> “Every year of delaying rapid and sustained emission reductions increases the requirements for CDR deployment in the long term.”

Chapter 7 | Scenarios

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Carbon Dioxide Removal (CDR) increases in all pathways that limit global temperature to 1.5°C and 2°C. How much we rely on CDR in the second half of the century depends critically on how quickly we reduce emissions in the first half.

Box 7.1 Key findings

- The cumulative amount of Carbon Dioxide Removal (CDR) deployed between 2020 and 2100 varies substantially across pathways that likely limit global temperature rise to 2°C or lower, ranging from 450 to 1,100 $GtCO_2$.

- All scenarios that likely limit warming to 2°C or lower involve substantial emission reductions prior to any significant scale-up of CDR. During the second half of the 21st century, CDR becomes increasingly important. However, near-term scale-up of CDR is critical to achieve required deployment in the long term.

- CDR is scaled up more quickly in scenarios that limit warming to 1.5°C with no or limited overshoot than in scenarios that likely limit warming to 2°C, but the latter often involve higher long-term annual CDR. Over the course of the century, both sets of scenarios see similar total CDR deployment.

- Scenarios that limit warming to 1.5°C with no or limited overshoot reduce annual net CO_2 emissions by 19 (14-27) $GtCO_2$ in 2030 relative to 2020. Annual CDR increases by 2.6 (0.8-5.4) $GtCO_2$ over the same time period and by 9.5 (5.5-16.0) $GtCO_2$ per year at the point of net-zero CO_2 emissions.

- Conventional CDR on land is responsible for 99% (78-100%) of CDR in 2030 in both 1.5°C and 2°C pathways. Conventional CDR levels continue to grow thereafter – peaking around 2050, approximately doubling in 1.5°C pathways and increasing by around 50% in 2°C pathways compared to 2020 levels. Novel CDR methods typically increase throughout the century.

- Almost all scenarios that limit warming to 1.5°C by 2100 involve some level of temporary temperature overshoot. On average, in “high overshoot” pathways that exceed 1.5°C by more than ~0.1°C before returning to it by the end of the century, about 14% more CDR is used cumulatively than in scenarios with no or limited overshoot.

- **Net-negative CO_2 emissions occur when annual levels of CDR exceed annual levels of gross positive CO_2 emissions and are a feature of almost all scenarios likely to limit warming to 2°C or lower.**
- **Almost all assessed scenarios (502 of 507) contain Bioenergy with Carbon Capture and Storage. A majority of scenarios also include conventional CDR on land (407 of 507).**
- **Limiting our dependence on CDR in the long term requires faster emissions reductions in the near term by increasing shares of renewable energy, enhancing energy efficiency, reducing energy demand and limiting or eliminating fossil fuel-based processes.**

7.1 Mapping alternative future pathways

Integrated assessment models provide possible pathways to achieve the Paris temperature goal.

To understand the role of Carbon Dioxide Removal (CDR) in meeting the Paris temperature goal, it is critical to take a long-term perspective. Given that the future could unfold in very different ways, we evaluate alternative mitigation scenarios† that limit global temperature rise to "well below 2°C" (see Chapter 1 – Introduction, Box 1.1). Integrated assessment models are a widely used tool to systematically map out these alternative pathways and the technological, economic and political choices that need to be made in the coming decades to keep the Paris temperature goal within reach (see Box 7.2).

The Paris Agreement contains a long-term temperature goal and a mitigation goal, which it defines in Articles 2 and 4, respectively, as:

> *"Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (Article 2) by "achiev[ing] a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Article 4)*[212].

