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Abstract

Novel carbon dioxide removal options and geological carbon storage will be necessary for achieving the Paris Agreement's long-term climate targets[1], but are characterized by low current deployment[2–4] and near-term upscaling challenges[5–7]. Here we use the REMIND Integrated Assessment Model with a wide representation of carbon removal technologies and informed by intertemporally consistent upscaling pathways for carbon storage to assess upscaling-constrained mitigation pathways limiting warming to 1.5°C. We find that, even under highly optimistic assumptions, geological carbon storage and novel carbon removal contribute only 32–51 $GtCO_2$ cumulatively by 2050 - approximately one year of current global CO_2 emissions - and reduce peak warming at most by about 0.025 °C. This limited effect arises because cumulative deployment remains small during the initial quasi-exponential scale-up phase. By contrast, cumulative contributions increase to 300–875 $GtCO_2$ by 2100, corresponding to 0.14–0.39 °C of post-peak temperature decline.
Rapid scale-up can still enable net-zero CO_2 emissions around mid-century, but cannot substitute for immediate and deep emissions reductions in limiting peak warming.

Introduction

Climate targets set out by the Paris Agreement, and national net-zero emission targets require strong emission reductions and at least some level of Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR)[8].
CDR serves three roles for climate change mitigation: Reducing net emissions faster, balancing residual emissions to reach net-zero (CO_2 or GHG), and enabling net-negative emissions, where more CO2 is removed from the atmosphere than emitted, which enables a drawdown of temperature back to 1.5°C

after a temporary temperature overshoot[9]. CDR methods fall into two categories: conventional, land-based CDR and novel CDR[4]. Land-based CDR includes forestry and land-management practices that store carbon in the biosphere. These methods are well established and at 2.2 GtCO2/yr currently deliver the bulk of global removals[10]. However, they are vulnerable to reversal and may store carbon only temporarily, which has led to debates around the equivalence of a ton emitted from fossil fuel combustion and a ton removed and stored in the biosphere[11–13]. Novel CDR (nCDR), on the other hand, comprises nascent technologies that have not yet been established at scale, but offer the potential for permanent CO2 removal. Some of the most important nCDR options are Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), Ocean Alkalinity Enhancement (OAE), biochar, and Enhanced Rock Weathering (ERW). Novel CDR currently delivers 2 MtCO2/yr, 0.1% of land-based CDR, primarily from biochar projects[10].
CCS can contribute to climate change mitigation by avoiding emissions from fossil fuels and industrial processes and is necessary for the nCDR technologies BECCS, DACCS and may be used to enhance the efficiency of OAE[14].
CCS has featured prominently in climate change mitigation scenarios for over 20 years[15]. A recent critical review on CCS[16] compiles benchmark values for 2030 and 2050 from multiple climate change mitigation scenarios and reports an average deployment of 1 GtCO2/yr by 2030 and 10 GtCO2/yr by 2050 to achieve net-zero emissions by mid-century. Critically, the prospect of future CCS and nCDR availability fueled political debates over whether fossil fuels should be phased out or whether abatement with CCS or compensation with nCDR could allow their continued use[17].
However, the current scale of CCS, at 9.7 MtCO2/yr of dedicated storage plus an additional 40 MtCO2/yr of injection capacity for enhanced oil recovery (EOR), is two orders of magnitude smaller than these benchmark values and three orders of magnitude smaller than global current CO2 emissions. Due to this discrepancy, the ability of CCS to reach climate-relevant scales has been questioned[2], with dramatic consequences for mitigation pathways:
Transformation pathways with limited CCS availability[7,18] reveal the need for deeper electrification, larger reliance on CCU, a faster fossil phase out[7,18–21] or the need for significant demand reduction, primarily in material demand, aviation and animal-based food[22].
It is therefore important to understand how quickly CCS and nCDR can realistically scale to climate-relevant levels, and to place this in context alongside conventional emission reductions in stringent climate change mitigation pathways.

Among all carbon management options, the diverse and complex value chains of CCS face particularly complex challenges: emitters are reluctant to invest in carbon capture due to a lack of political commitment and limited transport and storage availability, storage sites struggle to secure reliable CO2 suppliers in their vicinity, and large spatial uncertainty regarding the location of CO2 suppliers and storage sites deters investments in the required transport infrastructure[23]. On top of this coordination challenge, the lack of comprehensive and long-term climate policy support inhibits rapid deployment, as dedicated CO2 storage does not generate revenues on its own.
Beyond these challenges, lead times are another obstacle to rapid CCS deployment. They are especially long for geological CO2 storage (GCS) injection sites. It can take 6-13 years[24] from project announcement to operation, owing to time-consuming geological surveys for site selection, as well as licensing and permitting. GCS therefore presents a key bottleneck within the system-wide challenges of CCS upscaling that simultaneously constrains BECCS, DACCS and OAE.
Technology adoption typically follows an S-shaped curve, and such logistic growth models have successfully been used to describe upscaling processes in energy system transformations[25,26], CDR[27–31] and CCS[32,6,5].
Logistic growth curves are defined by three parameters: a starting value, a growth rate, and a market potential. While starting values can be informed by project announcements[3,5] and growth rates estimated from historical analogues[27], market potentials remain highly uncertain. Previously, they were estimated by comparison to historical oil and gas extraction[7,18], which underestimates the long-term potential for

countries with historically low oil and gas production. A prominent example is China's stated ambition to deploy CCS, despite historically low oil and gas production. Other studies use the total geological storage potential, the physical upper bound[6], to estimate the market saturation level, which overestimates the economic potential by assuming unlimited CO2 supply and willingness to pay for storage. Kazlou et al. 2024[5] instead estimate the CO2 available for capture from IPCC AR6 scenarios. However, near-term constraints on CCS availability may also reduce its long-term potential: early availability could sustain fossil fuel use through abatement and raise long term demand, whereas early scarcity would require reducing fossil fuels to meet the same climate target.

