2022-IP05: IPCC Climate Change 2022: Mitigation of Climate Change

The IPCC has finalized the third part of the Sixth Assessment Report (AR6), 'Climate Change 2022: Mitigation of Climate Change, the Working Group III (WGIII) contribution to the Sixth Assessment Report. It was approved on 4 April 2022 by 195 member governments of the IPCC, through a virtual approval session that started on 21 March. The WGIII contribution to AR6 assesses climate change mitigation progress and pledges and examines the sources of global emissions. It explains developments in emission reduction and mitigation efforts, assessing the impact of national climate pledges in relation to long-term emissions goals. The report introduces a new chapter on the social aspects of mitigation, which explores the demand side, acting as a partner to the sectoral chapters in the report, which explore the supply side of climate change - what produces emissions. There is also a cross-sector chapter on mitigation options that cut across sectors, including carbon dioxide removal (CDR) techniques. And there is a new chapter on innovation, technology development and transfer, which describes how a well-established innovation system at a national level can contribute to mitigation, adaptation and achieving the sustainable development goals (SDGs). The report comprises a very comprehensive 2913 pages and is structured into 17 chapters. Overall, the 278 authors from 65 countries have addressed more than 20k comments on the first order draft (FOD) and more than 30k comments on the second order draft (SOD). This report re-emphasises the urgency of action and the necessary and important roles for carbon capture and storage (CCS) and CDR.

This Information Paper (IP) extracts, summarises and discusses the key messages from the report related to CCUS and CDR technologies. For a more general and high-level summary of the overall key messages, we refer to the recent IEAGHG 2022-IP03 (see reference list at the end).

Messages related to CCS/CCUS (435/34 mentions)

Summary for Policy Makers (SPM)

1. CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources, provided geological storage is available. The technical geological CO_2 storage capacity is estimated to be on the order of 1000 gigatonnes of CO_2, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. (*high confidence*)
2. Limiting global warming to 2°C or below will leave a substantial amount of fossil fuels unburned and could strand considerable fossil fuel infrastructure (*high confidence*). Depending on its availability, CCS could allow fossil fuels to be used longer, reducing stranded assets (*high confidence*).
3. CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources, provided geological storage is available. When CO_2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO_2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological CO_2 storage capacity is estimated to be on the order of 1000 gigatonnes of CO_2, which is more than the CO_2 storage requirements through 2100 to limit

global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. (*high confidence*)

Comment on#1,3:
IEAGHG does not share the mentioned caveats on available storage, as international transport is possible and there is sufficient storage globally.

Technical Summary (TS)

1. Limiting warming to 2°C or 1.5°C will strand fossil-related assets, including fossil infrastructure and unburned fossil fuel resources (*high confidence*). The economic impacts of stranded assets could amount to trillions of dollars. Coal assets are most vulnerable over the coming decade; oil and gas assets are more vulnerable toward mid-century. CCS can allow fossil fuels to be used longer, reducing potential stranded assets.
2. Climate policies, other policies and regulations, innovation in competing technologies, and shifts in fuel prices could all lead to stranded assets. The loss of wealth from stranded assets would create risks for financial market stability, reduce fiscal revenue for hydrocarbon dependent economies, in turn affecting macro-economic stability and the prospects for a just transition.
3. Scenario evidence suggests that without carbon capture, the worldwide fleet of coal- and gas power plants would need to retire about 23 and 17 years earlier than expected lifetimes, respectively in order to limit global warming to 1.5°C and 2°C. Blast furnaces and cement factories without CCS, new fleets of airplanes and internal combustion engine vehicles and new urban infrastructures adapted to sprawl and motorisation may also be stranded.

Main report

1. Large unit scale technologies – such as full-scale nuclear power, CCS, low-carbon steel making, and negative emissions technologies such as BECCS – are often primarily built on site and include thousands to millions of parts such that complexity and system integration issues are paramount.
2. Around 80% of coal, 50% of gas, and 20% of oil reserves are likely to remain unextractable under 2°C constraints. Reserves are more likely to be utilized in a low-carbon transition if they can be paired with CCS. Availability of CCS technology not only allows continued use of fossil fuels as a capital resource for countries but also paves the way for CDR through BECCS.
3. For hydrogen to support decarbonisation, it will need to be produced from zero-carbon or extremely low-carbon energy sources. One such production category is “green hydrogen.” While there is no unified definition for green hydrogen, it can be produced by the electrolysis of water using electricity generated without carbon emissions (such as renewables). Hydrogen can also be produced through biomass gasification with CCS (BECCS), leading to negative carbon emissions. Additionally, “blue hydrogen” can be produced from natural gas through the process of auto-thermal reforming (ATR) or steam methane reforming (SMR), combined with CCS technology that would absorb most of the resulting CO2 (80-90%).