Aligning scenario temperature outcomes with global climate goals combines inherently scientific and political processes. It has become increasingly common in the scientific community to distinguish three classes of scenario relevant to the recent history of climate policy – categorised as C1, C2 and C3 by the Intergovernmental Panel on Climate Change (IPCC) (see Table 7.1). There are different opinions regarding the extent to which scenarios in different categories assessed in the recent IPCC Working Group III report reflect the increased long-term ambition of the Paris Agreement to limit warming to "well below" 2°C[213,214] relative to previous climate agreements to keep warming "below" 2°C[215]. In this report, we include in our analysis all three groups – scenarios that are "as likely as not" to keep warming below 1.5°C throughout the century (C1), scenarios that have a "high overshoot" of 1.5°C (C2), and scenarios likely to keep warming below 2°C (C3) – as relevant to, but not necessarily all consistent with, the Paris Agreement. Throughout this report, we refer to C1 scenarios as 1.5°C scenarios and C3 scenarios as 2°C scenarios.

† In this report, we use the terms 'scenarios' and 'pathways' interchangeably. In both cases, we refer to outcomes from scenarios as assessed by the IPCC.

Table 7.1. *Scenario definitions likely to keep global temperature increase to 2°C or lower*

Warming limit	IPCC category label	Description	Quantification	Peak warming level (°C, 50% probability)	Warming level in 2100 (°C, 50% probability)	No. of scenarios
1.5°C	C1	Below 1.5°C with no or limited overshoot	<1.5°C peak warming with ≥33% chance and <1.5°C end-of-century warming with >50% chance. Temperature overshoot limited to <0.1°C.	1.6 (1.4-1.6)	1.3 (1.1-1.5)	97
	C2	Below 1.5°C with high overshoot	<1.5°C peak warming with ≥33% chance and <1.5°C end-of-century warming with >50% chance. No limit on temperature overshoot.	1.7 (1.5-1.8)	1.4 (1.2-1.5)	133
2°C	C3	Likely below 2°C	<2°C peak warming with >67% chance.	1.7 (1.6-1.8)	1.6 (1.5-1.8)	311

Box 7.2 Methods: Climate policy scenarios from integrated assessment models

Integrated assessment models (IAMs) are complex models which connect representations of the global economy, energy and land-use systems. These interconnected systems are represented as a mix of different technologies, processes and practices that are deployed to meet the demand for energy and other services within a given set of policy targets or constraints. Such technologies include fossil fuel installations, renewable energy technologies, agricultural production practices and CDR methods, as well as end-use technologies such as road vehicles and appliances.

IAM scenarios depend on a set of key assumptions[216] – such as population growth, level of urbanisation and potential for technological progress – to evaluate the evolution of technologies and consumption patterns in alternative futures. Modelling teams combine these widely used assumptions with their own estimations and quantifications of the potential for technological change, as well as future availability and cost improvements of technologies, and then apply key policy constraints (such as a global temperature limit) to arrive at a pathway or scenario.

Many IAMs use a "cost-effective" approach[217] to estimate economic and energy transitions, in that they try to reach a given climate goal at minimal costs for the global economy. How future costs are valued relative to today (i.e. the assumed discount rate) is a normative assumption required for this approach that can affect key outcomes such as total CO_2 emissions until net zero[218]. Most scenarios assume idealised conditions where currently nascent mitigation technologies become available in the next decade or so, while stringent global climate action starts immediately. However, IAMs are also used to study scenarios in which climate policy and the low-carbon transition are delayed or in which not all technologies are (fully) available[219]. As such, IAMs are a key resource to explore the constraints or possibilities that shape how we meet climate goals, including the key roles of CDR methods in doing so.

We use the collection of scenarios compiled for the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6) as a starting point here[220]. The database features 1,202 scenarios with climate assessments from 14 modelling teams[221]. While scenarios provide standard data on novel CDR (mainly BECCS), conventional CDR on land was only partially assessed in AR6 because different models used different data reporting methodologies and approaches. Using the reduced-complexity climate model OSCAR[222], we develop reanalysed estimations of conventional carbon removal on land – such as via afforestation/reforestation – following definitions of national emissions inventory submissions to the United Nations Framework Convention on Climate Change[192]. We exclude "indirect" carbon removals from environmental changes on managed land (such as CO_2 fertilisation) from these estimates, in line with the definition of anthropogenic CDR utilised by the IPCC, as well as in Chapter 1, and the estimates of current CDR deployment in Chapter 6.