To address this gap, in this study we combine (i) realistic near-term upscaling of CCS with (ii) plausible long-term saturation. We introduce intertemporally consistent CCS deployment pathways into the integrated assessment model REMIND[33] and complement CCS with a broader portfolio of novel CDR options than considered in previous studies, including BECCS[34], DACCS, ERW[35], OAE[14,36] and biochar[37]. While previous studies focused on annual CCS capacities by mid-century, we extend the analysis to shed light on cumulative contributions and the impact of CCS and nCDR on peak temperatures and the potential to return from temperature overshoot. In this holistic approach, we include all Greenhouse Gases (GHG) to compare the contribution of CCS and nCDR to conventional emission reduction and contributions from the energy and land system transformation.

Results

Logistic growth model

The diffusion process of a novel technology that grows from a small niche market to widespread adoption can be described by an S-shaped logistic curve. Growth accelerates quasi-exponentially in the beginning, stabilises approximately linearly in the medium term, and eventually slows down when the technology approaches market saturation. The logistic growth curve is defined by three parameters: the initial capacity (here for the start year 2030), the logistic growth rate, and the market saturation (see Methods). To describe the future growth of GCS, we consistently vary assumptions on all three uncertain parameters.

We estimate the initial in 2030 capacity by assuming failure rates on current project announcements[38], following the approach of Kazlou et al. 2024[5], and estimate growth rates from historical analogues presented by Nemet et al.[27]. Because failure rates and growth rates both depend on policy and technology support, such as market incentives and infrastructure development, we vary the two assumptions jointly, creating three growth narratives: i) "slow GCS growth" with a continuation of current high failure and low growth rates, ii) "ambitious GCS growth" with reduced failure rates and median growth rates and iii) "emergency GCS deployment" with the lowest plausible failure rates and growth rates in the upper quartile of historical analogues. (See Table 1 for a summary of assumptions and detailed explanation on the rationales in Methods)

The market potential by region is uncertain and determined by economic and non-economic factors. Economic factors include climate policy stringency resulting in market incentives, and the cost-competitiveness of GCS with other abatement options. Non-economic factors include geophysical, environmental or social limitations such as uncertainties in total available storage space [39],[40], injection rate limits due to pressure build up in the reservoir[41,42], sustainability constraints[43] or limited societal acceptance[44]. Therefore, we analyse two different cases: an optimistic case, in which long-term deployment is not constrained and therefore only depends on economic competitiveness, and a cautious case, in which global deployment is capped at 5 GtCO2/yr (see Methods).

We derive regional market saturations for GCS in an intertemporally consistent way from REMIND scenarios. We first constrain near-term GCS deployment using the initial capacities and growth rates presented in Table 1, without imposing a pre-defined market saturation, in scenarios with ambitious climate change mitigation. The resulting endogenous, regional maximum GCS capacities are then used as market saturation in the logistic growth model. In the cautious case, an additional constraint limits global deployment to 5 GtCO2/yr. To ensure intertemporal consistency, logistic growth curves are then recalculated using near-term dynamics and REMIND derived market saturations. This iterative approach is illustrated in Supplementary Figure 1.

The market saturation is derived using optimistic assumptions regarding GCS deployment in mitigation pathways to enable an exploration of the upper limit of plausible GCS deployment. Other, less optimistic assumptions and their impacts on market saturation are detailed in Supplementary Table 1.

The combination of three growth narratives for regional starting values and global growth rates with two market saturation cases results in 6 GCS deployment pathways that we analyse in the next section. These logistic growth curves are then used to constrain GCS deployment in REMIND scenarios that we analyse in section "implications for mitigation pathways". For consistency, the REMIND scenarios have the same climate change mitigation ambition as those that were used to derive the market saturation.

	Slow growth	Ambitious growth	Emergency deployment
Initial capacity*	143 MtCO2/yr	220 MtCO2/yr	297 MtCO2/yr
Logistic growth rate	8.9%	15%	20%
Market saturation*	Optimistic: No exogenous constraints (~16 GtCO2/yr globally) Cautious: 5 GtCO2/yr max. globally		

*Table 1: Summary of logistic growth parameters based on variation in technology support (Slow growth, Ambitious growth and Emergency deployment) and market saturation (Optimistic, Cautious). Logistic growth rates are not regionally differentiated. A comparison of historical analogues is described in the methods. *Initial capacities and Market saturations are displayed as global aggregate values. Regional values are presented in Supplementary Table 1.*

Regionalised GCS deployment pathways

Stringent climate change mitigation ambition is reflected by a globally uniform carbon price, that increases exponentially to 500$/tCO2 in 2050 and remains constant thereafter. Therefore, emission reduction (before GCS) is almost identical across scenarios and we can explore the additional benefit from GCS availability separately.

Regionalised GCS deployment differs widely across the six pathways (Figure 1). Until 2050, annual global injection capacities remain scarce with values ranging from 0.7 GtCO2/yr for "slow growth" and between 3-5.8 GtCO2/yr for "emergency deployment". Delaying deployment by another 5 years would worsen this outlook: annual GCS capacity would remain limited to 0.4-3.4 $GtCO_2$/yr (Supplementary Figure 2). At the end of the century, we find that all scenarios apart from the "slow optimistic" reach their respective market saturation (i.e. around 16 GtCO2/yr for optimistic and 5 GtCO2/yr for cautious assumptions).

When comparing 2050 benchmark deployment presented in scenario ensembles published for the IPCC Sixth Assessment Report (AR6)[45] and the Scenario Compass Initiative (SCI)[46] we find that median values align with our most optimistic upscaling scenario: emergency deployment + optimistic market saturation. This shows that half of all submitted scenarios deploy GCS with a faster than plausible upscaling rate. Note that for comparability we chose to display 2045 values from the AR6 database as these scenarios assumed upscaling starting in 2025 rather than 2030 (median in 2050 from AR6 is 7.8 GtCO2/yr).

