IPCC extracts of CDR: carbon dioxide removal (-ve emissions) by BECCS

The most published method of CO2 removal is bioenergy with carbon capture and sequestration (BECCS), which is undeveloped. There are undeveloped technologies for direct air capture of CO2 (DAC), but these are treated as too expensive by the IPCC. At this time (2018) with global emissions still increasing (2017), CDR is needed to prevent catastrophic climate change and catastrophic ocean acidification. The IPCC has been showing the need for CDR since 2001.

IPCC TAR 2001

…, to reach a given stabilization target, emissions must ultimately be reduced well below current levels. For achievement of the stabilization categories I and II, negative net emissions are required towards the end of the century in many scenarios considered (Figure TS.8) (high agreement, much evidence) [3.3.5].

*Table TS.2: Classification of recent (Post-Third Assessment Report) stabilization scenarios according to different stabilizatior and alternative stabilization metrics [Table 3.5]. **Errata***

Rectangular Sr

Category	Additional radiative forcing (W/m^2)	CO_2 concentration (ppm)	CO_2-eq concentration (ppm)	Global mean temperature increase above pre-industrial at equilibrium, using "best estimate" climate sensitivity[a], [b]) (°C)	Peaking year for CO_2 emissions[c])	Change in global CO_2 emissions in 2050 (% of 2000 emissions)[c])
I	2.5-3.0	350-400	445-490	2.0-2.4	2000 - 2015	-85 to -50
II	3.0-3.5	400-440	490-535	2.4-2.8	2000 - 2020	-60 to -30

The 2007 IPCC AR4

The IPCC AR4 confirmed that due to the very long atmospheric lifetime of CO2 emissions, to stabilize climate CO2 emissions have to be zero. "In fact, only in the case of essentially complete elimination of emissions can the atmospheric concentration of CO2 ultimately be stabilized at a constant level.' (IPCC assessment 2007 FAQ 10.3). For a high chance of limiting equilibrium warming to 2°C CAD was determined to be needed.

IPCC 2007 AR4 SPM 5 for calculation for equilibrium warming stabilization of 2 to 2.4° C

Table SPM.5: Characteristics of post-TAR stabilization scenarios

Category	Radiative forcing (W/m^2)	CO_2 concentration[c)] (ppm)	CO_2-eq concentration[c)] (ppm)	Global mean temperature increase above pre-industrial at equilibrium, using "best estimate" climate sensitivity[b), c)] (°C)	Peaking year for CO_2 emissions[d)]
I	2.5-3.0	350-400	445-490	2.0-2.4	2000-2015

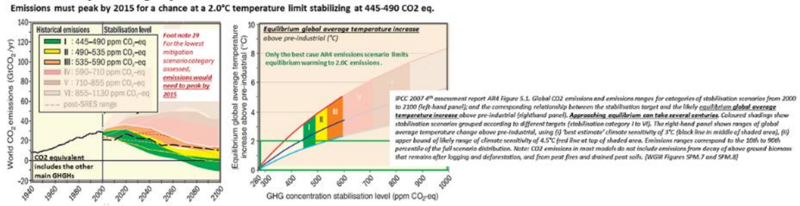
Footnotes

a) The emission reductions to meet a particular stabilization level reported in the mitigation assessed here might be underestimated due to missing carbon cycle feedbacks

C) Note that the global average temperature at equilibrium is different from the expected global average temperature at the time that stabilization of greenhouse gas concentrations due to the inertia of the climate system

CO2 emissions <u>and equilibrium temperature increases</u> for a range of stabilization levels IPCC 2007

Emissions must peak by 2015 for a chance at a 2.0°C temperature limit stabilizing at 445-490 CO2 eq.



