the decade[47,48]. A range of analyses have highlighted that energy system models often overestimate the cost of renewables, with the greatest discrepancies observed in solar power[49–52]. This suggests that some contributions to the debate may be based on outdated evidence.

On the other hand, CCS has in many ways suffered a 'lost decade', marked by limited deployment[53,54] and falling expectations[55] for the technology. The majority of CCS projects initiated in the past 30 years have failed[56,57]. As of 2020, carbon capture capacity was 38.5MtCO$_2$/y[58] – approximately 0.1% of global emissions[24]. Currently-planned projects, if all successfully deployed, would lead to 115MtCO_2/y being captured by 2030[58] – less than 10% the level required in the IEA's roadmap[11]. Multiple progress assessments have highlighted that CCS deployment is significantly behind the level required by many low-carbon scenarios[54,59].

There is an urgent need to revisit this debate and explore how real-world developments affect our understanding. If recent progress in renewables and the potential for significant further cost reductions are taken into account, does this undermine the case for CCS, and if so, how? This study aims to enrich the related literature by addressing this question. Using TIAM-Grantham, a global IAM (Experimental Procedures), we assess the value of CCS to policymakers concerned with achieving cost-effective decarbonisation. We do so on a sectorally-resolved basis, exploring the value of CCS in biomass applications (electricity and fuels), hydrogen production, industrial decarbonisation and fossil-based electricity generation. We explore whether cost reductions in wind and solar reduce the value of CCS, and if so, how and in which sectors of the energy system. The results of the analysis demonstrate the value of CCS in different energy system sectors, and how this value is affected by cost reductions in renewables. This can aid policymakers in designing investment strategies which prioritise the most valuable low-carbon technologies and help achieve cost-effective and successful decarbonisation.

RESULTS

Integrated assessment models overestimate the cost of renewables

Renewable generation technologies have demonstrated rapid cost declines in the past decade[46], and IAMs have been criticised for failing to account for this progress[49–52]. It is vital that models use up-to-date costs as inputs[60–63]. We conduct a recent literature review[11,49,64–69] to establish updated cost trajectories for solar PV, onshore and offshore wind, distinguishing between utility scale and decentralised installations where relevant. These costs are compared to those provided by Krey et al.[60], which reports the techno-economic assumptions of a range of well-known IAMs (Supplemental Note 1).

Cost assumptions for renewable technologies in IAMs are generally more conservative than projections from the recent literature (Figure 1). In all three technologies reviewed, the global average cost in Krey et al. is above the average cost from reviewed literature. The discrepancy is greatest in the case of solar PV, where recent literature suggests that capital costs could fall below \$200/kW by 2050 – 80% lower than Krey et al. In the case of onshore/offshore wind, IAM projections are within the uncertainty range of reviewed literature – however the literature still indicates the potential for substantial future cost reductions which exceed the level observed in Krey et al. The exact reasons for these discrepancies are unclear, but may include the difficulty of assigning modeller time to documentation/validation of inputs when the majority of funding is for applied research[70], and the challenge for academic institutions to keep abreast of real market development.

Interest is growing in improving the transparency and credibility of input assumptions to large-scale IAMs[62,71–73], and as such, updates to wind/solar costs may have occurred in some IAMs since the publication of Krey et al. However, central messages about the relative importance of low-carbon technologies, as summarised in reports such as AR5[74] and SR1.5[75], appear to be based in part on cost data that is substantially outdated. There is therefore value in revisiting this issue and exploring how results change when renewable costs are updated.

