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LETTER

Ratcheting ambition to limit warming to 1.5 °C–trade-offs between emission reductions and carbon dioxide removal

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Abstract

Mitigation scenarios to limit global warming to 1.5 °C or less in 2100 often rely on large amounts of carbon dioxide removal (CDR), which carry significant potential social, environmental, political and economic risks. A precautionary approach to scenario creation is therefore indicated. This letter presents the results of such a precautionary modelling exercise in which the models C-ROADS and En-ROADS were used to generate a series of 1.5 °C mitigation scenarios that apply increasingly stringent constraints on the scale and type of CDR available. This allows us to explore the trade-offs between near-term stringency of emission reductions and assumptions about future availability of CDR. In particular, we find that regardless of CDR assumptions, near-term ambition increase ('ratcheting') is required for any 1.5 °C pathway, making this letter timely for the facilitative, or Talanoa, dialogue to be conducted by the UNFCCC in 2018. By highlighting the difference between net and gross reduction rates, often obscured in scenarios, we find that mid-term gross CO_2 emission reduction rates in scenarios with CDR constraints increase to levels without historical precedence. This in turn highlights, in addition to the need to substantially increase CO_2 reduction rates, the need to improve emission reductions for non-CO_2 greenhouse gases. Further, scenarios in which all or part of the CDR is implemented as non-permanent storage exhibit storage loss emissions, which partly offset CDR, highlighting the importance of differentiating between net and gross CDR in scenarios. We find in some scenarios storage loss trending to similar values as gross CDR, indicating that gross CDR would have to be maintained simply to offset the storage losses of CO_2 sequestered earlier, without any additional net climate benefit.

1. Introduction

The parties to the United Nations Framework on Climate Change (UNFCCC), by adopting the Paris Agreement, articulated their desire 'to limit the temperature increase to 1.5 °C above pre-industrial levels.' The Paris decision also acknowledged that the mitigation ambition in Nationally Determined Contributions (NDCs) were insufficient to meet this objective (paragraph 17, decision 1/CP.21) and established a 'ratcheting mechanism' to increase ambition over time (paras 20, 23, 24, 1/CP.21; Article 14 Paris Agreement [1]).

This study explores emissions pathways to limit warming to 1.5 °C above pre-industrial levels by 2100. These pathways are all 'ratcheting' pathways in that they take the emissions level implied by the NDCs as a starting point, but increase, or 'ratchet,' this ambition level to enable pathways leading to global temperatures in 2100 of no more than 1.5 °C above pre-industrial levels, regardless of whether there was an earlier temperature overshoot. The central question for this study is how

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the level of carbon dioxide removal (CDR) deployment impacts near-term emission reduction requirements for 1.5 °C-compliant pathways. The study aims to help decision makers and the public navigate trade-offs between the stringency of near-term emission reduction pathways and the scale of future deployment of CDR by making the associated modeling assumptions transparent. Since these trade-offs will inevitably necessitate political and ethical decisions, it is the role of scholarship to highlight, rather than decide, the various climate mitigation choices and their implications. In this context, we pay particular attention to the difference between net and gross CDR, with the former being relevant to climate response and the latter being the relevant metric for decision-making with regards to CDR deployment. We are also attentive to the differences between net and gross emission reduction rates, noting that gross reductions better describe the required scale of implementation of mitigation activities.

It is well-documented [2–6] that the majority of published 1.5 °C-compliant mitigation scenarios rely heavily on CDR—for example, the scenarios examined in [2] include cumulative removal between 450 $GtCO_2$ and 1000 $GtCO_2$ by 2100. A larger portfolio of CDR technologies has been proposed in the literature, including afforestation, bioenergy with carbon capture and storage (BECCS), biochar, soil carbon management, direct air capture (DAC) and enhanced weathering (EW) [5, 7, 8]. However, scenarios tend to emphasize BECCS [9], wherein carbon dioxide (CO_2) is removed from the atmosphere through photosynthesis of bioenergy crops, which are then burned in bioenergy power plants or converted to liquid fuels, methane, or hydrogen for the transport sector [10], with the CO_2 emissions partially captured for geological storage. In scenarios, most of these removals typically occur during the second half of the 21st century, with annual total sequestration reaching as high as 20 $GtCO_2\ yr^{-1}$ [2]. Within a given carbon budget, more CDR deployment leads to less stringent near-term mitigation pathways. However, there are concerns that BECCS, or other CDR approaches, will not be able to deliver sequestration at the scales assumed—for example if they are limited by technological feasibility, land availability and competition with food crops, or storage permanence [5, 11–20]. Thus, embarking now on pathways with these relatively lenient near-term emission reductions that are conditional on the assumption of large-scale future CDR deployment, could lead to an irreversible breach of the pursued carbon budget should this deployment prove unachievable. Some scholars advocate for a precautionary approach to CDR in mitigation scenario design: 'the mitigation agenda should proceed on the premise that [CDR] will not work at scale' [12], while others suggest a more moderately precautionary approach that only considers CDR approaches and deployment scales that are least vulnerable to the above-mentioned risks [17]. This letter focusses on the relationship between levels of CDR deployment on one hand and near-term stringency of emission reductions on the other.