4. There is a lack of consensus about how CCS might alter fossil fuel transitions for limiting likely warming to 2°C or below. CCS deployment will increase the shares of fossil fuels associated with limiting warming, and it can ease the economic transition to a low-carbon energy system. While some studies find a significant role for fossil fuels with CCS by 2050, others find that retirement of unabated coal far outpaces the deployment of coal with CCS. Moreover, several models also project that with availability of CO_2 capture technology, BECCS might become significantly more appealing than fossil CCS even before 2050.
5. CDR and CCS can create significant land and water trade-offs (*high confidence*). For large-scale CDR and CCS deployment to not conflict with development goals requires efforts to reduce implications on water and food systems. The water impacts of carbon capture can be strategically managed (Giannaris et al. 2020c; Magneschi et al. 2017; Realmonte et al. 2019; Liu et al. 2019a). In addition, high-salinity brines are produced from geologic carbon storage, which may be a synergy or trade-off depending on the energy intensity of the treatment process and the reusability of the treated waters; if the produced brine from geologic formations can be treated via desalination technologies, there is an opportunity to keep the water intensity of electricity as constant. Both implications of CCS and CDR are related to SDG 6 on clean water. CDR discussions in the context of energy systems frequently pertains to BECCS which could affect food prices based on land management approaches. Several CDR processes also require considerable infrastructure refurbishment and electrification to reduce upstream CO_2 emissions. Large-scale CDR could also open the potential for low-carbon transport and urban energy (by offsetting emissions in these sectors) use that would create synergies with SDG 11 (sustainable cities and communities). Effective siting of CDR infrastructure therefore requires consideration of trade-offs with other priorities. At the same time, several SDG synergies have also been reported to accompany CCS projects such as with reduced air pollution (SDG 3) (Mikunda et al. 2021).

Comment on #5:

In our reviews of the FOD and SOD, we commented on the unbalanced presentation of water impacts related to CCS and provided references to research about how those impacts can be managed. We are happy to see our comments have been addressed in the final version of the report. Furthermore, we also commented on the impacts of CCS on the SDGs and positively note that the resulting paper from the IEAGHG study 2020-14 ‘CCS and the Sustainable Development Goals’ by Mikunda et al. has been used and cited in this context.

Messages related to CDR (489 mentions)

SPM

1. In modelled pathways that limit warming to 1.5°C with no or limited overshoot, global cumulative CDR during 2020-2100 from BECCS and DACCS is 30-780 and 0-310 $GtCO_2$, respectively. Total cumulative net negative CO_2 emissions in these modelled pathways are 20–660 $GtCO_2$. In modelled pathways that limit warming to 2°C, global cumulative CDR during 2020–2100 from BECCS and DACCS is 170–650 and 0–250 $GtCO_2$ respectively, and total cumulative net negative CO_2 emissions are around 40 [0–290] $GtCO_2$. (*high confidence*)
2. The removal and storage of CO_2 through vegetation and soil management can be reversed by human or natural disturbances; it is also prone to climate change impacts. In comparison, CO_2 stored in geological and ocean reservoirs (via BECCS, DACCS, ocean alkalinisation) and as carbon in biochar is less prone to reversal. (*high confidence*)

3. The impacts, risks and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale *(high confidence*). Reforestation, improved forest management, soil carbon sequestration, peatland restoration and blue carbon management are examples of methods that can enhance biodiversity and ecosystem functions, employment and local livelihoods, depending on context (*high confidence*). In contrast, afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure (*high confidence*).