Comparing the regional distribution, early movers such as the USA, Europe (EUR + NEU), and Canada, Australia, New Zealand (CAZ) contribute significant shares in 2050. However, by 2100, the picture becomes more balanced and regions with little to no announcements to date gain significant shares as well, especially in Sub-Saharan Africa (SSA), India (IND) and the reforming economies (REF). A world map highlighting the individual REMIND regions is shown in the Methods and a detailed mapping of countries to REMIND regions in Supplementary Table 3. For a comprehensive understanding of upscaling dynamics, regionalisation matters: upscaling considering only globally aggregated parameters overestimates near-term deployment as it cannot capture regional bottlenecks (see Supplementary Note 1 and Supplementary Figure 3).

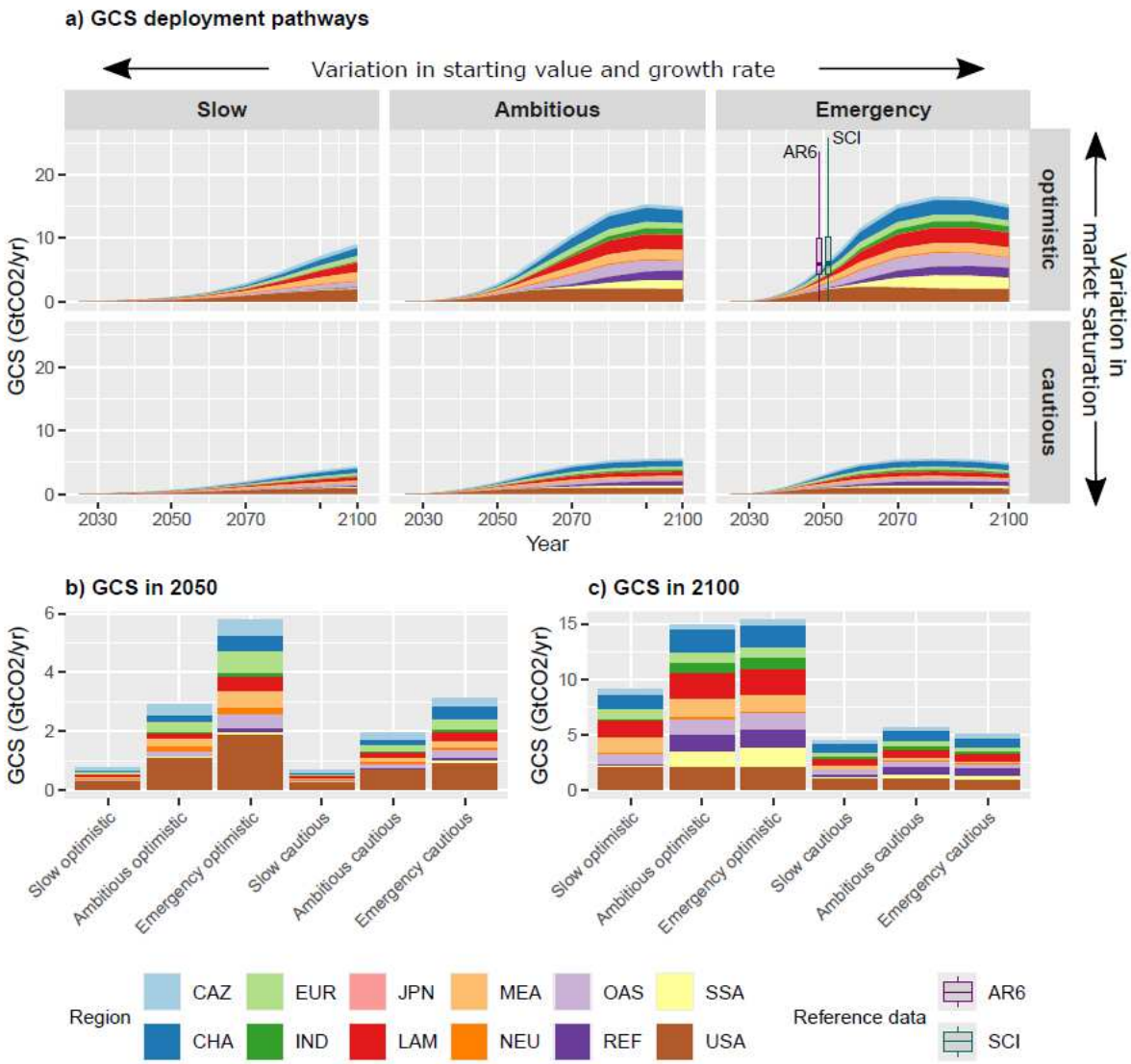

Figure 1: (a) Regionalised logistic upscaling projection across growth narratives (slow, ambitious and emergency) and assumptions on market saturation (optimistic and cautious) for REMIND 12 world regions. Growth narratives vary with respect to the regional starting value and globally uniform growth rate (see Table 1). In the optimistic case, the market saturation reaches 16 GtCO2/yr globally (in 2080) and slightly declines towards 2100, while it is limited to 5 GtCO2/yr in the cautious case. Annual GCS capacities in 2050 (b) and 2100 (c) per region are shown below. Note that while all regions deploy GCS up until the respective market saturation level, total GCS demand declines in some regions towards 2100 due to a reduction of economic competitiveness. For comparison, deployment ranges from published scenario datasets after 25 years of upscaling are shown in "Emergency optimistic" panel a (AR6[45] in 2045 and SCI[46] in 2050). Dot denotes median value, box 25th-75th quantile, whiskers max. and min values.

