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Assessing the relative costs of high-CCS and low-CCS pathways to 1.5 degrees

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SUMMARY

- The costs of reaching net zero CO_2 emissions around mid-century are calculated for pathways involving different amounts of carbon capture and storage (CCS).

- High-CCS pathways used in the study mitigate about half of today's emissions in 2050 with CCS, and low-CCS pathways about one-tenth.

- From 2021 to 2050, taking a low-CCS pathway to net zero emissions will cost at least US$30 trillion less than taking a high-CCS route – saving approximately a trillion dollars per year

- Land-use requirements for energy crops are smaller in low-CCS pathways by an area equivalent to half the size of Saudi Arabia.

- Assessing data from the past 40 years, no evidence is found for technological learning or associated cost reductions to date in any part of the CCS process – capture, transport or storage.

- CCS targeted to specific uses is still likely necessary to reach net zero, and in future for negative emissions.

- The current build rate of CCS needs accelerating even to meet levels in low-CCS net zero scenarios.

- Governments should rapidly scale up CCS but reserve it only for essential use cases.

- Using CCS to facilitate ongoing fossil fuel use would be, globally, highly economically damaging.

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Executive Summary

Almost all decarbonisation scenarios consistent with the 1.5°C target in the Paris Agreement contain some level of carbon capture and storage (CCS), either for abating emissions at source, removing carbon dioxide from the atmosphere, or both.[1] But the amount of CCS varies widely.[2] Therefore the scenarios, even when analysed in reports from the Intergovernmental Panel on Climate Change (IPCC), do not show policymakers a single 'optimum' or even 'preferable' pathway to 1.5°C, leaving room for alternative interpretations based on different priorities. And yet the timescale available for enacting policies to deliver such a pathway is extremely tight, with carbon emissions needing to halve before 2030, alongside major reductions in emissions of other greenhouse gases such as methane, and reach net zero around mid-century.[3]

Discussions between governments in the lead-up to the 2023 United Nations Climate Change Conference, COP28, have seen differences about preferred pathways laid bare.[4,5,6]

Some governments are pursuing a virtual end to fossil fuel use by mid-century.[7] On the other hand, states and companies with substantial fossil fuel interests claim that pathways to mid-century net zero that require an enduring and substantial (but undefined) amount of abated fossil fuel use would be more 'pragmatic' and 'realistic'.[8] In practice this would mean building vast amounts of CCS facilities on power stations, factories, oil refineries and other industrial units, and investing in negative-emission technologies that could include bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).

Although conspicuously absent from the debate so far, an important factor in deciding between the two approaches should be cost.

In this report we assess the relative costs of low-CCS and high-CCS pathways to 1.5°C using scenarios developed for the IPCC's Sixth Assessment Report (AR6).[2] Using a range of criteria, we select a 'high-CCS' group of scenarios and a 'low-CCS' group. On average, as a fraction of emissions today, the high-CCS scenarios deliver about half of the CO_2 emissions reductions needed in 2050 via CCS, while in low-CCS scenarios on average this fraction is about one-tenth.[1] The scenarios include all types of CCS, including on power stations, industrial facilities, BECCS and DACCS. All scenarios selected are compatible with the 1.5°C

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[1] CO_2 emissions are currently around 42Gt per year, while the average CCS capacity in 2050 in the high group is 19.2 $GtCO_2$ per year, and in the low group, 4.4 $GtCO_2$.

temperature goal, with varying degrees of overshoot, and all reach net zero CO_2 emissions around mid-century.

We then assess the cost of each scenario using a methodology developed by one of us (RW) and published last year.[9] The costs of solar and wind power and battery storage have been falling consistently for the last four decades, due to innovation and technological learning.[10] However, most technologies do not show such cost reductions. Via an extensive search of industry reports and academic papers, we find that, **in more than 40 years, estimates of the costs of fossil power with CCS have not declined at all, indicating a lack of technological learning in any part of the process**, from CO_2 capture to burial, even though all elements of the chain have been in use for decades. In particular, CO_2 capture using amine solution has been widely deployed in gas processing plants since the 1970s, yet this has not produced any appreciable technological learning.

The average costs of the low-CCS and high-CCS pathways analysed are remarkably different. We estimate that from 2021 to the global net zero date of 2050, taking a high-CCS pathway will cost at least US$30 trillion more than taking a low-CCS route. Put another way, **a low-CCS pathway is expected to produce average savings of at least US$1 trillion per year compared with a high-CCS route**, or around 22% of energy system expenditures on average.

These figures likely underestimate the cost difference between the two approaches because they suppose that the costs for all types of CCS facility are at the very lowest end of the ranges estimated in the academic and grey literature. Also, we do not factor in (i) the likely rise in costs of biomass feedstock for BECCS plants as demand rises, (ii) the costs incurred if CO_2 storage reservoirs fail (a real-world risk),[11,12] (iii) the implications of underperformance on CO_2 capture rates, or (iv) the cost of mitigating upstream methane emissions from the ongoing coal mining and oil and gas extraction that necessarily goes along with fossil CCS.

In general, high-CCS scenarios contain significantly more biomass burning than low-CCS scenarios. This entails a greater demand for land for energy crops. The requirement incurred in 2050 by the high-CCS scenarios is on average 1.3 million sq km more than in the low-CCS scenarios. The difference is more than one-third the size of India, or more than half the size of Saudi Arabia, the entirety of South Africa,or twice as big as Texas.

The fact that low-CCS routes to net zero emerge as clearly beneficial compared with high-CCS routes does not mean that 'no-CCS' would be better still. For a few particular industries, such as cement production and some chemical sector processes, CCS will almost certainly

be required, while scenarios also indicate a need for negative emissions before and beyond mid-century, which would likely include BECCS and DACCS.

However, the CCS industry is not developing at anything like the rate envisaged in scenarios. In 2022, the amount of CO_2 being captured worldwide stood at just 49 $MtCO_2$ per year.[13] Scaling up deployment to levels seen in the lowest of our low-CCS scenarios, 2.5 $GtCO_2$ per year in 2050, would entail a 50-fold expansion in just 25 years. Levels in our high-CCS scenarios (15-26 $GtCO_2$ per year by 2050) imply an increase of 310- to 530-fold.

The challenge is even greater when we look at 2030. On average, low-CCS scenarios envisage a total of 617 $MtCO_2$ per year in operation by then – twice the volume of all plants currently in operation, construction and planning. Governments would need to virtually double the existing pipeline and ensure all projects in it get built within the next seven years. The average capacity for 2030 in our high-CCS scenarios, by comparison, is 4.17 $GtCO_2$, requiring delivery of a volume 12 times bigger than the entire current pipeline.

Governments committed to the Paris Agreement goals therefore need to get serious about CCS. This means 1) increasing the current build rate, 2) targeting it only towards key sectors, and 3) banishing the idea that CCS is, or ever can be, a blanket solution. Our findings show that the claim put forward by some oil companies that providing cheap energy services to the poor entails continuing to use fossil fuels, but with emissions captured, is a fallacy; following recent dramatic improvements in renewable energy technologies, **widespread cheap energy now depends on a rapid scale-up of renewables and the near-elimination of fossil fuel use**.

Combined with the currently low volume of CCS, its dependence on enhanced oil recovery for revenue streams (29 of the 41 plants currently operating) and the wider concerns about technical feasibility and sustainability, our identification of a large cost difference between high- and low-CCS routes to net zero shows that, from a societal perspective, **widespread use of CCS to facilitate large-scale ongoing fossil fuel use would be economically damaging**. Governments putting CCS at the heart of national decarbonisation plans risk losing competitiveness to countries that opt for a much cheaper, and almost certainly more deliverable, strategy centred on renewable electricity, energy efficiency and electrification.

Low-CCS routes to 1.5°C offer far more feasibility with much lower sustainability risks, at far lower cost, than high-CCS routes. The most sensible approach to CCS globally is therefore to view it as a valuable and scarce resource – an option to be developed and deployed, but not treated as a blanket solution for continuing use of fossil fuels.

Introduction

Assessments of the remaining carbon budget compatible with the Paris Agreement 1.5°C global warming target have led to development of emission reductions trajectories that are consistent with meeting the target. Although reports from the IPCC and other scientific organisations contain considerable detail and nuance, the trajectory, in political, business and civil society discourse, is often described as 'halve CO_2 emissions around 2030 and reach net zero around mid-century'.[14] A total of 171 countries, together with states, regions, cities and companies, have set net zero emissions targets for all or part of their emissions portfolios – the vast majority before or in 2050[15] – and the setting of net zero targets has become the dominant organising principle for climate mitigation.[16]

However, neither the IPCC nor the Paris Agreement prescribe or even advise countries and other entities on optimum or preferred pathways for reaching their net zero targets, or indeed on the optimum pathway for reaching global net zero emissions. IPCC assessments and the scientific literature in general indicate that a portfolio of measures will be needed, deploying all or some of: energy-efficiency improvements, renewable energy, nuclear power, CCS for one or more sectors, and carbon removal using a range of methods, potentially including BECCS and/or DACCS. But there is no agreement between models and scenarios as to the optimum or preferred balance across these measures; in fact scenarios vary hugely in the relative amounts included, just as they vary in other parameters.[17]

One consequence of this is that **the extent of ongoing fossil fuel use that is compatible with the 1.5°C target is extremely ill-defined**. AR6 concludes that, in scenarios compatible with the 1.5°C target with no or limited overshoot, the 5th and 95th percentile range for permissible coal use in 2050 equates to a reduction of between 60% and 100% from the 2019 baseline. For oil, the range is a 25-90% decline; while for gas, scenarios include anything between a 30% decline and an 85% increase.[3] The IPCC makes clear that reductions at the moderate end of these ranges are possible only with extensive use of CCS; without it, for example, gas use must fall.

The wide range of different measures deployed in 1.5°C-compatible scenarios, and therefore in pathways to reach net zero CO_2 emissions by 2050, allows different entities to claim that their own preferred pathway is in line with science. At one end of the spectrum are climate campaigners who hold that science mandates the end of all energy-related fossil fuel use by 2050 or even earlier.[18] At the other end are fossil fuel companies and countries with major fossil fuel interests which claim that their plans to maintain or even increase production and

use of fossil fuels are entirely compatible with reaching net zero emissions by mid-century and holding global warming to 1.5°C.[19] The compatibility of ongoing fossil fuel use with Paris Agreement temperature goals necessarily depends on major rollout of CCS or negative emissions, or both.

The high land use requirements for negative emissions in the net zero plans of fossil fuel companies has been abundantly highlighted in academic literature and by civil society,[20] and repeating that is not the purpose of this analysis. Nor is it our purpose to explore the feasibility of different scenarios, although we do discuss dimensions of feasibility in our concluding section. Instead, we ask a simple and straightforward question: **is it preferable to reach net zero emissions on a trajectory compatible with the 1.5°C target by employing CCS in abundance, or as a resource to be used only sparingly?**

In defining 'preferable', we focus principally on cost; therefore, 'is it likely to be cheaper for humanity to get to 1.5°C on a CCS-heavy or a CCS-light trajectory?' is the central question. We also compare land-use requirements for both approaches, and highlight the different progress being made in some core technologies.

In order to be as relevant as possible to policymaking, we base our cost calculations as closely as possible on real-world data, and we highlight its absence or lack of clarity in some critical areas and indicate what this implies for the accuracy of various scenarios and for real-world choices and costs. We focus on the target year of 2050, for two reasons:

- Reaching global net zero emissions in 2050 has, since the IPCC's Special Report on the 1.5°C temperature target, become the central focus of discourse within politics, business and civil society, and a major focus of research.
- The date is compatible with planning and investment processes across energy and other infrastructure; 2100, by contrast, is too far distant to guide action today, whereas the energy mix in 2030 will largely be determined by decisions already taken.

CARBON CAPTURE AND STORAGE

The process of capturing carbon dioxide from a mixture of gases was first demonstrated in the 1920s. It entered deployment in subsequent decades as the gas business expanded in the United States.[2] Commercial and safety considerations required setting a maximum level of impurities, and hence natural gas processing plants were fitted with a range of purification equipment, including amine scrubbing units to remove the carbon dioxide and hydrogen

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[2] The US produced over 90% of the world's natural gas outside the Soviet bloc until the early 1960s.

sulphide.[21] The captured CO_2 was typically vented into the atmosphere. But in the early 1970s, several facilities in the US began using captured CO_2 from gas processing plants for enhanced oil recovery (EOR) – pumping it into oil wells that were becoming depleted, to increase the rate of oil extraction.[22] Thus the origins of CCS lie not in climate mitigation, but in fossil fuel extraction.

As of 2023, there were 41 CCS projects in operation worldwide, with a further 351 in the pipeline.[13] Applications of current facilities are shown in Table 1.

Table 1. Applications of existing CCS facilities (see text for data source).

Type of CCS facility	Number of facilities
Fossil gas processing	15
Hydrogen/ammonia/fertiliser production	7
Ethanol production	4
Iron and steel	1
Power and heat	3
Chemical production	6
Oil refining	2
CO_2 transport and storage	2
DACCS	1

In 29 of the 41 operational facilities, some or all of the captured CO_2 is used for EOR. This figure includes nine of the 11 that have come online within the last year, illustrating that **revenue streams other than EOR, while the subject of ongoing exploration, remain elusive**.

As a potential tool for decarbonisation, the International Energy Agency (IEA) assigns uses for CCS into four categories:[23]

1. Tackling emissions from existing energy infrastructure such as power and industrial plants.

2. Providing a solution for some of the most challenging emissions from heavy industries like cement and chemicals, as well as from aviation.

3. Offering a cost-effective pathway for low-carbon hydrogen production in many regions.

4. Removing CO_2 from the atmosphere (negative emissions).

It should be noted that, conceptually, CCS performs two distinct roles in decarbonisation. In the first three IEA categories, the purpose is to prevent CO_2 from entering the atmosphere, or at least to reduce the amount doing so. By contrast, the fourth category seeks, on a net basis, to draw CO_2 from the air *after* it has been emitted. 'Negative emissions' methods involving technological carbon capture include BECCS and DACCS.

CCS IN DECARBONISATION SCENARIOS

Analysts' standard resource for exploring decarbonisation pathways is the AR6 Scenario Explorer and Database, hosted by the International Institute for Applied Systems Analysis (IIASA).[2] The database includes more than 3,000 scenarios available for consideration in AR6. Research teams use Integrated Assessment Models (IAMs) to develop scenarios with ranges of parameters, inputs, assumptions and calculation methodologies. After uploading, scenarios are validated against a number of criteria, notably their implications for global temperature rise.

Broadly speaking, there are trade-offs between scenarios that result in similar temperature outcomes. For example, a scenario heavy with CCS-equipped power stations is likely to be relatively light in renewables. But these are far from binary questions. Scenario development for AR6 was guided by five Shared Socio-economic Pathways (SSPs), which sketch out possible futures for global political, social and economic development.[24] A scenario developed to align with an SSP that envisages high economic and population growth, for example, could be heavier in all forms of primary energy than one guided by an SSP with lower growth. Also, a scenario can be light on both renewables and power-sector CCS if it includes a substantial amount of demand reduction. A scenario that permits significant ongoing fossil fuel use in the power sector can either achieve net zero emissions through mandating CCS throughout that sector, or by including unabated power stations alongside

large amounts of negative emissions elsewhere (using either BECCS, DACCS, other technologies or land-use sequestration).

The vast majority of scenarios assessed as being compatible with the Paris Agreement 1.5°C target include some CCS, but the volumes vary hugely. At one end of the scale, the Low Energy Demand scenario from the MESSAGEix-GLOBIOM 1.0 model uses no CCS at all, instead concentrating on curtailing primary energy as much as possible.[3,25] At the other end is the SSP1_SPA1_19l_LIRE scenario from the IMAGE 3.2 model, which includes 25.8 $GtCO_2$ sequestration annually via CCS in 2050 (alongside a further 8 $GtCO_2$ of land use sequestration).[26] For comparison, global emissions of CO_2 in 2023 are likely to be about 42Gt.[27]

The database provides a powerful tool with which to probe the implications of various policy choices. And as recent scenarios were prepared for the IPCC's AR6, and as IPCC assessments are commissioned and endorsed by virtually all of the world's governments, one can infer that the existence, use and credibility of the scenario database are all broadly endorsed by the very governments that will be making essential policy choices on decarbonisation in the years ahead.

TECHNOLOGY COSTS

IAMs can treat the economic costs and benefits of decarbonisation in a number of ways.[28] They can, for example define desired outcomes in economic terms, such as 'decarbonisation at lowest cost,' or can allow any overall cost where the scenario is aiming for a different outcome. For technologies, models can set floor or ceiling prices, or not; they may or may not include technological learning; and they may set cost curves exogenously or allow them to be generated endogenously by other elements in the scenario as it unfolds.

AR6 scenarios, and indeed the entire field of Integrated Assessment Modelling, have been criticised for (for example) including amounts of various technologies that are either technically infeasible or would pose major challenges to sustainable development.[29] They may routinely over-estimate the volume of CO_2 storage available by ignoring regional differences.[30,31] Another criticism is that they do not always reflect real-world costs and technology learning rates.[9,32]

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[3] We did not, though, include this scenario in our analysis as it was developed too long ago to pass our age filter (see *Methods* section).

However, any analysis, whether or not using an IAM, faces another substantial obstacle: costs for some technologies are currently highly uncertain, as is the trajectory of future costs.

Assessing the overall cost history of nuclear energy, for example, is extremely challenging because many countries' programmes were developed either for dual-use reasons or as an instrument of diplomacy, and true costs are opaque.[33] In societies that now encourage transparent costing, such as the United States and Western Europe, the projections of industry have proved hugely wide of the mark.[34]

Assessing the true costs of CCS is also problematic, for reasons expanded on below. Taking these into account, Figure 1 (below) includes the first comprehensive compilation of CCS cost estimates of which we are aware in the academic literature, showing no evidence for technology learning or associated cost reductions.