2. Methods

We used two different system-dynamics models, C-ROADS (version 5.005) and En-ROADS (version 96) for this study. C-ROADS is a simple climate model, consisting of a system of differential equations representing the carbon cycle, budgets and stocks of greenhouse gases (GHGs), radiative forcing and the heat balance of the Earth, including the atmosphere, land and ocean. C-ROADS closely replicates GHG concentrations, global mean surface temperature, and other climate metrics from 1850, and future climate response projections of complex Earth systems models as reported in the IPCC Assessment Reports [21, 22] across a wide range of Representative Concentration Pathways.

C-ROADS separately represents emissions of each Kyoto Protocol GHGs (CO_2, methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), and multiple species of PFCs and HFCs), Montreal Protocol GHGs (multiple species of CFCs), and short-lived sources (aerosols and black carbon). The model explicitly tracks the fluxes and stocks of the long-lived, well-mixed Kyoto Protocol GHGs and their resulting radiative forcings. It takes the radiative forcings of Montreal Protocol GHGs, short-lived sources, and natural forcings (volcanic, solar, albedo, mineral dust) as exogenous time series. Importantly, C-ROADS does not make choices based on cost optimization (but instead on user judgement) and so we were able to explore scenarios outside the constraints of economic parameters, which is of particular usefulness for this study. Users specify future emissions of the different GHGs for each nation or region of the world. C-ROADS supports multiple levels of aggregation for the emissions pathways, including 3, 6, 15 or 20 countries/regions. C-ROADS enables users to develop any pathways for GHG emissions so as to be able to explore a wide range of scenarios. C-ROADS is designed to allow rapid scenario generation; model results are available within seconds, enabling rapid, real-time experimentation and policy analysis. Limitations of C-ROADS are discussed in supplementary text 7 available at stacks.iop.org/ERL/0/064028/mmedia, section 5.

In contrast, the En-ROADS model embeds the C-ROADS carbon cycle and climate system model in an explicit model of the energy system and economy. In En-ROADS, GHG emissions result from interactions among population and economic growth, stocks of and use of energy-producing and energy-consuming capital (disaggregated by energy source and end use), and energy prices and policies. The model disaggregates the production, conversion and use of coal, oil, natural gas, nuclear, biomass, and renewables, each with its own resource base, supply chain, processing and

conversion into end-use energy. Energy consumption for each end-use energy type is determined by fuel-specific stocks of energy-consuming capital. The model captures endogenous technical change (experience curves) that lower costs for each type of primary energy. Users set policies that condition the development of the energy system, including carbon prices, taxes and subsidies, fuel mix standards, energy efficiency programs, and others. Instead of assuming perfect foresight and global optimization, key decisions are modeled using well-tested decision rules consistent with the principles of behavioral economics [23–26]. Both C-ROADS and En-ROADS have been developed by Climate Interactive, MIT Sloan, and Ventana Systems and are freely available (supplementary texts 1, 7, 8).

We develop the scenarios here as follows. We first use C-ROADS to achieve the given climate response—warming of no more than 1.5 °C above preindustrial levels in 2100—by varying GHG emissions and levels of CDR. Next, En-ROADS policies and assumptions are chosen to closely replicate the global emissions trajectories obtained from the C-ROADS scenarios; this step provides insight into the energy and climate policies and economic assumptions needed to achieve each scenario's global GHG emissions pathways. Here we focus on the C-ROADS scenarios with only a brief summary of En-ROADS results.

2.1. Scenario descriptions

We develop a reference scenario and three main 1.5 °C scenarios using each model. Scenarios are designed to result in expected warming in 2100 at a maximum level of 1.5 °C above pre-industrial levels. The scenarios build from the emissions level implied by the unconditional NDCs, which we assume will be fully implemented. Further, we assume that the ratcheting mechanisms of the Paris Agreement will lead to further mitigation ('ratcheting success'), including shifting the target date of the current NDCs from 2030 to 2025, early move from a trajectory consistent with NDC implementation to a more ambitious trajectory, and increasing the rate of GHG emission reduction after implementation of the current NDCs. Finally, the scenario assumptions differ regarding constraints we place upon CDR: allCDR, has a full portfolio of CDR options (supplementary text 7, section 3.6; [8, 21–25, 27, 28]); limCDR ('limited' CDR), where CDR is limited to reforestation and afforestation, while other approaches are deferred until proven [17]; and noCDR, where no additional CDR (besides the afforestation pledged in China's NDC) develops, following the suggestion of [12]. Table 1 summarizes the main assumptions and constraints used in the scenarios.