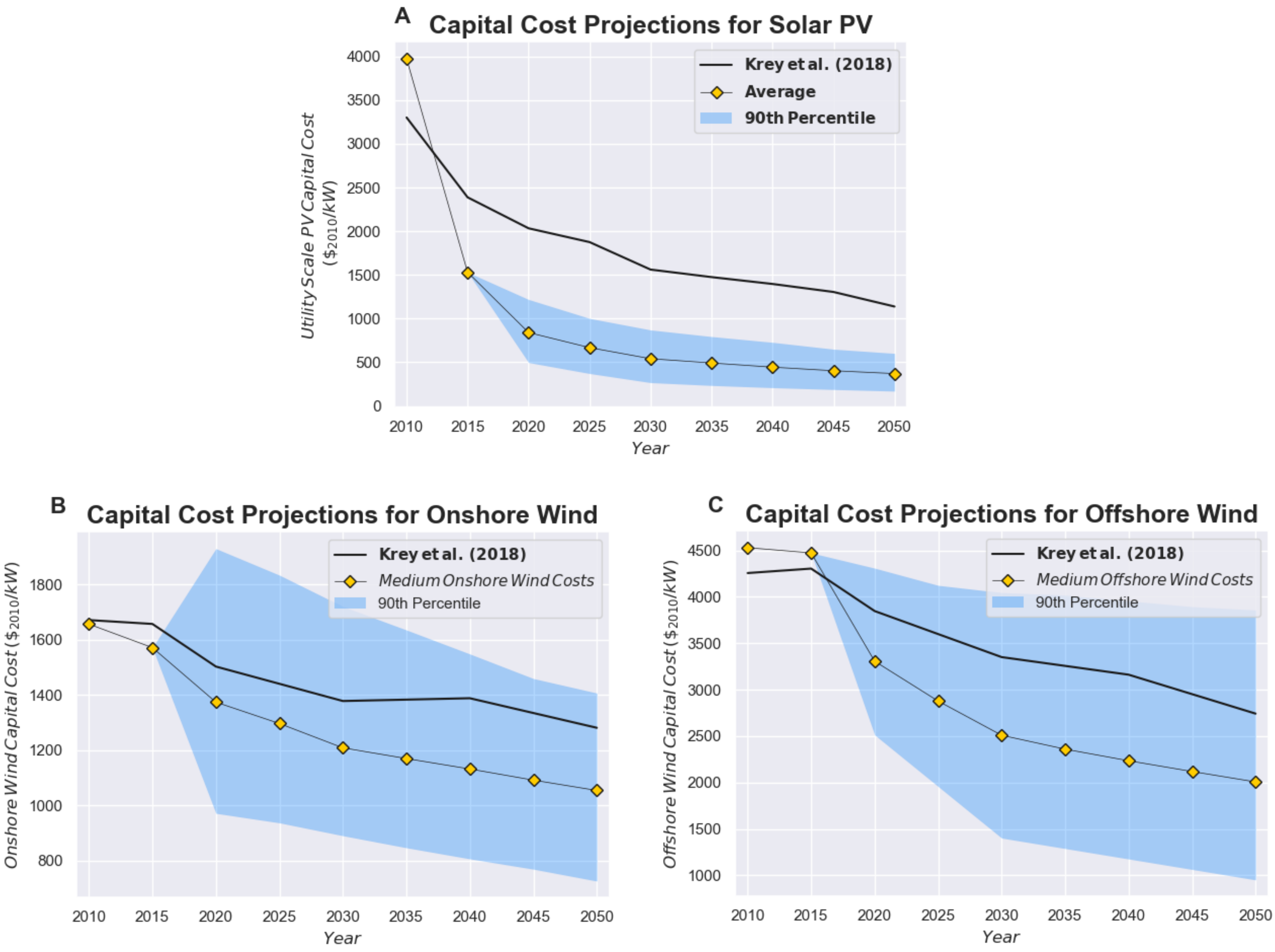

Figure 1 | Cost projections for wind and solar
Figure 1 presents the capital cost of (A) solar PV, (B) onshore and (C) offshore wind in Krey *et al* (2019), alongside capital costs as calculated from a literature review of recent sources. The average of the literature review is shown in yellow diamonds, while the envelope presents the 90th percentile confidence interval. All data represents global average capital costs.

We use the data in Figure 1 to construct three cost trajectories for wind and solar – high, medium and low. High wind/solar costs are represented by Krey et al., with medium costs represented by the mean of the literature review. Low costs are represented by the 10th percentile (Experimental Procedures). We use these cost trajectories to explore whether, and how, cost reductions in renewables erode the value of CCS in mitigation pathways.

Cost reductions in renewables erode the value of CCS

Cost reductions in renewables erode the value of CCS significantly in almost all energy sectors (Figure 2). As the cost of wind/solar falls, the value of CCS in different energy system sectors is reduced by between 15 and 96% of its value under scenarios with high cost projections for wind and solar (Table 1). The only exception is the use of CCS in bio-liquids production, where the value of CCS increases very slightly with falling renewable costs. By underestimating the contribution that wind and solar can play in mitigating climate change[50], IAMs may have overestimated the role and value of CCS in mitigation pathways.

Sector	2 °C	1.75 °C
BECCS (Total)	-26%	-15%
BECCS (Liquids)	+6%	+14%
BECCS (Power)	-36%	-16%
Fossil CCS	-71%	-61%
Hydrogen CCS	-96%	-84%
Industrial CCS	-35%	-31%

Table 1|The erosion in CCS value due to cost reductions in wind/solar generation
This table shows how the system value of CCS falls when moving from scenarios with high wind/solar costs to those with low costs. This is expressed as a percentage reduction in system value – for example, in 2 °C scenarios, the value of industrial CCS is 35% lower in scenarios with low wind/solar costs compared to scenarios with high wind/solar costs. Note that there is a small synergy between falling renewable costs and the system value of BECCS for liquids production (Supplemental Note 3.3).

The value of CCS, and the extent to which low-cost renewables erode this value, varies substantially between different sectors of the energy system. In modelled pathways, bioenergy with CCS (BECCS) has the greatest value. BECCS is most valuable when deployed in the power sector, rather than liquids production (Supplementary Note 2.1). Industrial CCS is the second most valuable application, while the use of CCS in fossil fuel-based electricity generation and hydrogen production has much lower value in modelled scenarios, reducing mitigation costs by the order of only 1-2%.

This merit order for carbon capture projects is also observed in the relationship between CCS and renewables. BECCS displays the lowest levels of value erosion, with its value falling by 15-30% under different temperature targets as the cost of renewables declines. The value of CCS in industry is reduced by approximately a third if cost reductions in wind/solar continue at rapid rates, compared to the more conservative projections from Krey et al. Meanwhile the value of CCS in electricity and hydrogen production, already low, is reduced substantially by low-cost renewables, falling by 61-96%.

In modelled scenarios, cost reductions in renewables do erode the value of CCS noticeably. However, CCS retains value in reducing mitigation costs – particularly through use in industry and in combination with bioenergy to provide negative emissions. This suggests that targeted CCS deployment could remain a viable mitigation strategy.