- Carbon capture is a necessary component of many natural gas processing plants (dependent on the level of CO_2 in the gas being processed); the added cost components concern transport and storage. For other sources, such as iron and steel works, the capture element must be installed additionally and can make up 70-90% of the total cost.[35]

- The capture cost varies depending on the concentration of CO_2 in the mixture entering the capture unit.

- The majority of facilities receive revenue from selling the captured CO_2 for enhanced oil recovery. This means that the unit may only operate to the extent that oil producers require CO_2, rendering comparisons hard with plants that are aiming to operate full-time; and also means that costs are not transparent, as commercial contracts are involved.

- Several facilities are financed by governments or oil companies as demonstration projects, thus they are bespoke ventures that do not have to grasp opportunities for cost savings.

- There is no systematic study of costs within the industry, and neither the IEA nor the industry lobby group, the Global Carbon Capture and Storage Institute (GCCSI) publishes costings.

In the near-complete absence of real-world cost data for full, operational CCS facilities, most analysis in the literature hinges on estimates. But estimates may not prove reliable. Van der Spek et al. (2017) examined two different cost estimates for the same CCS project, both made by credible bodies, and found a 65% difference between the two.[36] Estimated costs for BECCS span the range US$15-$400/tCO_2.[37]

Turning to estimates of technological learning, Rubin et al. (2015) compared then-current estimates of costs for CCS-equipped power plants with those collated a decade previously for the IPCC Special Report on CCS. They found that costs had increased – for the fossil fuel power plant, for the gas and coal to fuel it, and for the CCS unit.[38] For CCS on iron- and steel-works, Leeson et al. (2017) estimate a learning rate of 3.5%.[39] One key factor is that amine scrubbing, in which CO_2 is captured from a mixture of gases, has been in routine use for many decades in various types of facility, including natural gas processing plants,[64] and does not appear to have fallen in cost (see *Discussion* section).

It is notable that a 2017 study from the GCCSI predicts only modest cost reductions between FOAK (first-of-a-kind) and NOAK (nth of a kind) facilities, for example – 13-19% for post-combustion capture on super-critical pulverised coal power stations, 17% for iron & steel, and 6% for bioethanol.[40]

Literature indicates that IAMs may routinely underestimate the cost of CCS and overestimate the likelihood of technological progress. Smith et al. (2021) note that IAMs routinely use a cost of US$10/$tCO_2$ for transport and storage costs, but that in the real world costs can span US$5-45/$tCO_2$.[41] They and others argue that transport and storage costs are unlikely to decline going forward, as they are based on established and basic processes such as pipelines, gas pumps and shipping. In principle, transport and storage costs can be reduced when facilities equipped with CCS form a geographical cluster; in practice, this has yet to be demonstrated.

True storage costs will only become evident after significant real-world experience. For example, what will average costs be for monitoring a CO_2 reservoir for integrity, including for multiple decades after it is full? At what rate will reservoirs develop issues that require storage to be stopped, as occurred, for example, with the Salah project in Algeria and the Snøhvit facility in Norway?[11,12,42] And what will be the costs, in such eventualities, of repairing any breaches or addressing unexpected irregularities that might occur, locating a suitable replacement reservoir, or closing down the facility and building another one?

For renewable energy, and for other clean energy devices such as storage batteries and electric vehicles, real-world cost data is by contrast available in prodigious amounts.

The Covid pandemic and Russia's aggression against Ukraine have both strained supply chains, and the latter has stoked inflation. Both events have exerted a temporary upward pressure on costs. But these events apart, the deployment curves for wind, solar, storage batteries, EVs and (in some countries) heat pumps all show exponential growth while costs are falling in parallel, as expected for technologies that have been observed to follow

Wright's Law. The principal results of interest are that wind and solar generation combined has shown approximately 20% annual compound growth for the last 20 years.[43] From 2010 to 2022, the cost of offshore wind power fell by 59%, onshore wind by 69% and solar PV by 89%.[10]

Costs for nuclear, hydropower and geothermal generation over the same period, by comparison, have remained approximately level, with some analyses showing a small rise.[10] Climate change will present an increasing challenge to nuclear and hydropower through the rising impact of drought and heat waves on water availability.

The price of fossil fuels, which are required on an ongoing basis in CCS-equipped power stations, is highly volatile and hard to predict. This is partly due to the influence of events such as conflicts, pandemics, and pipeline and production faults. A second factor, at least with oil and gas, is that the price is not only set by market conditions but by production cartels, which manipulate the supply and thus the price for political and economic ends.[44] Futures trading also plays a role.[45]

This being so, predicting the price of fossil fuels in the future, when demand is likely to be falling and producers financially challenged, is beset with uncertainties. The historically adaptable nature of oil cartels does not allow one to predict with any confidence that falling demand will inevitably result in enduringly low prices.[46] Yet in scenarios with relatively high use of coal or gas CCS, fuel will make up a significant proportion of the annual cost.

Figure 1 shows that, in contrast to solar and wind electricity costs, which have been falling systematically for many decades, unabated coal- and gas-fired electricity costs have been relatively stable. **Solar and wind are now the cheapest form of new-build electricity generation in most places on the planet.** In addition to the basic costs of coal- and gas-fired electricity, fossil power with CCS requires extra capital and running costs.

Figure 1 also shows estimates of the cost of fossil power with CCS observed in the academic literature and industry reports over the last 40 years. Many of these reports stated that costs were expected to decline in future, due to technological learning. However, the plot makes clear that these expectations have so far not been realised. In fact, quite the opposite – as further information about the technology has been gained, cost estimates have generally risen.

Figure 1. Techno-economic estimates of the cost of different power-plus-CCS technologies found in the literature since 1980 (mostly N-of-a-kind plants, with 90% capture rate). PC is pulverised coal (post-combustion capture). IGCC is integrated gasification combined-cycle (pre-combustion capture). Gas power plants are combined-cycle plants (post-combustion capture). (Coal power cost data during 1988-1995 has never been identified by the research community.) LCOE on the y-axis refers to the levelized cost of electricity. See Table 6 of the Appendix for data sources.
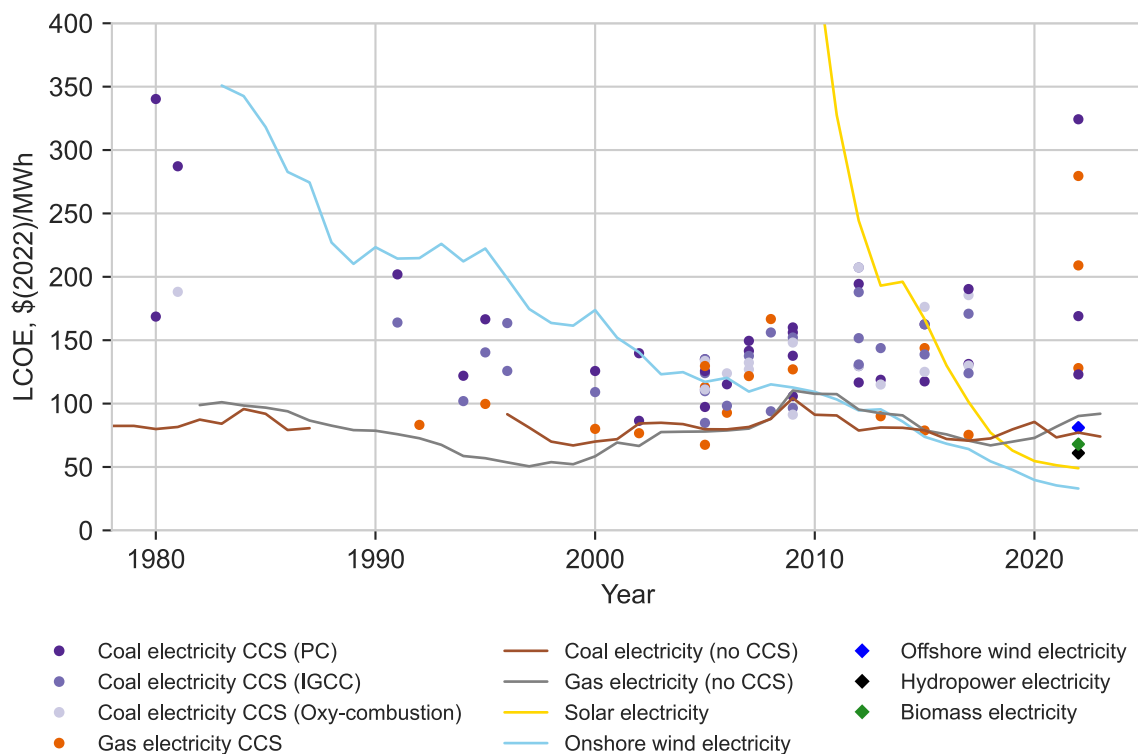
Scenarios compatible with the 1.5°C target routinely include burning of biomass, abated and unabated, sometimes in significant amounts. As an extreme example, the REMIND-MAgPIE 1.5 SSP2-19 scenario sees 46% of primary energy coming from biomass in 2050; the vast majority of this (41%) would be consumed in CCS-equipped biomass power stations, amounting to 100% of total CCS.

Biomass is a heterogenous product, the supply and pricing of which is often highly dependent on locality and other factors. With increasing biomass use comes the potential for unrest and conflict, leading to supply chain disruptions, as observed during the 'dash to biofuels' in the late 2000s.[47] Climate change produces an additional and increasing level of uncertainty on costs and supply, given the potential for extreme events such as droughts, heatwaves and wildfires to affect availability.

CAPTURE RATES AND THEIR IMPLICATIONS

One further confounding factor for the costs of all applications of CCS is the capture rate – the proportion of CO_2 that the equipment captures. Typically, IAM scenarios assume a capture rate of 85-95%. But it is far from proven that rates this high would be routinely applicable.

Leeson et al. (2017) cite capture rates from 13 previous studies of performance in the iron and steel sector that range from 8% to 65%. They give no details on targeted capture rates, so some of the low numbers could have occurred by design. Eighteen studies of petroleum refinery CCS give capture rates of 8-50%, with many data points missing; and two studies of CCS in the pulp and paper sector yield capture rates of 62% and 75%.[39]

Robertson and Mousavian (2022) surveyed 13 more current facilities (ten in operation, one recently mothballed, two recently failed) whose combined theoretical capture volumes would have accounted for more than half of the global total in 2022. Only two facilities performed at or close to 90%, while more than half of the 13 captured significantly less than their target rates.[48] These included:

- Boundary Dam coal-fired power station in Canada. Intended to capture 90% of CO_2 emissions, its actual capture rate over seven years of operation averaged 50%. The owners, Saskpower, disputed the figure, but their own estimate of 68% is also well short of the target.[49]

- Gorgon gas processing facility in Australia. Captured about 40% of the promised volume over its first five years of operation.

- Illinois Industrial bio-ethanol plant in the United States. Intended to capture 22% of the facility's CO_2 emissions, but has averaged only 12%.

Robertson and Mousavian also note that many CCS projects do not openly disclose capture rates.

Zhang et al. (2022) found that, across 20 CCS facilities with a claimed capture capacity of 36 $MtCO_2$/yr, only 29 Mt was stored in 2019.[50] They indicate that, because of a lack of uniformity in how the theoretical or intended capture rate is reported, it is not clear whether this shortfall is all down to underperforming capture equipment. If it were, and if the average intended capture rate were 90%, this would equate to a real-world capture rate of 72.5%.

Underperformance on capture rates has major implications for decarbonisation scenarios. Budinis et al. (2018) conclude it is a more important issue than cost in determining whether

power sector CCS has a significant role in the second half of the century.[51] But it is also critical for assessing the real cost of abatement with CCS. **If CCS equipment removes less CO_2 than a scenario assumes, this creates a greater need for negative emissions to remove the additional CO_2 emitted.** Indeed Chevron, the operator of the Gorgon plant, had to purchase 5.23 Mt CO_2 of carbon credits to make up the shortfall due to its poor capture record.[52]

Additional negative emissions capacity would, at least in models, often take the form of BECCS, which is widely assumed to be cheaper than other carbon removal methods. If the additional BECCS also underperformed, this would result in a need for yet more negative emissions capacity.

As an example, a scenario may contain 1 $GtCO_2$ of industrial CCS and assume a 90% capture rate. The 10% emissions remaining could be removed with BECCS, whose capacity for this purpose – assuming a 90% capture rate for these facilities too, and leaving aside emissions generated upstream and downstream – would need to be 0.11 $GtCO_2$, giving a total CCS capacity of 1.11 $GtCO_2$.

However, if the real-world capture rate for the industrial units turns out to be 60%, this would imply a need for 0.44 $GtCO_2$ of BECCS operating at 90%. If the BECCS plants also capture only at 60%, the need is for 0.67 $GtCO_2$, resulting in a total CCS capacity of 1.67 $GtCO_2$. The cost of abatement for these industrial facilities would therefore rise 50% above that cited in the scenario, with an increased need for energy crops and therefore land as well. The real-world evidence thus far indicates that this degree of capture rate overestimation in models is far from impossible.

Taken together, these factors indicate that the **AR6 scenarios are likely to significantly overestimate the mitigation provided by CCS**, and thus likely also to significantly underestimate the scale of CCS and/or negative emissions needed (and therefore the cost) to deliver mitigation outcomes.

Methods

The strategy in this study is to select one group of net zero 2050 scenarios from the IPCC AR6 Scenario Database that use relatively low levels of CCS (and which also tend to be low in their requirement for carbon dioxide removal (CDR)), and another group that use relatively high levels of CCS. Then we estimate the scenario costs and observe any differences between the two groups.

To do this, we first apply a series of criteria designed to select high-CCS and low-CCS scenarios that are otherwise comparable. We then select a small group of scenario variables that, together, represent most technology deployment and energy use within the global energy system, plus the key CCS and CDR technologies. Finally, we model future technology costs in each scenario conditional on technology deployment, then calculate total expenditures on each technology, and sum these to estimate total scenario costs. These steps are described in greater detail in this section. We use a time horizon of 2050 for our cost analysis because this is an especially important year from a policymaking perspective, but note that all results hold when time horizons much further in the future are considered too.

Performing a cost analysis in this way serves two purposes. First, it allows us to extract useful information from the existing scenario database about the likely contribution of CCS (including BECCS) costs to total scenario costs. By using up-to-date technology cost data, this offers a new perspective on the breakdown of scenario costs and can shed light on the question of which kind of scenarios are likely preferable. Second, by ensuring technology cost assumptions are the current, this process acts as an external sense-check and explores the extent to which scenarios are consistent with recent cost changes. This is important because many clean energy technology costs have changed rapidly in the last decade.

IAMs create scenarios by simultaneously constructing deployment and cost trajectories that are internally consistent, given a vast array of input assumptions and policy settings. Imposing external cost assumptions breaks the logic of self-consistency, because if today's costs had been used to initialise the models when they were run, they likely would not have produced the scenarios they did. This is intentional though, and yields useful results precisely because, on average, over long enough time periods, scenarios with similar macro-scale characteristics should yield roughly similar costs and benefits. If this is not the case when updated technology cost assumptions are applied, then it is important to understand why and update our knowledge appropriately.

SELECTING NET-ZERO SCENARIOS

We begin with the full set of vetted scenarios within the AR6 Scenario Database hosted by the International Institute of Applied Systems Analysis (IIASA).[53] We select from this database according to these criteria:

1. To ensure compatibility with the Paris Agreement 1.5°C temperature target, we select only scenarios that have been validated as either staying within or returning to 1.5°C by 2100 (known as C1 and C2 scenarios respectively).
2. To ensure that models used to develop scenarios were relatively current, we discard scenarios that were developed long enough ago to have been included in the IPCC Special Report on the 1.5°C temperature target (SR15)[54] (published in 2018).
3. We discard groups of scenarios from two model families for which either documentation or the scope of the model itself is incomplete.[4]
4. We include only scenarios that reach net zero CO_2 emissions before 2060, and whose net emissions in 2050 are approximately zero. We define 'approximately zero' as between -4.2 $GtCO_2$ and +4.2 $GtCO_2$ – i.e., within ± 10% of today's emissions. The effect of this is to exclude scenarios that take highly unusual paths to net zero and include those featuring a smooth downwards emissions trajectory.

From this set of scenarios, we select a low-CCS group and a high-CCS group according to the levels of CCS in 2050. For the low-CCS group, we set an upper bound of 6.2 $GtCO_2$; for the high-CCS group, we set a lower bound of 14 $GtCO_2$.

The choice of these bounds allows for clear delineation between these very different approaches to decarbonisation. The figure of 14 $GtCO_2$ roughly equates to one-third of current emissions, so the high-CCS group can be described as 'scenarios that do at least one-third of CO_2 mitigation with CCS.' The 6.2 $GtCO_2$ bound approximates to one-seventh of current emissions, so the low-CCS group can be described as 'scenarios that do at most one-seventh of CO2 mitigation with CCS.' Our reason for choosing the 6.2 $GtCO_2$ upper bound for the low-CCS group was that this is the level contained in the 2022 update to the IEA Net Zero Scenario,[55] which we planned to include in our analysis. However, in the end we did not include it, as it is based on an energy system model rather than an IAM, so does not include all the necessary variables to fulfil the requirements of our study.

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[4] GEM-E3 (V2021) and C-ROADS-5.005 respectively.

To avoid the over-dependence of either the low- or high-CCS group on one particular IAM, we limit the number of scenarios from any model family[5] in each group to three. In the low-CCS group, we choose the three from each model family with the lowest CCS values. In the high-CCS group, we choose the three from each model family with the highest CCS values.