TS

1. Pathways likely to limit warming to 2°C or 1.5°C require some amount of CDR to compensate for residual GHG emissions, even after substantial direct emissions reductions are achieved in all sectors and regions (*high confidence*). CDR options in pathways are mostly limited to BECCS, afforestation and DACCS. CDR through some measures in AFOLU can be maintained for decades but not over the very long term because these sinks will ultimately saturate (*high confidence*).
2. All the illustrative mitigation pathways (IMPs) assessed in this report use land-based biological CDR (primarily A/R) and/or BECCS. Some also include DACCS (*high confidence*). Across the scenarios likely limiting warming to 2°C or below, cumulative volumes of BECCS reach 328 (168–763) GtCO$_2$, net CO$_2$ removal on managed land (including A/R) reaches 252 (20–418) GtCO$_2$, and DACCS reaches 29 (0–339) GtCO$_2$, for the 2020-2100 period. Annual volumes in 2050 are 2.75 (0.52–9.45) GtCO$_2$ for BECCS, 2.98 (0.23–6.38) GtCO$_2$ for the net CO$_2$ removal on managed land (including A/R), and 0.02 (0 -1.74) GtCO$_2$ for DACCS.

Main report

1. Creating net negative emissions can be an important part of a mitigation strategy to offset remaining emissions or compensate for emissions earlier in time. There are different ways to potentially achieve this, including A/R and BECCS (as often covered in IAMs) but also soil carbon enhancement, DACCS and ocean alkalinization. Except for reforestation, these options have not been tested at large scale and often require more R&D. Moreover, the reliance on CDR in scenarios has been discussed given possible consequences of land use related to biodiversity loss and food security (BECCS and afforestation), the reliance on uncertain storage potentials (BECCS and DACCS), water use (BECCS), energy use (DACCS), the risks of possible temperature overshoot and the consequences for meeting SGDs. In the case of BECCS, it should be noted that bioenergy typically is associated with early-on positive CO$_2$ emissions and net-negative effects are only achieved in time (carbon debt), and its potential is limited (most IAMs have only a very limited representation of these time dynamics).
2. The energy system is not the only source or sink of CO$_2$ emissions. Terrestrial systems may store or emit carbon, and CDR options like BECCS or DACCS can be used to store CO$_2$, relieving pressure on the energy system. The location of such CDR options is ambiguous, as it might be deployed within or outside of the energy sector, and many CDR options, such as DACCS, would be important energy consumers. If CDR methods are deployed outside of the energy system (e.g., net negative agriculture, forestry, and land use CO$_2$ emissions), it is possible for the energy system to still emit CO$_2$ but have economy-wide emissions of zero or below. When global energy and industrial CO$_2$ emissions reach net zero, the space remaining for fossil energy emissions is determined by deployment of CDR options.

3. There are many possible configurations and technologies for zero- or net-negative-emissions electricity systems (*high confidence*). These systems could entail a mix of variable renewables, dispatchable renewables (e.g., biomass, hydropower), other firm, dispatchable ("on-demand") low-carbon generation (e.g., nuclear, CCS-equipped capacity), energy storage, transmission, CDR options (e.g., BECCS, DACCS), and demand management.
4. While CDR is likely necessary for net zero energy systems, the scale and mix of strategies is unclear –nonetheless some combination of BECCS and DACCS are likely to be part of net zero energy systems (*high confidence*). Studies indicate that energy-sector CDR may potentially remove 5–12 $GtCO_2$/yr globally in net zero energy systems. CDR is not intended as a replacement for emissions reduction, but rather as a complementary effort to offset residual emissions from sectors that are not decarbonized and from other low-carbon technologies such as fossil CCS.
5. While many governments have included A/R and other forestry measures into their NDCs under the Paris Agreement, and a few countries also mention BECCS, DACCS and EW in their mid-century low emission development strategies, very few are pursuing the integration of a broad range of CDR methods into national mitigation portfolios so far.
6. Depending on emission-reduction target, the portfolio of mitigation options chosen, and the policies developed to support their implementation, different land-use pathways can arise with large differences in resulting agricultural and forest area. Stronger mitigation action in the near term targeting non-CO_2 emissions reduction and deployment of other CDR options (DACCS, EW, ocean-based approaches) can reduce the land requirement for land-based mitigation.