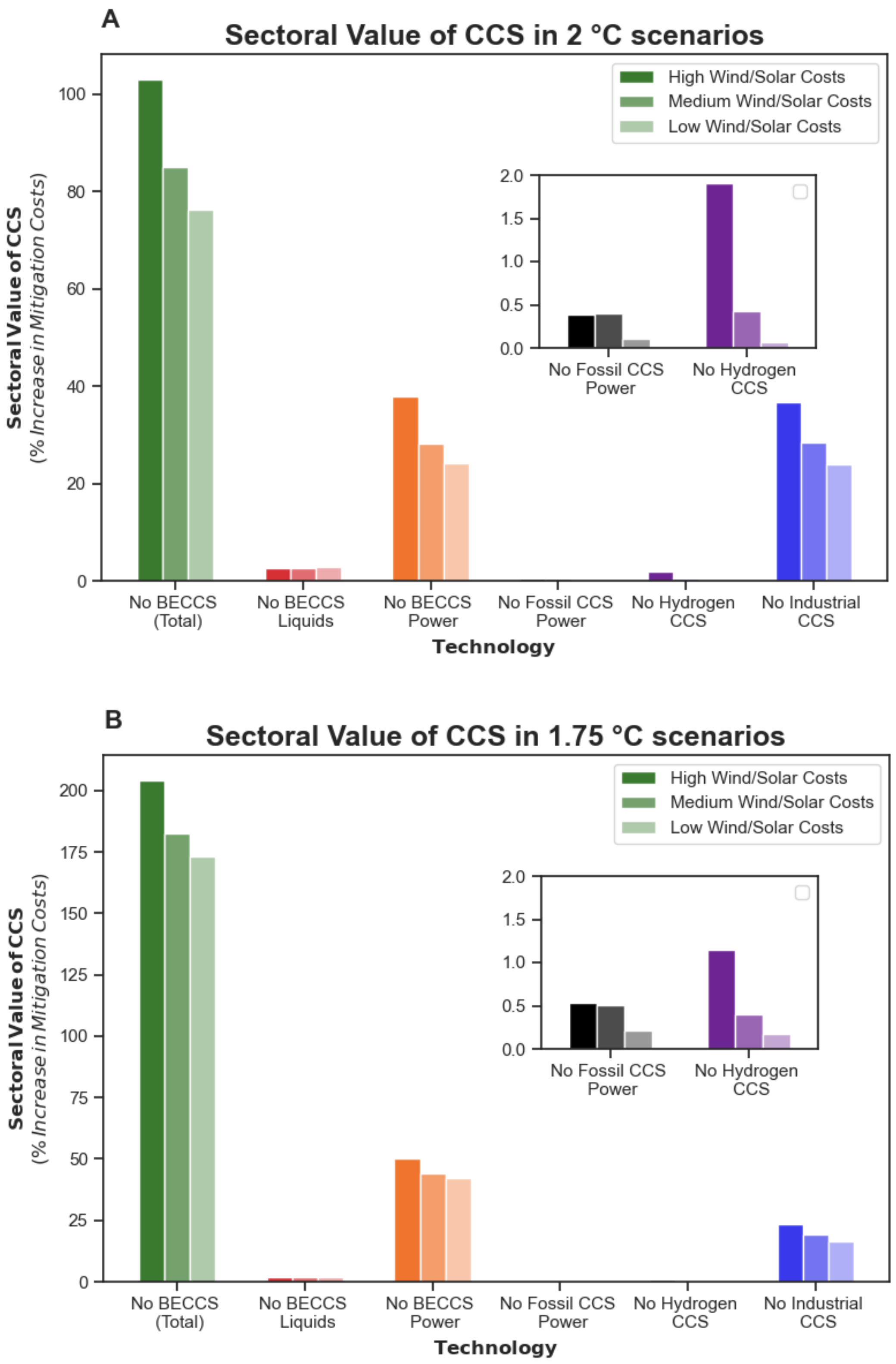

Figure 2|Sectoral Value of CCS. (A) 2°C scenarios **(B)** 1.75°C scenarios.
Shows the value of CCS across the different sectors of the energy system, for three different wind/solar cost trajectories. The high-cost trajectory represents cost data taken from Krey et al., while the medium and low costs are the results of a literature review conducted by the authors. The sectoral value of CCS is measured by the increase in energy system costs that occurs when CCS is unavailable in each sector. This is expressed as a percentage increase from the default mitigation scenario, which is taken to be a scenario with full availability of CCS and with central cost projections for solar/wind generation (Experimental Procedures).

Channels by which low-cost renewables erode the value of CCS

We now explore the channels by which cost reductions in renewables erode the value of CCS. Exploring the underlying mechanisms by which high-level results such as Figure 2 are produced can highlight policy relevant insights from the analysis and can also help non-specialists to understand a complex model's behaviour. This can improve the transparency and utility of models to policymakers[73]. Supplemental Note 2 provides an in-depth exploration of energy transition dynamics.

BECCS

Many IAMs deploy large amounts of BECCS to help achieve long-term temperature goals[76]. However, the feasibility of BECCS remains uncertain, as successful BECCS deployment requires successfully upscaling *both* CCS infrastructure and sustainable biomass supply[38,77]. IAMs have been criticised for excessive reliance on BECCS[78], and this analysis restricts the biomass potential to 100EJ/y to avoid unsustainable levels of biomass consumption[79] (Experimental Procedures). BECCS deployment in modelled scenarios is consistent with recent expert estimates of the feasible potential for BECCS[80] (Supplemental Figure 1).

The use of BECCS to generate electricity and fuels (both liquids and hydrogen) has the greatest value in modelled scenarios. In 2 °C scenarios, mitigation costs approximately double in the absence of BECCS, and in 1.75 °C scenarios costs almost triple. This high value should be understood in the context of BECCS being the only negative emission technology (NET) represented in the analysis. With other NETs modelled, then the value of BECCS would most likely be lower[18]. The value of BECCS in this analysis should therefore be seen not as a direct requirement for specific biomass technologies, but a demonstration of the high value of carbon dioxide removal (CDR) in modelled scenarios. In the main text we focus on the value of BECCS as a group of technologies. Supplemental Note 2.1 discusses the relative value of BECCS across different sectors, which reflects a trade-off between maximising the energetic and emissions value of biomass.

In modelled pathways, BECCS has value predominantly as a means of shifting mitigative effort into the future (Supplemental Figure 2). BECCS allows TIAM-Grantham to overshoot a given carbon budget in the near-term, compensating for this by negative emissions in the latter half of the century. This shifts mitigation costs into the future, reducing overall system costs on a net present value (NPV) basis. Without the flexibility provided by BECCS, there must be much greater near-term decarbonisation. The rate of emissions reductions in the 2020s almost doubles from 2.4%/y to 4.3%/y in 2 °C scenarios without BECCS, while in 1.75 °C scenarios the rate grows from 4.4%/y to 9.1%/y in the absence of BECCS.

This greater near-term action is driven by renewable electricity. A range of fuel-switching dynamics are observed, including greater use of hydrogen, biofuels and solar thermal heating (Supplemental Figure 3). However, all end-use sectors display faster electrification in the absence of BECCS (Supplemental Figure 4). In 2 °C scenarios, mid-century electricity demand rises by 12-16% in scenarios without BECCS, compared to those with. The rate of electrification accelerates even further in 1.75 °C scenarios, with electricity demand in 2050 rising by 36-42% in scenarios without BECCS. At the same time there is a faster phaseout of unabated fossil fuels in the power sector (Supplemental Figure 4), with coal-fired generation phased out by 2030, and unabated gas generation falling an additional 7-17% in 2 °C scenarios without BECCS and falling an additional 10-62% in 1.75 °C scenarios.

Wind and solar play a central role in electrifying end-use sectors and accelerating the fossil fuels in the power sector if BECCS is unavailable, with deployment accelerating to provide the necessary clean electricity supply (Figure 3). In the near-term, the additional demand for clean electricity is met predominantly by solar PV, which provides over half of additional renewable generation in 2030. In the longer-term, offshore wind emerges as a key source of low-carbon electricity, meeting 45-60% of the demand increase in 2050. Cost reductions in renewables enable this highly electrified energy system to be achieved at much lower costs, which reduces the economic value of BECCS to policymakers.