The noCDR scenario is a useful boundary case to explore the level of near-term ambition necessary to ensure that the carbon budget is not breached, even if CDR is not forthcoming. Several recent studies suggested that climate change might have already turned some of the world's forests from sinks to sources [30, 31]. The noCDR case highlights the possibility that land-based CDR may be severely restricted due to biogeochemical, technical, economic, social or political constraints. However, generally some level of CDR is consistent with a world in which mitigation ambition is increased substantially, even without dedicated human intervention, e.g. through natural regeneration of forest ecosystems after halting deforestation [32]. Hence, the question arises how much CDR can be conservatively assumed to be implemented in a world serious about mitigation. For the limCDR scenario, we follow [17] who estimate a CDR potential that is screened for social, environmental and technical risks, and compatibility with the Sustainable Development Goals. Lastly, as an additional boundary case it is useful to consider near-term emission reduction in a scenario where CDR is widely deployed: The allCDR scenario features a comprehensive CDR portfolio, with the maximum scale of each CDR approach derived from the literature (supplementary text 7, section 3.6). Near-term emission reductions in this scenario can be understood as the minimum level of ambition required to limit warming to 1.5 °C, under very optimistic assumptions with regards to CDR. Note that because the potential and risks of CDR technologies are poorly known today, the allCDR scenario violates the precautionary principle as advocated by [12, 17].

2.2. General approach

Our general approach to scenario creation in C-ROADS begins with the NDCs communicated by parties as of March 2018 and the maximum CDR given the restrictions in each scenario described above. Each of these initial scenarios led to warming above 1.5 °C in 2100, indicating that the full implementation of the Paris commitments by all parties is not sufficient to limit warming to 1.5 °C. We then implemented an iterative process, applying increasingly stringent interpretations of 'ratchet success' (increasing the ambition of current NDCs and post-current-NDC reduction rates) until the combination of ratchet success and CDR constraint led to a 1.5 °C outcome (see table 1). Throughout this iterative process, the C-ROADS model is run in its 20-region setup (supplementary text 7, section 3.3.4) with NDC commitments and ratcheting applied regionally. The level of ratcheting success in these scenarios differs between the developed and developing countries. To reflect the different stages of economic development across regions, and consistent with the principle of 'common but differentiated responsibilities', assumed 'ratchet success' for developing nations involves earlier and deeper reductions beyond current NDCs compared to developing countries. In the context of equitable effort sharing, e.g. [33], developing countries would receive support to implement these reductions. Note, however, that a full treatment of equity is beyond the scope of the present study. Overall, our approach

Table 1. Mitigation scenario assumptions and constraints.

	allCDR	limCDR	noCDR
Prescribed climate response	No more than 1.5 °C warming above pre-industrial levels in 2100, based on default C-ROADS settings		
NDC and post-current-NDC ratcheting success	• Developed countries … achieve current NDCs in 2025 (for most this is 5 years earlier), USA achieves 150% of its 2025 NDC effort; after 2025, post-current-NDC reduction rate		
	• Developing countries … achieve current NDCs; then follow post-current-NDC reduction rate	follow trajectory toward target level and date in current NDCs until 2025; then, follow post-current-NDC reduction rate	
	• post-current-NDC gross GHG emission reduction rate: 4% reduction p.a. after 2025 for developed; 3.5% p.a. after 2030 for developing countries	• 5.5% reduction p.a. after 2025 for developed; 4.5% p.a. after 2025 for developing countries	• 9% reduction p.a. after 2025 for developed; 8.5% p.a. after 2025 for developing countries
CDR constraints	All CDR technologies deployed; deployment rate and scale are constrained to 50% of the maximum values found in the literature (see supplementary text 7, section 3.6)	CDR is limited to 21st century removal from afforestation and reforestation, activities are ramping up from 2018 to 2050 and are explicitly modelled based on the available land area and sequestration along the aging chain of forest (supplementary text 7); no other CDR types are deployed	Afforestation pledges in NDCs (i.e. China) are implemented; no further CDR
Non-CO_2 GHGs	NDC reduction rates, and post-current-NDC reduction rates, applied to all GHGs (in CO_2eq), with CO_2eq ratio of gases as in reference scenario, no reduction below minimum (floor) emissions levels of non-CO_2 GHGs consistent with SSP1–2.6 marker scenario (see supplementary text 2)		
Other forcings	Follow SSP2–2.6 marker scenario time series (exogenous data) for radiative forcings other than those of the well-mixed GHGs (see supplementary text 3 for discussion)		
GDP and population	Population follows UN projections, medium variant (exogenous data) [29]; GDP is modelled using UN population data and own GDP/capita projections, where near-term projections follow a curve fitted to historical data by region, with convergence of all regions to 1% annual growth (see supplementary text 7, section 3.3). No feedback effects between climate response, population and GDP are modelled (e.g. effects on population and/or GDP from adverse climate impacts).		

allows us to explore the minimum required near-term and long-term ambition levels needed to keep 1.5 °C within reach, given different potentials and constraints on CDR.