7.2 Scenarios that limit warming to 1.5°C and 2°C

All scenarios that limit global temperature rise to 1.5°C or 2°C feature substantial increases in CDR in addition to sustained and deep emission reductions. Failing to deliver these emission reductions in the short term increases scale and dependence on CDR in the long term.

All emissions pathways that limit global warming to 2°C or lower feature multiple gigatonnes of CDR annually (see Figure 7.2), making CDR a critical component of any mitigation strategy relevant to the Paris Agreement. In assessed scenarios, CDR does not play this role in the near term, however, as absolute emission reductions dominate mitigation activities during the first half of the 21st century. For example, by 2030 net CO_2 annual emissions decline by 19 (14-27) $GtCO_2$ and 8 (0-17) $GtCO_2$ relative to 2020 levels in 1.5°C and 2°C pathways, respectively. During that same timeframe, annual deployment of conventional CDR on land – such as via afforestation/reforestation – increases by 0.8 (-0.1 to 3.0) $GtCO_2$, while novel CDR – such as via Bioenergy with Carbon Capture and Storage (BECCS) or Direct Air Carbon Capture and Storage (DACCS) – increases by 0.01 (0-0.83) $GtCO_2$. CDR levels expand faster in 1.5°C pathways than 2°C pathways, growing by 2.6 (0.8-5.4) $GtCO_2$ removals annually by 2030 compared with 2020 levels. Both CDR types reach their maximum deployment only after mid-century (see Chapter 1 – Introduction for our definitions of "conventional" and "novel"). Conventional CDR on land is responsible for 99% (78-100%) of 2030 CDR in both 1.5°C and 2°C pathways. Conventional CDR on land continues to grow thereafter until its peak around 2050, approximately doubling in 1.5°C pathways and increasing by around 50%

in 2°C pathways compared with 2020 levels. Novel CDR methods such as BECCS or DACCS are typically scaled up throughout the century.

1.5°C scenarios achieve net-zero CO_2 emissions by around mid-century, and the vast majority (93%) of 2°C scenarios do so on average about two decades later. CDR grows steadily in these deep mitigation pathways. At the time of net-zero CO_2, CDR levels range between 5.5 and 16 GtCO_2 per year in 1.5°C pathways and between 6.8 and 16 GtCO_2 per year in 2°C pathways. During the second half of the century, after the point of net-zero CO_2 emissions, CDR becomes an increasingly dominant feature of climate change mitigation efforts. All 1.5°C and most 2°C pathways feature a sustained period of net-negative CO_2 emissions from enhanced levels of CDR that reduces atmospheric carbon concentrations and (often) leads to a drawdown in global mean temperatures. Almost all pathways achieve net-zero or net-negative CO_2 emissions through utilisation of CDR, and many achieve net-zero greenhouse gases (GHGs) in the long term. However, as Chapter 3 (Innovation) illustrates, new technologies can take decades to mature and reach large-scale adoption. Steady near-term progress in deploying novel CDR – such as BECCS and DACCS – is critical to achieving the required scale-up in the long term.

The level and composition of CDR deployed in scenarios varies widely and depends on a number of factors within a given scenario, as discussed in Section 7.3. Table 7.2 shows cumulative CDR deployment across the 21st century, where values for 2°C pathways range between 440 GtCO_2 and 1,100 GtCO_2, with a median value of 630 GtCO_2. More ambitious scenarios that limit warming to 1.5°C with no or limited overshoot show very similar levels of CDR deployment, reaching a median value of 740 GtCO_2 with a range of 420-1,100 GtCO_2. To still limit warming to 1.5°C in 2100 but with a high temporary overshoot of temperatures (>0.1°C), the range of required cumulative CDR increases by about 110 GtCO_2 on average. This is about 14% higher than in limited-overshoot 1.5°C scenarios. The additional CDR is needed to draw down temperature levels after peaking[223]. As a result, every year of delaying rapid and sustained emission reductions increases the requirements for CDR deployment in the long term[4,37,224].