Messages related to BECCS (287 mentions)

TS

1. Pathways limiting warming to 1.5°C with no or limited overshoot show an increase in forest cover of about 322 million ha (-67 to 890 million ha) in 2050 (*high confidence*). In these pathways the cropland area to supply biomass for bioenergy (including BECCS) is around 199 (56-482) million ha in 2100. The use of bioenergy can lead to either increased or reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and how, and where, the biomass is produced (*high confidence*).
2. The provision of biomass for bioenergy (with/without BECCS) and other biobased products represents an important share of the total mitigation potential associated with the AFOLU sector, though these mitigation effects accrue to other sectors (*high confidence*). Recent estimates of the technical bioenergy potential, when constrained by food security and environmental considerations, are within the ranges 5–50 and 50–250 EJ/yr by 2050 for residues and dedicated biomass production systems, respectively.[1]
3. Decent living standards, which encompasses many SDG dimensions, are achievable at lower energy use than previously thought (*high confidence*). Mitigation strategies that focus on

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[1] These potentials do not include avoided emissions resulting from bioenergy use associated with BECCS, which depends on energy substitution patterns, conversion efficiencies, and supply chain emissions for both the BECCS and substituted energy systems. Estimates of substitution effects of bioenergy indicate that this additional mitigation would be of the same magnitude as provided through CDR using BECCS. Biobased products with long service life, e.g., construction timber, can also provide mitigation through substitution of steel, concrete, and other products, and through carbon storage in the biobased product pool.

lowering demand for energy and land-based resources exhibit reduced trade-offs and negative consequences for sustainable development relative to pathways involving either high emissions and climate impacts or pathways with high consumption and emissions that are ultimately compensated by large quantities of BECCS.

Main report

1. The annual BECCS deployment is 0.08 [0–1.09] $GtCO_2$/yr, 2.75 [0.52–9.45] $GtCO_2$/yr, and 8.96 [2.63–16.15] $GtCO_2$ /yr for these years, respectively.
2. By sequestering carbon in biomass and soils, soil carbon management, and other terrestrial strategies could offset hard-to-reduce emissions in other sectors. However, large-scale bioenergy deployment could increase risks of desertification, land degradation, and food insecurity, and higher water withdrawals, though this may be at least partially offset by innovation in agriculture, diet shifts and plant-based proteins contributing to meeting demand for food, feed, fibre and, bioenergy (or BECCS with CCS).
3. Many factors influence the deployment of technologies in the IAMs. Since AR5, there has been fervent debate on the large-scale deployment of BECCS in scenarios. Hence, many recent studies explore mitigation pathways with limited BECCS deployment. While some have argued that technology diffusion in IAMs occurs too rapidly, others argued that most models prefer large-scale solutions resulting in a relatively slow phase-out of fossil fuels. While IAMs are particularly strong on supply-side representation, demand-side measures still lag in detail of representation despite progress since AR5.
4. The effect of bioenergy and BECCS on mitigation depends on a variety of factors in modelled pathways. In the energy system, the emissions mitigation depends on the scale of deployment, the conversion technology, and the fuel displaced. Limiting or excluding bioenergy and/or BECCS increases mitigation cost and may limit the ability of a model to reach a low warming level.
5. Pathways with very high biomass production for energy use typically include very high carbon prices in the energy system, little or no land policy, a high discount rate, and limited non-BECCS CDR options (e.g., afforestation, DACCS). Higher levels of bioenergy consumption are likely to involve trade-offs with mitigation in other sectors, notably in construction (i.e., wood for material and structural products) and AFOLU (carbon stocks and future carbon sequestration), as well as trade-offs with sustainability and feasibility concerns. Not all of these trade-offs are fully represented in all IAMs.
6. IAM pathways rely on afforestation and BECCS as CDR measures, so delayed mitigation action results in substantial land use change in the second half of the century with implications for sustainable development. Shifting to earlier mitigation action reduces the amount of land required for this, though at the cost of larger land use transitions earlier in the century. Earlier action could also reduce climate impacts on agriculture and land-based mitigation options
7. Lower demand – e.g., for energy and land-intensive consumption such as meat – represents a synergistic strategy for achieving ambitious climate mitigation without compromising SDGs (*high confidence*). This is especially true for reliance on BECCS. Options that reduce agricultural demand (e.g., dietary change, reduced food waste) can have co-benefits for adaptation through reductions in demand for land and water.
8. Bioenergy and BECCS can increase water withdrawals and water consumption (*high confidence*).
9. Climate change mitigation actions to reduce or slow negative impacts on ecosystems are likely to support the achievement of SDGs 2, 3, 6, 12, 14 and 15. Some studies show that stringent and constant GHG mitigation practices bring a net benefit to global biodiversity even if land-

based mitigation measures are also adopted, as opposed to delayed action which would require much more widespread use of BECCS. Scenarios based on demand reductions of energy and land-based production are expected to avoid many such consequences, due to their minimized reliance on BECCS.