2.3. CDR storage loss

In scenarios that deploy large amounts of CDR, storage loss is an important modelling consideration, since sequestration into non-permanent storage merely delays, rather than avoids, climate change [34, 35]. We follow IPCC AR5 findings (table 6.15 of [35]) in assuming permanence (i.e. no storage loss) for DAC, EW and BECCS. For the other CDR approaches a fraction of the storage pool that is accumulated is later released back to the atmosphere. For biochar, we model 0.2% annual loss, based on a 80% long-term permanence assumption [36]. For soil carbon management the annual rate is 1%, for afforestation 2%; these figures follow modelling findings from [37]. Since the uncertainty of these default values is high, a sensitivity analysis was conducted (supplementary text 4). Reducing modelled storage loss rates to half of default values resulted in 0.04 °C and 0.03 °C less warming in 2100 in limCDR and allCDR, respectively, while doubling them added 0.05 °C to limCDR, and 0.04 °C to allCDR.

3. Results

3.1. Ratchet success and CDR

If NDCs are implemented as communicated, total greenhouse gas emissions in 2030 are estimated to reach 56 $GtCO_2$eq [38]. To align with any of our 1.5 °C-compatible scenarios, near-term greenhouse gas reductions that are additional to current NDCs are required. Relative to the level of mitigation implied by the NDCs, the allCDR, limCDR and noCDR scenarios require 9.8, 17.1, and 24.0 $GtCO_2$eq of additional GHG reductions in 2030, respectively. In allCDR, near-term ratcheting requires early or strengthened implementation of the NDCs for all developed countries, while no ratcheting of current NDCs is required for developing countries. After 2025 and 2030, developed and developing countries reduce gross emissions at a rate of 4% and 3.5% per year, respectively. The allCDR scenario uses the least ambitious near-term ratchet success, but is only 1.5 °C-consistent, if high levels of CDR deployment are achieved. The cumulative 21st century gross CDR in this scenario is 1046 $GtCO_2$, matching the high end of the range of the 1.5 °C scenarios analyzed in [2]. CDR in this scenario utilizes a full portfolio of approaches (figure 1, panel (*d*)); the deployment scale of each approach is constrained to