Scenarios to date have focused on a narrow set of CDR methods, principally afforestation/reforestation and BECCS. This requires great care in the interpretation of the scale of CDR methods in climate change mitigation as well as the role of individual CDR methods. In this report, we interpret BECCS deployments as being representative of a broader set of novel CDR methods and afforestation/reforestation as being representative of conventional CDR on land. Modelling teams have recently begun to incorporate other novel CDR methods, such as DACCS or enhanced rock weathering, into their modelling frameworks[225]. As teams expand their representation of CDR methods, trade-offs across the CDR portfolio have become more apparent.

Table 7.2 highlights the variability in the composition of CDR portfolios in existing scenarios.BECCS is present in almost all scenarios considered (502 of 507), and deployment levels vary widely, spanning 170-760 GtCO_2 cumulatively throughout the century. Conventional CDR on land is also included in a majority of scenarios (407 of 507) and has a slightly smaller span of cumulative removals (130-560 Gt CO2).

In contrast, fewer than 1% of considered pathways include active contributions from enhanced rock weathering. A range of studies have reported that including other CDR methods in addition to BECCS might reduce not only the range of mitigation costs but also the impact of CDR on energy use, emissions, land and water. However, contributions of these methods to CDR are sensitive to the rate at which they can be scaled up, which remains highly uncertain (Box 7.3).