Implications for mitigation pathways

Due to regional scale-up constraints, GCS and nCDR only have a limited potential for emissions abatement until 2050, particularly in comparison with conventional emission reductions from energy and land-use system transformations (Figure 2). GCS and nCDR combined achieve a cumulative contribution until 2050 of 32 – 51 $GtCO_2$, avoiding or offsetting an amount comparable to only one year of current emissions (blue bar Figure 2c). In total, this translates to a temperature change of only 0.025°C, a negligible effect on peak temperatures, using a simplified relation between cumulative CO2 emissions and temperature change (see methods). In contrast, we quantify the effect of conventional emission reduction from energy and land system transformation with respect to a continuation of current policies (baseline emissions): We find that until 2050, conventional emission reduction could contribute 365 GtCO2 of avoided emissions compared to baseline, translating to 0.16°C lower temperatures.

Annual CO2 emissions are reduced from 40 GtCO2/yr to 5 GtCO2/yr, bringing net-zero CO2 emissions and therefore temperature stabilization within reach. This shows that both level and timing of peak temperature are primarily determined by emission reductions, with only marginal effects of GCS and nCDR.

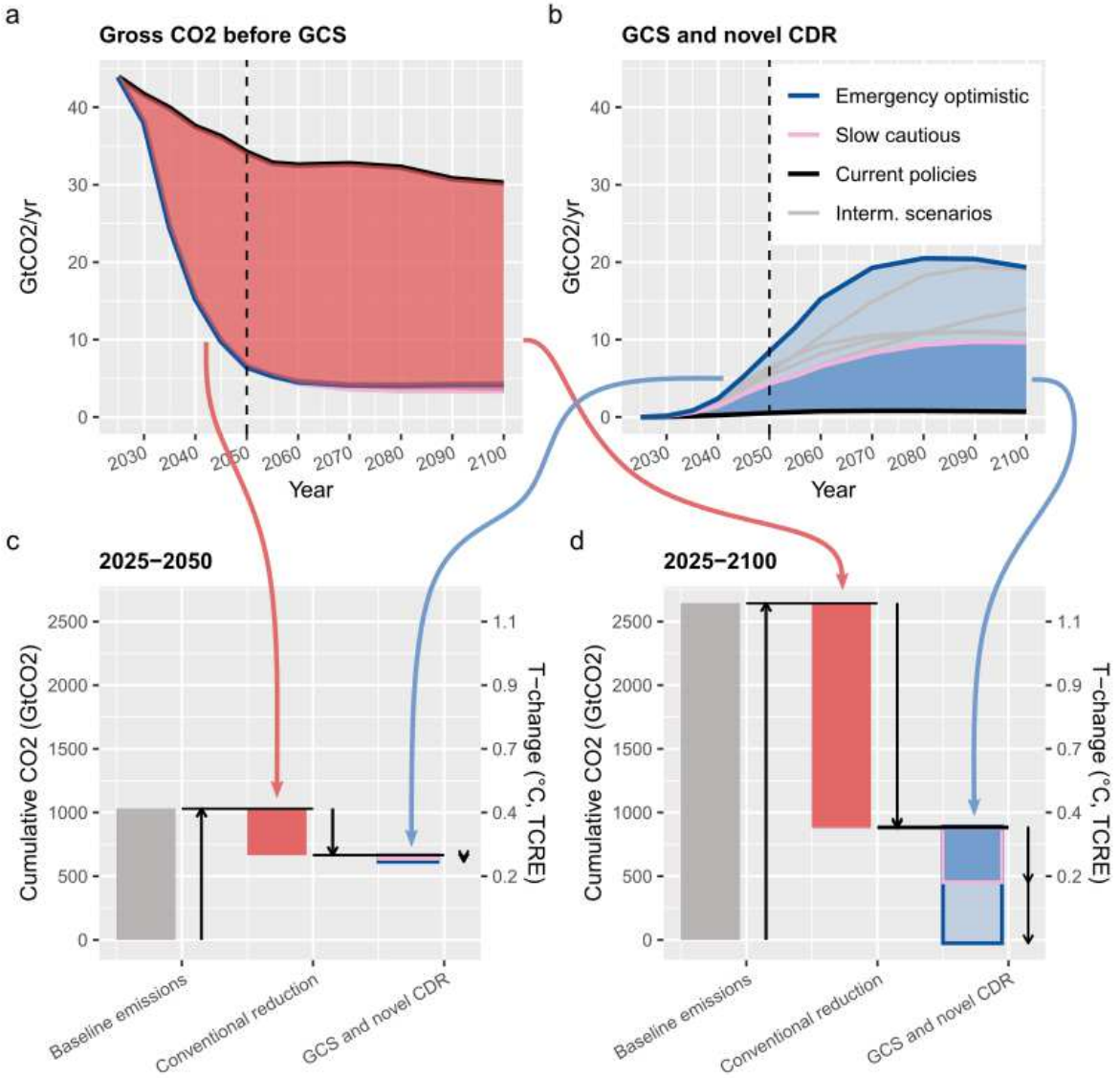

Figure 2: Comparison of emissions abatement from GCS and nCDR with conventional emission reductions from energy and land-use transformations. a) Gross CO2 emissions (before GCS and novel CDR). b) GCS and novel CDR deployment. Coloured areas indicate the difference between mitigation pathways and the baseline scenario. c) Cumulative contributions from conventional emission reductions and GCS and nCDR until 2050. d) Cumulative contributions from conventional emission reductions and GCS and nCDR until 2100. Panels c) and d) also indicate the corresponding avoided temperature increase, using a transient climate response to cumulative emissions of carbon dioxide (TCRE) of 0.45 °/ 1000 Gt CO2 (see methods).

Figure 2 panels a) and b) explain why the contribution to peak temperature remains limited: CO2 emission reductions from baseline emissions can make a major contribution towards emission neutrality, both on an annual level in 2050 as well as cumulatively (Fig. 2a). In comparison, the integral under the quasi-exponential growth in the early phase of scale-up (Fig. 2b) remains small, even under optimistic growth assumptions. Due to constraints on GCS, the nCDR options BECCS, DACCS, and OAE are directly limited in their upscaling dynamics, too, and compete for GCS with CO2 captured from fossil fuels and industrial processes.