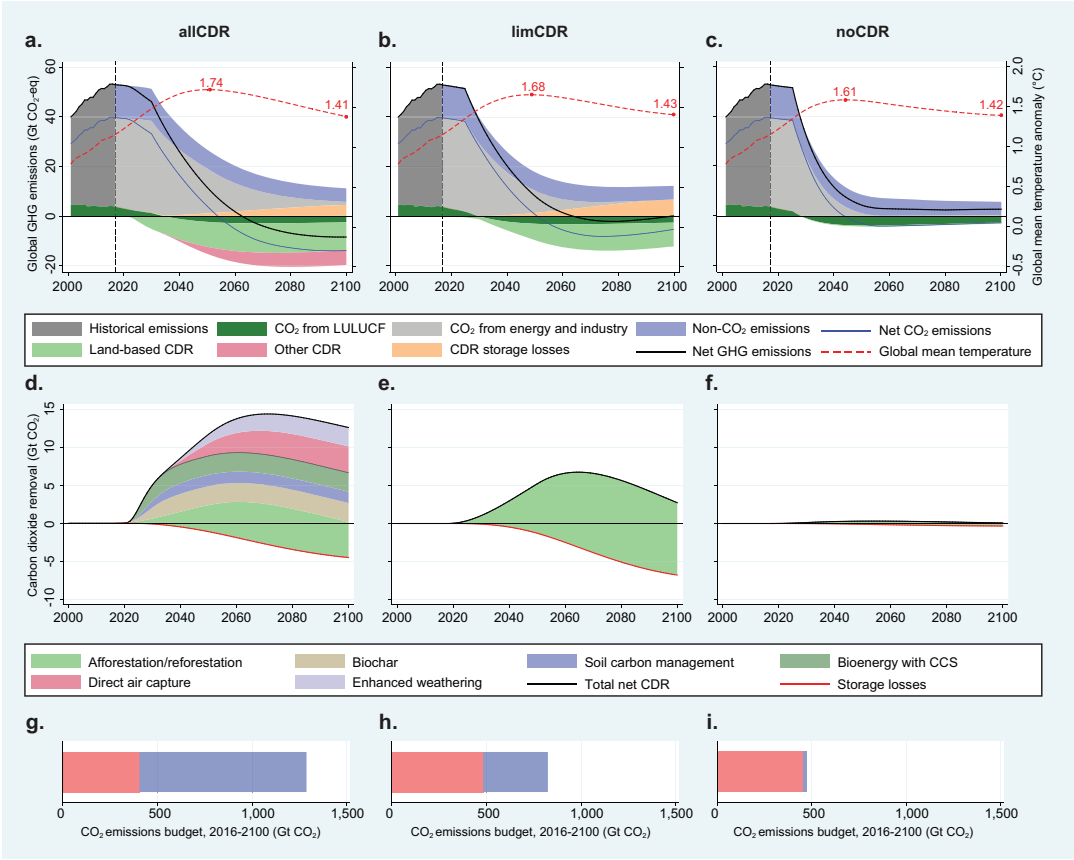


Figure 1. Greenhouse gas emissions and removals, temperature response, CO_2 emissions budgets. Panels (*a*)–(*c*) show global greenhouse gas emissions and CDR for the 21st century as well as the warming response. 'Land-based CDR' includes BECCS, biochar, soil carbon management and afforestation/reforestation; 'other CDR' includes DAC and enhanced weathering; (*d*)–(*f*) show storage loss (red line), annual gross sequestration of CDR approaches (stacked coloured areas) and resultant total net CDR (black line); (*g*)–(*i*) show the total gross CO_2 emissions budget available in each scenario between 2016 and 2100; including the additional emissions budget enabled through CDR (purple area).

half of the maximum potential in the literature (supplementary text 7, section 3.6; [5, 7, 8, 27, 28, 39–57]) to reflect uncertainties and social, environmental, technical, cost, and political risks associated with large scale deployment. However, if near-term ratcheting success only satisfied the minimum interpretation applied here, these risks and barriers would have to be overcome to implement CDR at this large scale to keep 1.5 °C within reach.

In the limCDR scenario, CDR approaches that have not yet been demonstrated as feasible at scale are deferred until greater certainty has been established, thus, only afforestation and reforestation are included, resulting in significantly reduced sequestration. In the limCDR scenario, cumulative gross CDR is only 573 $GtCO_2$ (342 $GtCO_2$ net), about half of the allCDR scenario. This amount is well in the range of other studies that take a more precautionary approach to CDR [17] and is close to the total amount of removals from reforestation (400 $GtCO_2$ net) in another recent study [58], where the combination of different stringent mitigation strategies, including life-style changes, freed up agricultural land for reforestation and eliminated the need for other CDR approaches. The limCDR scenario's CDR constraint necessitates deeper near-term emission reductions to meet the 1.5 °C objective. Specifically, in addition to the early implementation of developed country NDCs as above, developing countries depart in 2025 from a trajectory toward their current NDCs. After 2025, annual gross GHG reduction rates are increased to 5.5% and 5% p.a. for developed and developing countries, respectively.

Finally, in the noCDR scenario, all future CDR is disallowed (except China's existing NDC afforestation pledge). As a result, further strengthening of near-term emission reductions is required. The trajectory to 2025 remains identical to limCDR, but after 2025 steeper gross emission reductions are required compared to limCDR—at 9% and 8.5% p.a.

3.2. Temperature overshoot and peak

All three scenarios exhibit temperature overshoot, where warming temporarily exceeds 1.5 °C and subsequently returns to lower levels. Table 1 shows the peak temperature as well as the timing and length of a temperature overshoot. Overshoot lasts 21, 38, and 45 years for noCDR, limCDR, and allCDR respectively, suggesting that scenarios that rely more heavily on CDR to meet their temperature objective have higher peaks and longer overshoot periods. Since overshoot scenarios

involve insufficiently well understood risks (for example with regards to the reversibility of impacts [59]), variants of the noCDR and limCDR scenarios have been created that achieve the 1.5 °C warming limit without overshoot. Unsurprisingly, these scenarios would require deeper and earlier emission reductions and, in the case of limCDR, earlier and faster ramp up of reforestation and afforestation efforts. Detailed results are included as supplementary text 5.

3.3. CDR storage loss

CDR storage losses cause annual net sequestration to fall after 2060 in both allCDR and limCDR scenarios. This is a result of non-permanent storage being in the allCDR portfolio and the only option in limCDR. While in both cases the net annual sequestration remains positive throughout the century, over time sequestration and re-emission in the limCDR scenario will reach parity, after which stage gross sequestration has to be maintained simply to offset the re-emission of CO_2 sequestered earlier, without any additional net climate benefit. Explicitly considering storage loss in any mitigation scenario that relies heavily on CDR is important since reporting only net values, the approach chosen by most studies, obscures the scale of CDR deployment required for the scenario, and thus the magnitude of the associated social, economic, political, and environmental consequences. While net values are important to assess the response of the climate system, gross sequestration reflects the amount of CDR that needs to be implemented to achieve these net values.