10. Demand-side actions hold sustainability advantages over the intensive use of bioenergy and BECCS, but also enable land use for bioenergy by saving agricultural land for food.
11. Some early opportunities for low-cost BECCS are being utilized in the ethanol sector but these are applicable only in the near-term at the scale of ≤100 MtCO$_2$/yr. Several technological and institutional barriers exist for large-scale BECCS implementation, including large energy requirements for CCS, limit and cost of biomass supply and geologic sinks for CO_2 in several regions, and cost of CO_2 capture technologies (*high confidence*). Besides BECCS, biofuels production through pyrolysis and hydrothermal liquefaction creates biochar, which could also be used to store carbon as 80% of the carbon sequestered in biochar will remain in the biochar permanently.
12. The lifecycle emissions of BECCS remain uncertain and will depend on how effectively bioenergy conversion processes are optimized.
13. BECCS has value as an electricity generation technology, providing firm, dispatchable power to support electricity grids with large amounts of VRE sources, and reducing the reliance on other means to manage these grids, including electricity storage. BECCS may also be used to produce liquid fuels or gaseous fuels, including hydrogen. For instance, CO_2 from bio-refineries could be captured at <45 USD/tCO$_2$. Similarly, while CO_2 capture is expensive, its integration with hydrogen via biomass gasification can be achieved at an incremental capital cost of 3-35%. As with all uses of bioenergy, linkages to broad sustainability concerns may limit the viable development, as will the presence of high-quality geologic sinks in close proximity.
14. There is substantial uncertainty about the amount of CDR that might ultimately be deployed. In most scenarios that limit warming to 1.5°C, CDR deployment is fairly limited through 2030 at less than 1 GtCO$_2$/yr. The key projected increase in CDR deployment (BECCS and DAC only) occurs between 2030 and 2050 with annual CDR in 2050 projected at 2.5-7.5 GtCO$_2$/yr in 2050 in scenarios limiting warming to 1.5°C with limited or no overshoot and 0.7-1.4 GtCO$_2$/yr in 2050 in scenarios limiting warming to 2°C with limited or no overshoot. This characteristic of scenarios largely reflects substantial capacity addition of BECCS power plants. BECCS is also deployed in multiple ways across sectors. For instance, the contribution of BECCS to electricity is 1-5% in 2050 in scenarios limiting warming to 1.5°C with limited or no overshoot and 0-5% in scenarios limiting likely warming to below 2°C. The contribution of BECCS to liquid fuels is 9-21% in 2050 in scenarios limiting warming to 1.5°C with limited or no overshoot and 2-11% in scenarios limiting likely warming to below 2°C. Large-scale deployment of CDR allows flexibility in timing of emissions reduction in hard-to-decarbonize sectors.
15. Poorly planned deployment of biomass production and afforestation options for in-forest carbon sequestration may conflict with environmental and social dimensions of sustainability (*high confidence*). The global technical CDR potential of BECCS by 2050 (considering only the technical capture of CO_2 and storage underground) is estimated at 5.9 (0.5-11.3) GtCO$_2$/yr , of which 1.6 (0.8-3.5) GtCO$_2$/yr is available at below USD 100/tCO$_2$ (*medium confidence*). Bioenergy and other bio-based products provide additional mitigation through the substitution of fossil fuels based products (*high confidence*).

Messages related to DACCS (117 mentions)

SPM

1. Specifically, maturity ranges from lower maturity (e.g., ocean alkalinisation) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (<1 $GtCO_2$/yr, e.g., blue carbon management) to higher potential (>3 $GtCO_2$/yr, e.g., agroforestry); costs range from lower cost (e.g., 45-100 USD/tCO_2 for soil carbon sequestration) to higher cost (e.g., 100-300 USD/tCO_2 for DACCS) (*medium confidence*). Estimated storage timescales vary from decades to centuries for methods that store carbon in vegetation and through soil carbon management, to ten thousand years or more for methods that store carbon in geological formations (*high confidence*).