At the conclusion of this triaging process, our low-CCS group includes nine scenarios from three model families (MESSAGEix-GLOBIOM, REMIND-MAgPIE and WITCH). Our high-CCS group includes 13 scenarios from five model families (MESSAGEix-GLOBIOM, AIM, GCAM, REMIND and IMAGE). (See Appendix Table 7 for the full list of scenarios.) The low-CCS scenarios sequester an average of 4.4 $GtCO_2$ per year with a minimum of 2.5 $GtCO_2$. The high-CCS scenarios, in contrast, sequester an average of 19.1 $GtCO_2$, reaching a maximum of 25.8 $GtCO_2$. Thus, we can say that on average the low-CCS scenarios deliver an average of one-tenth of mitigation via CCS, while the high-CCS scenarios on average deliver approximately half. We also identify a smaller set of mid-range scenarios, with CCS values of 6.2-14 $GtCO_2$ in 2050. This is simply to sense-check conclusions coming from comparisons of the high and low groups: if any given parameter emerges as markedly different, the mid-range group should logically have a mid-range value on that parameter.

Figure 2 (a) shows net CO_2 emissions over time for our selected low (blue dashed lines), medium (yellow dash-dotted lines) and high (red dotted lines) CCS scenarios, and for all the other C1 and C2 scenarios in the AR6 Explorer that were not selected (grey solid lines). The black dotted line marks the year 2060, by which our selected scenarios must reach net zero, while the green band and the black solid and dashed line highlight the $\pm10\%$ of today's emissions that our selected scenarios must fall between in 2050. **Figure 2** (b) shows CO_2 sequestered by CCS in 2050 in our selected scenarios.

SELECTING VARIABLES TO APPROXIMATE THE ENERGY SYSTEM AND CARBON SEQUESTRATION

Scenarios in the AR6 database typically contain hundreds of variables, each representing a different aspect of the modelled energy-economic-climate system. For example, they contain time series of final energy, primary energy, investment, technology costs, land use, water consumption, agricultural production and GHG emissions, each categorised by technology, sector of the economy, region, or other properties.[6]

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[5] By 'model family' we mean models developed by teams in various institutions that are based on different concepts and modelling processes. See the IIASA AR6 Explorer for more detail.

[6] See Appendix for details of primary energy, power sector mix, breakdown of CCS/CDR types & other variables.

Figure 2. (a) Net CO₂ emissions over time for our low (blue dashed lines), medium (yellow dash-dotted lines) and high (red dotted lines) CCS scenarios, and all the other C1 and C2 scenarios (grey solid lines). The black dotted line marks the year 2060, which is the latest year we require selected scenarios to reach net zero. The green band and the vertical black solid and dashed line highlight the corridor of ±10% of today's CO₂ emissions, which we require our scenarios to fall into in 2050. (b) CO₂ sequestered by CCS in 2050 for our low (blue dots), medium (yellow diamonds) and high (red squares) CCS scenarios, and all the other C1 and C2 scenarios (grey triangles). The green dashed line marks the minimum amount of CCS we require our high CCS scenarios to have (14 Gt CO₂). The brown dash-dotted line marks the maximum amount of CCS we require our low CCS to have (6.2 GtCO₂).
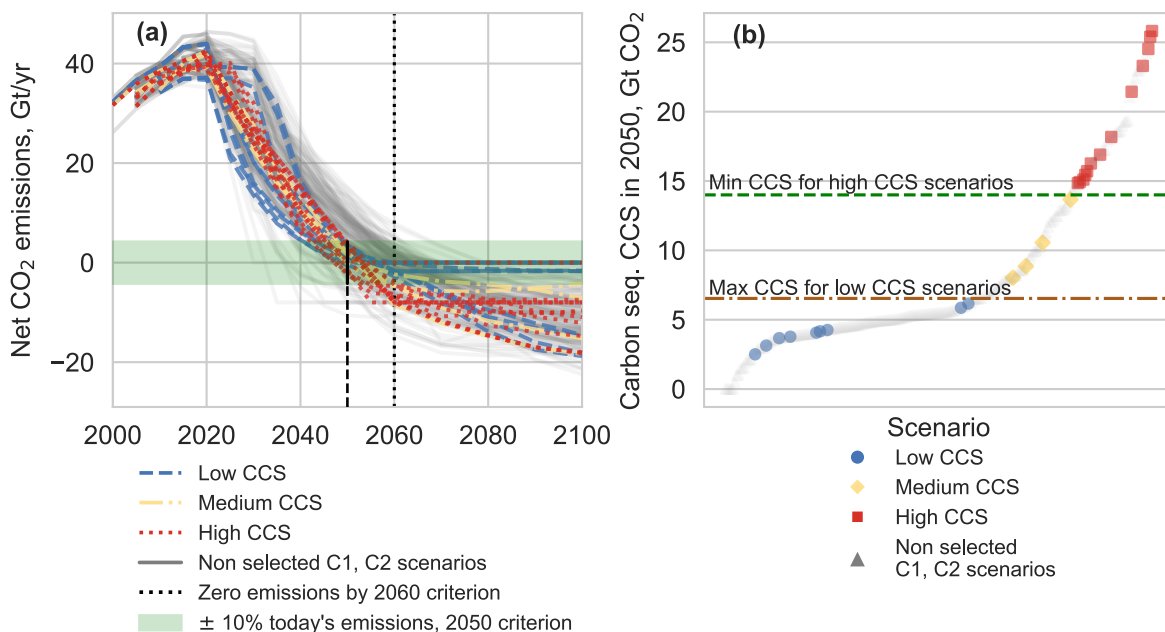
The scenarios selected for comparison in this analysis each contain around 500-800 variables. To make meaningful comparisons between scenarios and observe high-level trends, it is necessary to select a subset of variables that adequately represent some subsystem of interest. We construct a reduced-complexity representation of the energy system and carbon sequestration technologies by selecting 15 variables representing global deployment of the most important non-CCS-related technologies of the energy system, and nine variables representing global deployment of the most important CCS-related technologies included in the AR6 database; these are shown in **Table 2**. By representing all major global energy flows and energy technologies, and all technology-based CCS and CDR methods, these variables together approximately represent global final energy, and all essential intermediate steps.

Table 2. **Variables selected to construct a reduced-complexity representation of the energy system and carbon sequestration technologies. See Table 8 of the Appendix for further details.**

15 non-CCS-related technologies	Solids, liquids, gases	Final energy from oil, coal and gas Hydrogen from electrolysis Solid and liquid fuels from biomass
	Electricity generation	Coal, gas, nuclear, hydropower, bioenergy, wind, solar
	Electricity-related	Electricity networks, energy storage
9 CCS-related technologies	Solids, liquids, gases	Liquids from biomass, with CCS Hydrogen from coal, gas and biomass, with CCS
	Electricity generation	Coal, gas and bioenergy, with CCS
	Non-energy CCS	Industrial CCS DACCS

AR6 scenarios are highly diverse, and contain very different characteristics regarding economic growth, population size, energy services, behaviour change, etc. The criteria we apply to select scenarios for comparison significantly reduce the diversity of the scenarios in terms of these macro-scale characteristics (see, e.g.,). The only macro-component over which significant diversity remains is final energy. This is because, given the energy technologies available to meet energy demand, there are broadly two routes to meeting the emissions-reduction constraints imposed: deploy more fossil fuels and more CCS, or deploy more electrification and less CCS. Due to the relative inefficiency of fossil fuels in delivering useful energy (i.e. energy services), the former route has higher final energy, while the latter has lower final energy.

It is important to emphasise that final energy alone does not provide enough information to determine useful energy or energy service levels in a given scenario[7] – there can be high and low final energy scenarios that provide exactly the same amount of useful energy to the economy.

To observe whether differences in final energy across selected scenarios are indicative of important structural differences or not, we calculate the approximate levels of energy services provided globally in each scenario. To do this we apply a constant final-to-useful-energy conversion factor to each energy carrier in our reduced-complexity energy system. This approximates the useful energy of the system, which we assume is equivalent to the provision of energy services. For simplicity, and due to finding no evidence to the contrary, we assume final-to-useful-energy conversion factors are constant over the model period. Following Way et al (2022),[9] we take these conversion factors to be 0.25 for liquid fuels, 0.6 for solid fuels, 0.6 for gaseous fuels and 0.9 for electricity. Final energy and approximate useful energy of all selected scenarios are shown in **Figure 3**.

Figure 3 (a) shows that high-CCS scenarios generally have higher final energy and low-CCS scenarios have lower final energy, which is consistent with the expectation that high-CCS scenarios provide energy services far less efficiently, as more energy is wasted in combustion processes. **Figure 3** (b) confirms this by showing, first, that the range of useful energy values covered by scenarios is generally smaller than for final energy, and second, that high- and low-CCS scenarios are more evenly distributed across this range. The high- and low-CCS scenarios selected therefore provide roughly equivalent levels of useful energy, and energy services, so there is no obvious structural difference between them. (In the results section we report results both in terms of final energy and when normalised by useful energy, and the difference is seen to be small). Therefore, by analysing our selected scenarios in terms of the simulated energy system and CCS technologies represented by the 24 variables chosen, we are able to perform a reasonable apples-to-apples comparison between scenarios. Any selection of multiple scenarios from the AR6 database will necessarily yield scenarios with different final and useful energy, but the selection process used here significantly reduces this variation.

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[7] Primary energy is the energy in a resource, such as in coal or oil, before it is burned. Secondary energy is the amount remaining after the primary energy resource has been transformed into the form in which it is to be used (e.g. after oil has been refined into petrol, or gas used to generate electricity). Final energy is the amount available to a consumer after delivery of the secondary energy resource. Useful energy is the amount that a consumer can use from the delivered final energy resource, i.e. after accounting for efficiency losses incurred in use, for example in combusting petrol. Energy services refers to the functions that are performed by the useful energy resource.

Figure 3. (a) Final energy of all selected scenarios. (b) Useful energy of all selected scenarios. Useful energy is approximated by assuming constant final-to-useful energy conversion factors that are specific to each energy carrier.
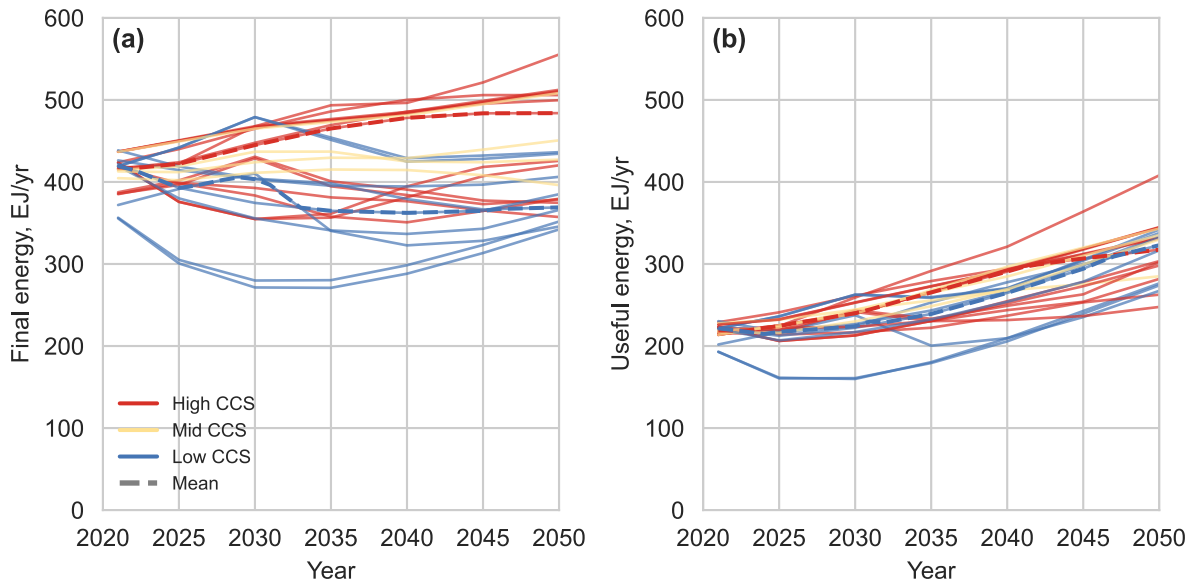
Figure 4 shows the approximate energy system represented by the scenario variables outlined in **Table 2** for two example scenarios. In both cases the useful energy trajectories are similar, indicating that the scenarios provide similar levels of energy services. Also observe that for these scenarios the selected energy system components add up to slightly more than the final energy values reported by the scenarios (i.e. the stack of system components is slightly higher than the blue line). Non-exact alignment is to be expected, as there is no simple, unique or optimal way to represent or report the energy system, due to its high complexity. However, in all our selected scenarios, including those shown here, final energy is consistently close to the sum of the selected components. This gives confidence that our approximation of the energy system is performing as intended and can be used to generate reliable insights.

In addition to the energy supply technologies shown in **Figure 4**, there are five other variables included in our model system: electricity storage investment, industrial CCS quantity, DACCS quantity, electricity network investment, and electrolyser installations. The first three of these are drawn directly from the AR6 scenario database, and the final two are calculated from other variables (specifically, final electricity and electrolytic hydrogen). These are all either facilitating infrastructure technologies or non-energy CCS technologies, and therefore cannot be represented easily on these plots. Yet they are essential for the scenarios to make sense from the engineering and emissions perspectives, so they are of course included in the cost analysis.

The two scenarios presented in this example demonstrate the pattern mentioned previously: to meet emissions-reductions targets, scenarios may either use more fossil fuels and more CCS, or more electrification and less CCS. This is highlighted by the difference in the area above the black line in the two scenarios. The specific scenarios shown here also differ because in the low-CCS scenario electrolytic hydrogen is substituted for a high fraction of solid biomass by 2050. Such differences are inevitable across scenarios, but by including a range of scenarios from different models in our analysis we reduce the chance of our results being systematically impacted by these. Rather, our analysis considers average differences between high- and low-CCS groups.

Figure 4. The energy system as represented by the variables shown in Table *2*Table 2. *Variables* selected to construct a reduced-complexity representation of the energy system and carbon sequestration technologies. See Table 8 of the Appendix for further details.

, for two example scenarios, one from the high CCS group (model: IMAGE 3.2, scenario: SSP1_SPA1_19I_LIRE, left) and one from the low CCS group (model: REMIND-MAgPIE 2.1-4.3, scenario: DeepElec_SSP2_ HighRE_Budg900). Technologies related to CCS are above the black line and have no colour transparency. Technologies unrelated to CCS are below the black line and have slight colour transparency. Hatching denotes solid, liquid and gaseous energy carriers, while non-hatching denotes electricity-generating technologies.
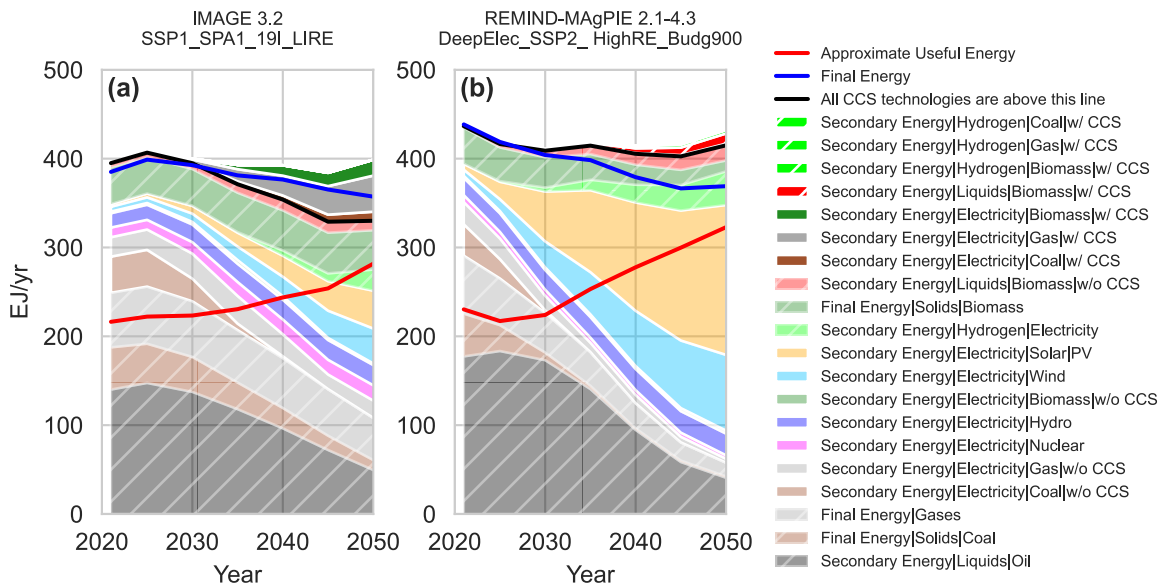
HOW WE ESTIMATE SCENARIO COSTS

To estimate scenario costs, we largely follow the methodology used in Way et al. (2022),[9] but with two major modifications. In that paper, energy system scenarios are constructed exogenously. Then for each scenario probabilistic technology cost forecasts are generated for each technology, conditional upon the deployment in that scenario. These cost forecasts are used to calculate annual expenditures on each technology in the scenario, which are then summed to estimate total annuitised[8] expenditures on the energy system each year. Total annual expenditures are then discounted and summed to calculate the probability distribution of present discounted scenario costs, from which the expected value may then be determined. Finally, relative scenario costs are calculated.

The first modification we make to this method is to model all technology costs deterministically rather than stochastically. This is because (as noted earlier) there is not enough observed CCS technology data to make reliable data-driven cost forecasts, so there would be little benefit in conducting a probabilistic analysis. As a result, this study is designed so that ranges of outcomes are explored predominantly via scenario diversity, rather than technology cost diversity. A probabilistic treatment of costs is not necessary to address the research question here and would only complicate the results.