*IPCC 2007 4th assessment report AR4 Figure 5.1. Global CO2 emissions and emissions ranges for categories of stabilisation scenarios from 2000 to 2100 (left-hand panel); and the corresponding relationship between the stabilisation target and the likely equilibrium **global average temperature increase** above pre-industrial (righthand panel). **Approaching equilibrium can take several centuries.** Coloured shadings show stabilisation scenarios grouped according to different targets (stabilisation category I to VI). The right-hand panel shows ranges of global average temperature change above pre-industrial, using (i) 'best estimate' climate sensitivity of 3°C (black line in middle of shaded area), (ii) upper bound of likely range of climate sensitivity of 4.5°C (red line at top of shaded area. Emissions ranges correspond to the 10th to 90th percentile of the full scenario distribution. Note: CO2 emissions in most models do not include emissions from decay of above ground biomass that remains after logging and deforestation, and from peat fires and drained peat soils. [WGIII Figures SPM.7 and SPM.8]*

GHG emissions for stabilization categories focused on 445 to 590 ppm CO eq and corresponding equilibrium temperature from IPCC 2007 4th assessment AR4 Greenhouse gas emissions.

The IPCC AR4 WG3 had a section https://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch4s4-3-6.html on Carbon dioxide capture and storage (CCS)

Estimates of the role CCS will play over the course of the century to reduce GHG emissions vary. It has been seen as a 'transitional technology', with deployment anticipated from 2015 onwards, peaking after 2050 as existing heat and power-plant stock is turned over, and declining thereafter as the decarbonization of energy sources progresses (IEA, 2006a). Other studies show a more rapid deployment starting around the same time, but with continuous expansion even towards the end of the century (IPCC, 2005). Yet other studies show no significant use of CCS until 2050, relying more on energy efficiency and renewable energy (IPCC, 2005)

IPCC Expert Meeting on Geoengineering Lima, Peru 20-22 June 2011

BECCS: Considerable concern has been expressed in the technical literature about the inherent conflict between using land to grow food to feed a growing global population and using land to grow energy crops. Concerns have been expressed in terms of: broad sustainability issues including environmental justice and equity concerns (see for example, Adger et al., 2006; Toth, 1999), whether or not there will be net reductions in greenhouse gas emissions from large scale bioenergy production and consumption (Melillo et al., 2009), whether it is possible to move the required volumes of biomass (Richard, 2010) and even in terms of technical feasibility given a changing climate that could result in lower net primary productivity over large swaths of the earth's prime agricultural areas (Lobell and Asner, 2003; Solomon et al., 2009). While not minimizing these concerns, it is important to note that most of these adverse impacts will become manifest at large levels of bioenergy production (e.g., on the order of 100s of EJ/year) and there are steps that can be taken to minimize the worst of these impacts. For example Wise et al. (2009) demonstrated that a climate policy that places an equal value on carbon emissions from the industrial sector as well as from agriculture and land use can simultaneously incentivize the large scale production of bioenergy as well as incentivize afforestation and protect carbon already stored in above ground and below ground biomass and soils. While Luckow et al (2010) make it clear that "The ability to draw on a diverse set of biomass-based feedstocks helps to reduce the pressure for drastic large-scale changes in landuse and the attendant environmental, ecological, and economic consequences those changes would unleash." However, to support BECSS on the scale of 100s of EJ/year would require large bioenergy plantations and significant international trade in bioenergy feedstocks, which could imply significant changes in key global ecosystems (see for example, Thomson et al., 2010). However by adopting technologies that would push densification, dehydration, and pelletization of the purpose grown biomass early into the harvesting process large scale international trade in biomass should be possible and thus there would not need to be a strict correspondence between where the bioenergy crops are grown and where the bioenergy crops are used and therefore where the CO_2 needs to be stored in suitable deep geologic formations (Hamelinck et al., 2005; Luckow et al., 2010). The extent to which there are continued improvements in crop productivity including efforts to enhance the efficiency of natural photosynthesis will be a significant determinant in the extent to how much bioenergy can be produced (Berndes et al., 2003; Blankenship et al., 2011; Thomson et al., 2010; Wise et al., 2009) and therefore on the cost and market potential for BECSS. According to the literature surveyed here, large scale BECSS production on this scale should be well underway at carbon permit prices less than \$100/tCO_2 (Krey and K. Riahi, 2009; Luckow et al., 2010).