Comment on #1:

The cost range cited here seems on the optimistic side, more so as no qualifying criteria/assumptions are given. Recent IEAGHG study 2021-05 'Global Assessment of Direct Air Capture Costs' found 350-700 USD/net-tCO_2 removed for first-of-a-kind (FOAK) DACCS plants and 150-230 USD/net-tCO_2 removed for nth-of-a-kind plants (NOAK) but can be higher for smaller scale plants of less than 1 $MtCO_2$/yr capacity (range depends on type of DAC technology, type of energy input, CO_2 transport and storage set up, plant size, cost of capital etc.; see also comments below).

TS

1. Decarbonisation options for shipping and aviation still require R&D, though advanced biofuels, ammonia, and synthetic fuels are emerging as viable options (*medium confidence*). The production of synthetic fuels using low-carbon hydrogen with CO_2 captured through DACCS/BECCS could provide jet and marine fuels but these options still require demonstration at scale (*low confidence*). Ammonia produced with low-carbon hydrogen could also serve as a marine fuel (*medium confidence*).
2. Despite limited current deployment, estimated mitigation potentials for DACCS, EW and ocean-based CDR methods are moderate to large (*medium confidence*). The potential for DACCS (5–40 $GtCO_2$/yr) is limited mainly by requirements for low-carbon energy and by cost (100-300 (full range: 84–386) USD/tCO_2). DACCS is currently at a medium technology readiness level. EW has the potential to remove 2–4 (full range: <1 to ~100) $GtCO_2$/yr, at costs ranging from 50 to 200 (full range: 24–578) USD/tCO_2. Ocean-based methods have a combined potential to remove 1–100 $GtCO_2$/yr at costs of 40–500 USD/tCO_2, but their feasibility is uncertain due to possible side-effects on the marine environment. EW and ocean-based methods are currently at a low technology readiness level.

Comment on #2:

See previous comment, the full cost range cited as this point is slightly larger but still relatively optimistic, also compare with the comment on #8 in the next section.

Main report

1. Pathways with DACCS include potentially large removal from DACCS (up to 37 $GtCO_2$/yr in 2100) in the second half of the century and reduced cost of mitigation. At large scales, the use of DACCS has substantial implications for energy use, emissions, land, and water; substituting DACCS for BECCS results in increased energy usage, but reduced land use change and water withdrawals. The level of deployment of DACCS is sensitive to the rate at which it can be scaled up, the climate goal or carbon budget, the underlying socioeconomic scenario, the availability

of other decarbonization options, the cost of DACCS and other mitigation options, and the strength of carbon cycle feedbacks. Since DACCS consumes energy, its effectiveness depends on the type of energy used; the use of fossil fuels would reduce its sequestration efficiency. Studies with additional CDR options in addition to DACCS find that CO_2 removal is spread across available options.

2. The heat required by DACCS could be effectively supplied by inherent heat energy in nuclear plants, enhancing overall system efficiency.
3. DACCS offers a modular approach to CDR, but it could be a significant consumer of energy. DAC could also interact with other elements of the energy systems as the captured CO_2 could be reused to produce low-carbon methanol and other fuels. DACCS might also offer an alternative for use of excess electricity produced by variable renewables, though there are uncertainties about the economic performance of this integrated approach.
4. The annual DACCS deployment reaches 0 [0–0.02] $GtCO_2$/yr by 2030, 0.02 [0–1.74] $GtCO_2$/yr by 2050, and 1.02 [0–12.6] $GtCO_2$/yr by 2100.
5. IAMs are starting to include other CDR methods, such as DACCS and EW, which are yet to be attributed to specific sectors in IAMs.
6. The life-cycle net emissions of DACCS systems can be negative, even for existing supply chains and some current energy mixes. The GHG-intensity of energy sources is a key factor.
7. Compared to other CDR methods, the primary barrier to upscaling DAC is its high cost and large energy requirement (*high confidence*), which can be reduced through innovation.
8. **Costs**: As the process captures dilute CO_2 (~0.04%) from the ambient air, it is less efficient and more costly than conventional carbon capture applied to power plants and industrial installations (*high confidence*) (with a CO_2 concentration of ~10%). The cost of a liquid solvent system is dominated by the energy cost (because of the much higher energy demand for CO_2 regeneration, which reduces the efficiency) while capital costs account for a significant share of the cost of solid sorbent systems. The range of the DAC cost estimates found in the literature is wide (60–1000 USD/tCO_2) partly because different studies assume different use cases, differing phases (FOAK vs. NOAK), different configurations, and disparate system boundaries. Estimates of industrial origin are often on the lower side. Fuss et al. (2018) suggest a cost range of 600–1000 USD/tCO_2 for FOAK plants, and 100–300 USD/tCO_2 as experience accumulates. An expert elicitation study found a similar cost level for 2050 with a median of around 200 USD/tCO_2 (*medium evidence, medium agreement*). NASEM (2019) systematically evaluated the costs of different designs and found a range of 84–386 USD_{2015}/tCO_2 for the designs currently considered by active technology developers. This cost range excludes the site-specific costs of transportation or storage.
9. **Potentials:** There is no specific study on the potential of DACCS but the literature has assumed that the technical potential of DACCS is virtually unlimited provided that high energy requirements could be met (*medium evidence, high agreement*) since DACCS encounters less non-cost constraints than any other CDR method. Focusing only on the Maghreb region, Breyer et al. (2020) reported an optimistic potential 150 $GtCO_2$ at less than 61 USD/tCO_2 for 2050. Fuss et al. (2018) suggest a potential of 0.5–5 $GtCO_2$/yr by 2050 because of environmental side effects and limits to underground storage. In addition to the ultimate potentials, Realmonte et al. (2019) noted the rate of scale-up as a strong constraint on deployment. Meckling and Biber (2021) discuss a policy roadmap to address the political economy for upscaling. More systematic analysis on potentials is necessary; first and foremost on national and regional levels, including the requirements for low-carbon heat and power, water and material demand, availability of geological storage and the need for land in case of low-density energy sources such as solar or wind power.