The second modification we make is that, since it is beyond the scope here to make empirically validated cost forecasts for CCS technologies (whether probabilistic or deterministic), we model future CCS costs by simply setting them equal to values estimated in the literature. While wide ranges of cost estimates for different CCS technologies exist, we consistently use the lowest possible cost estimates for all CCS technologies. We use this simple strategy because, due to our model structure, this leads to results that are robust to the widest range of possible future CCS costs.

To estimate scenario costs, we first must model future technology costs. We do this in one of five ways, depending on the technology:

1. For solar electricity, wind electricity, bioenergy electricity and electrolysers, we forecast declining costs using the experience curve forecasting model described in Way et al. (2022)[9] (though in a deterministic form). We also model constant hydropower and nuclear electricity costs in this way, with learning rates set to zero.

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[8] Annuitised or levelised costs are those obtained by considering all upfront capital costs plus all ongoing running costs (operations and maintenance (O&M), interest payments etc.) to be distributed evenly over the lifetime of a product or asset, subject to discounting. They are a good way of approximating 'average' annual costs, and they provide an important alternative to the perspective of capital investment expenditures.

2. For fossil fuel-related technologies that are observed to exhibit stable long-run cost trends (oil, coal, gas, coal electricity, gas electricity), we forecast costs as reverting to their long-run trends using an autoregressive order-1 model, as in Way et al. (2022)[9] (though in a deterministic form).

3. For all CCS technologies, we model costs as constant. We consider three CCS cost specifications. Our main specification involves setting CCS technology costs to the lowest we have observed anywhere in the literature, whether current or future estimates, real or modelled. We also consider two alternative specifications, or 'side cases'. In one, CCS costs are set even lower (around half the lowest cost estimates seen in the literature), and in the other CCS costs are slightly higher (in the low-to-mid range of all cost estimates). For all CCS technologies except DACCS and industrial CCS, costs are given in terms of technology deployment specified in scenarios. Due to scenario data limitations, however, costs for DACCS and industrial CCS are given in terms of quantities of CO_2 sequestration specified in scenarios.

4. Electricity networks investment is modelled by assuming that current annual investments scale linearly with the amount of final electricity in a scenario. (This is similar to the method used in Way et al., 2022.)[9]

5. For electricity storage, annual investment amounts are taken directly from the scenario database. (Ideally, we would model battery and storage costs using the experience curve model, but since battery quantity data are not provided consistently across scenarios, we use this method instead.)

It is important to emphasise that, by setting CCS technology costs at the lowest values observed in the literature, our modelled costs are at least as low as the most aggressive existing learning curve projections, made on the assumption of strong technological learning (despite there being no empirical or theoretical evidence for this). Furthermore, since we set costs at these low values immediately and in perpetuity, we are effectively modelling a situation of much faster and deeper CCS cost reductions than even the most aggressive learning curve projections. The purpose of this is to explore the hypothetical case of unexpectedly rapid progress in CCS technologies, as well as more standard cost-reduction assumptions.

Note that not all scenarios include industrial CCS, DACCS, or electricity storage investments, so there is some variation in the number of components included in our cost analysis; this is inevitable due to the variation in the data provided in the AR6 database.

To estimate total costs of a given scenario, we model the costs of all energy system and CCS technology components in each year from 2021 to 2050. We calculate annual

expenditures on each of these components and sum them to give total annual annuitized costs. These total annual costs are summed, with exponential discounting applied, to give the present discounted cost of each scenario. We perform this calculation for a variety of discount rates. Finally, we select a central scenario (model: GCAM 5.3, scenario: NGFS2 Net-Zero 2050) and calculate the present discounted cost of each scenario relative to this, for a variety of discount rates. This perspective is useful because it highlights relative scenario costs, which is ultimately what we are interested in here.

Approximation of scenario costs is inherent to our modelling strategy. This is because in distilling highly complex IAM scenarios down to a much smaller system that can be represented in a simple model, and run quickly to perform supplementary analyses, much of the original IAM detail is necessarily lost. Nevertheless, the approach is still valid and informative. In addition, the structure of variables in IAMs is diverse and sometimes inconsistent, so it is often technically impossible to make precise apples-to-apples comparisons between scenarios. Despite the inevitable variation in scenarios, and the model approximation process, we believe that the overarching strategy implemented is consistent and reliable.

An important feature to highlight is the difference between annuitised system expenditures and capital investment expenditures. Energy infrastructure investments are large and lumpy, and decarbonisation will require large upfront investment outlays. But these are always financed at some point of the development process, so that income and expenditures roughly balance out from an operational perspective. It is these latter, annuitised expenditures that we focus on here, as they provide a good perspective on the long-run economic competitiveness of different scenarios.

Table 3 shows the costs of non-electricity-related technologies used in the main specification of the model and provides context for the values chosen. Note that all our modelled CCS technology costs are right at the lowest end of the ranges of costs considered plausible by experts in the literature.

Table 3. Technology costs for non-electricity-related technologies in the main cost specification (see point 3 *above*), in US$(2022) throughout.

Technology	#	Estimates of current cost	Others' estimates of cost in 2040-50	Our initial cost in 2021	Our modelled costs in 2040-2050
Oil	1	75 – 85 $/bbl	25 – 80 $/bbl	79.2 $/bbl (13.0 $/GJ)	52.0 $/bbl (8.5 $/GJ)
Coal	2	68.5 – 155.4 $/metric tonne	45 – 72 $/metric tonne	55.2 $/metric tonne (2.1 $/GJ)	63.0 $/metric tonne (2.1 $/GJ)

Gas	3	5.1 – 32.3 $/MMBtu	2.0 – 7.8 $/MMBtu	6.5 $/MMBtu (6.2 $/GJ)	5.2 $/MMBtu (4.9 $/GJ)
Solid fuels from biomass	4	6 – 14 $/GJ		8 $/GJ	
Liquid fuels from biomass	5	1.4 – 9.2 $/gge		1.4 $/gge (11.0 $/GJ)	
Liquid fuels from biomass with CCS	6	1.6 – 9.6 $/gge		1.6 $/gge (12.8 $/GJ)	
Hydrogen from biomass with CCS	7	6.0 $/kgH$_2$	3.5 – 7.2 $/kgH$_2$	3.5 $/kgH$_2$ (24.7 $/GJ H$_2$)	
Hydrogen from gas with CCS	8	1.2 – 3.3 $/kgH$_2$ (SMR) 1.6 – 2.6 $/kgH$_2$ (Advanced)	1.8 – 3.2 $/kgH$_2$ (SMR) 1.5 – 4.1 $/kgH$_2$ (Advanced)	1.2 $/kgH$_2$ (8.5 $/GJ H$_2$)	
Hydrogen from coal with CCS	9	2.2 – 3.8 $/kgH$_2$	2.9 – 4.0 $/kgH$_2$	2.2 $/kgH$_2$ (15.3 $/GJH$_2$)	
Industrial CCS	10	50 – 120 $/tCO$_2$		50 $/tCO$_2$	
DACCS	11	455 $/tCO$_2$	85 $/tCO$_2$	85 $/tCO$_2$	

Units:
bbl   barrel of oil
Btu   British thermal unit
GJ   gigajoule
gge   gasoline gallon equivalent
kgH$_2$ kilogram of hydrogen

Sources:
1-3   IEA *World Energy Outlook* (WEO) (2023), Fig. 3.19 (p131), Table 3.7 (p140), Table 3.6 (p135)
2   Current costs: BP *Statistical Review of World Energy 2022*, "Coal prices" tab
4   IRENA (2019): *Solid biomass supply for heat and power*, Figure 3 (p31)
5-9   IPCC AR6 WGIII (2022): Table 6.4 (p645), Table 6.7 (p657)
10-11   Energy Transitions Commission (2022): *Carbon Capture, Utilisation & Storage in the Energy Transition*, Exhibit 20 (p44)

Our modelled costs:
1-3   Costs obtained from AR(1) model calibrated as in Way et al. 2022 (adjusted to US$(2022)).
4   Value selected from low end of current range estimate.
5-11   Lowest value selected from all observed estimates.

Table 4 shows the costs of electricity-related technologies used in the main specification of the model and provides context for the values chosen. Note again that our modelled CCS technology costs are right at the lowest end of the ranges found in the literature.

Table 4. Technology costs for electricity-related technologies (in the main cost specification, see point 3 *above*), in US$(2022) throughout.

Technology	#	Estimates of current cost, $/MWh unless stated otherwise	Others' estimates of cost in 2040-50	Our initial cost in 2021	Our modelled costs in 2040-2050
Coal electricity	1	60-220	40-65	67	60
Coal electricity with CCS	2	123-300	160	123	
Gas electricity	3	95-220	50-140	56	60
Gas electricity with CCS	4	76-280	120	76	
Nuclear electricity	5	68-350	65-125	101	
Hydro electricity	6	43-61		52	
Bioenergy electricity	7	80-136		81	75-80
Bioenergy electricity with CCS	8	90-194		90	
Wind	9	33-42	25-50	46	22-32
Solar	10	44-49	15-30	63	12-24
Electrolyser	11	1070-1640 $/kW	330-740 $/kW	1468 $/kW	400-800 $/kW
Electricity networks investment	12	Annual investment is US$11.6bn(2022)/PWh of final electricity. Final electricity values are given in AR6 scenarios under variable named 'Final Energy|Electricity'			
Electricity storage investment	13	Annual investment values are given in AR6 scenarios under variable named 'Investment|Energy Supply|Electricity|Electricity Storage'			

Sources:
1,3   IEA *WEO* (2023) Table B.4b (p302).
2, 4   See Figure 1, plus Energy Transitions Commission (2022): *Carbon Capture, Utilisation & Storage in the Energy Transition* for future cost estimates, Exhibit 11 (p31) **Figure *1***
5   Current: Bloomberg Terminal (accessed August 2023). Future: IEA WEO (2023)
6   IRENA (2023): Renewable power generation costs in 2022.
7-8   IPCC AR6 (2022) *WGIII* Table 6.4 (p645).
9-10   Current costs: IRENA, BNEF. Future cost estimates: IEA WEO 2023
11   IEA WEO (2023) Table B.5 (p305)

Our modelled costs

1,3	AR(1) model calibrated as in Way et al. 2022 (adjusted to $(2022)).
2,4,8	Lowest value selected from all estimates.
5-7,9-11	Experience curve model calibrated as in Way et al. (2022) (adjusted to US$(2022)). Learning rates are: 0% for nuclear and hydropower, 3% for bioelectricity, 13% for wind, 20% for solar, 9% for electrolysers.

In **Figure 5** we demonstrate the application of our cost analysis method to the two scenarios featured in **Figure *4***. The two panels on the left ((a) and (c)) show annual deployment from 2021-2050 for the 26 scenario variables chosen to represent the energy and CCS system (*cf.* **Figure *4***). We model technology costs to 2050 for each technology in each scenario and use these to calculate annual expenditures on each technology, which are plotted in the two panels on the right ((b) and (d)).

Notice how in panel (c) there is large deployment of solar and wind electricity, yet the corresponding expenditures in panel (d) are relatively small. This is because these two technologies, like many other modern clean energy technologies, follow the learning curve cost dynamic – the more cumulative production occurs, the cheaper they become, causing total expenditures to remain lower. In contrast, technologies that do not follow learning curves do not get cheaper with deployment, so total expenditures just track deployment. The latter behaviour has been observed for all fossil fuel-related technologies historically, and is likely to apply to CCS technologies too, due to their closeness to the network of fossil fuel technologies (and given the lack of evidence of technological learning compiled in **Figure 1**). It is the interplay between these two very different technology cost regimes that leads to different scenarios having very different costs.

Figure 5. Example to illustrate how each scenario leads to a system cost estimate. (a) and (c) show technology deployment in each scenario from Figure *4*, (b) and (d) show the resulting estimates of expenditures on each technology in each case. Technologies related to CCS are above the black line and have no colour transparency. Technologies unrelated to CCS are below the black line and have slight colour transparency. Hatching denotes solid, liquid and gaseous energy carriers, while non-hatching denotes electricity-generating technologies.
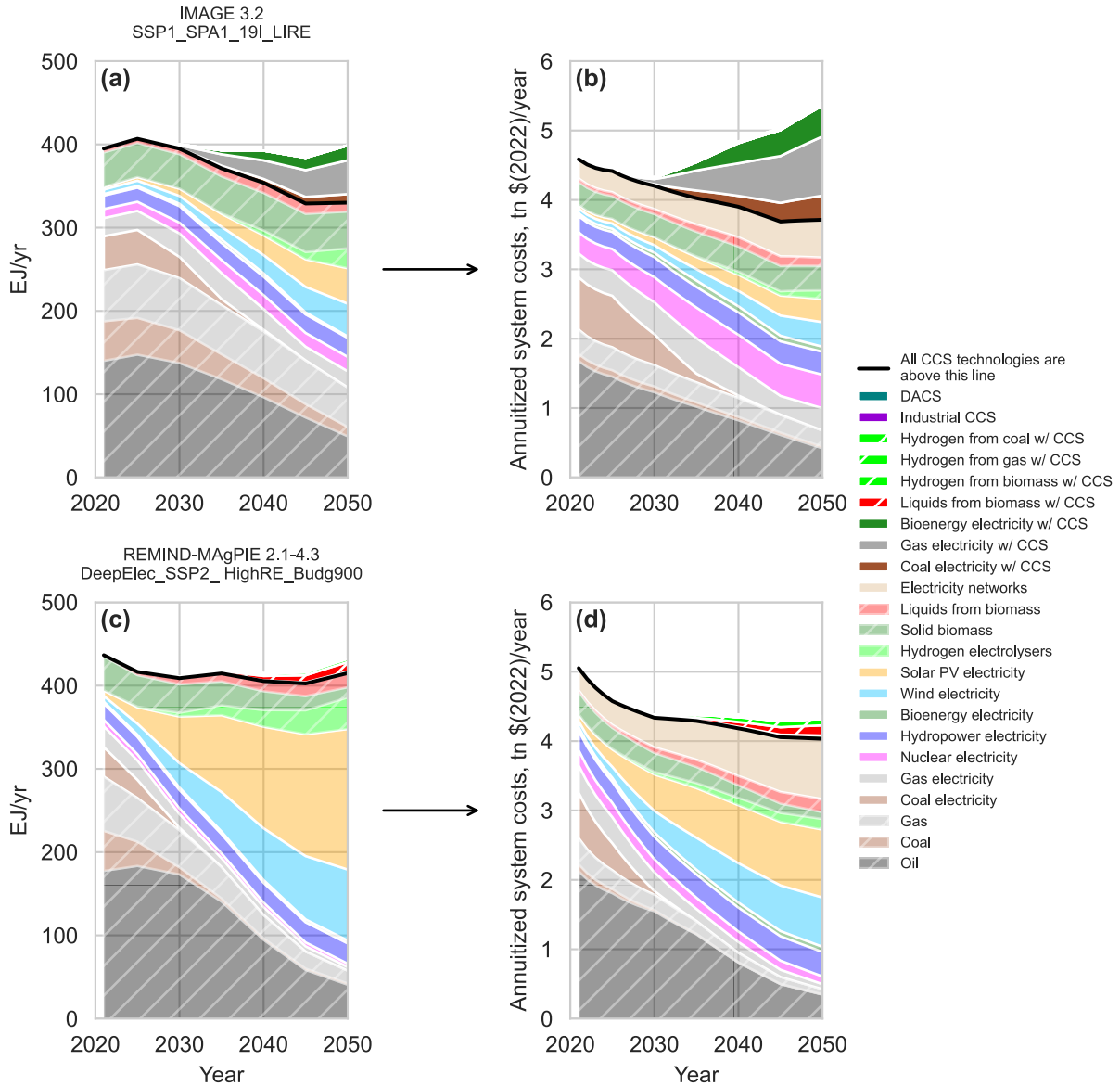
Results

MAIN RESULTS: SYSTEM COSTS FOR HIGH-CCS AND LOW-CCS SCENARIOS

Figure 6 (a) shows annuitised system costs for high-CCS scenarios (red) and low-CCS scenarios (blue) from 2021-2050. There is a clear division between the groups, with high-CCS scenarios costing in the order of US$1tn(2022) more per year than low-CCS scenarios. Mid-CCS scenarios generally lie between the two groups, as expected. The cost dynamic illustrated in **Figure 5** appears to occur generally, as low-CCS scenarios, which rely more on clean electrification and learning curve technologies to achieve decarbonisation, also achieve lower costs.

The total undiscounted difference between mean expenditures over the 30-year model horizon is US$29.5tn(2022), and the average annual difference in expenditures is US$0.98tn(2022). Mean annuitised energy system expenditures for low-CCS scenarios are on average 21.6% lower than for high-CCS scenarios.