IPCC 2014 WG3 SPM

Mitigation scenarios reaching about 450ppm CO2eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500ppm to about 550ppm CO2eq in 2100. Depending on the level of the overshoot, overshoot scenarios typically rely on the availability and widespread deployment of BECCS and afforestation in the second half of the century. The availability and scale of these and other Carbon Dioxide Removal (CDR) technologies and methods are uncertain and CDR technologies and methods are, to varying degrees, associated with challenges and risks (high confidence) (see Section SPM.4.2). CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. There is uncertainty about the potential for large-scale deployment of BECCS, largescale afforestation, and other CDR technologies and methods. P. 12

AR5 WG3 6.9.1 Carbon dioxide removal

Proposed CDR methods involve removing CO2 from the atmosphere and storing the carbon in land, ocean, or geological reservoirs. These methods vary greatly in their estimated costs, risks to humans and the environment, potential scalability, and notably in the depth of research about their potential and risks. Some techniques that fall within the definition of CDR are also regarded as mitigation measures such as afforestation and BECCS (see Glossary). The term 'negative emissions technologies' can be used as an alternative to CDR (McGlashan et al., 2012; McLaren, 2012; Tavoni and Socolow, 2013). The WG I report (Section 6.5.1) provides an extensive but not exhaustive list of CDR techniques (WG I Table 6.14). Here only techniques that feature more prominently in the literature are covered. This includes (1) increased land carbon sequestration by reforestation and afforestation, soil carbon management, or biochar (see WG III Chapter 11); (2) increased ocean carbon sequestration by ocean fertilization; (3) increased weathering through the application of ground silicates to soils or the ocean; and (4) chemical or biological capture with geological storage by BECCS or direct air capture (DAC). CDR techniques can be categorized in alternative ways. For example, they can be categorized (1) as industrial technologies versus ecosystem manipulation; (2) by the pathway for carbon dioxide capture (e.g. McLaren, 2012; Caldeira et al., 2013); (3) by the fate of the stored carbon (Stephens and Keith, 2008); and (4) by the scale of implementation (Boucher et al., 2013). Removal of other GHGs, e.g., CH4 and N2O, have also been proposed (Boucher and Folberth, 2010; de Richter and Caillol, 2011; Stolaroff et al., 2012). All CDR techniques have a similar slow impact on rates of warming as mitigation measures (van Vuuren and Stehfest, 2013) (see WG I Section 6.5.1). An atmospheric 'rebound effect' (see WG I Glossary) dictates that CDR requires roughly twice as much CO2 removed from the atmosphere for any desired net reduction in atmospheric CO2 concentration, as some CO2 will be returned from the natural carbon sinks (Lenton and Vaughan, 2009; Matthews, 2010). Permanence of the storage reservoir is a key consideration for CDR efficacy. Permanent (larger than tens of thousands of years) could be geological reservoirs while nonpermanent reservoirs include oceans and land (the latter could, among others, be affected by the magnitude of future climate change) (see WG I Section 6.5.1). Storage capacity estimates suggest geological reservoirs could store several thousand GtC; the oceans a few thousand GtC in the long term, and the land may have the potential to store the equivalent to historical land-use loss of 180 ± 80 GtC (also see Table 6.15 of WG I)(IPCC, 2005; House et al., 2006; Orr, 2009; Matthews, 2010).

Ocean fertilization field experiments show no consensus on the efficacy of iron fertilization (Boyd et al., 2007; Smetacek et al., 2012). Modelling studies estimate between 15 ppm and less than 100 ppm drawdown of CO_2 from the atmosphere over 100 years (Zeebe and Archer, 2005; Cao and Caldeira, 2010) while simulations of mechanical upwelling suggest 0.9 Gt/yr (Oschlies et al., 2010). The latter technique has not been field tested. There are a number of possible risks including downstream decrease in productivity, expanded regions of low-oxygen concentration, and increased N_2O emissions (See WG I Section 6.5.3.2) (low confidence). Given the uncertainties surrounding effectiveness and impacts, this CDR technique is at a research phase with no active commercial ventures. Furthermore, current international governance states that marine geoengineering including ocean fertilization is to be regulated under amendments to the London Convention/London Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, only allowing legitimate scientific research (Güssow et al., 2010; International Maritime Organization, 2013).