3.4. Net vs gross reduction rates; non-CO_2 GHGs and energy efficiency

It is instructive to compare net and gross reduction rates for CO_2 emissions. While the annual reduction rates of our ratcheting success definitions apply to all gross GHG emissions, net GHG reduction rates are also highly sensitive to the relevant CDR constraints of a scenario. Table 2, rows 7–8, allows a comparison of net and gross rates by showing average annual reductions for GHG emissions per decade between 2020 and 2050. The net values reflect total GHG emissions and removals, including land use, forestry and CDR; while the gross values do not take land use, land use change and forestry (LULUCF), or CDR removals into account. Gross values are always lower, and in the case of the allCDR scenario, substantially lower than the net values. The disaggregation allows us to present the ramp up of sequestration separately from gross emission reductions. Merely reporting net emission reductions, on the other hand, would obscure the level of emission reduction effort needed to address gross emissions, even though gross emission reduction rates are the more relevant quantity for economies and societies to plan their emission reductions.

Likewise, disaggregation of overall GHG emission reductions into different gases is useful. In the scenarios with CDR constraints (no CDR and limCDR), ratcheting success in the immediate near-term (before 2030) leads to higher non-CO_2 reduction rates than in allCDR (table 2, row 9). For each of the non-CO_2 GHGs, a minimum emissions level is generally assumed to be unavoidable. For example, the 2.6 W m^{-2} scenarios in the SSP database [60–65], assume a minimum of 4–8 $GtCO_2eq\,yr^{-1}$ in residual non-CO_2 emissions, while this figure remains similar at 2.5–7 $GtCO_2eq\,yr^{-1}$ in the recently quantified 1.9 W m^{-2} SSP scenarios, chiefly for agriculture [6]. Steep early reduction results in emission levels to reach these floor levels quickly (table 2, rows 2–3), limiting any further reduction potential for these gases. To nonetheless achieve a given GHG reduction, CO_2 reductions increase (see supplementary text 2). This leads to improvement rates of CO_2 intensity of GDP that are historically unprecedented. Based on the historical emissions and GDP data in C-ROADS [66–70], global decadal averages for carbon intensity improvements have historically never exceeded 2.7% (a value reached only in the context of the Great Depression in the 1930s), but have consistently been between 1.5% and 2% since the mid-1970s. In contrast, the modelled scenarios typically require rates well in excess of 5%.

3.5. Carbon budgets

Figure 1, panels g–i show the CO_2 emissions budgets for each scenario. These budgets take their scenario's non-CO_2 emissions into account and therefore represent the amount of CO_2 that can be emitted during the 2016–2100 period in addition to the non-CO_2 GHGs of the scenario while satisfying the 1.5 °C objective. These budgets consist of an 'inherent' component, available regardless of CDR, and an additional component that reflects CO_2 emissions that are re-sequestered through CDR activities. Unsurprisingly, the total emissions budget for the allCDR scenario is 2.5 times larger than that of the noCDR scenario, due to the large amount of CDR deployed. The difference in the net CO_2 budgets (CO_2 that can be emitted without having to be removed by CDR) across the scenarios is due to different stringencies of reductions of non-CO_2 GHGs. More stringent non-CO_2 reductions result in less warming impact of non-CO_2 GHGs, enabling higher cumulative CO_2 emissions under the same temperature objective. The 404–483 $GtCO_2$ range is broadly in line with other studies: For the same period, the IPCC's AR5 reported (adjusted for 2011–2015 emissions of 186 $GtCO_2$ [67]) budgets of 364 and 214 $GtCO_2$ for 50% and 66% probability of 1.5 °C. A recent SSP-based study reports a −175 to 475 $GtCO_2$ range for 1.5 °C-compliant scenarios [6], while an earlier study, again adjusted for 2011–2015 emissions, reported 14–229 $GtCO_2$ [2]. Another recent study suggests that budgets may be substantially larger, at 730–880 $GtCO_2$ [71]. However, results are not directly comparable due to several profound methodological differences ([72, 73], supplement of [6]).

Table 2. Key scenario results, emissions and climate response from the C-ROADS model.