Figure 6. (a) Annual levelised system costs 2020-2050. (b) Average useful energy costs 2020-2050.
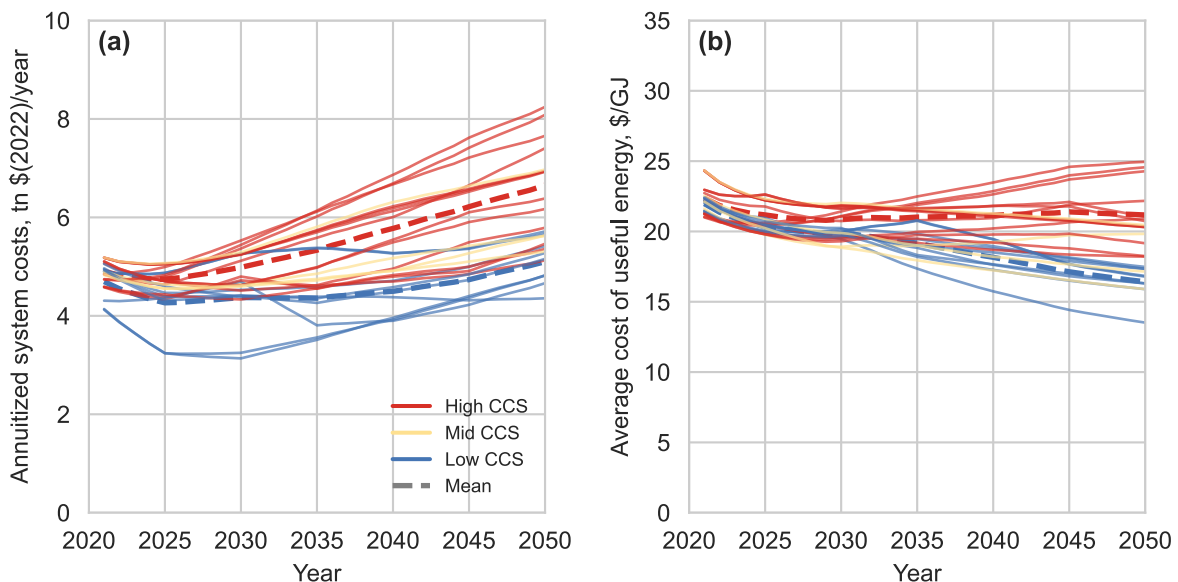

Figure 6 (b) shows the annual average cost of useful energy for each scenario. This is calculated by dividing the total annuitised annual cost (**Figure 6** (a)) by the useful energy of the scenario in the corresponding year (**Figure 3** (b)). This shows that low-CCS scenarios are expected to have a lower cost per unit of useful energy provided than high-CCS scenarios. In other words, energy services are expected to be cheaper in low-CCS scenarios. This is

ultimately because, for many fossil fuel technologies and applications, it is cheaper to reduce emissions by replacing them with clean electricity technologies than by adding CCS (including BECCS and DACCS).

Figure 7 (a) shows total present discounted costs, from 2021 to 2050, of each of our selected scenarios, relative to one central scenario, for a variety of discount rates. The central scenario (specified in *Methods*) acts as a baseline against which other scenarios are compared and has no greater meaning. At 2% discount rate the high-CCS scenario group is on average US$20.2tn(2022) more expensive than the low-CCS scenario group. At 5% discount rate, the high CCS group average is US$12.0tn(2022) more expensive than the low-CCS group. (As observed via **Figure 6** (a) already, the difference at 0% discount rate is US$29.5tn(2022).)

Figure 7. (a) Present discounted savings 2021-2050 for each scenario relative to a central scenario, for varying discount rates. (b) The same but normalised to average total useful energy over all scenarios.
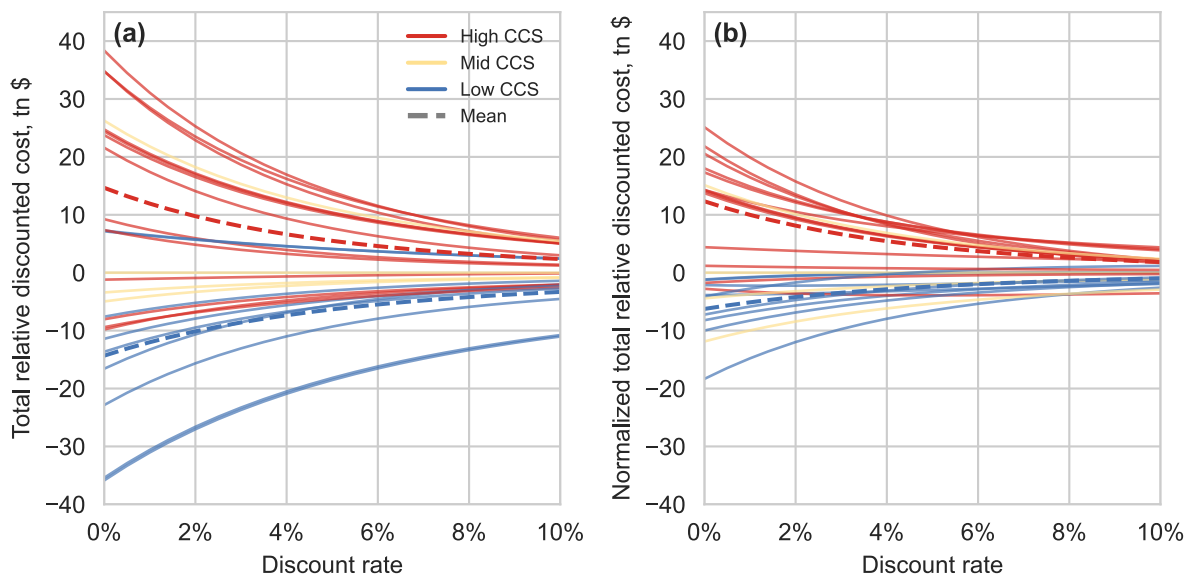
Although differences in useful energy between scenarios have been shown to be small (**Figure 3** (b)), note that relative scenario costs in **Figure 7** (a) are compared regardless of these differences. **Figure 7** (b) addresses this by normalising scenarios to constant equivalent cumulative useful energy supplied, and scaling the present discounted costs of scenarios up or down by these normalisation factors. (For the constant equivalent value of cumulative useful energy over the period 2021-2050 we use 254 EJ, as this is the mean of all selected scenarios.) There is no well-established or preferred method for performing such a normalisation, and this simple, transparent method is adequate for our purpose here.

When normalised by useful energy, the magnitude of differences between present discounted costs is smaller. This is to be expected, as the final energy metric exaggerates differences in energy supply. The total undiscounted difference between mean expenditures of the normalised high and low-CCS scenario groups over the 30-year model horizon is US$19.1tn(2022). On average, the normalised high-CCS group is US$0.64tn(2022) more expensive per year. At 2% discount rate, the normalised high-CCS scenario group is on average US$12.7tn(2022) more expensive than the normalised low-CCS scenario group, and at 5% discount rate, the difference is US$7.07tn(2022).

### WHY ARE HIGH-CCS NET ZERO PATHWAYS MORE EXPENSIVE?

Low-CCS pathways deploy more solar, wind, electrolysers and energy storage earlier, so the costs of these technologies come down faster. As well as creating cheap and early emissions reductions, faster deployment makes even more substitution of fossil fuel technologies possible at subsequent lower cost than in high-CCS pathways, which compounds the differences as time passes.

shows that high-CCS scenarios have lower solar deployment, and correspondingly higher per-unit solar costs, than low-CCS pathways. shows the same pattern for electrolysers.

Figure 8. (a) Solar deployment. (b) Solar costs.
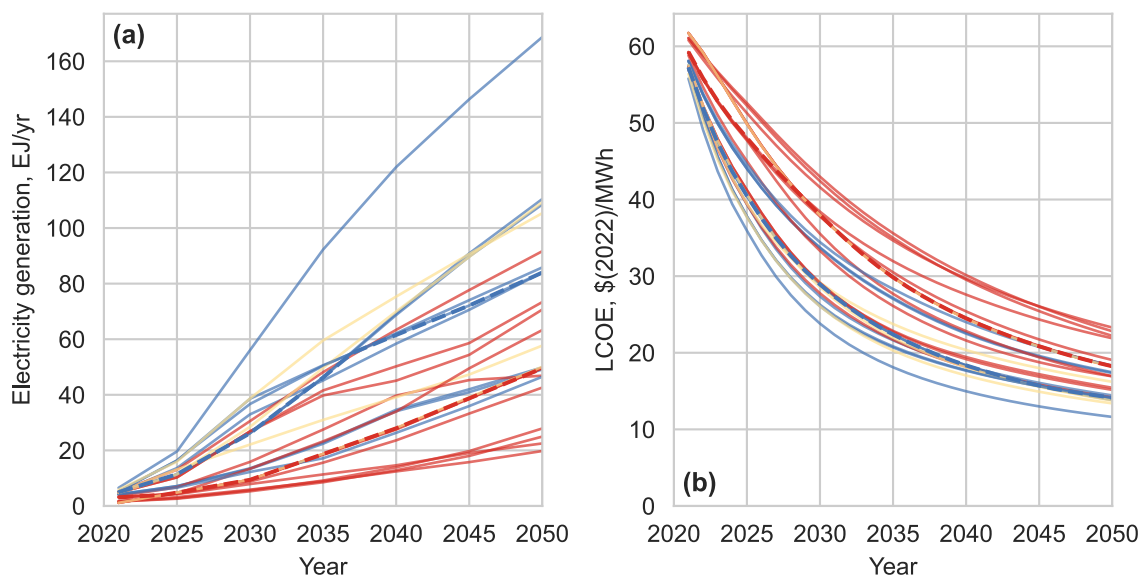
**Figure 9. (a) Electrolyser deployment. (b) Electrolyser costs.**
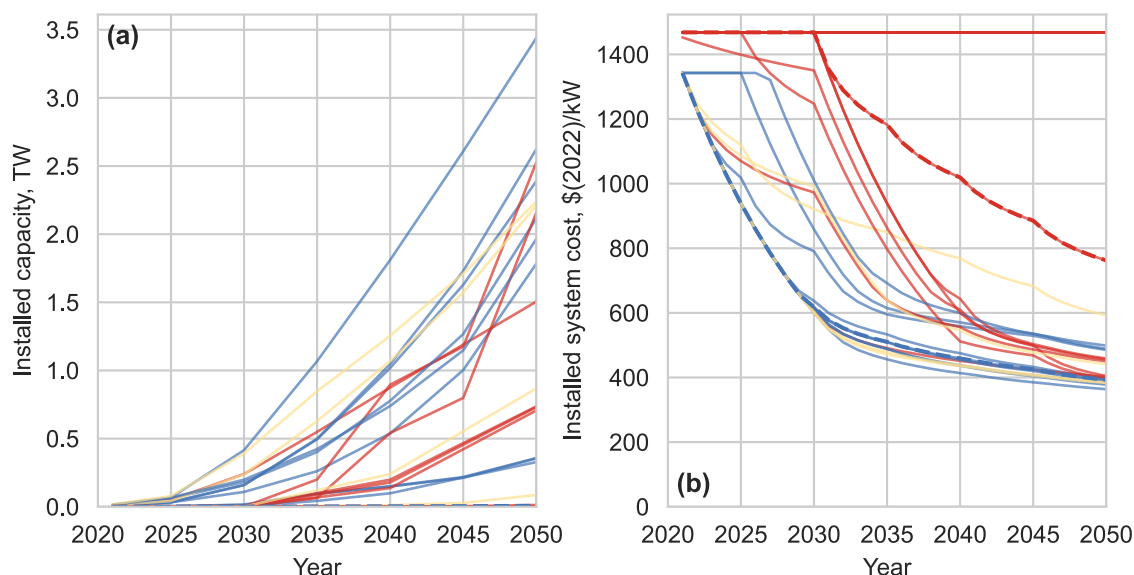
Although electric vehicles and grid-scale batteries are not modelled explicitly by learning curves in our approximate energy system, due to data limitations of IAM scenarios, learning effects in these technologies may be included implicitly if they were present in the original scenario data. In any case we should expect to observe the same differences between high- and low-CCS scenarios in these technologies as we do for solar, wind and electrolysers (as well as several other modern, electricity-related low-carbon technologies such as heat pumps, thermal energy storage systems, smart grid technologies, etc).

Figure 10 shows scenario expenditures disaggregated into four important technology groups, which together explain the differences in expected costs between high- and low-CCS scenarios. Panel (a) shows that, because average fossil fuel costs are not expected to fall (beyond the short-term regression to the long-term mean), continuing to rely heavily on fossil fuels in high-CCS scenarios keeps fossil fuel spending high. CCS merely adds extra expenditures on top of continued high fossil fuel spending (even with the very low CCS cost assumptions used in this work). In contrast, in low-CCS scenarios combined spending on fossil fuels and CCS decreases rapidly and remains low.

Panel (b) shows that the extra clean technology expenditures required in the low-CCS group to compensate for reduced fossil fuel use (while maintaining the same levels of energy services) are not much higher than the expenditures required in the high-CCS group. Therefore, compared to the high-CCS scenario group, the low-CCS group has much larger reductions in fossil fuel expenditures and only slightly larger increases in clean energy

expenditures, resulting in large net savings. Panels (c) and (d) further illustrate the point, with CCS expenditures in 2050 costing around US$1.5tn(2022) more for high-CCS scenarios than low-CCS scenarios, while the difference in expenditures on electricity networks and energy storage are only hundreds of billions of dollars.

Figure 10. Expenditure on (a) fossil fuels plus CCS technologies, (b) clean power, energy storage, electrolysers and electricity networks, (c) CCS technologies, and (d) electricity networks and energy storage investments, for 2021-2050.
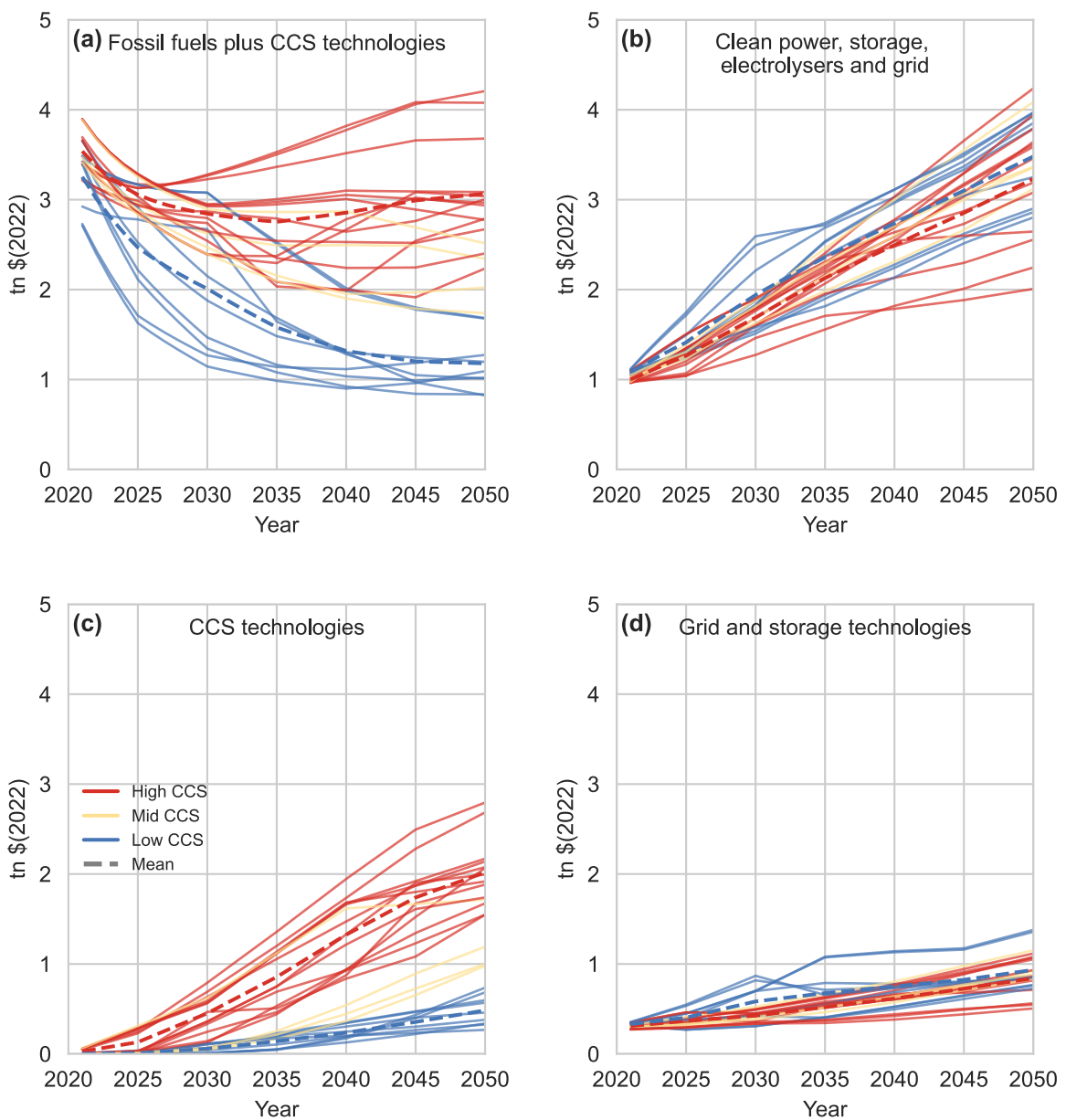
These results are consistent with the breakdown of costs by technology shown for the two example scenarios in **Figure 5**.

RESULTS FOR LOWER AND HIGHER CCS COSTS

We now consider two alternative CCS cost specifications, in order to explore how the main results depend on CCS technology cost assumptions. **Table 5** shows CCS costs in the main specification and the two side cases. (See *How we estimate scenario costs* for further details.)

Table 5. CCS technology costs in two side cases. See Table 3 and Table 4 for data sources.