This picture changes when looking at 2100: the contribution of GCS and nCDR grows to a total of 300-875 GtCO2 until 2100, corresponding to a contribution to a temperature drawdown after overshoot of 0.14° – 0.39° (Figure 2d). In comparison, the contribution of conventional emission reduction amounts to 1750 Gt until 2100, which avoids a temperature increase of 0.79°.

Notably, market saturation is less relevant for the contribution of GCS and nCDR until peak temperature than policy and technology support, reflected by initial capacities and growth rates. However, in the long-term, cumulative GCS contributions heavily depend on the market saturation, where the primary limitation may not be societal preferences and support, but arising geophysical, environmental, or technological limits. Still, ambitious technology support is essential even beyond mid-century: More ambitious upscaling could increase cumulative contributions until the end of the century from 190 Gt GCS under slow growth assumptions (corresponding to a continuation of current growth) to 530 Gt for ambitious or 715 Gt for emergency deployment in the optimistic case. In the cautious case, with limitations on annual global GCS capacities of 5 GtCO2/yr, cumulative contribution following slow growth remains at 117 Gt but could still almost double to 229 Gt for ambitious and reach 274 Gt for emergency upscaling.

In Figure 3a, we show the net CO2 emissions including energy- and land systems that become net-negative in all mitigation scenarios after 2050. In Figure 3b, we show the change in global mean surface temperature (with 67% confidence). Here all GHG emissions are included, allowing us to put the impact on global temperature change from GCS and nCDR into perspective with all mitigation options. Cumulatively, 73 GtCO2eq until 2050 and 378 GtCO2eq until 2100 are avoided or removed in comparison to the baseline scenario from the AFOLU sector in all climate change mitigation scenarios (see Supplementary Figure 4 for CH4 and N2O emissions).

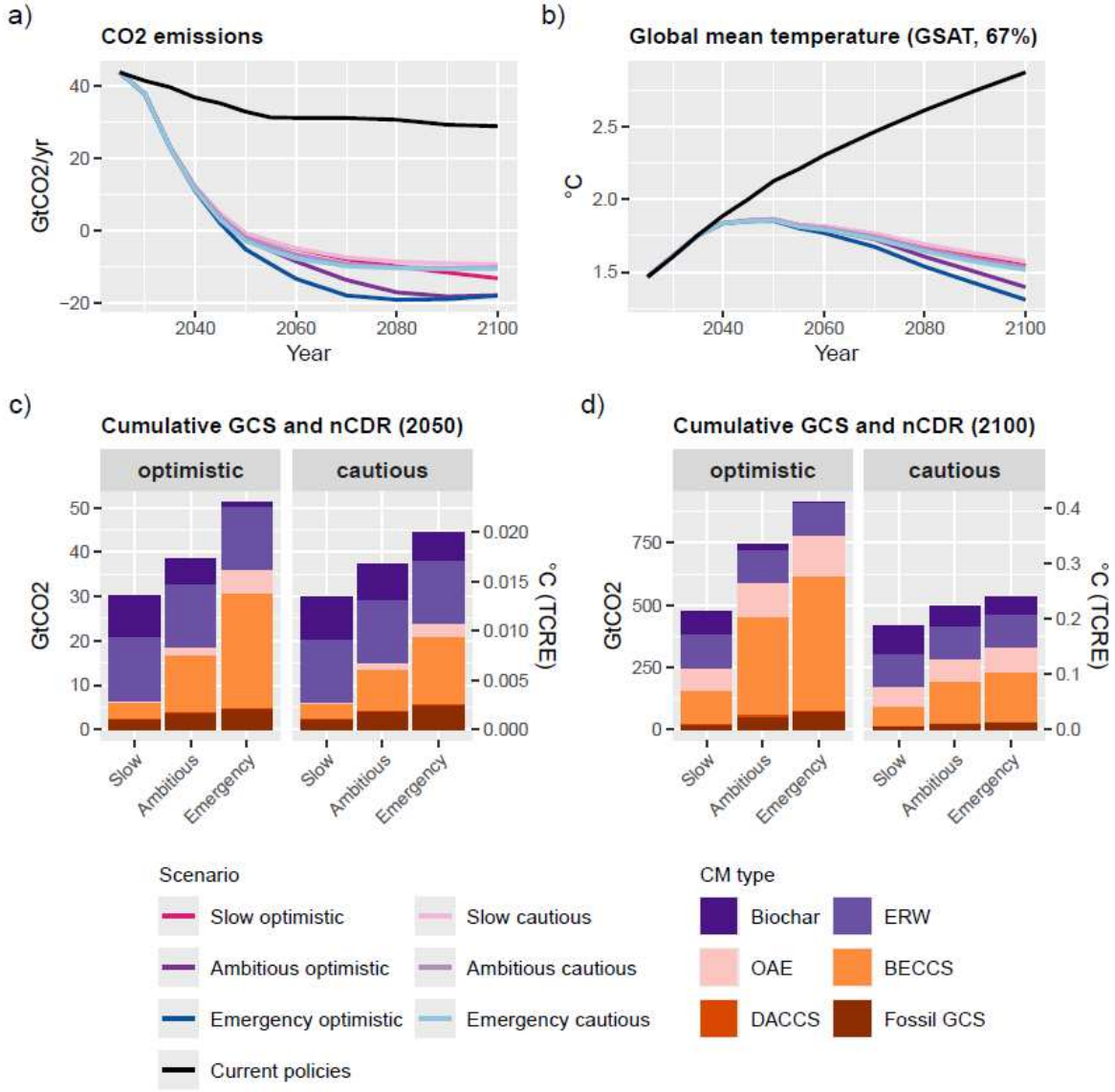

Figure 3: Net CO2 emissions (a) and global mean temperature 67% certainty (b) for baseline and climate change mitigation scenarios with varying constraints on GCS deployment. c) Cumulative emissions abatement of GCS and nCDR by technology until 2050. d) Cumulative emissions abatement of GCS and nCDR by technology until 2100. Orange colours denote options that rely on GCS, purple colours are independent of GCS infrastructure.