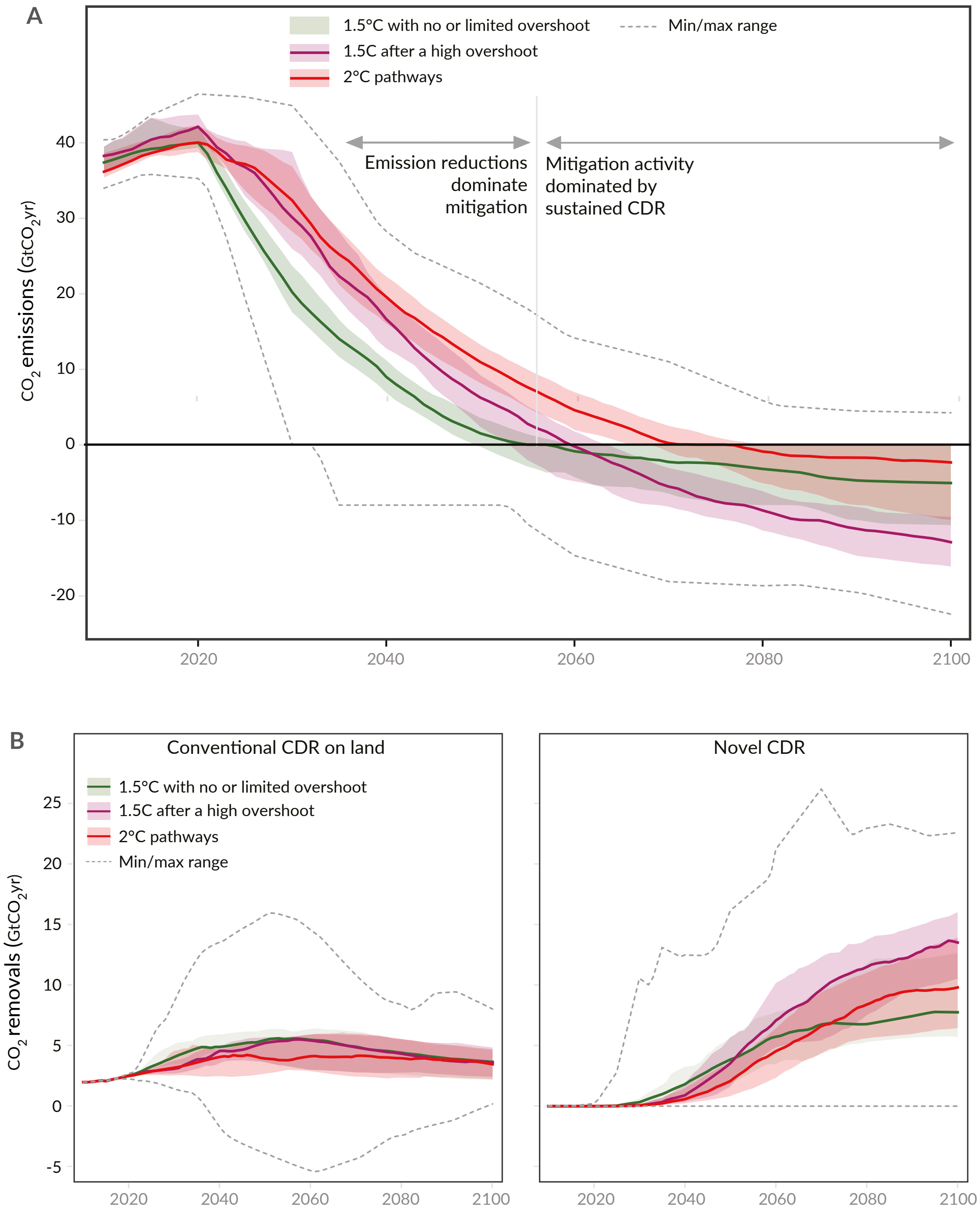

Figure 7.1. *(A) Global net carbon dioxide (CO_2) emissions in scenarios assessed in the Intergovernmental Panel on Climate Change Sixth Assessment Report and (B) upscaling of Carbon Dioxide Removal (CDR) methods under different pathway categories, as described in Table 7.1. Shaded regions show the 5-95th percentile ranges.*

Table 7.2. *Cumulative Carbon Dioxide Removal (CDR) from 2020 to 2100 in GtCO$_2$ in assessed pathways, highlighting the median and 5-95% range of values. "Number of scenarios" indicates the total number of scenarios evaluated by a range of models that include the CDR method as a variable. Statistical total CDR values presented here do not equal the sum of their components, as values are calculated on a per-scenario basis. Definitions: Bioenergy with Carbon Capture and Storage (BECCS); Direct Air Carbon Capture and Storage (DACCS).*

CDR method	Below 1.5°C with no or limited overshoot (C1)		Below 1.5°C with high overshoot (C2)		Likely below 2°C (C3)		Total (all pathways)	
	Total CDR	Number of scenarios	Total CDR	Number of scenarios	Total CDR	Number of scenarios	Total CDR	Number of scenarios
Total (all CDR options)*	740 (420-1100)	70	850 (590-1,300)	106	630 (440-1,100)	231	700 (450-1,100)	407
Conventional CDR on land*	370 (170-560)	70	360 (160-520)	106	310 (110-560)	231	360 (130-560)	407
Novel CDR	400 (24-860)	91	500 (130-860)	122	390 (160-660)	294	400 (110-790)	507
BECCS	330 (32-780)	91	460 (230-840)	122	290 (170-650)	289	330 (170-760)	502
DACCS	30 (0-310)	31	110 (0-540)	24	19 (0-250)	91	29 (0-340)	146
Enhanced rock weathering	0 (0-47)	2	0 (0-0)	1	0 (0-0)	1	0 (0-0)	4

* Total number of scenarios is lower than for novel CDR because data required for the estimation of conventional CDR on land is not available for all scenarios.

Box 7.3 Carbon Dioxide Removal methods in mitigation scenarios

Historically, mitigation scenarios have focused on a limited set of Carbon Dioxide Removal (CDR) methods, mostly implementing representations of Bioenergy with Carbon Capture and Storage and afforestation/reforestation. However, a portfolio of CDR methods will most likely be deployed to achieve global and national climate targets. The composition of the portfolio will depend on available resources, technologies and preferences, and will change over time. Inclusion of additional CDR methods in models tends to increase the total CDR deployment in scenarios[43]. As more CDR methods are added to the portfolio, however, a given amount of CDR can be reached with reduced deployment of individual CDR methods, thus also limiting negative side-effects[43].