Enhanced weathering on land using silicate minerals mined, crushed, transported, and spread on soils has been estimated to have a potential capacity, in an idealized study, of 1 GtC/yr (Köhler et al., 2010). Ocean-based weathering CDR methods include use of carbonate or silicate minerals processed or added directly to the ocean (see WG I Section 6.5.2.3). All of these measures involve a notable energy demand through mining, crushing, and transporting bulk materials. Preliminary hypothetical cost estimates are in the order of 23–66 USD/tCO_2 (Rau and Caldeira, 1999; Rau et al., 2007) for land and 51–64 USD/tCO_2 for ocean methods (McLaren, 2012). The confidence level on the carbon cycle impacts of enhanced weathering is low (WG I Section 6.5.3.3).

BECCS The use of CCS technologies (IPCC, 2005) with biomass energy also creates a carbon sink (Azar et al., 2006; Gough and Upham, 2011). BECCS is included in the RCP 2.6 (van Vuuren et al., 2007, 2011b) and a wide range of scenarios reaching similar and higher concentration goals. From a technical perspective, BECCS is very similar to a combination of other techniques that are part of the mitigation portfolio: the production of bio-energy and CCS for fossil fuels. Estimates of the global technical potential for BECCS vary greatly ranging from 3 to more than 10 GtCO_2/yr (Koornneef et al., 2012; McLaren, 2012; van Vuuren et al., 2013), while initial cost estimates also vary greatly from around 60 to 250 USD/tCO_2 (McGlashan et al., 2012; McLaren, 2012). Important limiting factors for BECCS include land availability, a sustainable supply of biomass and storage capacity (Gough and Upham, 2011; McLaren, 2012). There is also a potential issue of competition for biomass under bioenergy-dependent mitigation pathways.

Direct air capture uses a sorbent to capture CO_2 from the atmosphere and the long-term storage of the captured CO_2 in geological reservoirs (GAO, 2011; McGlashan et al., 2012; McLaren, 2012). There are a number of proposed capture methods including adsorption of CO_2 using amines in a solid form and the use of wet scrubbing systems based on calcium Assessing Transformation Pathways 6 Chapter 6 or sodium cycling. Current research efforts focus on capture methodologies (Keith et al., 2006; Baciocchi et al., 2006; Lackner, 2009; Eisenberger et al., 2009; Socolow et al., 2011) with storage technologies assumed to be the same as CCS (IPCC, 2005). A U.S. Government Accountability Office (GAO) (2011) technology assessment concluded that all DAC methods were currently immature. A review of initial hypothetical cost estimates, summarizes 40–300 USD/tCO_2 for supported amines and 165–600 USD/tCO_2 for sodium or calcium scrubbers (McLaren, 2012) reflecting an ongoing debate across very limited literature. Carbon dioxide captured through CCS, BECCS, and DAC are all intended to use the same storage reservoirs (in particular deep geologic reservoirs), potentially limiting their combined use under a transition pathway.