Differences in carbon management technologies across scenarios

Looking at the technology portfolio until 2050, GCS contributes 6-36 GtCO2 (including fossil GCS, BECCS, DACCS and OAE) and additional nCDR 24-17 GtCO2 together from ERW and biochar (Figure 3c). We find that GCS resources are primarily allocated for nCDR and only a small portion is reserved for CO2 of fossil origin.

Although the effect on cumulative abated emissions until mid-century is small across all scenarios, the dominant nCDR technologies differ widely. In the slow cautious scenario, ERW and biochar dominate, whereas in the emergency optimistic scenario, BECCS plays the largest role already by 2050, largely replacing biochar deployment (Figure 3c). The main reason is that biochar can utilise the CDR potential of bioenergy without relying on the GCS bottleneck. ERW contributes similarly across scenarios. GCS resources are primarily allocated for nCDR and only a small portion is reserved for CO2 of fossil origin. Until 2100, the potential cumulative contribution of GCS varies largely between 116 GtCO2 in the "Slow cautious" scenario to 715 GtCO2 in "Emergency optimistic" with BECCS contributing to the

majority of stored CO2. Additionally, nCDR without GCS varies between 202 GtCO2 in the "Emergency optimistic" to 306 GtCO2 in "Slow cautious". DACCS only plays a minor role across scenarios, due to a lack of economic competitiveness.

Discussion

We analyse intertemporally consistent GCS upscaling pathways based on logistic growth curves in the context of global efforts to limit warming to below 1.5°C and quantify the annual and cumulative contributions of GCS and nCDR in comparison to conventional emission reductions. We find that GCS and nCDR only have a marginal impact on peak temperature, even under optimistic upscaling assumptions, but are essential to return global temperatures towards 1.5°C during the second half of the century.

Cumulative contributions of GCS and nCDR combined result in 32-51 GtCO2 until 2050, which is comparable to one year of current emissions. In contrast, conventional emission reduction could avoid 365 GtCO2 emissions in the same period, around 7-10 times as much. Hence, the energy system's influence on peak temperature is primarily determined by the ambition level of conventional emission reduction, dominated by the fossil fuel phase down, as scaling up nascent GCS and nCDR technologies to climate relevant amounts will take decades. This gap reflects differences in technology maturity and current market deployment. Conventional emissions reduction relies substantially on electrification technologies that are already decades into their market diffusion such as solar PV, electric vehicles or heat pumps. In comparison, GCS and nCDR are nascent technologies and will take time to grow to climate-relevant scales.

While the cumulative effect until 2050 is limited, GCS and nCDR capacities around mid-century might still reach 5 GtCO2/yr, the median of global mitigation pathways after 25 years of upscaling, which is critical for many net-zero pledges. However, technology support has to start immediately. Even more so, GCS and nCDR combined can vastly contribute to return to 1.5C in the second half of the century, avoiding and removing up to 300-875 GtCO2 by 2100. Therefore, the timely development of GCS and nCDR enables future generations to choose between higher climate damages from sustained higher temperatures and the risks arising from large amounts of net-negative emissions and GCS deployment that are necessary to return from a temperature overshoot.

To the best of our knowledge, there is only one paper reporting a cumulative contribution of GCS until 2050 of 92 GtCO2/yr[47] and no assessment of cumulative CDR until peak temperature yet. In comparison to this, we find a cumulative contribution of 6-36 GtCO2 from GCS and additionally 24-17 GtCO2 from ERW and biochar. The annual capacities in 2050 from this work of 0.7 – 5.8 GtCO2/yr from GCS are significantly smaller than the average of 10 GtCO2/yr in 2050 reported by a recent critical review on CCS[16] and on the medium to lower end of studies that include near-term upscaling constraints[6] (1-16 GtCO2/yr). One reason is that in this work we include regionalised upscaling constraints and near-term consistent market saturation. Another important factor is the time-lag between studies: GCS deployment in studies usually assumes immediate and ambitious upscaling efforts. However, with every year of delay in real-world GCS deployment, benchmark values will also be achievable only when given the additional time for upscaling or would need to be compensated with implausibly fast upscaling. Therefore, we used 2045 GCS deployment from the mitigation pathways from the AR6 database as comparison, as these scenarios were produced 5-10 years ago and assumed strong climate change mitigation policies from 2020 onwards.

While median GCS deployment values of the AR6 database and the more recent Scenario Compass Initiative are comparable to our most optimistic upscaling scenarios, still half of all scenarios reported

in both databases exhibit faster than plausible GCS upscaling. This has to be addressed in future mitigation pathway modelling to and provide decision-makers with up-to-date information based on feasible pathways.

We find that GCS resources remain scarce and are primarily allocated to nCDR with only a small portion for fossil and industrial process emissions. In stark contrast, however, announced carbon capture projects are primarily planning to capture fossil CO2 with a total current announced capacity of 565 MtCO2/yr[3]. Only 48 MtCO2/yr[3] are from atmospheric or biogenic CO2 sources and another 39 MtCO2/yr[3] from the cement sector. There is a clear mismatch of what role GCS should play for stringent climate change mitigation and which emissions and sectors the infrastructure is currently built for.

This study has a strong energy system perspective, but land-system policies, which are outside the scope of this analysis, can have a significant influence on peak-temperature warming[22]. Land sector abatement options such as abatement of short-lived methane[48,49], nature conservation and conventional CDR on land[50] are shown to have large potentials to reduce peak warming[51,52].