10. **Risks and impacts:** DACCS requires a considerable amount of energy (*high confidence*), and depending on the type of technology, water, and make-up sorbents, while its land footprint is small compared to other CDR methods, but depending on the source of energy for DACCS (e.g., renewables vs. nuclear), it could require a significant land footprint. For the solid sorbent technology, low-temperature heat could be sourced from heat pumps powered by low-carbon sources such as renewables, waste heat, and nuclear energy. Unless sourced from a clean source, this amount of energy could cause environmental damage. Because DACCS is an open system, water lost from evaporation must be replenished. Water loss varies, depending on technology (including adjustable factors such as the concentration of the liquid solvent) as well as environmental conditions (e.g., temperate vs. tropical climates). Some solid sorbent technologies actually produce water as a by-product. Large-scale deployment of DACCS would also require a significant quantity of materials, and energy to produce them. Hydroxide solutions are currently being produced as a by-product of chlorine but replacement (make-up) requirement of such materials at scale exceeds the current market supply. The land requirements for DAC units are not large enough to be of concern. Furthermore, these can be placed on unproductive lands, in contrast to biological CDR. Nevertheless, to ensure that CO$_2$-depleted air does not enter the air contactor of an adjacent DAC system, there must be enough space between DAC units, similar to wind power turbines. In contrast, large energy requirements can lead to significant footprints if low-density energy sources (e.g., solar PV) are used.
11. **Co-benefits:** While Wohland et al. (2018) proposed solid sorbent-based DAC plants as a Power-to-X technology that could use excess renewable power (at the time of low or even negative prices), such operation would add additional costs. Solid sorbent DAC designs can potentially remove more water from the ambient air than needed for regeneration, thereby delivering surplus water that would contribute to SDG 6 (Clean Water and Sanitation) in arid regions.
12. **Trade-offs and spill over effects:** Liquid solvent DACCS systems need substantial amounts of water, although much less than BECCS systems, which could negatively affect SDG 6 (Clean Water and Sanitation). Although the high energy demand of DACCS could affect SDG 7 (Affordable and Clean Energy) negatively through potential competition or positively through learning effects, its impact has not been thoroughly assessed yet.
13. **Role in mitigation pathways:** There are a few IAM studies that have explicitly incorporated DACCS. Stringent emissions constraints in these studies lead to high carbon prices, allowing DACCS to play an important role in mitigation. Chen and Tavoni (2013) found that incorporating DACCS reduces the overall cost of mitigation and tends to postpone the timing of mitigation. The scale of capture goes up to 37 GtCO$_2$/yr in 2100. Marcucci et al. (2017) showed that DACCS allows for a model solution for the 1.5°C target, and that DACCS substitutes for BECCS under stringent targets, capturing up to 38.3 GtCO$_2$/yr in 2100. Realmonte et al. (2019) showed that in deep mitigation scenarios, DACCS complements, rather than substitutes, other CDR methods such as BECCS, and that DACCS is effective at containing mitigation costs. Fuhrman et al. (2021a) identified a substantial role of DACCS in mitigation and a decreased pressure on land and water resources from BECCS, even under the assumption of limited energy efficiency improvement and conservative cost declines of DACCS technologies.
14. There is limited evidence to assess social-cultural, environmental/ecological, and institutional dimensions as the literature is still nascent for DACCS and EW, while these aspects are positive for blue carbon and mixed or negative for ocean fertilization.