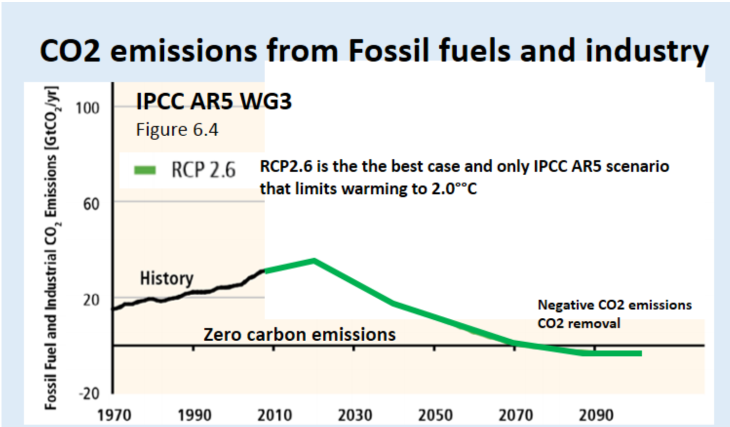
There are some constraints to the use of CDR techniques as emphasized in the scenario analysis. First of all, the potential for BECCS, afforestation, and DAC are constrained on the basis of available land and/or safe geologic storage potential for CO2. Both the potential for sustainable bio-energy use (including competition with other demands, e.g., food, fibre, and fuel production) and the potential to store > 100 GtC of CO2 per decade for many decades are very uncertain (see previous section) and raise important societal concerns. Finally, the largescale availability of CDR, by shifting the mitigation burden in time, could also exacerbate inter-generational impacts

6.9.3 Summary

Despite the assumption of some form of negative CO2 emissions in many scenarios, including those leading to 2100 concentrations approaching 450ppm CO2eq, whether proposed CDR or SRM geoengineering techniques can actually play a useful role in transformation pathways is uncertain as the efficacy and risks of many techniques are poorly understood at present. CDR techniques aim to reduce CO2 (or potentially other GHG) concentrations. A broad definition of CDR would cover afforestation and BECCS, which are sometimes classified as mitigation techniques, but also proposals that are very distinct from mitigation in terms of technical maturity, scientific understanding, and risks such as ocean iron fertilization. The former are often included in current integrated models and scenarios and are, in terms of their impact on the climate, directly comparable with techniques that are considered to be conventional mitigation, notably fossil CCS and bio-energy use. Both BECCS and afforestation may play a key role in reaching low-GHG concentrations, but at a large scale have substantial land-use demands that may conflict with other mitigation strategies and societal needs such as food production. Whether other CDR techniques would be able to supplement mitigation at any significant scale in the future depends upon efficacy, cost, and risks of these techniques, which at present are highly uncertain. The properties of potential carbon storage reservoirs are also critically important, as limits to reservoir capacity and longevity will constrain the quantity and permanence of CO2 storage. Furthermore, some CDR techniques such as ocean iron fertilization may pose transboundary risks. The impacts of CDR would be relatively slow: climate effects would unfold over the course of decades

Synthesis Report SYR

There are multiple mitigation pathways that are likely to limit warming to below 2°C relative to pre-industrial levels. **These pathways would require substantial emissions reductions over the next few decades and near zero emissions of CO2 and other long-lived greenhouse gases by the end of the century.**



Implementing such reductions poses substantial technological, economic, social and institutional challenges, which increase with delays in additional mitigation and if key technologies are not available. Limiting warming to lower or higher levels involves similar challenges but on different timescales. {3.4}

Without additional efforts to reduce GHG emissions beyond those in place today, global emissions growth is expected to persist, driven by growth in global population and economic activities. Global mean surface temperature increases in 2100 in baseline scenarios—those without additional mitigation—range from 3.7°C to 4.8°C above the average for 1850–1900 for a median climate response. They range from 2.5°C to 7.8°C when including climate uncertainty (5th to 95th percentile range) (high confidence). {3.4}14

Emissions scenarios leading to CO2-equivalent concentrations in 2100 of about 450 ppm or lower are likely to maintain warming below 2°C over the 21st century relative to pre-industrial levels15. These scenarios are characterized by 40 to 70% global anthropogenic GHG emissions reductions by 2050 compared to 2010, and emissions levels near zero or below in 2100.

Mitigation scenarios reaching concentration levels of about 500 ppm CO2-eq by 2100 are more likely than not to limit temperature change to less than 2°C, unless they temporarily overshoot concentration levels of roughly 530 ppm CO2-eq before 2100, in which case they are about as likely as not to achieve that goal. In these 500 ppm CO2-eq scenarios, global 2050 emissions levels are 25 to 55% lower than in 2010. Scenarios with higher emissions in 2050 are characterized by a greater reliance on Carbon Dioxide Removal (CDR) technologies beyond mid-century (and vice versa).