			allCDR	limCDR	noCDR
1	Year net CO_2 emissions become zero		2054	2052	2044
2	Year CH_4 emissions reach emissions floor [floor level in $MtCO_2eq\,yr^{-1}$]		2055 [5177.9]	2041 [6117.2]	2030 [7286.7]
3	Year N_2O emissions reach emissions floor [floor level in $MtCO_2eq\,yr^{-1}$]		2045 [2044.4]	2033 [2197.1]	2029 [2276.8]
4	Carbon budget, total cumulative *net* CO_2 emissions [cumulative gross CO_2 emissions; cumulative net CDR], in $GtCO_2$, by period	2016–2050	893 [1092; 199]	797 [865; 68]	628 [633; 6]
		2051–2100	−489 [195; 684]	−314 [−40; 274]	−170 [−159; 11]
		2016–2100	404 [1287; 883]	483 [825; 342]	457 [474; 17]
5	Net CO_2 [net Kyoto GHG] emissions in $GtCO_2\,yr^{-1}$ [$GtCO_2eq\,yr^{-1}$], in year	2020	39.4 [52.7]	39.2 [52.4]	39.2 [52.4]
		2025	37.0 [50.2]	38.3 [51.4]	38.6 [51.8]
		2030	33.2 [46.1]	28.3 [38.9]	22.2 [32.0]
		2050	4.1 [11.6]	0.9 [8.4]	−3.0 [4.4]
		2100	−13.9 [−8.4]	−5.3 [0.2]	−2.6 [2.8]
6	Average annual reduction for annual gross CO_2 emissions by decade, in $MtCO_2\,yr^{-1}\,yr^{-1}$ [as percentage of period begin][a]	2020–2030	−66 [−0.2%]	690 [1.9%]	1296 [3.6%]
		2030–2040	1063 [2.9%]	1201 [4.1%]	1648 [7.1%]
		2040–2050	822 [3.1%]	811 [4.7%]	567 [8.4%]
7	Average annual reduction for annual gross GHG emissions by decade, in $MtCO_2eq\,yr^{-1}\,yr^{-1}$ [as percentage of period begin][a]	2020–2030	−26 [−0.1%]	953 [1.9%]	1639 [3.3%]
		2030–2040	1408 [2.8%]	1421 [3.6%]	1795 [5.4%]
		2040–2050	1011 [2.8%]	908 [3.5%]	662 [4.4%]
8	Average annual reduction for annual net GHG emissions by decade, in $MtCO_2eq\,yr^{-1}\,yr^{-1}$ [as percentage of period begin][b]	2020–2030	655 [1.2%]	1352 [2.6%]	2040 [3.9%]
		2030–2040	2008 [4.4%]	1833 [4.7%]	2047 [6.4%]
		2040–2050	1442 [5.5%]	1221 [5.9%]	718 [6.2%]
9	Average annual reduction rate for non-CO_2 GHG emissions, by decade	2020–2030	0.3%	2.0%	2.7%
		2030–2040	2.8%	2.5%	1.8%
		2040–2050	2.3%	1.3%	1.2%
10	Average annual improvement rate for CO_2 intensity of GDP in gross CO_2/2010$, by decade	2020–2030	3.2%	5.2%	7.1%
		2030–2040	5.7%	7.7%	13.9%
		2040–2050	5.8%	8.2%	__[b]
11	Average annual increase for annual gross CDR, in $MtCO_2\,yr^{-1}\,yr^{-1}$, by decade	2020–2030	514	110	13
		2030–2040	392	233	17
		2040–2050	375	307	11
12	Gross annual CDR in $GtCO_2\,yr^{-1}$, in year	2020	0.0	0.0	0.0
		2025	2.0	0.4	0.1
		2030	5.2	1.1	0.1
		2050	12.8	6.5	0.4
		2100	17.2	9.5	0.4
13	Peak warming [peak year]		1.74 °C [2051]	1.68 °C [2049]	1.61 °C [2044]
14	Overshoot period		2033–2081	2033–2075	2034–2061
15	Warming in 2100		1.41 °C	1.43 °C	1.42 °C
16	Sea level rise in 2100 (relative to 2000) in mm		886	869	849

[a] The figure in brackets is calculated by dividing the first figure by the level of emissions at the beginning of the decade in question, to allow for inter-decadal comparison, e.g. for the 2020–2030 decade: $\left(\left(E_{2030}-E_{2020}\right)/10\right)/E_{2020}$. Negative values indicate emissions growth.

[b] Gross CO_2 emissions reach zero in this scenario during this decade, making the average annual reduction rate (of an exponential decline function) an inappropriate value to report.

4. Discussion

Our analysis shows how 1.5 °C-compliant pathways can be constructed using varying levels of CDR constraints and correspondingly stringent 'ratcheting success' emission reduction pathways. Ratcheting up existing NDCs prior to their target date and further strengthening ambition in the coming rounds of NDCs emerges as an essential condition for 1.5 °C pathways. Even when assuming large scale CDR deployment, it was not possible to model a pathway where the emissions up to 2030 follow current NDCs without ratcheting. This is consistent with findings elsewhere [33, 74–76]. The minimum definition of ratcheting success, where developed countries meet their NDC commitments on an accelerated timeline, and all countries apply stringent reductions afterwards, features annual reduction rates of gross emissions that are broadly consistent with isolated historical experiences of emission reductions [77–80], but, contrary to historical precedence, these rates would have to be sustained and would also require unprecedented deployment of a full CDR portfolio at high levels. These approaches are currently unproven at scale and have considerable potential risks, as they may, for example compete for land, energy, water and financial resources.