Comment on #8:

The cost discussion in the main part of the report is more detailed and comprehensive as the ranges extracted for the SPM and TS. It becomes clear that (a) the cited range of 100-300 USD/tCO_2 is for NOAK plants, thus mainly in line with recent the IEAGHG study: and (b) the total range reported in literature is 60-1000 USD/tCO_2, the variation mainly being due to differences in configurations as well as system and spatial boundaries. The IEAGHG study concluded that long-term costs are significantly higher than the industry target of 100 USD/tCO_2 captured, except under ambitious cost-performance assumptions and favourable conditions. These favourable conditions may come to exist but commenting on the size of the opportunity is difficult. The IEAGHG DACCS report was not published in time to be considered for AR6, so it is good to see that the cost ranges are somewhat in line but the WGIII report could have included a stronger disclaimer regarding the optimistic assumptions needed that lead to the cost numbers at the lower end of the range. In addition, since no large-scale plants are built to date, inherent uncertainties on most parameters are high.

Comment on #10,11,12:

We note positively that the water and land issues related to DACCS have been discussed in a detailed and balanced way, in contrast to the WGII report. The WGIII report cites the paper by Fuhrman et al. on the food-water-energy nexus of certain NETs (especially DACCS) in the correct contexts and with substantiated conclusions. One issue which could have been discussed in more detail are the lifecycle emissions. The IEAGHG report on DACCS found that emissions are primarily associated with the energy inputs (electricity and heat) and upstream methane emissions if natural gas is used in the process (such as in FOAK liquid DACCS processes). The lifecycle emissions associated with DACCS range from 7-17% of the CO_2 captured for FOAK plants and 3-7% for NOAK plants (if low carbon energy is used). Therefore, reducing the carbon intensity of energy sources is of paramount importance.

Conclusions and IEAGHG actions

In conclusion, we need immediate and deep reductions across all sectors otherwise 1.5°C is out of reach. Options described to reduce emissions focus on the high-emitting energy and industry sectors. Some mitigation options can reduce environmental impacts, enhance health and increase employment and business opportunities. As climate change is the result of more than a century of unsustainable energy and land use, lifestyles and patterns of consumption and production, the report shows how taking action now can move us towards a fairer, more sustainable world. In the energy sector major transitions are required and reducing fossil fuel use and using CCS is one option listed, followed by the other low-carbon options. Decarbonising the transport sector relies substantially on decarbonising the power sector. Achieving net zero in industry sectors is challenging, but CCS is a solution. CDR will be necessary to achieve net-zero and engineered CDR such as DACCS and BECCS need to be proven at scale, and to have agreed monitoring, reporting and verification (MRV) of its GHG achievements.

As well as working on CCS for 30 years, IEAGHG is increasingly working on engineered CDR, including DACCS, and addressing the issues emphasised by this new IPCC report. IEAGHG were expert reviewers and provided nearly 100 substantive comments to the WGIII draft reports, which appear to have been acted upon, and we are pleased to see IEAGHG reports and papers being cited.

Reference list:

Climate Change 2022: Mitigation of Climate Change:

https://www.ipcc.ch/report/ar6/wg3/

IEAGHG (2022), 2022-IP03: "IPCC approves the Summary for Policymakers for Working Group III Mitigation of Climate Change"

Further Reading (incl. IEAGHG reports and papers cited in WGIII report):

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Fuhrman, J., McJeon, H., Patel, P. et al. Food–energy–water implications of negative emissions technologies in a +1.5 °C future. Nat. Clim. Chang. 10, 920–927 (2020). https://doi.org/10.1038/s41558-020-0876-z

Jasmin Kemper

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