Further investigation of the geospatial location of CO2-emitters and storage sites with a source-sink matching approach and the inclusion of geopolitical circumstances on international cooperation and shared infrastructure will enhance the understanding of regional GCS upscaling dynamics. In that context, future research needs to scrutinize national upscaling dynamics and help guide governments' expectations on GCS and CDR availability for national climate targets[53,54].

Scaling up the full CCS chain from the capture sites, transportation, and storage is a coordinative challenge, and achieving emergency deployment growth rates entails overcoming the bottlenecks on all three parts simultaneously. Recent literature[5,6] has criticised scenario studies from 5-10 years ago pointing out that GCS has not materialised as expected. But without sufficient climate policy support, growth will remain insufficient. Upscaling has to start now to enable sufficient availability in the second half of the century.

Methods

Logistic growth model

The logistic growth curve of the technology's capacity $y(t)$ is described by (eq. (1)). K denotes the market saturation, t_0 the starting year of the analysis (here $t=2030$), $y_0=y(t_0)$ the initial capacity and r the logistic growth rate.

$$. \; y(t) = \frac{K}{1+\left(\frac{K-y_0}{y_0}\right)e^{-r(t-t_0)}} \; (1)$$

Growth rates r

For the growth rate r we use a globally uniform assumption. In the "Slow growth" scenario we assume that growth will not be accelerated beyond current growth of 8.6%[5,32]. For the "Ambitious growth" and "Emergency deployment" scenarios we use the Median value (15%/yr growth rate) and the upper quartile (20%/yr growth rate) from a large dataset of historical analogues to CDR deployment, as reported in Nemet et al. 2023[27].

The "emergency deployment" growth rate of 20%/yr corresponds to historical growth observed for nuclear energy globally (logistic growth rate from a logistic fit of global deployment data[55]). There was strong policy support and coordination enabling a fast scale-up to its current somewhat stable market

saturation. For comparison, global renewable power generation grew with a growth rate of around 14%/yr, comparable to the assumption used for the "Ambitious growth" scenario of 15%/yr.

Cumulative capacities of global gas and coal power plants have historically grown with rates of 9% and 10% respectively, close to our "Slow growth" assumption.

Globally uniform growth rates are a simplification, but regional differentiation is difficult to predict. On the one hand, early movers in GCS deployment might provide stronger policy support that justify faster growth rates. On the other hand, late movers might benefit from the experience of early movers and pick up the pace with faster growth curves to catch up (leapfrogging). For the sake of transparency and simplicity, we refrain from a regional differentiation of growth curves in this work.

Starting value *y0*

For the initial capacity we adopt the approach from Kazlou et al. 2024[5] based on project announcements from the IEA CCUS Project Database 2024[38]. We consider projects of Project type "Full Chain", "T&S" and "Storage" that announce a start year up until 2030. Capacities from projects with the status "operational" and "under construction" are considered to be available by 2030. For projects with the status "planned" we apply failure rates depending on the growth narrative. For "Slow growth" we assume a continuation of current failure rates (88%) and for the most optimistic "Emergency deployment" narrative that failure rates are halved (44%), as previously been explored by ref[5]. Translated into storage capacities, this yields 143 MtCO2/yr for "Slow growth" and 296 MtCO2/yr for "Emergency deployment" in 2030. For the "Ambitious growth" narrative we choose the mid-value between the upper and lower bounds presented above. Please note that we include CO2 injection into the subsurface for EOR rather than only dedicated storage, which is an optimistic assumption. EOR and dedicated storage technologies are largely identical and learnings in one will also benefit the other. However, while dedicated storage's only value lies in climate protection, EOR generates revenues from oil extraction and with that undermines the purpose of stringent climate change mitigation.

The IEA CCUS project database has country-level resolution. From this we aggregate the country-level starting values to the 12 default world regions of REMIND (see Methods Fig. 4).

In the special cases of REF and IND, there are no project announcements so far. However, we assume that these regions catch up and GCS capacities may be available from 2035, which is optimistic, but not implausible. We vary the starting value in 2035 both, with respect to the regions' 2020 CO2 emissions and by growth narrative as follows:

- Slow growth: 0.05% of 2020 emissions
  - REF = 1.3 MtCO2/yr
  - IND = 1.5 MtCO2/yr
- Ambitious growth: 0.1% of 2020 emissions
  - REF = 2.7 MtCO2/yr
  - IND = 3 MtCO2/yr
- Emergency deployment: 0.2% of 2020 emissions
  - REF = 5.4 MtCO2/yr
  - IND = 5.9 MtCO2/yr

Market saturation

Long-term limitations:

In the optimistic case, we assume that the market saturation is given by the economic competitiveness of GCS, which also takes the economic competitiveness or various carbon capture technologies into

account. No other geophysical limits are considered. In particular, this optimistically assumes that geological constraints due to pressure build up in the reservoir are manageable and do not limit long-term GCS injection rates at the scales projected by IAMs. Smith et al. 2024 [4] suggest that under favourable well-positioning, limitations from pressure constraints could still sustain maximum injection rates as high as 121 GtCO2/yr after thirty years of continuous injection, which is much larger than the economic market shares resulting from REMIND scenarios.

In the cautious case, we assume that global GCS deployment will not exceed 5 GtCO2/yr to reflect concerns around feasibility, sustainability and public desirability. This reflects concerns around feasibility, sustainability and desirability, which are hard to quantify under current knowledge. A cap of 5 GtCO2/yr has previously been used by IAMs for a "sustainability limitation" for GCS deployment.