As some methods show a strong regional concentration – for example, the potential for afforestation/reforestation and for enhanced rock weathering is highest in the tropics – the availability of a CDR portfolio also changes the regional distribution of CDR. This becomes more balanced with the introduction of more CDR options.

The development of a CDR portfolio therefore hedges not only against technological risks but also against institutional risks (by balancing regional deployment) and against ecological risks (by limiting the deployment of single methods).

7.3 The role of CDR in scenarios that limit warming to 1.5°C and 2°C

The amount of CDR differs widely across scenarios that limit warming to 1.5°C and 2°C, depending on when and how we choose to transform the global economy towards net-zero CO_2 and GHG emissions.

The previous section highlighted that 1.5°C scenarios differ considerably from 2°C scenarios, featuring much faster emissions reductions to net-zero CO_2 emissions and a more rapid CDR scale-up. At the same time, total cumulative CDR across the 21st century is very similar, but within each class of scenarios there is a wide range in deployments – from a few hundred gigatonnes to over a thousand – through the course of the century. This range is a reflection of the different mitigation choices available and their direct implications for the level and timing of CDR deployments.

The scale of CDR deployments in 1.5°C and 2°C pathways depends crucially on political responses to climate change, alongside social and economic developments in the coming decades. Key factors that shape CDR deployment in scenarios are (1) the stringency of the temperature limit achieved; (2) the magnitude and duration of any temperature overshoot and eventual drawdown; (3) the speed and depth of near-term emission reductions; (4) the availability of measures to reduce energy demand; (5) the breadth of the portfolio of available CDR methods as well as other mitigation options.

Individually, these key factors shape the level of CDR deployments in scenarios by shaping the risk of carbon budget exceedance (e.g. stringency, delay, demand reduction), as well as the size of the residual emissions that need to be compensated at net-zero CO_2 and net-zero GHGs (e.g. fossil fuel dependence, demand reduction, technological availability). Delay of GHG emission reductions tends to increase CDR requirements in scenarios that achieve a given temperature outcome, while energy demand reductions decreases it. More technological flexibility (for example, increased usage of CCS in industrial processes like cement production) limits CDR requirements by lowering residual emissions, while availability of more CDR options can lead to increased overall deployment by providing potentially cheaper alternatives to some of the more expensive emission reduction options. Scenario evidence indicates that more CDR is utilised after having initially exceeded a specific warming level in order to draw net emissions and temperatures down at a faster pace later in the century, such as in 1.5°C high overshoot scenarios compared with 1.5°C scenarios with no or low overshoot.

Three focus scenarios

To show how different approaches to climate change mitigation are related to different levels and types of CDR, we analyse three “Focus Pathways” (Figure 7.2). These three pathways highlight strategies that focus on emission reductions mainly through demand reduction, renewable energy or carbon removal while limiting warming to 1.5°C.

The *Focus on Demand Reduction* scenario displays how rapid near-term emission reductions facilitated by radical energy efficiency improvements and lower energy demand levels can limit dependence on CDR substantially, with a maximum yearly removal rate of 4.8 $GtCO_2$ in 2050. Cumulative removals across the 21st century (2020-2100) of 330 $GtCO_2$ are provided exclusively from conventional CDR on land, showcasing that novel CDR is not strictly necessary to meet the Paris temperature goal. However, this is one of the few assessed scenarios that limits the cumulative CDR deployments necessary through aggressive near-term mitigation. The *Focus on Demand Reduction* scenario results in an end-of-century net emissions level of around 0.8 $GtCO_2e$, with residual non-CO_2 emissions mostly balanced by net-negative emissions from land use, land-use change and forestry.