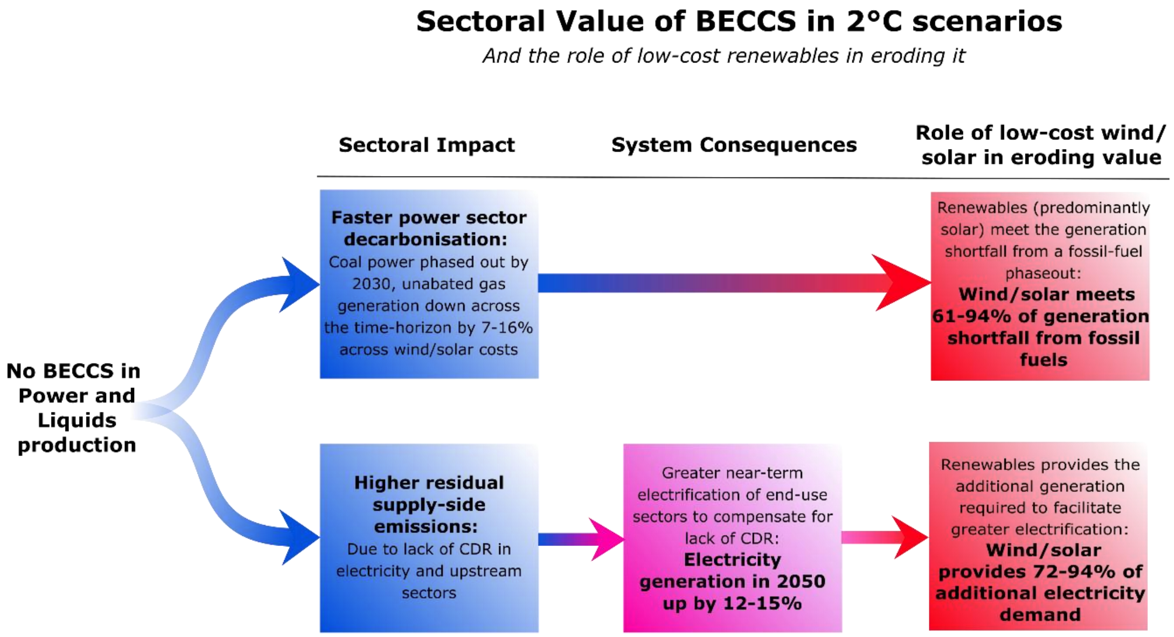

Figure 3|The value of BECCS, and how cost-reductions in renewables erode this value
Shows the impact on the energy system when BECCS is no longer available in the energy system in 2 °C scenarios. The impact is presented as a causal chain, distinguishing between the impact on the power/fuels production sectors, the wider system consequences, and the role that renewables play in compensating for the lack of BECCS. For a comparable figure for 1.75 °C scenarios, see Supplemental Figure 6.

Industrial CCS

CCS can be applied to a wide range of industrial processes to reduce emissions from both fuel combustion industrial processes such as clinker production[81–85]. TIAM-Grantham represents over 20 different industrial CCS technologies, including options in steel, cement and chemicals production and onsite generation via gas CHP plants (Supplemental Table 4).

Without industrial CCS, there is greater use of electricity and hydrogen to reduce emissions, with a faster switch from fossil fuels to electrification in chemicals manufacture, from blast-furnaces to green hydrogen in steel production, and from onsite fossil generation w/ CCS to renewable electricity for heat and power provision. Electricity therefore plays a more substantial role in industrial decarbonisation, providing 85% of final energy by 2100, up from 70% in scenarios in which CCS is available (Supplemental Figure 11).

Without CCS, the pace and extent of industrial decarbonisation is slower. In the mid-term (out to 2050), the availability of zero-carbon electricity and hydrogen is limited, and so fossil fuels continue to be used. CCS could capture emissions from transitional fossil fuel use while zero-carbon alternatives scale, and so the absence of CCS leads to higher industrial emissions in the mid-term. There are also higher long-term industrial emissions due to limited decarbonisation of the cement sector. Here CCS is the only option to deal with process emissions that represent ~60% of cement's carbon footprint[86].

To compensate for these higher industrial emissions, there is greater near-term mitigation in the end-use sectors of buildings/transport. This is predominantly driven by a faster scale-up of hydrogen in transport, and faster deployment of district heating in the buildings sectors. As with BECCS deployment failure, there is also greater near-term power sector decarbonisation. In 2 °C scenarios without industrial CCS, coal generation in 2030 is reduced by 25% compared to scenarios with industrial CCS. In 1.75 °C scenarios, fossil fuels are already being phased out of the power sector at very rapid rates, with a global coal phaseout by 2030. However, there is a faster gas phaseout, with 2030 gas generation 15% lower in scenarios without industrial CCS compared to those with.

This suggests that industrial CCS provides value through three channels:

1. CCS plays a significant role in cost-optimal industrial decarbonisation. In some sectors (chemicals and steel) this role is transitional, with CCS reducing emissions from continued fossil fuel use while the availability of zero-carbon electricity and hydrogen scales up to meet demand. In other sectors such as cement manufacture, CCS has a long-term role due to its unique ability to abate process emissions.
2. By facilitating deep mitigation in industry (particularly cement), industrial CCS allows the pace of near-term mitigation in the end-use sectors of buildings/transport to be relaxed.
3. This deeper industrial decarbonisation reduces the pace of fossil fuel phaseout in the power sector required.

As in the case of BECCS, low-cost renewables erode the value of industrial CCS by enabling cheaper and faster electrification of end-use sectors (in this case predominantly industry) and accelerating the phaseout of fossil fuels in the power sector. In the absence of industrial CCS, solar and wind provide much of the long-term electricity generation required to electrify industry and the near-term generation required to drive fossil fuels out of the power sector (Figure 4). Cost reductions in renewables allow this to occur at a lower cost, thereby eroding the value of industrial CCS in modelled scenarios.

Fossil CCS in electricity and hydrogen production

In these sectors, CCS has value as a source of low-carbon energy. This value is the lowest of all CCS applications and is also most sensitive to the falling cost of renewables, falling by 64-96% if wind/solar continue their rapid cost reductions.