Technology	Estimates of current cost	Others' estimates of cost in 2040-50	Main case (lowest cost estimate)	Side case 1 (half of lowest cost estimate)	Side case 2 (more central cost estimate)
Liquid fuels from biomass	1.4 – 9.2 $/gge		1.4 $/gge (11.0 $/GJ)	0.7 $/gge (5.5 $/GJ)	3.0 $/gge (23.6 $/GJ)
Liquid fuels from biomass with CCS	1.6 – 9.6 $/gge		1.6 $/gge (12.8 $/GJ)	0.8 $/gge (6.4 $/GJ)	3.2 $/gge (25.6 $/GJ)
Hydrogen from biomass with CCS	6.0 $/kgH$_2$	3.5 – 7.2 $/kgH$_2$	3.5 $/kgH$_2$ (24.7 $/GJ H$_2$)	1.8 $/kgH$_2$ (12.4 $/GJ H$_2$)	5.0 $/kgH$_2$ (35.3 $/GJ H$_2$)
Hydrogen from gas with CCS	1.2 – 3.3 $/kgH$_2$ (SMR) 1.6 – 2.6 $/kgH$_2$ (Advanced)	1.8 – 3.2 $/kgH$_2$ (SMR) 1.5 – 4.1 $/kgH$_2$ (Advanced)	1.2 $/kgH$_2$ (8.5 $/GJ H$_2$)	0.6 $/kgH$_2$ (4.3 $/GJ H$_2$)	2.2 $/kgH$_2$ (17.0 $/GJ H$_2$)
Hydrogen from coal with CCS	2.2 – 3.8 $/kgH$_2$	2.9 – 4.0 $/kgH$_2$	2.2 $/kgH$_2$ (15.3 $/GJH$_2$)	1.1 $/kgH$_2$ (7.7 $/GJH$_2$)	3.0 $/kgH$_2$ (20.7 $/GJH$_2$)
Industrial CCS	50 – 120 $/tCO$_2$		50 $/tCO$_2$	25 $/tCO$_2$	100 $/tCO$_2$
DACCS	455 $/tCO$_2$	85 $/tCO$_2$	85 $/tCO$_2$	42 $/tCO$_2$	150 $/tCO$_2$
Coal electricity with CCS	123-300	160	123	62.5	150
Gas electricity with CCS	76-280	120	76	60[9]	100

[9] 60$/MWh is the lowest long-run cost of unabated gas electricity in this model, so is used as the lowest cost of gas electricity with CCS too.

Bioenergy electricity with CCS	90-194		90	75[10]	120

Figure 11 and **Figure 12** show that re-running our main cost analysis with CCS technology costs set to the values specified in the two side cases (i.e. either higher or lower than the main case) does not change the conclusions. Notably, even if CCS costs are half the lowest estimates observed in the literature, high-CCS scenarios are on average still trillions of dollars more expensive then low-CCS scenarios. The savings available by rapidly replacing fossil fuel technologies with clean electricity-based technologies are so large that even if CCS costs are extremely low, high-CCS scenarios are still not likely to be economically competitive.
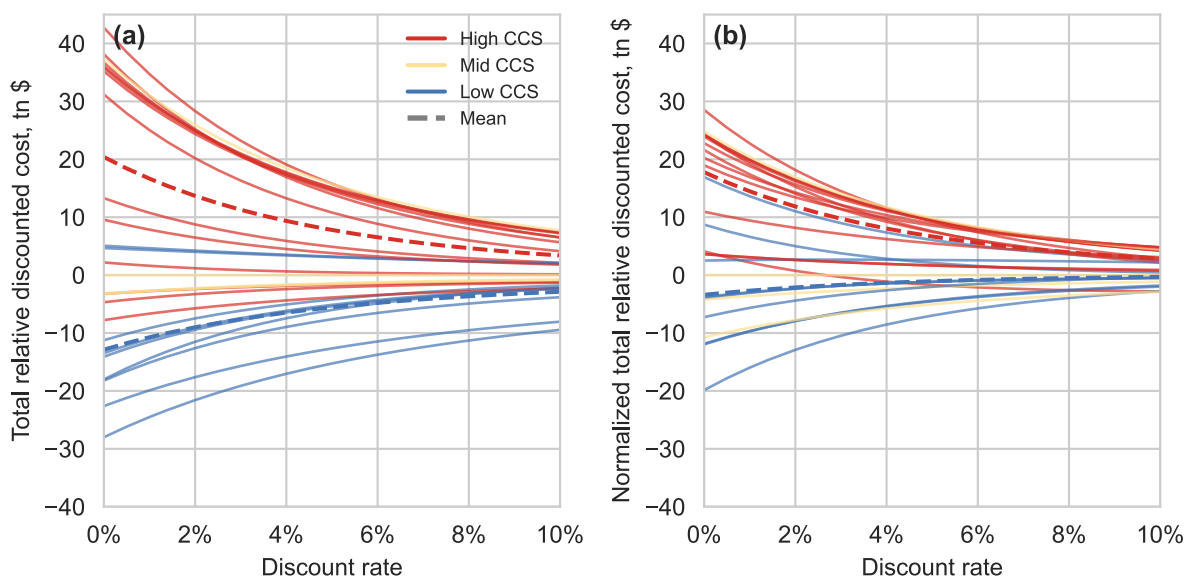
Figure 11. Side case 1: CCS technology costs set to half of the lowest all-time cost estimates.

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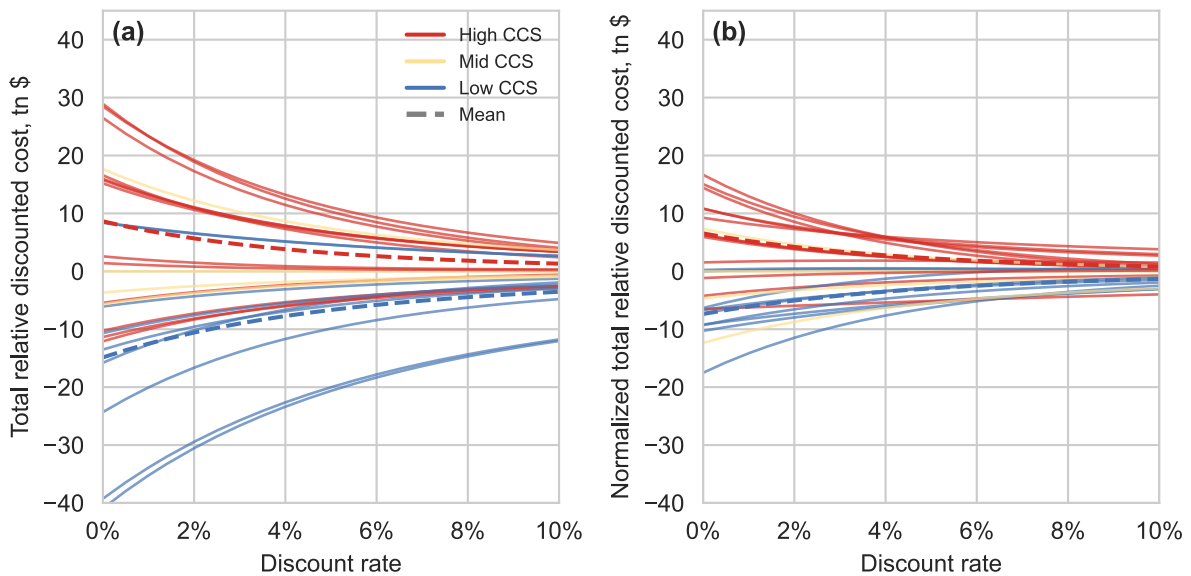
[10] 75$/MWh is the lowest long-run cost of unabated bioenergy electricity in this model, so is used as the lowest cost of bioenergy electricity with CCS too.

Figure 12. Side case 2: CCS technology costs set to mid-to-low end of range of cost estimates.
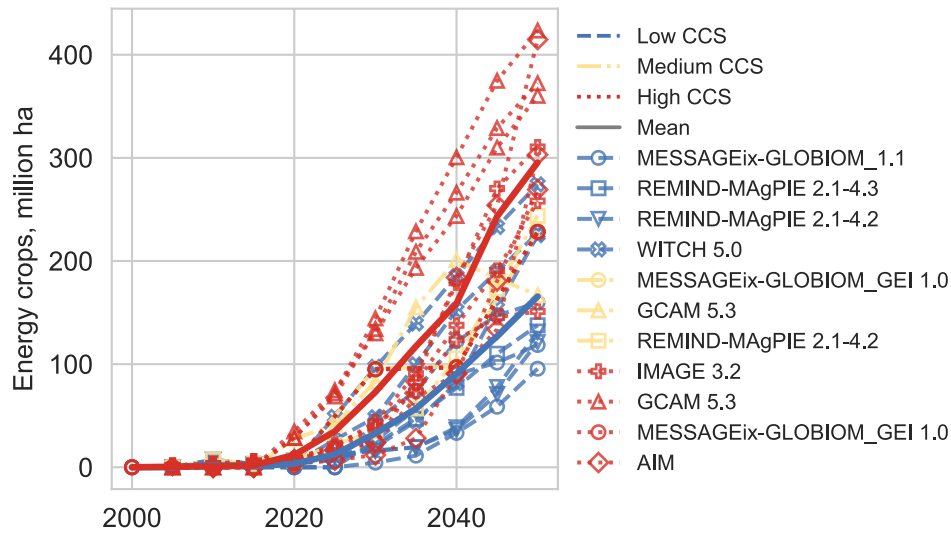

LAND USE FOR ENERGY CROPS

Scenarios that are high in CCS are self-evidently high in abated use of fossil fuels and/or biomass, but also tend to be relatively high in unabated use of both, as well.

In practice, all our high-CCS scenarios have higher levels of BECCS than all of the low-CCS scenarios (3.7-11.7 $GtCO_2$ in the high group vs 1.0-3.3 $GtCO_2$ in the low group). High-CCS scenarios mostly also derive more primary energy from biomass than low-CCS scenarios (107-226 EJ for the high group, 85-119 EJ for the low group).

Higher levels of biomass use, whether in BECCS facilities or unabated, entails a higher demand for energy crops and thus for land on which to grow them.

Figure 13 shows the land dedicated to energy crops (both first- and second-generation) for our low, mid- and high-CCS scenarios over time. (**Figure 13** does not include two scenarios coming from the REMIND model; they do not report any information regarding land-use because in these scenarios REMIND is not coupled, as it often is for other scenarios, with a land-use model such as MAgPIE. These scenarios instead use exogenous information from MAgPIE to determine the net CO_2 emissions from the Agriculture, Forestry and Other Land Use (AFOLU) sector and agricultural production costs.)[56]

Figure 13. Land area dedicated to energy crops in million hectares (ha) for our low (blue dashed line), medium (yellow dash-dotted line) and high (red dotted line) scenarios. For both plots, different dot styles correspond to different model families. Two scenarios coming from REMIND do not report any information regarding land-use because REMIND is not coupled with a land-use model; these scenarios are "R2p1 SSP5-PkBudg900" (low CCS) and "CEMICS GDPgrowth 1p5" (medium CCS).

In 2050, low-CCS scenarios require an average of 1.65 million sq km of land for energy crops, and high-CCS scenarios require an average of 2.96 million sq km. Six of the 13 high-CCS scenarios feature even higher land use, of between 3.29 million sq km (the size of India) and 4.24 million sq km. The mid-CCS scenarios fall, as expected, in the middle, requiring an average 2.13 million sq km.

Thus, on average, taking a high-CCS route to mid-century net zero would require an additional 1.3 million sq km of land for energy crops compared with a low-CCS route. We have not attempted to calculate how much extra demand for water and other resources would be created by this additional land-take, nor have we factored into our cost calculation the fact that land for growing biomass feedstock would be expected to increase in price as demand escalates. This finding adds to the established and well-documented concerns about the sustainability of scenarios containing multiple gigatonnes of BECCS.[57–60]

Discussion

COST-EFFECTIVE MITIGATION

We have shown that a low-CCS pathway to net zero emissions, as defined in our study, is likely to be far cheaper than a high-CCS route. It will also have a significantly smaller impact on land availability, resulting specifically from lower biomass requirements for BECCS, during a period when the need for land for food production may well be increasing, and when climate change impacts are impinging on crop yields via a number of pathways. Rapid, widespread electrification powered by renewable energy should therefore logically be the centrepiece of any decarbonisation strategy, while continuing high fossil fuel use with increasing abatement should not.

For electricity, new wind and solar generation is already cheaper than new fossil-fuelled generation, and increasingly also cheaper than running existing fossil-fuelled power stations.[10] The cost difference will grow as more renewables are built; and the faster they are built, the faster their costs will fall. So, **opting for blanket CCS rollout as a substitute for building a renewables-based energy system will not only elevate the cost of energy in the short term, but also perpetuate that elevation**. Most individual countries that invest in CCS at the expense of focusing on renewables with electrification are likely to find themselves at a competitive disadvantage as others invest in a cheaper renewables-based energy system.

Although our analysis focuses on 2050, the benefits of rapid and deep investment in renewables will endure and increase well beyond that date, with costs continuing to fall in wind and solar power, battery storage and 'green' hydrogen.

However, the large expected economic benefit of taking a low-CCS vs a high-CCS pathway does not mean that taking a 'no-CCS' pathway would be cheaper still. Modelling studies suggest that **in at least some major economies, getting to net zero without any CCS at all would be harder and more expensive than deploying a small amount**, at least in the absence of breakthrough advances in harder-to-abate sectors.[61] Industrial decarbonisation is the use case most cited, with some studies also suggesting that a small amount of CCS in the power sector could be economically beneficial in some countries, despite its cost, as a provider of dispatchable generation.[62] However, in the power system, the rapid cost reductions seen in renewable energy and storage are fast eroding the value of CCS for this application,[32] and advances in alternatives to decarbonising industrial processes could erode the current cost benefit of CCS for these purposes too.[63]

In addition to foreseeable costs, blanket rollout of CCS as a substitute for (rather than a small complement to) renewables plus electrification would entail increasing risks of events that could increase the cost via mechanisms that are at present unpredictable. If CCS power plants continue to experience sub-optimal capture rates, or if a significant proportion of storage reservoirs prove to carry leak risks, or if extreme weather perturbs the biomass supply chain for BECCS, the amount of mitigation provided by each CCS facility would fall, and the costs of overall mitigation via this route therefore rise substantially.

TECHNOLOGICAL LEARNING SHOULD NOT BE ASSUMED

The evidence assembled and reviewed for this report suggests that hopes of seeing the costs of CCS come down significantly, and perhaps at all, due to learning effects are likely to be unfulfilled.

There is consensus in the literature that costs for CO_2 transport and storage are unlikely to fall, as equipment consists of mature engineering components such as steel pipes and gas pumps. That still leaves open the possibility of a learning effect in the capture equipment, which, in industrial applications, would likely be the biggest component of the overall cost.

The main technology for CO_2 capture, amine scrubbing, has been used for nearly a century for applications including natural gas processing.[64] Rochelle (2009) relates that 'CO_2 removal by adsorption and stripping with aqueous amine is a well-understood and widely used technology… Hundreds of plants currently remove CO_2 from natural gas, hydrogen, and other gases…'.[64] Although we have been unable to find a total for the total number of natural gas processing plants built globally, there were 727 in 1995 and 530 in 2004 in the United States alone, indicating that global numbers have probably been in the low thousands for several decades given the historical US share of gas production.[65]

If significant cost reductions due to innovation and technological learning were possible at all for amine scrubbing, then deployment on this scale would have been expected to have generated such cost reductions; and if capture costs had declined, this should have fed through into cost estimates for CCS reported in the scientific literature at various times. The facts that a) no cost reductions have been reported within studies (and, in the case of Rubin et al. (2015), a cost *increase* was reported), and b) that no cost trend is identifiable by comparing studies suggests that **carbon capture technologies may not exhibit any appreciable technological learning in future**, which is consistent with observations from other applications involving chemical processes.[66]

If governments and companies advocating widespread use of CCS wish to contest the statement that technology learning is unlikely, their only feasible way forward would appear to be to build a large number of plants and allow independent evaluation of the costs.

More novel techniques for CO_2 capture are routinely discussed in the literature and could potentially lead to lower costs. However, technological leaps are also possible in other types of equipment, such as solar panels, batteries, nuclear reactors and electrolysers. There is no way to predict how new generations of technology will perform under real-world conditions or what the real-world costs will be; therefore caution and appropriate uncertainty analyses must be applied when implementing future cost assumptions in models, until they have become something more tangible than hypotheses.

Based on real-world evidence and estimations in the literature, it would be prudent for policymakers and businesses to assume that CCS will continue to cost roughly what it does now; and also to acknowledge that the cost of CCS, in applications other than natural gas processing, is at present still highly uncertain, particularly by contrast with costs for solar and wind power and battery storage. It is hard to say what a new CCS-equipped steelworks or BECCS plant will cost when there are virtually none currently in operation.

LAND USE CAUTIONS

The additional land take necessitated by high-CCS routes could have significant consequences for food availability and price, human rights, biodiversity and access to resources such as water.

For context, **the amount of land required for energy crops in the high-CCS scenarios, at 2.96 million sq km, approximates to the increase in land used for agriculture between 1961 and 2021 (3.51 million sq km)**.[67] Taking this allocation from existing agricultural land would have obvious implications for food security and prices. If the energy crops were grown on currently unexploited land, the Intergovernmental Platform on Biodiversity and Ecosystem Services notes that "the largescale deployment of intensive bioenergy plantations, including monocultures, replacing natural forests and subsistence farmlands, will likely have negative impacts on biodiversity and can threaten food and water security as well as local livelihoods, including by intensifying social conflict". [68]

Countries in regions where biomass is not plentiful but whose plans for ongoing emissions could oblige them to implement BECCS on a large scale, such as those in the Persian Gulf, are highly likely to turn to supply chains from the Global South. As the 'dash to biofuels' in the early 2000s demonstrated, **an escalation in demand for energy biomass can provoke**

disputes over land rights and access, food price rises and eventually conflict.[47] It is therefore difficult to comprehend that countries aiming to work in harmony with the Global South would promote routes to decarbonisation that are replete with such risks when other options, with far less need for biofuels, are available.

SCALING UP FOR ESSENTIAL USES

Our analysis highlights the disparity between current deployment rates for CCS and the volumes required in even 'low-CCS' scenarios.

All of the scenarios in both of our groups include CCS for industrial facilities – the volumes are fairly invariant across scenarios compared with the differences seen in biomass and fossil CCS, with the majority spanning the range 0.7-1.1 $GtCO_2$ captured per year in 2050. Sequestering this amount would entail approximately a 20-fold scaling up from the current level of 49 $MtCO_2$. Reaching the average level across all sectors seen in our low-CCS scenarios, 4.4 $GtCO_2$, would entail approximately a 90-fold expansion.