The *Focus on Renewables* scenario involves fast and deep emission reductions facilitated by a rapid expansion of renewables. In this case, cumulative carbon removals are 500 $GtCO_2$ between 2020 and 2100, with a maximum annual rate of 8.2 $GtCO_2$ in 2055. CDR in *Focus on Renewables* is provided through a combination of conventional CDR on land and novel CDR, notably BECCS. If CCS facilities can be scaled in time, the geological storage of CO_2 this affords is more durable and less reversible than storage in trees and soils via conventional CDR on land. The *Focus on Renewables* scenario achieves net-zero GHG emissions by around 2090, and net-negative GHG emissions persist thereafter.

Finally, in the *Focus on Carbon Removal* scenario, GHG emissions reductions occur rapidly in the first half of the century and eventually reach net-zero levels by around 2070. Emissions remain to a large extent in the transportation, residential and commercial, and industry sectors, and are balanced at net zero by larger levels of novel CDR methods as well as net-negative CO_2 emissions from land use, land-use change and forestry. Significantly more CDR is deployed throughout the century due in strong part to balancing remaining residual non-CO_2 emissions in, for example, the agricultural sector. Cumulative removals from 2020 to 2100 arrive at 690 $GtCO_2$ and reach a maximum level of 10 $GtCO_2$ per year in 2050. This level is maintained thereafter, of which 75% is from conventional CDR on land at the end of the century.

While there are many scenarios – particularly those with high temperature overshoot– that involve CDR deployments far beyond what is represented in these three Focal Pathways, it is highly questionable whether such levels of CDR can be developed in a sustainable manner, which introduces strong trade-offs with other Sustainable Development Goals.