REMIND model

The model description is taken from (Strefler et al 2021)[56]. "We use the global multi-regional energy-economy-climate model REMIND[57] Version [3.5.0][58] for our analysis. REMIND is open source and available on GitHub at https://github.com/remindmodel/remind. The technical documentation of the equation structure can be found at [https://rse.pik-potsdam.de/doc/remind/3.5.0]. In REMIND, each single region is modelled as a hybrid energy-economy system and is able to interact with the other regions by means of trade. Tradable goods are the exhaustible primary energy carriers coal, oil, gas and uranium, a composite good, and emission permits. The economy sector is modelled by a Ramsey-type growth model which maximizes utility, a function of consumption. Labour, capital, and end-use energy generate the macroeconomic output, i.e. GDP. The produced GDP covers the costs of the energy system, the macroeconomic investments, the export of a composite good, and consumption. The energy sector is described with high technological detail. It uses exhaustible and renewable primary energy carriers and converts them to final energies as electricity, heat, and fuels. Various conversion technologies are available, including technologies with carbon capture and storage."

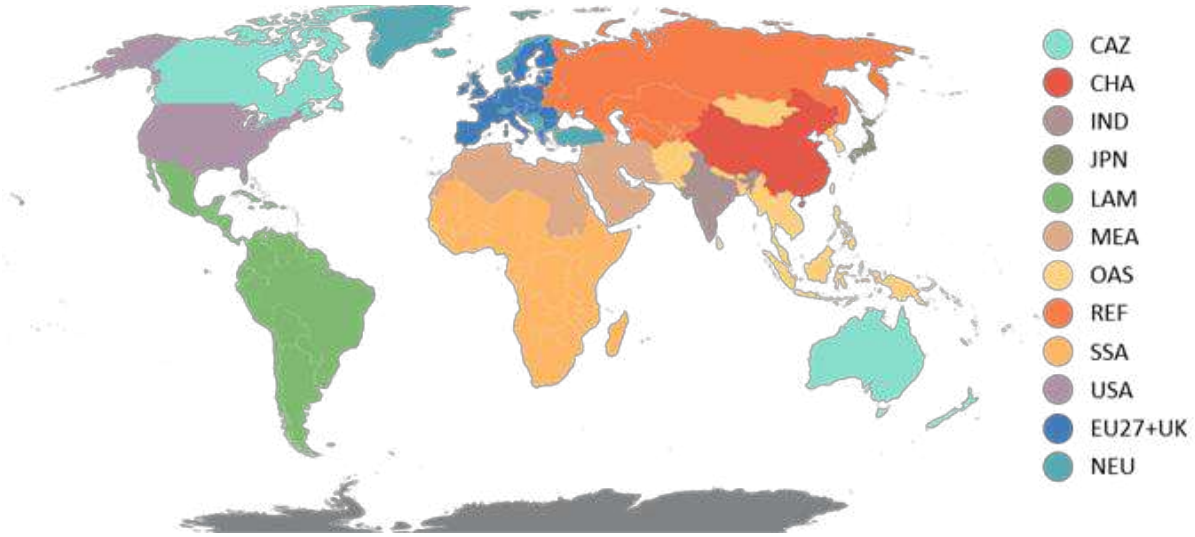

Figure 4: REMIND default 12 world regions. Note that within a region, REMIND assumes full cooperation regarding the CCS and nCDR value chains. However, REMIND does not feature inter-regional CO2 transport. That means, CO2 captured in one region cannot be stored in another region. A detailed list of countries per REMIND region can be found in Supplementary table 3.

Next to the nCDR technologies BECCS[34], DACCS and OAE[14,36], REMIND also has the option to deploy biochar[37] and EW[35]. While we do not perform separate upscaling modelling for these technologies, deployment in the model is constrained:

EW has a maximum growth limitation to 20% per year and application is limited to 15 kg/rock per m^2 on 50% of current agricultural land area.

Biochar does not have explicit upscaling constraints, but deployment in scenarios is limited by limited biomass availability and high competition with BECCS and bioenergy uses.

Temperature estimates

To estimate the temperature change for cumulative CO2 emissions, we use the mean value for the Transient Response to Cumulative CO2 emissions of 0.45°C per 1000 GtCO2 presented in MacDougall[59] (full range 0.22-0.68). The temperature response of the entire mitigation pathway including all GHG emissions (Fig. 3 b) is calculated using the simplified climate model MAGICCv7.5.3[60].

Limitations:

We acknowledge that we do not apply the same level of scrutiny in constraining the upscaling dynamics of biochar and EW, as it is outside the scope of this study. Including more details in upscaling constraints on biochar and EW will most likely reduce their overall contribution to peak warming and our results therefore only serve as an upper estimate on plausible contributions, especially given the current lack of global and regional CDR governance[61,62].

Data availability

The underlying data of the logistic growth modelling and the REMIND scenario analysis are available for reviewers on https://cloud.pik-potsdam.de/index.php/s/jYtdRT8EQqSXnRk (password: nCDR_GCS_Upscaling). Data will be uploaded and published on Zenodo upon acceptance.

Code availability

The REMIND code is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub https://github.com/remindmodel/remind. We use a model version REMINDv3.5.0, archived on Zenodo: https://doi.org/10.5281/zenodo.15147820 .The technical documentation of the equation structure can be found at [https://rse.pik-potsdam.de/doc/remind/3.5.0].

The logistic growth model as well as code for scenario analysis and plot functions are available for reviewers on https://cloud.pik-potsdam.de/index.php/s/jYtdRT8EQqSXnRk (password: nCDR_GCS_Upscaling). Code will be uploaded and published on Zenodo upon acceptance.

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Author contributions

A.M., I.d.J.A., T.D., C.C.G., G.L., E.K., A.O. and J.S, conceived the study. A.M., J.S., G.L., and E.K. conceived the experiments. A.M, T.D., C.C.G, F.L., G.L., D.K., E.K. and J.S. contributed to developing the energy-economy-climate model. A.M. performed the experiment. A.M., A.O. and J.S. performed data analysis and created the figures. A.M wrote the manuscript with input and feedback from all authors.

Competing interests

The authors declare no competing interests.

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