As CDR technologies are increasingly ruled out in the limCDR and noCDR scenarios, in accordance with a precautionary approach, annual CO_2 reduction and decarbonization rates reach magnitudes well outside historical precedence and well outside what is typically envisioned in emission reduction scenarios that do not constrain CDR in such a manner [2, 81]. This points to the main trade-off between the scale of CDR on one hand and stringency of GHG reductions on the other: where societies choose to proceed with cautious assumptions about the scale and availability of CDR, they will have to pursue rates of GHG reductions well outside of what is currently deemed achievable, based on historical experience and standard modelling. On the other hand, embarking on particular decarbonization pathways on optimistic assumptions about CDR deployment would result in exceeding the limits of the carbon budget if the assumed CDR fails to materialize.

As mentioned above, as part of this study we modelled the same scenarios with the En-ROADS model to explore their energy and climate policy implications. A detailed discussion of the En-ROADS modelling results is beyond the scope of the present letter, but summary charts and an overview of the modeling assumptions and results are included in supplementary text 6. In summary, it proved impossible to model the noCDR scenario, without changing assumptions about population growth or GDP projections. This is broadly in line with a recent IAM study [58], which examines how alternative mitigation options to those of 'default' 1.5 °C mitigation strategies can lower the need for CDR, and which finds that BECCS can only be eliminated if all of their identified options (which includes a low population growth assumption) are pursued. In En-ROADS, most of the climate and energy policy settings are identical for limCDR and allCDR, despite the latter generally requiring less stringent mitigation. The main differences between both scenarios are annual energy efficiency improvements (2–3 percentage point higher), and limCDR requiring a policy which rapidly ramps up over the next 10 years to require all newly-built stationary energy use (commercial and residential building, and industry) to be electric by 2028, in addition to transportation where both scenarios require all new end use being electric by 2028. In the En-ROADS implementations of the scenarios we find that the energy intensity of the economy initially declines rapidly but then plateaus at the assumed lower limit of energy intensity, before increasing slightly in the last quarter of the century. The increase arises primarily from rebound effects due to low energy prices resulting from scale economies and learning by doing for low-carbon energy technologies. Consequently, total energy demand increases markedly during the same period as GDP continues to grow and energy intensity slightly rebounds. In both limCDR and allCDR, modern non-biomass renewables provide the largest share of energy starting from the mid-2030s and 2040s, respectively. In addition, once explicit subsidies for renewables are phased out (in 2038, per the scenario policy assumptions), and high carbon prices make carbon-intensive energy sources unattractive, nuclear energy experiences renewed growth. Nuclear capacity grows five-fold between 2050 and 2100, at annual growth rate of approximately 3%, substantially lower than the rates observed in the 20th century [82]. Nuclear (and non-biomass renewables) play a larger role in limCDR compared to allCDR due to the exclusion of BECCS, which limits bioenergy utilization. Nuclear energy in these scenarios is greater than in some other studies (see, for example [83]), which assume that future social and political preferences lead to lower nuclear deployment (see supplementary text 6 for details); lower nuclear generation would require larger deployment of non-biomass renewables.

5. Conclusion

Current NDCs are insufficient to limit end-of-century warming to 1.5 °C, the aspirational objective of the Paris Agreement, under any scenario explored here, regardless of the level of CDR assumed to become available. This highlights the importance of the Agreement's 'ratcheting mechanism,' in particular the facilitative, or Talanoa, dialogue in 2018 and the request for parties to submit new NDCs before 2020 (paragraphs 20, 23 and 24, 1/CP.21 respectively [1]). The analysis clearly shows that ambitious ratcheting needs to apply to the

current round of NDCs, and to lead to substantially lower emissions in 2025 and 2030 than implied by current NDCs—we found no scenario where 1.5 °C remained within reach without significantly ratcheting pre-2030 ambition. As such, the global stocktake, another crucial component of the Paris Agreement's ratcheting mechanism, is not sufficient as a ratcheting device, because its first instance will not take place until 2023—too late to substantially impact ambition in 2025.

While near-term ratcheting is a necessary condition for keeping a 1.5 °C warming limit possible, it is not sufficient; stringent mitigation ambition is required throughout the 21st century. Importantly, as policy-makers and societies make decisions about which mitigation pathways to embark upon, decisions need to be made with regards to the trade-offs between near-term emission reduction efforts and potential CDR deployment later in the century. In this context, it is important to note that higher levels of CDR deployment enable less stringent near term emission reductions, but on the other hand commit future societies to successful CDR implementation at scale lest carbon budgets and temperature objectives are breached, with profound implication for intergenerational equity. Hence, precautionary approaches suggest planning near-term mitigation under conservative estimates of future CDR deployment, to minimize this risk.

Here, we highlighted three scenarios representing three different levels of constraints on CDR deployment to explore the resultant near- to mid-term emission reduction requirements. Emission reduction rates in the limCDR and noCDR cases are very steep, and, in particular after exhausting current mitigation potential of non-CO_2 GHGs, reach levels well beyond historical precedent.

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