These numbers look challenging, for a number of reasons:

- The volume of CO_2 captured globally has approximately doubled over the last decade.[13] Continuation of this trend, even assuming exponential rather than linear growth, would see only a few hundred $MtCO_2$ being captured in 2050 – an order of magnitude less than the average in our low-CCS scenarios.
- Only three of the 41 existing CCS facilities are in the power generation sector, and none in the biomass/BECCS sector; yet these are the two use cases most prominent in high-CCS scenarios.
- Although the GCCSI lists projects totalling 312 $MtCO_2$ capacity that are in the planning or construction phase, the completion rate on CCS facilities is low. In 2011 the capacity in planning and construction totalled about 130 $MtCO_2$, with approximately 20 $MtCO_2$ already in operation; a decade later, operational capacity totalled about 40 $MtCO_2$, showing that the vast majority of planned projects were abandoned.
- The role of EOR as a revenue stream is likely to shrink as global oil demand contracts. EOR currently supports 29 of the 41 operating facilities, and other revenue streams from using captured CO_2 are not remotely scaling up to compensate.

The challenge appears even more acute when one looks at the build rate of CCS in the scenarios in our study to 2030.

If every CCS plant in the GCCSI's database currently in the construction and planning phases gets built by 2030, this would deliver 361MtCO$_2$ of capture in 2030. (That outcome would appear highly unlikely, given the historically high rate of cancellations noted above.)

By comparison, the average volume captured in 2030 in our group of low-CCS scenarios is 617 MtCO$_2$. In terms of sheer volume, then, all these projects and then nearly the same number again would have to enter operation within the next seven years to get on track for the low-CCS scenarios.

The average capacity in 2030 in high-CCS scenarios is 4.16 GtCO$_2$ – which would entail governments and businesses coming forward with facilities delivering 12 times the volume in the current pipeline, and ensuring they all get built. With the average facility capturing 1.2 MtCO$_2$ per year, this would necessitate building about 3,500 CCS units, complete with pipeline or ship transport, burial and monitoring, in just seven years.

The conclusion must be, then, that if governments wish to see CCS facilities built at even the scale seen in our low-CCS scenarios, a step-change in approach is needed. Policy measures proposed that could provide this step-change include:

- A carbon take-back obligation, under which producers of oil, coal, gas and limestone (for cement) would be obliged to capture and store the emissions generated by using their products.[69] The size of the obligation would rise progressively, thus stimulating investment, and reach 100% of emissions from energy and industrial processes by mid-century.
- Use of Contracts for Difference (CfDs) for CCS-equipped power plants (and possibly hydrogen production) that provide revenue at least equivalent to the cost increase incurred by adding CCS to the process in question.[70]
- Extending carbon markets from biological to geological storage.[71]
- Establishing CCS hubs and clusters with public-private partnerships, so sharing transport and storage costs between facilities.[72]
- Use of blanket mechanisms such as tax credits, subsidies, product standards or other regulatory instruments.

A number of governments, in particular the US, are now enacting measures that could stimulate a limited building programme for CCS plants. However, given the recent history of plants with under-performance (Boundary Dam, Gorgon) and those that experienced reservoir problems (Snøhvit, Salah, Gorgon), not to mention the risk of project cancellation

following government changes, the planned build-out is manifestly not yet of the order needed to deliver volumes seen in even our low-CCS scenarios.

STUDY LIMITATIONS

One limitation of this analysis is that we do not consider emissions from farming and land use. A related one is that we do not consider greenhouse gases other than CO_2. Some of the BECCS and DACCS capacity included in scenarios may be present to compensate for ongoing land-use emissions, including gases such as methane. However, we do not see this making a meaningful difference to the conclusions.

A second limitation is that we do not go beyond 2050 in our analysis. This means that we do not compare the groups of high- and low-CCS scenarios during the period after 2050, when they may contain different levels of negative emissions (including BECCS and DACCS), depending on the levels of overshoot. However, the benefit of concentrating on 2050 is that this is a timescale relevant to policymaking and investment. It is just 27 years hence – shorter than the operating lifetime of a new fossil-fuelled power station, steelworks or oil refinery, virtually identical to that of a wind farm, and not much longer than that of a solar farm. Decisions made now by policymakers and investors are critical to reaching net zero emissions around mid-century, which we believe fully justifies our decision to focus on the implications of decisions made now.

We would have liked to explore other social and ecological dimensions of the additional CCS volume in the high scenarios group, such as water use, impact on biodiversity and potential competition with food supply. However, the impact that additional land-take has for such issues is sufficiently well documented to make at least qualitative conclusions about the relative desirability, on these grounds, of a low-CCS path vs a high-CCS path to net zero.

Conclusion

The main conclusion from this study is clear: taking a low-CCS route to mid-century net zero emissions (4.4 $GtCO_2$ on average in 2050, about one-tenth of mitigation needed from today) will be a lot cheaper, by an average of about \$1 trillion per year, than taking a high-CCS route (average 19.2 $GtCO_2$ – about half of mitigation). The vast majority of scenarios conclude that some CCS will be needed for industry, and (absent other technologies of sufficient scale) for negative emissions. However, our report shows that, economically, the pragmatic option is to view CCS as a necessary option, but one that will most likely only be needed sparingly, for purposes where other options are unavailable or very expensive. **High-CCS routes will waste trillions of dollars compared with low-CCS routes, with low-CCS routes being in addition more feasible, secure and sustainable.**

The logic of both climate change and economics encourages as a central priority the rapid build-out of renewables, grids and flexibility during the coming decade, an increase in the rate of energy-efficiency improvements, and rapid electrification of transport, heating and industry. This approach will tackle easier-to-decarbonise sectors (which make up the majority of global emissions) as quickly as possible, preserving as much as possible of the remaining carbon budget for 1.5°C for the smaller, harder-to-decarbonise sectors.

Scaling up CCS this decade is also necessary. By doing so, governments would build transport and storage infrastructure which can then be used to accommodate emissions from multiple facilities. Comparing the current state of CCS globally with the scale contained in our low-CCS scenarios indicates the need for rapid action. However, comparing the current situation with the volumes contained in high-CCS scenarios suggests that such volumes are probably unattainable even if they were desirable – which, as we show, they definitely are not.

CCS is likely to prove an expensive and precious resource. Governments and businesses should see it as such, understand that it has a specific, small but important role to play in meeting the Paris targets, and plan decarbonisation policies accordingly.

Appendix

1. DATA SOURCES FOR FIGURE 1

Non-CCS technology data are from IRENA[10] and various sources given in Way et al (2022).[9]

Table 6. Sources of historical techno-economic cost estimates of power plants with CCS

| |
|---|
| Herzog 1998 - The economics of CO_2 capture |
| IEAGHG 2012 - CCS Cost Workshop Proceedings (Foster Wheeler slides) |
| IEAGHG 2012 - CCS Cost Workshop Proceedings (EPRI slides) |
| David and Herzog 2000 - The cost of carbon capture |
| IEAGHG 2006 - Estimating the Future Trends in The Cost of CO_2 Capture Technologies |
| IPCC 2005 - SRCCS Carbon Dioxide Capture and Storage |
| GCCSI 2017 - Global Costs of Carbon Capture and Storage |
| Energy Transitions Commission 2022 - Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited |
| Rubin et al 2015 - The cost of CO_2 capture and storage |
| Hamilton, Herzog & Parsons 2009 – Cost and US public policy for new coal power plants with carbon capture and sequestration |
| Keith 2002 - Towards a Strategy for Implementing CO_2 Capture and Storage in Canada |
| Porter et al. 2017 - Cost and performance of some carbon capture technology options for producing different quality CO_2 product streams |
| IEA 2011 - Cost and Performance of Carbon Dioxide Capture from Power Generation |
| IEAGHG Davison 2013 – OPEC Vienna CCS Costs and Economics |
| Albanese & Steinberg 1980 - Environmental control technology for atmospheric carbon dioxide |
| Horn & Steinberg 1982 - Control of carbon dioxide emissions from a power plant (and use in enhanced oil recovery) |
| Bloomberg Terminal (accessed August 2023) |

2. SCENARIO GROUPS

Table 7. Our selected low, medium (for sense-checking only) and high CCS scenarios, with the total CO_2 captured in 2050 for each.

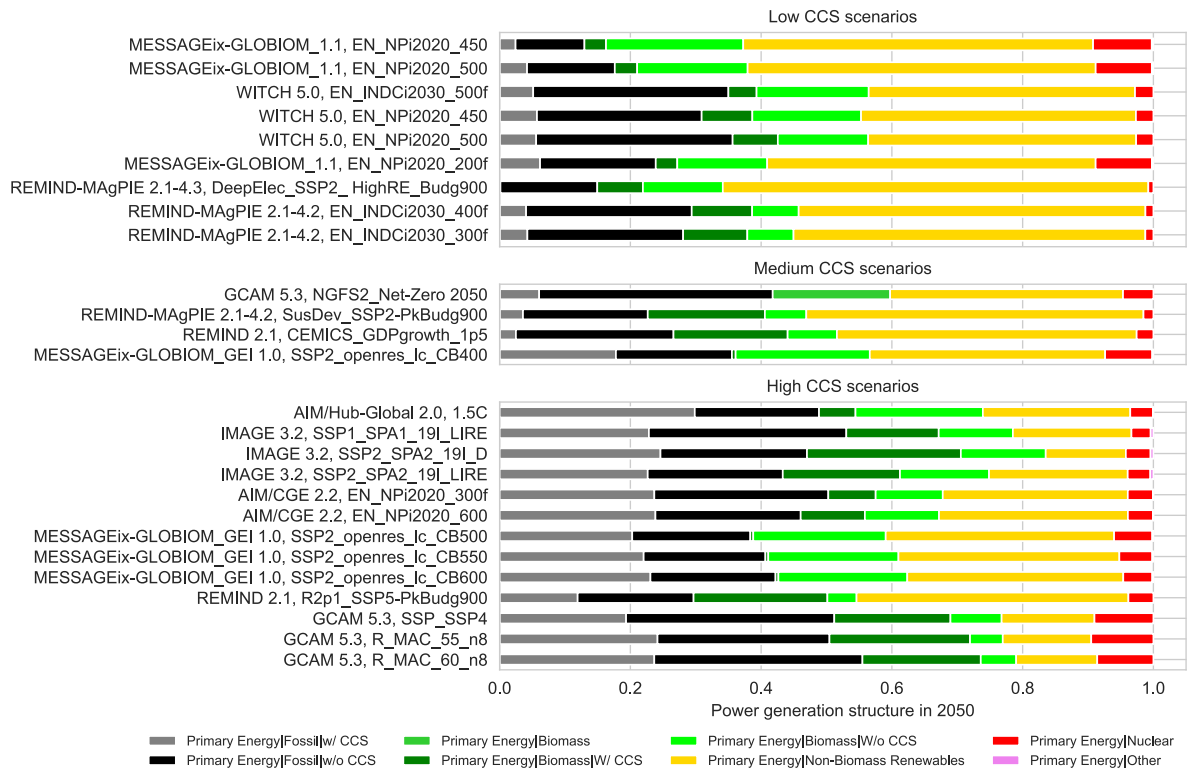| Model	Scenario	Carbon sequestration CCS, Gt CO_2	CCS group
MESSAGEix-GLOBIOM_1.1	EN_NPi2020_450	2.51	Low
MESSAGEix-GLOBIOM_1.1	EN_NPi2020_500	3.14	Low
REMIND-MAgPIE 2.1-4.3	DeepElec_SSP2_ HighRE_Budg900	3.67	Low
MESSAGEix-GLOBIOM_1.1	EN_NPi2020_200f	3.78	Low
REMIND-MAgPIE 2.1-4.2	EN_INDCi2030_400f	4.07	Low
WITCH 5.0	EN_INDCi2030_500f	4.17	Low
REMIND-MAgPIE 2.1-4.2	EN_INDCi2030_300f	4.26	Low
WITCH 5.0	EN_NPi2020_500	5.86	Low
WITCH 5.0	EN_NPi2020_450	6.16	Low
REMIND-MAgPIE 2.1-4.2	SusDev_SSP2-PkBudg900	8.03	Medium
REMIND 2.1	CEMICS_GDPgrowth_1p5	8.86	Medium
GCAM 5.3	NGFS2_Net-Zero 2050	10.56	Medium
MESSAGEix-GLOBIOM_GEI 1.0	SSP2_openres_lc_CB400	13.67	Medium
MESSAGEix-GLOBIOM_GEI 1.0	SSP2_openres_lc_CB500	14.85	High
AIM/CGE 2.2	EN_NPi2020_300f	14.93	High
AIM/Hub-Global 2.0	1.5C	15.1	High
REMIND 2.1	R2p1_SSP5-PkBudg900	15.44	High
MESSAGEix-GLOBIOM_GEI 1.0	SSP2_openres_lc_CB550	15.71	High
MESSAGEix-GLOBIOM_GEI 1.0	SSP2_openres_lc_CB600	16.26	High
AIM/CGE 2.2	EN_NPi2020_600	16.9	High
GCAM 5.3	SSP_SSP4	18.18	High
GCAM 5.3	R_MAC_60_n8	21.44	High
GCAM 5.3	R_MAC_55_n8	23.3	High
IMAGE 3.2	SSP2_SPA2_19I_LIRE	24.52	High
IMAGE 3.2	SSP2_SPA2_19I_D	25.4	High
IMAGE 3.2	SSP1_SPA1_19I_LIRE	25.82	High

3. SCENARIOS – PRIMARY ENERGY

Figure 14. Primary energy (EJ) in 2050 for low (top panel), medium (second panel) and high (bottom panel) CCS scenarios broken down into fossil energy with CCS (grey) and without CCS (black); biomass with CCS (lime), without CCS (dark green), and with and without CCS as a cumulative figure (green); renewable energy other than biomass (yellow); nuclear (red); and other types (pink). Scenario "NGFS2 Net-Zero 2050" from GCAM 5.3 is the only one that does not report biomass with and without CCS separately, so we show the cumulative figure. Other types of primary, if any, is usually very small, reaching a maximum of 3 EJ. The blue dots show total primary energy as reported in the IPCC AR6 Scenario Database. Three scenarios, all coming from the IMAGE model family, have a discrepancy between the reported primary energy and that calculated by summing up the different types of primary energy.
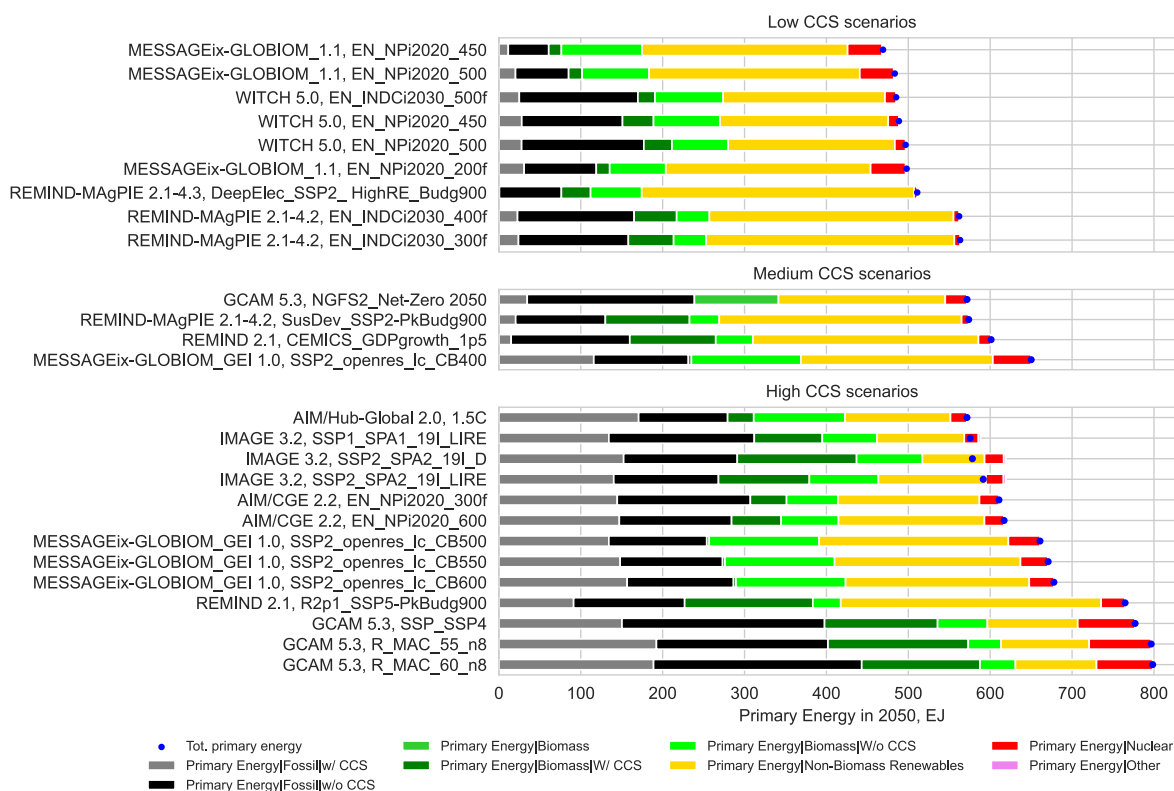
4. Scenarios – Power System