In modelled scenarios, the deployment of fossil CCS in the power sector is relatively low. Coal-fired CCS generation is never deployed, and the deployment of gas with CCS is minimal. In 2°C scenarios, fossil CCS provides 0.04-0.2% of electricity generation over the time horizon, while in 1.75 °C scenarios it is slightly higher, at 0.2-0.4%. This limited deployment is reflected in the value of CCS in the power sector, with mitigation costs in TIAM-Grantham only rising by <0.5% if this technology is excluded. Cost reductions in renewables erode the value of CCS in the power sector by directly competing with CCS as a low-carbon electricity source. In 2 (1.75) °C scenarios, moving from high to low wind/solar cost projections reduces fossil CCS generation by 76 (41) %. By providing an alternative and cheaper source of low-carbon power and directly reducing CCS deployment, low-cost solar and wind significantly erode the value of CCS in modelled pathways.

Blue hydrogen is produced by converting methane into hydrogen and CO_2, capturing and storing the CO_2 produced[21]. In modelled scenarios, blue hydrogen has value as a bridging technology, enabling the scaleup of hydrogen markets while the availability of green hydrogen remains low due to limited availability of

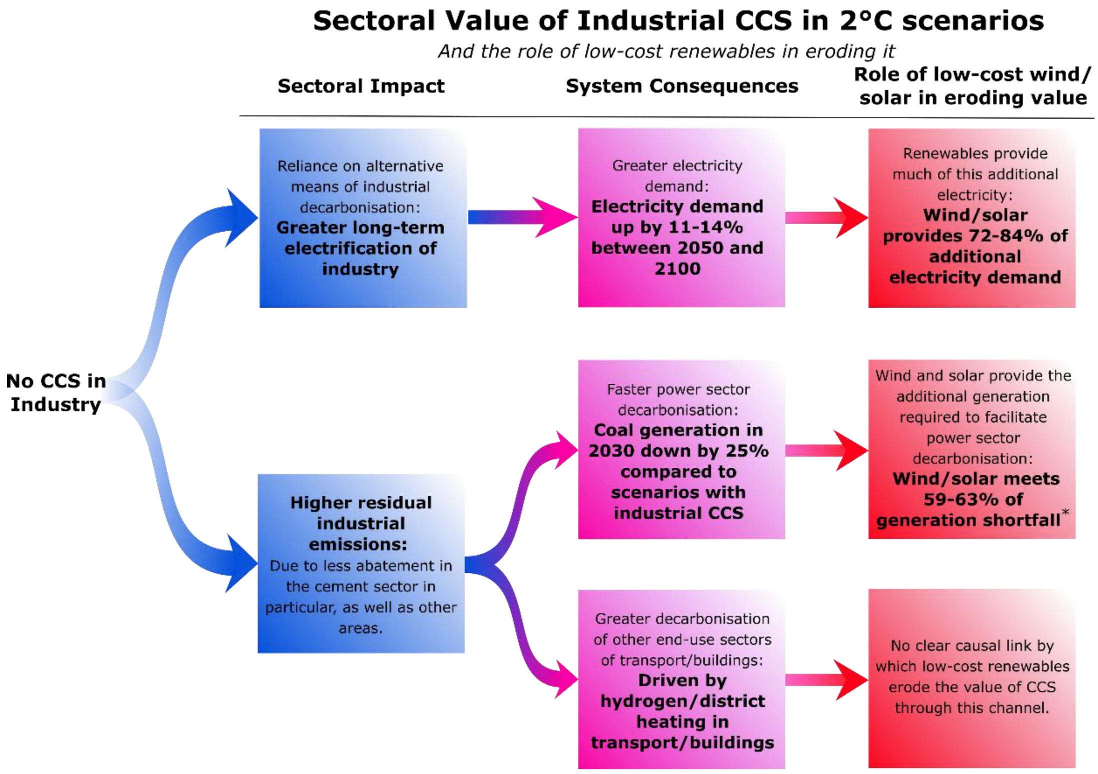

Figure 4|The value of industrial CCS, and how cost reductions in renewables erode this value
Shows the impact on the energy system when industrial CCS industry is unavailable. The impact is presented as a causal chain, distinguishing between the impact on the industrial sector, the impact on other energy system sectors, and the role that low-cost wind/solar generation plays in eroding the value of CCS. For a comparable figure covering 1.75 °C scenarios, see Supplemental Note 2.2

**In 2°C pathways, only scenarios with medium or low wind/solar costs see renewables displacing coal generation. In scenarios with high wind and solar costs, there is coal-to-gas switching instead.*

surplus renewable electricity for electrolysis. In both 2 and 1.75 °C scenarios, blue hydrogen produced by methane reforming with CCS is the predominant near-term source of hydrogen production, but then is scaled back as electrolysis takes over. As a bridging technology, blue hydrogen demonstrates substantial transition risk, with the potential for significant asset stranding as CCS is phased out in favour of electrolysis if too much capacity has been installed on the way up the bridge. This poses a challenge to blue hydrogen investment strategies.

Cost reductions in renewables erode the value of CCS in hydrogen production by making electrolysis a more competitive route for hydrogen production. This reduces the scale of CCS deployment in hydrogen production, with deployment falling by 60-90% as wind/solar costs fall. Cost reductions in renewables also reduce the cost of deploying additional electrolysis if CCS is unavailable in hydrogen production. As a result, low-cost renewables severely undermine the value case for CCS in hydrogen production, reducing its system value by 87-96%.

This exploration of the channels by which renewables and CCS interact demonstrates that achieving deep decarbonisation without CCS requires greater reliance on renewable electricity to reduce emissions. Cost reductions in renewables erode the value of CCS by three different dynamics. In some sectors (CCS in electricity/hydrogen production), low-cost renewables directly outcompete and displace CCS. In other sectors (industry and BECCS), CCS and renewables are not direct competitors, but cost reductions in renewables enable faster power sector decarbonisation and greater electrification of end-use sectors, which can compensate for deployment failure in CCS. However, even in the event of significant cost-reductions in renewables, CCS maintains considerable value in these sectors.

The impact of discount rate variations and CCS cost on results

Equity considerations should be central to the assessment of mitigation pathways[87–89]. In central analytical scenarios, a discount rate of 5% is applied to all future energy system costs. To assess how different perspectives on intergenerational equity affect results, these scenarios were reproduced using lower discount rates of 3% and 1% (Supplemental Note 3). The relationship between the value of CCS and the cost of renewables is robust to variations in the discount rate. However, the value of some CCS applications is highly sensitive to the discount rate applied. The value of BECCS falls by two-thirds when moving from a discount rate of 5% to 1%, while the value of industrial CCS remains robust to variations in the discount rate. This suggests the value of BECCS may be overestimated by scenarios with high discount rates of 3.5-5%[90], which display a structural disposition to delay near-term action in preference for late-term CDR.