Trajectories that are likely to limit warming to 3°C relative to pre-industrial levels reduce emissions less rapidly than those limiting warming to 2°C. A limited number of studies provide scenarios that are more likely than not to limit warming to 1.5°C by 2100; these scenarios are characterized by concentrations below 430 ppm CO2-eq by 2100 and 2050 emission reduction between 70% and 95% below 2010. For a comprehensive overview of the characteristics of emissions scenarios, their CO2-equivalent concentrations and their likelihood to keep warming to below a range of temperature levels, see Figure SPM.11 and Table SPM.1. {3.4}

Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO2 emissions (see Section 2.2.5 for the relationship between CO2 emissions and global temperature change.). A large fraction of anthropogenic climate change resulting from CO2 emissions is irreversible on a multi-century to millennial timescale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period (Figure 2.8a, b). {WGI SPM E.1, SPM E.8, 12.5.2}

Mitigation scenarios reaching about 450 ppm CO_2-eq in 2100 (consistent with a likely chance to keep warming below 2°C relative to pre-industrial level) typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm CO_2-eq to about 550 ppm CO_2-eq by 2100 (Table 3.1). Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and afforestation in the second half of the century (high confidence). The availability and scale of these and other Carbon Dioxide Removal (CDR) technologies and methods are uncertain, and CDR technologies and methods are, to varying degrees, associated with challenges and risks (see Box 3.3)3924. CDR is also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive.

Box 3.3 | Carbon Dioxide Removal and Solar Radiation Management Geoengineering Technologies—Possible Roles, Options, Risks and Status Geoengineering refers to a broad set of methods and technologies operating on a large scale that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most methods seek to either reduce the amount of absorbed solar energy in the climate system (Solar Radiation Management, SRM) or increase the removal of carbon dioxide (CO_2) from the atmosphere by sinks to alter climate (Carbon Dioxide Removal, CDR, see Glossary). Limited evidence precludes a comprehensive assessment of feasibility, cost, side effects and environmental impacts of either CDR or SRM. {WGI SPM E.8, 6.5, 7.7, WGII 6.4, Table 6-5, Box 20-4, WGIII TS.3.1.3, 6.9} CDR plays a major role in many mitigation scenarios. Bioenergy with carbon dioxide capture and storage (BECCS) and afforestation are the only CDR methods included in these scenarios. CDR technologies are particularly important in scenarios that temporarily overshoot atmospheric concentrations, but they are also prevalent in many scenarios without overshoot to compensate for residual emissions from sectors where mitigation is more expensive. Similar to mitigation, CDR would need to be deployed on a large scale and over a long time period to be able to significantly reduce CO_2 concentrations (see Section 3.1). {WGII 6.4, WGIII SPM 4.1, TS.3.1.2, TS 3.1.3, 6.3, 6.9}

Several CDR techniques could potentially reduce atmospheric greenhouse gas (GHG) levels. However, there are biogeochemical, technical and societal limitations that, to varying degrees, make it difficult to provide quantitative estimates of the potential for CDR. The emission mitigation from CDR is less than the removed CO_2, as some CO_2 is released from that previously stored in oceans and terrestrial carbon reservoirs.

The most comprehensive assessment of BECCS in the IPCC AR5 is IPCC 2014 AR5 WG3 11.13 **Appendix Bioenergy: Climate effects, mitigation options, potential and sustainability implications**

Important summery quote. BECCS features prominently in many mitigation scenarios. BECCS is deployed in greater quantities and earlier in time the more stringent the climate policy (Section 6.3.5). Whether BECCS is essential for mitigation, or even sufficient, is unclear. In addition, the likelihood of BECCS deployment is difficult to evaluate and depends on safety confirmations, affordability and public acceptance.

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