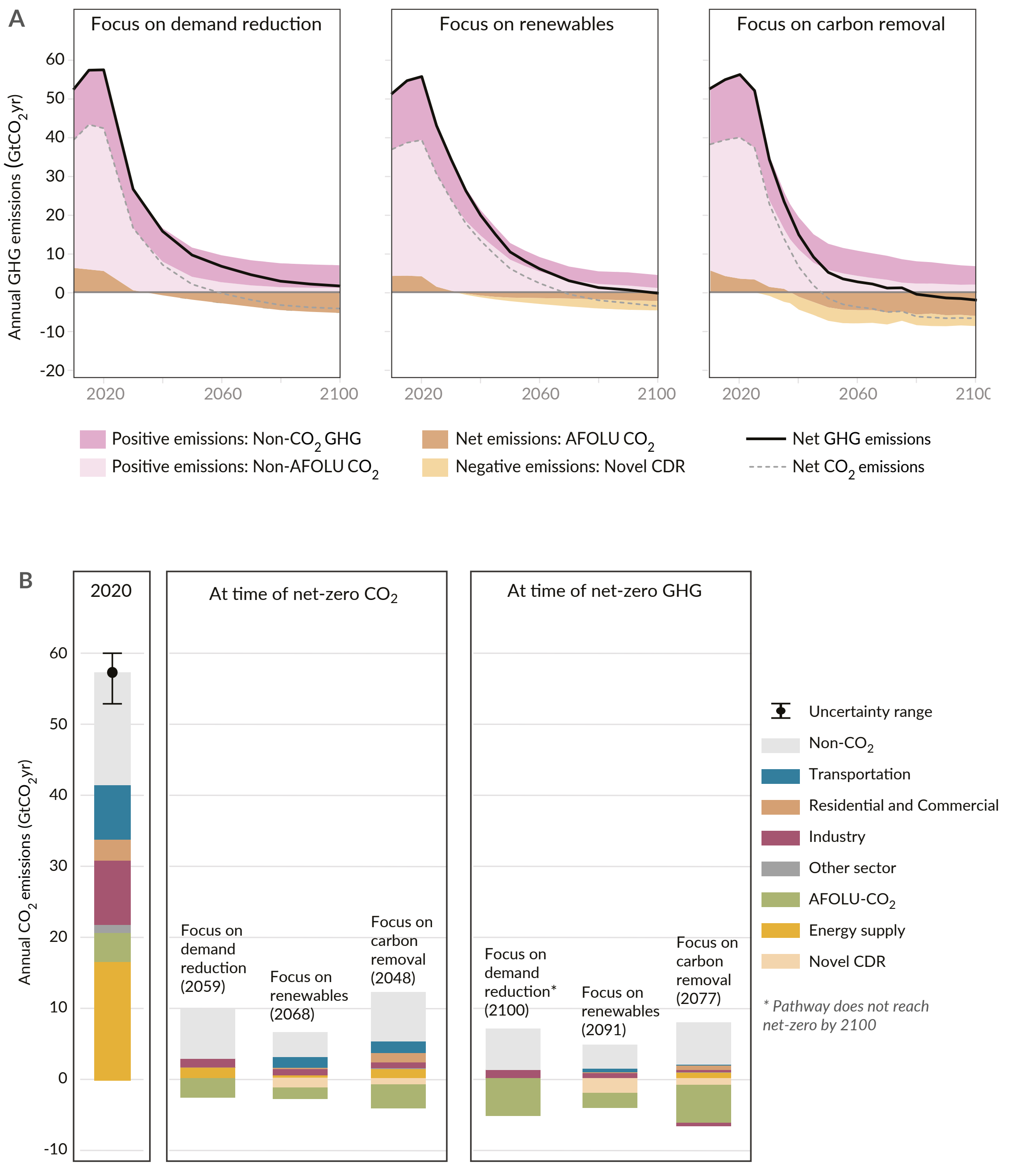

Figure 7.2. *(A) Emissions trajectories across Focus Pathways and (B) sectoral contributions to carbon dioxide (CO_2) emissions and removals at the time of net zero CO_2 and net zero greenhouse gases. Definitions: agriculture, forestry and other land use (AFOLU); Carbon Dioxide Removal (CDR); greenhouse gas (GHG).*

7.4 Limiting future reliance on CDR

Given uncertainties about scaling up CDR, our dependence on it can be limited by reducing emissions fast and using energy more efficiently.

Scenarios produced by the scientific community provide a wide set of possible pathways to meet global climate targets. As such, they provide general guidance on different approaches that can be used to limit global temperature rise, including near eliminating dependence on fossil fuels, electrifying most sectors of the economy, halting deforestation, as well as actively developing and deploying conventional CDR on land and novel CDR. Whether new technologies represented in models will become available at the scale assumed by different scenarios is highly uncertain, however.

The processes and technologies necessary to enable limiting warming to 1.5°C are already presently available – namely, shifting towards higher shares of renewable electricity and electrifying energy processes more broadly while beginning to use energy more efficiently. Current estimates of emissions from existing fossil-based extraction and infrastructure already risk exceeding the Paris Agreement long-term temperature goal, highlighting the importance of transitioning away from these energy sources[2??,2??,2??]. Simultaneously, novel CDR methods represented in pathways are either nascent, not currently deployed at scale, or still conceptual in nature. Thus, while most scenarios show that a non-trivial amount of novel CDR will be needed eventually, the degree to which different CDR methods will be able to sustainably achieve scale-up is highly uncertain. The most prudent approach is therefore to limit future reliance on novel CDR by actively reducing emissions with current technologies and enhancing regional cooperation to support countries outside of the Organisation for Economic Co-operation and Development to avoid carbon lock-in.

Caution should be taken when trying to use scenarios to directly measure CDR needs against emissions inventories reported by countries to the United Nations Framework Convention on Climate Change. Modelled scenarios consider human-induced (or "direct") emissions and reductions; countries, in their National Greenhouse Gas Inventories (NGHGIs) also consider natural areas when accounting for their total present-day emissions (see Chapter 8 – The CDR gap, Section 8.2). When accounting for the additional forested area considered by countries in the NGHGIs, present-day global CO_2 emissions are around 5.5 Gt lower than calculated by scientific studies such as the Global Carbon Budget. Further, the efficacy of this additional forested area in continuing to remove carbon will change over time depending on the future evolution of global mitigation. Better aligning these values and definitions between scientists and the policymaking community is an area of active development.