Previous analysis has found that CCS deployment in the power sector is sensitive to its investment cost[91]. Using three different cost trajectories for CCS (Experimental Procedures), we explore how cost reductions in CCS affect the results. The sensitivity of system value to the cost of CCS varies substantially across different CCS applications (Supplemental Figure 15). The greatest sensitivity is observed in fossil CCS for electricity generation, whose value varies by ±60% across different CCS cost trajectories. The next most sensitive sectors are CCS for hydrogen production and bio-liquids production, where the value of CCS varies by 20% as CCS costs vary. The value of CCS in industry and bio-electricity is least sensitive to variations in CCS capital costs, with system value changing by only 1-2%.

DISCUSSION

The notion of technology value is becoming increasingly critical, as policymakers with limited time and resources must now make decisions around the role, value and hence prioritisation of different low-carbon technologies. Alongside other areas for improved IAM analysis including greater representation of societal transformations[92] and new scenario frameworks[93], better understanding of the value of different low-carbon technologies and interaction between potentially competing technologies is essential. Here we perform a detailed investigation into how cost reductions in onshore wind, offshore wind and solar PV erode the value of CCS in different energy system sectors. As well as exploring high-level IAM results, we assess the underlying channels by which CCS has value, and by which renewables can erode this value. Greater exploration of model behaviour and the role of key techno-economic assumptions in governing model results can improve both model transparency and legitimacy, helping ensure results are of greatest utility to policymakers.

Using this approach, we demonstrate that cost reductions in renewables erode the value of CCS in mitigation pathways by 15-96% across different sectors of the energy system. It is essential that debates around the value of different low-carbon technologies use best available evidence on technology costs. This is particularly true in the case of wind/solar, where costs continue to fall rapidly. By underestimating the pace of technological progress in renewables, IAMs may overestimate the value of CCS in achieving deep decarbonisation. Despite challenges in doing so, models can, and should, do better in keeping abreast of technological developments. This has implications for a range of scenarios and models in the literature which have been criticised for failing to account for technological progress in renewables[49–52].

Our results also show that it is unhelpful to explore the value of CCS as a single, catch-all technology, as in previous studies[12,13]. CCS can be deployed in diverse contexts, and its value, and the resilience of this value to low-cost renewables, varies substantially across energy system sectors. Our analysis demonstrates that key to the question of technology value is the concept of substitutability. When one low-carbon technology can be readily substituted by another, then its value is likely to be lower, and it will also be more sensitive to cost reductions in the competitor technology. This is the case for CCS in the power sector and in hydrogen production, where renewable electricity is a direct competitor. Here the value of CCS is limited and is also substantially eroded by cost reductions in renewables. The economic case for CCS deployment in these sectors is therefore minimal, particularly if the cost of renewables continues to fall. Our analysis highlights that this value is also most sensitive to uncertain CCS costs, which could further undermine the value if sufficient cost reductions are not achieved. Other work has highlighted substantial challenges to the energetic case for CCS in the power sector[94], as renewables exhibit much better returns on energy invested. Considering the energetic and economic challenges summarised here, CCS deployment in the power sector appears to be a technology of very limited value in achieving deep decarbonisation.

On the other hand, our analysis suggests that priority areas for CCS deployment are for provision of CDR, and to capture industrial emissions, particularly process emissions from cement production. These are areas where CCS provides a unique function, and the direct substitutability with renewables is low. Low-cost renewable electricity cannot abate process emissions in the industrial sector, or directly lead to CDR. As a result, CCS has greater system value in these sectors, and, while cost reductions in renewables do erode this value noticeably, it is more robust to technological progress in wind and solar than the value of CCS elsewhere.

The heterogeneous value of CCS across different applications suggests that targeted, rather than blanket, support for CCS represents the best climate policy. We note that CCS deployment in industry/BECCS could in principle be entirely decoupled from fossil fuel consumption, with CCS facilitating removals and capturing process-based emissions even in a 100% renewable energy system. Targeted CCS deployment could therefore occur alongside an aggressive fossil fuel phaseout, rather than being seen as inherently supporting continued fossil fuel consumption.

In contrast to wind and solar, which have a proven track-record of rapid deployment and significant cost reductions over the past decade, CCS faces significant barriers to achieving large-scale deployment[33–37]. Experience of the past three decades[56,57] and current investment plans[58] suggest a non-negligible possibility that CCS will fail to be deployed at scale. This again highlights the value of targeted, rather than blanket, support for CCS. Our analysis demonstrates that cost reductions in renewables can increase resilience to CCS deployment failure. In some sectors (fossil generation and hydrogen production), renewables can directly replace CCS, while in other sectors (industrial CCS and BECCS), renewables can insure against deployment failure by driving faster power sector decarbonisation and greater electrification of end-use sectors. Policymakers can use low-cost wind and solar to build resilience against CCS failure, by providing policy frameworks which prioritise renewables over fossil CCS in hydrogen/electricity generation, by seizing the opportunity presented by low-cost renewables to drive fossil fuels out of the power sector, and by supporting electrification in the end-use sectors of transport, buildings and industry. This can reduce the value of CCS in mitigation pathways, and thereby build resilience to potential CCS deployment failure.

This analysis focuses on the economic value of technologies in reducing CO_2 emissions. However, technologies have numerous other social and environmental impacts, which should also be accounted for by policymakers when assessing the relative merits of different technologies. Impacts of central concern include the land/material requirements for a given technology, the health impacts, and the potential for technologies to support economic activity[27]. In each of these dimensions, CCS and renewables could have very different effects. We review existing literature on these wider sustainability considerations (Table 2).