Figure 15. Power generation structure in 2050 for low (top panel), medium (second panel) and high (bottom panel) CCS scenarios. Broken down into fossil energy with CCS (grey) and without CCS (black); biomass with CCS (lime), without CCS (dark green), and with and without CCS as a cumulative figure (green); renewable energy other than biomass (yellow); nuclear (red); and other types (pink). Scenario "NGFS2 Net-Zero 2050" from GCAM 5.3 is the only one that does not report biomass with and without CCS separately, so we show the cumulative figure. Other types of primary, if any, is usually very small, reaching a maximum of 3 EJ.
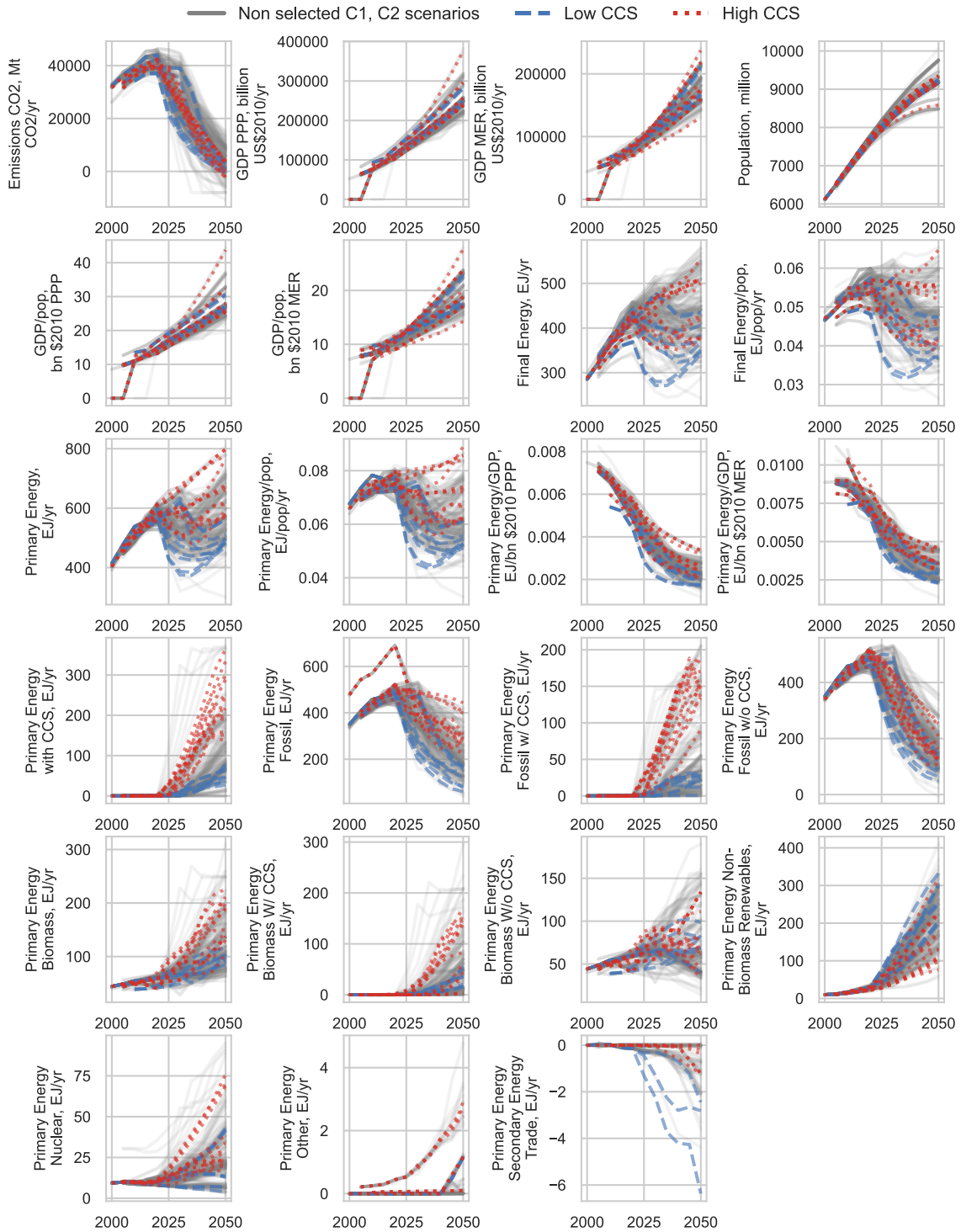
5. **CARBON SEQUESTERED**

Figure 16. Carbon sequestration (Gt CO2) by type for low (top panel), medium (second panel) and high (bottom panel) CCS scenarios in 2050. We show the CO2 sequestrated by CCS on fossil fuel (grey) and biomass (green) power plants, and on industrial processes (yellow). We also show the CO2 sequestered by direct air capture (light blue) and feedstocks (magenta). Direct air capture and feedstocks are only marginally deployed in scenarios. We do not show the emissions sequestered by land-use (e.g. afforestation and reforestation) because it is not consistently reported across the scenarios.
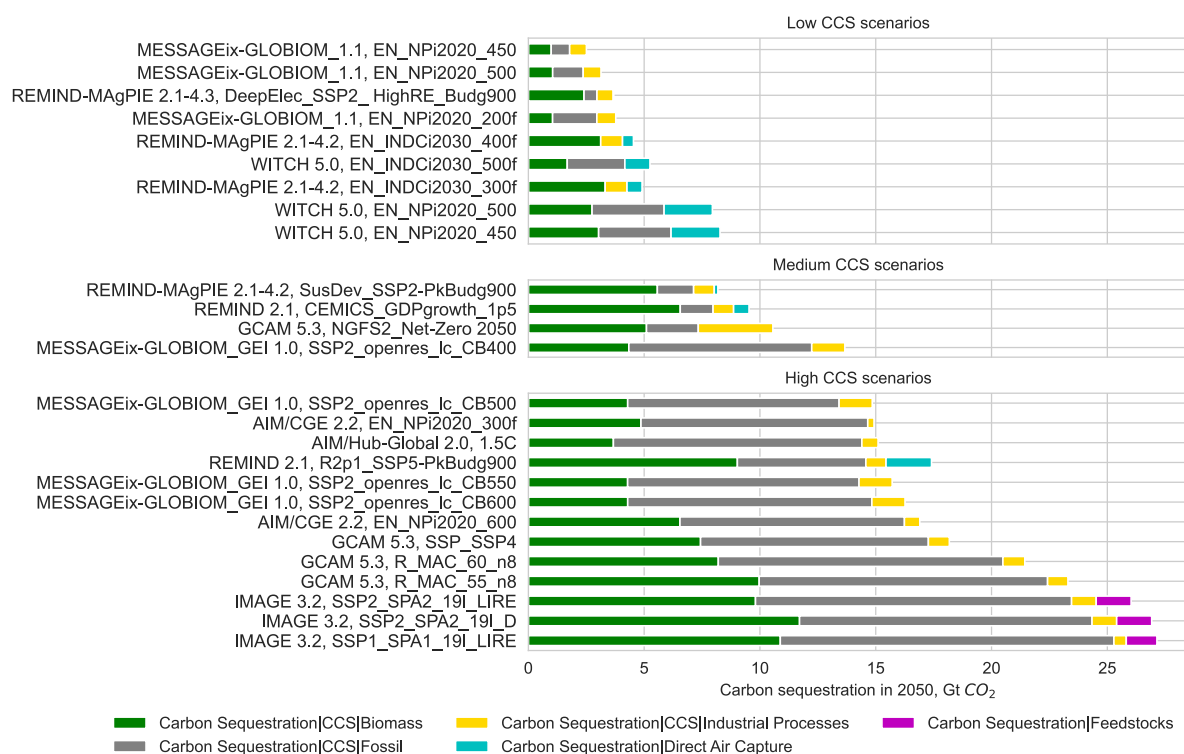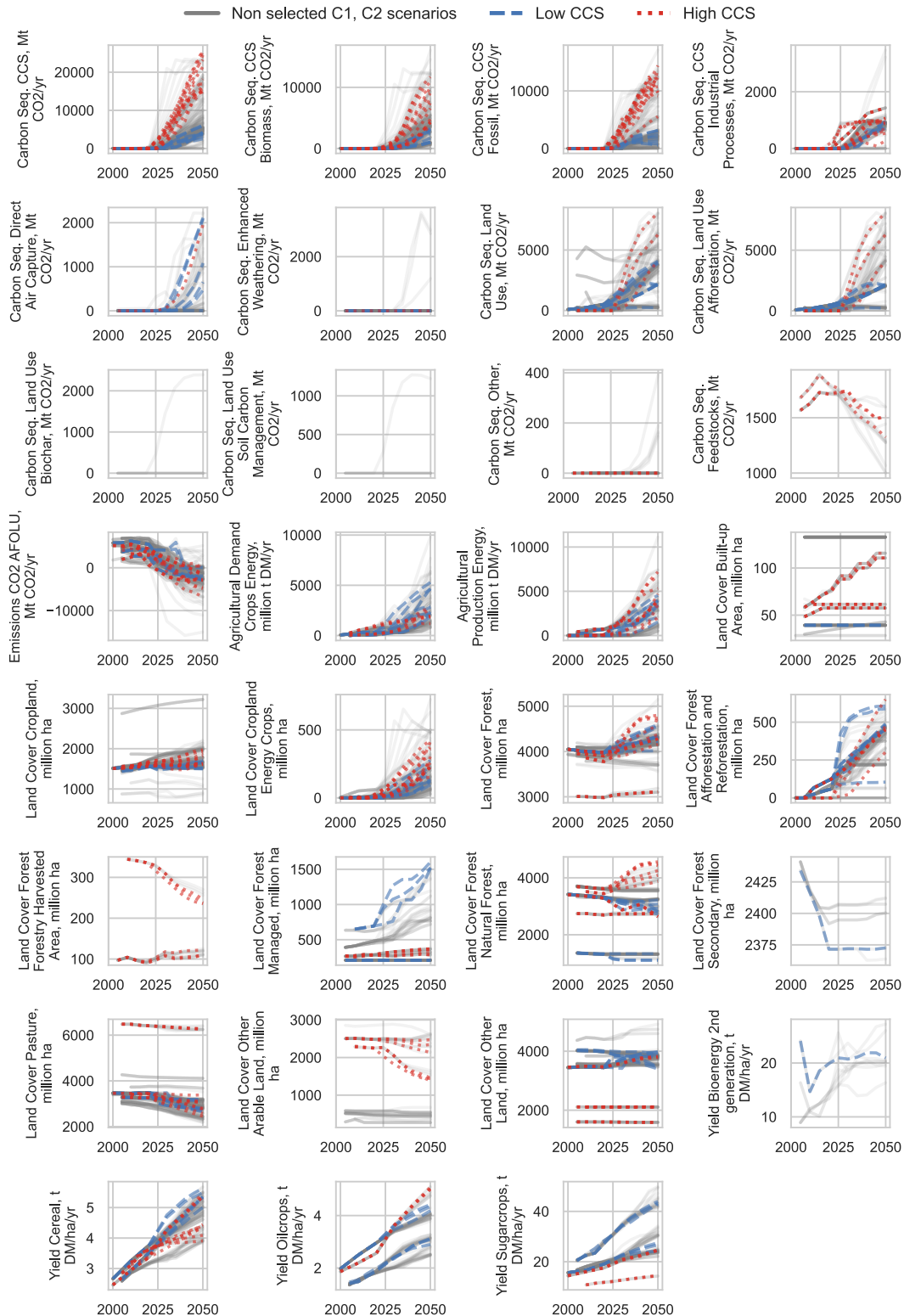

6. **SCENARIOS – OTHER VARIABLES**

Figure 17, **Figure 18** and **Figure 19** show the time series of a variety of variables that characterise mitigation scenarios, for our low CCS scenarios (blue dashed lines), high CCS scenarios (red dotted lines) and all the other C1 and C2 scenarios (grey solid lines).

Figure 17. Time series describing GDP, net CO_2 emissions, population (pop), final energy and primary energy for our low (blue dashed lines) and high (red dotted lines) CCS scenarios, and all the other C1 and C2 scenarios (grey solid lines).

Figure 18. Time series describing carbon sequestration, net CO_2 emissions for the AFOLU sector, agricultural demand and production, land uses and yields for our low (blue) and high (red) CCS scenarios, and all the other C1 and C2 scenarios (grey solid line).

Figure 19. Time series describing total installed capacity for our low (blue) and high (red) CCS scenarios, and all the other C1 and C2 scenarios (grey solid line).
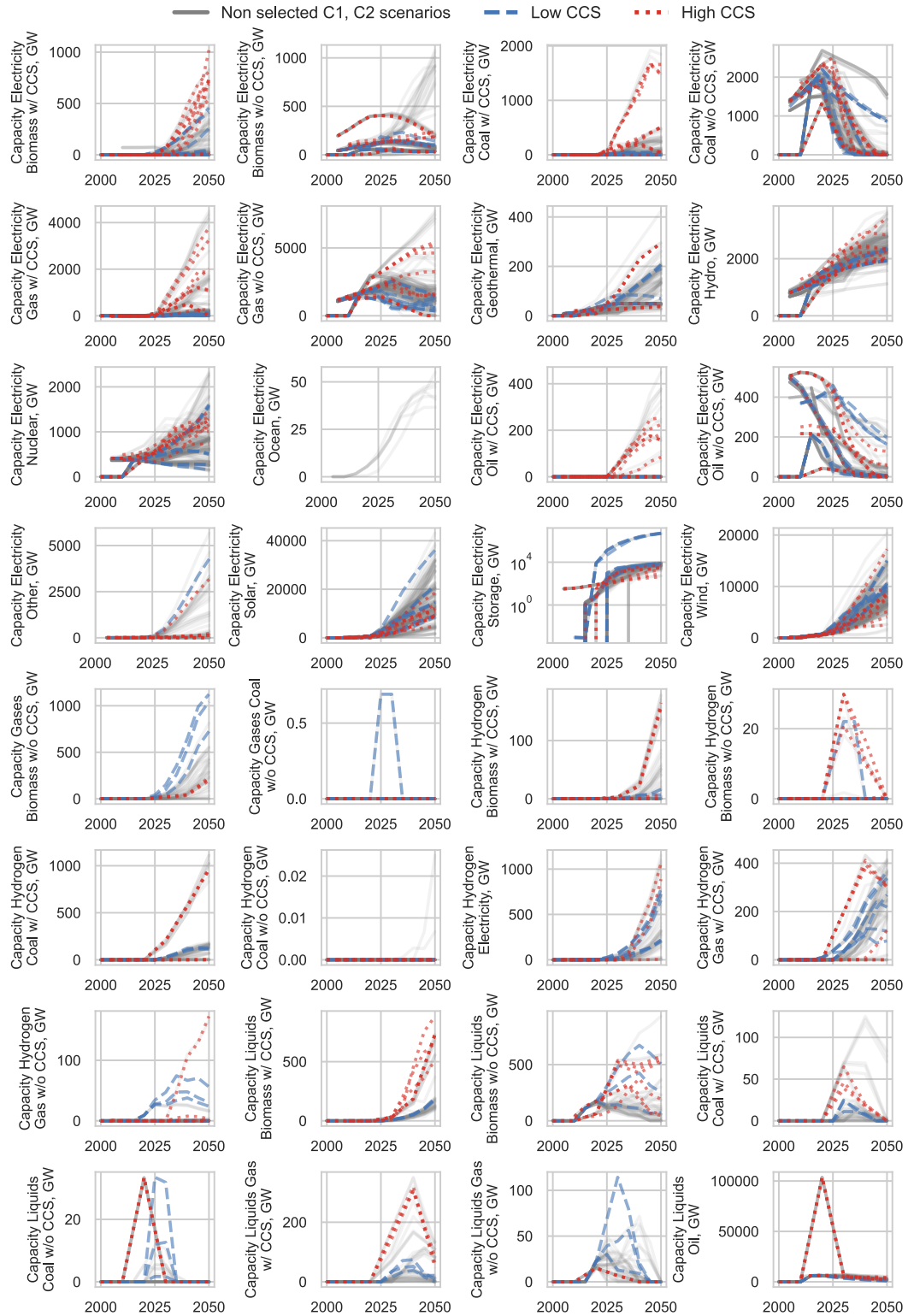
7. SELECTION OF VARIABLES FOR APPROXIMATE ENERGY SYSTEM REPRESENTATION

Table 8. AR6 database variables selected to approximately represent the energy system and carbon sequestration.

AR6 database variable name	Energy system components represented in energy system cost calculation
Non-CCS-related technologies	
Secondary Energy | Liquids | Oil	Final oil
Final Energy | Solids | Coal	Final coal
Final Energy | Gases	Final gas
Secondary Energy | Electricity | Coal | w/o CCS	Coal electricity (no CCS)
Secondary Energy | Electricity | Gas | w/o CCS	Gas electricity (no CCS)
Secondary Energy | Electricity | Nuclear	Nuclear electricity
Secondary Energy | Electricity | Hydro	Hydropower electricity
Secondary Energy | Electricity | Biomass | w/o CCS	Bioenergy electricity (no CCS)
Secondary Energy | Electricity | Wind	Wind electricity
Secondary Energy | Electricity | Solar | PV	Solar electricity
Secondary Energy | Hydrogen | Electricity	Hydrogen from electrolysers Electrolyser capacity
Final Energy | Solids | Biomass	Solid fuel from biomass
Secondary Energy | Liquids | Biomass | w/o CCS	Liquid fuel from biomass
Final Energy | Electricity	Electricity network investment
Investment | Energy Supply | Electricity | Electricity Storage	Electricity storage investment
CCS-related technologies	

Secondary Energy | Electricity | Coal | w/ CCS	Coal electricity with CCS
Secondary Energy | Electricity | Gas | w/ CCS	Gas electricity with CCS
Secondary Energy | Electricity | Biomass | w/ CCS	Bioenergy electricity with CCS
Secondary Energy | Liquids | Biomass | w/ CCS	Liquid fuel from biomass with CCS
Secondary Energy | Hydrogen | Biomass | w/ CCS	Hydrogen from biomass with CCS
Secondary Energy | Hydrogen | Gas | w/ CCS	Hydrogen from gas with CCS
Secondary Energy | Hydrogen | Coal | w/ CCS	Hydrogen from has with CCS
Carbon Sequestration | CCS | Industrial Processes	Industrial CCS investment
Carbon Sequestration | Direct Air Capture	DACCS investment

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