Impact Variable	CCS	Wind/solar generation
Land requirements	Can have high land requirements, particularly if dedicated biomass crops are used for BECCS[77,95,96]. With an ecologically constrained biomass potential (as assumed in this analysis), land requirements are reduced as some of the biomass can be sourced from residues[79,97].	Minimal land requirements compared to alternative power generation technologies[9,27,98]
Material requirements	Has significant water requirements which could pose a barrier to deployment[33], and continued fossil fuel utilisation leads to large non-renewable resource requirements[98]. Dedicated biomass crops can have largescale fertiliser demands[77,95].	Requires rare earth metals and minerals in excess of most alternative generation technologies[98,99]. Current and future supply of critical minerals falls short of the level needed to rapidly accelerate renewables deployment[99], and so expanding and diversifying supply chains will be essential. Increased recycling rates and material efficiency can also reduce this footprint[100].
Health Impacts	Biomass/fossil combustion for energy production results in PM_{10} and $PM_{2.5}$ formation[101]. Fossil fuel extraction can also lead to toxic substances released into the biosphere[102].	No particulate formation from electricity generation. Toxic metals can be released during use or end-of-life stage of solar PV[103].
Ability to create jobs	CCS requires expertise in process and industrial engineering, which can be a source of high quality employment for localities[104]. CCS is a design-intensive, providing a large number of local jobs in infrastructure deployment[105,106]. CCS could help facilitate a just transition by reducing job losses in the fossil fuel industry[107].	Studies suggest that the job-creation potential of renewables could more than offset job losses in the fossil fuel sector[9,27,108]. Solar PV is a manufacturing-intense technology with a global supply-chain, and thus fully capturing the job-creation potential in any given locality could prove challenging[106]. Wind turbines are relatively easy to manufacture, and so localisation of production may be more achievable. However, the capabilities required for design and system integration of wind turbines are high, and so it may be harder to capture this element of the value chain[106].

Table 2 – The wider implications of CCS and renewables
Summarises recent research on the land, resource, health and employment impacts of CCS and wind/solar.

Ultimately, the wider implications of both CCS and solar PV deployment will be project- and context-specific and should be accounted for by policymakers. However, the literature suggests that CCS is more likely to transgress sustainability boundaries around land, material and health impacts than renewables. Potential sustainability concerns around CCS deployment again suggest that CCS should be prioritised for use-cases where substitute technologies are lacking or limited (sustainable biomass with CCS and capturing process-based emissions), rather than areas where low-cost renewables represent a feasible alternative (fossil-based hydrogen/electricity generation). Further work could account for a wider range of societal goals in the valuation of technologies and explore how the results change under broader perspectives[109].

Further work could also expand this analysis to assess how the value of CCS is affected by cost reductions in other key low-carbon technologies such as battery storage[110], electrolysis[111] and high-temperature electric heat[112], all of which will be essential in moving to a fossil-free energy system. By performing a detailed analysis on the relationship between CCS and renewables, this study has been able to explore the underlying model dynamics in detail, but could be complemented by analysis which considers a larger number of uncertainties concurrently[113,114]. As well as expanding the technological scope of analysis, it would be beneficial to explore how results depend on a wider range of uncertain factors, including future demand growth[115], variations in socio-economics[116] and deviations from cost-optimality[117]. The factors assessed here (cost of renewables, cost/availability of CCS, discount rate and temperature target) have been identified by the authors as salient uncertainties in the relationship between CCS and renewables, which can address the needs of IAM stakeholders making contemporary policy decisions[118], but other factors could also prove influential in scenario production[119]. Whilst our approach sets out a clear story of the relationship between CCS and renewables, it is not necessarily the only story[120]. We therefore encourage further research into this critical area, using a range of models and futures analysis methods[121]. The transparency with which we describe underlying model dynamics should, however, help guide decision-making in further CCS investment in light of costs reductions in renewables, as well as help to provide ex-post validation of them in light of real-world developments[117,119]. Finally, variations in the spatiotemporal resolution of analysis are critical in modelling high penetration of renewables appropriately[122–124]. This analysis uses a global model with a long-term time horizon and could be complemented by additional analysis using high-resolution energy system models. These factors mean that the value of CCS as presented in this analysis should be seen as an upper estimate, which would be reduced when the broader sustainability agenda[27], more granular modelling[28–30], consideration of other competing technologies[110–112] and representation of limits to CCS deployment[33–37] are accounted for.

CCS has in many ways suffered a ‘lost decade’, marked by limited deployment[58] and falling expectations[55] for the technology. Despite this, CCS remains valuable in meeting the goals of the Paris Agreement, and demonstration and deployment should be welcomed. However, not all forms of CCS should be supported, with our analysis suggesting that targeted CCS deployment in particular sectors, complementing renewable energy as the primary form of decarbonisation, can provide the best value case for CCS investment and avoid transgressing wider sustainability boundaries. This will require targeted demonstration projects in the near-term to accelerate appropriate CCS deployment. Previous demonstration projects have been poorly coordinated[53], and a similar lack of coherency is currently observable, with many CCS projects still focused on power sector CCS[58], despite the limited value case for this technology. This risks squandering a critical decade for CCS on applications for which there is a weak or non-existent rationale.

This analysis highlights that the falling cost of renewable electricity erodes the value of CCS substantially by directly competing with CCS, driving faster power sector decarbonisation and facilitating greater electrification of end-use sectors. Nevertheless, CCS remains valuable in industry and bioenergy applications if we are to reduce emissions in a least-cost manner. Policymakers must therefore redouble their efforts to develop and deploy CCS in these applications as soon as possible.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the Lead Contact, Neil Grant (n.grant18@imperial.ac.uk).

Materials Availability

This study did not generate new unique reagents.

Data and Code Availability

All data presented in this paper is available in the Supplemental Data, and also at the following DOI: 10.5281/zenodo.5521118.

TIAM-Grantham

The integrated assessment model used in this study, TIAM-Grantham, represents all major processes governing the operation of the energy system. TIAM-Grantham is a least-cost optimisation model, calculating the portfolio of technologies which meet future energy service demands at minimum cost, subject to user-defined constraints such as cumulative carbon budgets. The analysis assumes partial equilibrium within energy markets, allowing demand to respond endogenously to changes in energy prices. In this analysis, TIAM-Grantham is run with perfect foresight.

TIAM-Grantham is a bottom-up technology-rich model[125–127], representing over 30 different CCS technologies (Supplemental Table 1). This detailed representation of energy conversion technologies, coupled with the least-cost optimising solution method, makes TIAM-Grantham ideally suited to exploring the sectoral value of CCS in mitigation pathways. A literature review was undertaken to ensure that the costs of relevant technologies were up to date (Supplemental Tables 2-4).

The critically important notion of technology value has not been firmly defined in the literature and here we set out our own definition. We take a global perspective, examining how global energy system costs change when the cost and availability of different technologies are varied. We also take a long-term perspective, considering the present value of the energy system over the remainder of this century. Discount rates of 1, 3 and 5% are applied to future energy system costs. The system value of a technology is defined as the increase in net present energy system costs to meet a given emissions target that occurs when that technology is unavailable. In this sense we closely follow other analysis[12,13,17,128].

IAMs have come under increasing pressure to improve transparency around the role of model inputs and structure in driving results[129,130]. A variety of solutions have been proposed, including open-source modelling[131], model diagnostics[132,133], and publication of model inputs[60]. In this analysis we publish all relevant input assumptions and model outputs to improve transparency (Supplemental Tables 2-4 and Supplemental Data), as well as conducting a detailed exploration of the underlying dynamics, which can help end-users understand model behaviour.

IAMs have also been criticised for exhibiting structural bias against complete energy system transitions[134], due to the common assumption of constant elasticity of substitution (CES) in underlying model structure. TIAM-Grantham does not use CES functions and therefore can model complete substitution of technologies in the energy mix. In all sectors, alternative low-carbon technologies to CCS are represented that can entirely displace fossil fuel consumption, except in the case of cement, where all deep decarbonisation measures modelled (alternative cement chemistries, greater biomass utilisation or use of CCS) involve some continued fossil fuel consumption.

Scenario Design

Mitigation scenarios presented apply cumulative CO_2 constraints to limit end-of-century warming to one of two long-term temperature goals, 2 and 1.75 °C. Carbon budgets from 2018-2100 are 1170GtCO_2 and 800GtCO_2 for 2 and 1.75 °C targets respectively[75], which are associated with a 66% probability of achieving this temperature threshold. While significant benefits of limiting warming to 1.5 °C have been demonstrated in the literature, 1.5 °C scenarios are not assessed. This is because our analytical method involves taking a central mitigation scenario and further constraining it by limiting CCS availability. In a scenario design which has stringent limits on the feasible scale of negative emissions, 1.5 °C scenarios are already near the threshold of feasibility. Further constraining 1.5 °C scenarios lead to TIAM-Grantham being unable to solve, and so meaningful information on the value of CCS cannot be extracted. We focus instead on the temperature goals of 1.75° and 2 °C, for which information on the value of CCS can be extracted.

Our scenario design encompasses variations in the cost of renewables, CCS costs, and CCS availability. All scenarios included use demographic and socio-economic drivers aligned with the Shared Socioeconomic Pathway SSP2[135] and include a limit on biomass utilisation of 100EJ/y, a sustainable biomass potential for which there is high agreement in the literature[79].

We use three levers to create a scenario set exploring the value of CCS given cost reductions in renewables. We first vary the sectoral availability of CCS, precluding deployment in a certain sector – for example in industry. By calculating the change in total energy system costs relative to a mitigation scenario with full technology availability, we can calculate the system value of CCS on a sectoral basis.

Second, we vary the cost of renewables, using three different cost trajectories constructed on the basis of the literature review (Supplemental Note 1). This allows us to understand how the value of CCS is eroded by cost reductions in wind/solar. The cost of energy storage technologies will be crucial in enabling intermittent renewables to displace conventional power systems[28–30]. In this analysis, PV and wind generation is accompanied by the deployment of battery storage, based on detailed power sector assessments of the storage requirements for high penetrations of renewables[136], with cost projections are taken from recent literature[137]. Further work could explore how additional cost reductions in storage could further erode the value of CCS across different energy system sectors.

Third, we conduct sensitivity analysis into how future cost reductions in CCS affect its value. The central analysis in this work assumes that the incremental cost of CCS declines by 40% over the century due to technological learning. We construct two alternative cost trajectories – an advanced progress scenario, in which incremental costs falls 70% over the century, and a frozen progress scenario in which there are no cost reductions in CCS technologies. We model these cost reductions as an exponential cost decline over time[138]. In this way we follow the same rates of technological progress as assumed by other work in the literature exploring the role of CCS in mitigation pathways[14].

Analysis is repeated for both long-term temperature goals, and for three different discount rates. These variations allow us to explore the sectoral value of CCS for a given long-term temperature goal (LTTG), wind/solar cost trajectory, CCS cost and discount rate (Equation 1).

$$
\begin{aligned}
\boldsymbol{Value}_{Sector_{\alpha},LTTG_{\beta},WS_{\gamma},CCS_{\delta},DR_{\varepsilon}} &= \boldsymbol{SystemCost}_{NoCCSinSector_{\alpha},LTTG_{\beta},WS_{\gamma},CCS_{\delta},DR_{\varepsilon}} \\
&- \boldsymbol{SystemCost}_{FullTechPortfolio,LTTG_{\beta},WS_{\gamma},CCS_{\delta},DR_{\varepsilon}}
\end{aligned}
$$

where:

- α represents the sector under consideration (e.g., hydrogen production)
- β represents the LTTG under consideration
- γ represents the cost trajectory for wind and solar PV
- δ represents the CCS cost trajectory
- ε represents the discount rate applied

This is expressed as a percentage increase of the mitigation cost in our reference mitigation scenario, which is a scenario with the same LTTG, but with central wind, solar and CCS cost projections and a full technology portfolio. Combining these assumptions gives a set of over 250 scenarios, which form the basis of the analysis (Table 3). Individual scenarios can be identified by a combination of these assumptions.

Long-Term Temperature Goal	Sectoral Availability of CCS	Wind/Solar Cost Trajectory	CCS Cost Trajectory	Discount Rate
2 °C **1.75 °C**	Full technology portfolio No BECCS in all sectors No BECCS in power sector No BECCS in liquids production No CCS in fossil power sector No CCS in hydrogen production No CCS in industry	High Costs Medium Costs Low Costs	High Costs Medium Costs Low Costs	1% 3% 5%

Table 3|Scenario Design Framework

Table describes the main parameter variations which create the set of scenarios which are used in the analysis. CCS and discount rate variations are applied separately, creating a set of 2x7x3x(3+3)=252 scenarios, which form the basis of the analysis.

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AUTHOR CONTRIBUTIONS

N.G. developed the initial research hypothesis and experimental design, performed the modelling, produced the figures and wrote the manuscript. A.G. contributed to the research hypothesis and experimental design and supported in writing the manuscript. A.H and T.N. provided advice on experimental design, research direction and reviewed and revised the manuscript.

DECLARATION OF INTERESTS

None to declare.

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