Towards net zero – Carbon dioxide removal and utilisation

Insights from the Australian-German Energy Transition Hub

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About the Australian-German Energy Transition Hub

The Australian-German Energy Transition Hub is a bilateral initiative for applied research on energy transition opportunities. The Hub is supported by the Australian Department of Foreign Affairs and Trade and the German Federal Ministry for Education and Research.

The Hub brings together leading research organisations that are central to energy transition in each country. The Hub is providing an innovative and effective architecture for collaboration. Virtual conferencing and regular collaborations through video conferencing are enabling close working relationships and knowledge exchange. It is fostering closer links between researchers, industry, and government entities.

The bilateral relationship between Australia and Germany is strengthened through Hub research, dialogue, and stakeholder engagement that helps to identify and harness the opportunities for both countries in the transition to a net-zero emissions world economy. It has highlighted the complementary opportunities created by Germany's *Energiewende* experience and Australia's substantial energy and mineral resources. This is clearly evident two years into the Energy Transition Hub. Faster identification of policy lessons and investment and trade opportunities, and a deeper exchange of useful research methods and findings, are being enabled through this initiative.

The Hub is co-led by the University of Melbourne and the Australian National University in Australia. In Germany, the Hub is co-led by the Potsdam Institute for Climate Impact Research, the Mercator Research Institute for Global Commons and Climate Change, and the University of Münster. In addition to these five core partners, the Hub now has eight research partners: five in Australia and three in Germany.

This document presents some of the principal findings of research supported through the Hub. A more comprehensive collection of research, web tools and engagement undertaken is available at the Energy Transition Hub website energy-transition-hub.org

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INTRODUCTION

Energy transition is happening globally and in Australia and Germany. It is occurring in response to rapidly changing technology costs and as countries move to implement policies in line with the Paris Agreement goals. This transition poses policy and technological challenges. If managed well, it can also deliver great economic opportunities in both Australia and Germany.

Insights about the implications of the global energy transition for Australia and Germany that have become evident from the Energy Transition Hub's work include:

1. Rapid deployment of renewables in Australia is an essential part of a cost-efficient transition to a net-zero emissions economy. There is the potential to create an export industry based on Australia's renewable energy resources (as much as, or even more than, doubling Australia's domestic electricity demand).
2. Substantial and complementary export opportunities emerge for Germany and Australia as a result of the move to energy networks powered by renewables, electrification of other sectors of the economy, the transition to zero-emissions synthetic fuels and growing demand for zero-emissions metals and energy intensive goods.
    - Australia, with its plentiful wind and solar energy resources, available land, and stable regulatory and institutional environment, is well positioned to become a leading exporter of renewable energy and renewable-based energy-intensive goods.
    - Germany, as a leading manufacturer and engineering innovator of energy transition technologies, can benefit from an increasingly global deployment of technologies for renewable energy generation, storage and the electrification of energy end-uses.
3. Large-scale carbon dioxide removal (CDR) is another essential component of any transition that limits warming to 1.5°C, or even to 2°C, unless the pace of mitigation to 2030 increases significantly. CDR is needed to complement the transformation in other sectors: it is not an alternative to rapid deployment of low-emissions technologies across the economy. CDR could create opportunities for Australia as a source of nature-based solutions, bioenergy with carbon capture and storage (BECCS) or direct air capture with CCS (DACCS), and for Germany as a provider of carbon capture and utilisation (CCU) technologies.
4. Policy has an important role to play. A cost-effective, timely energy transition that unlocks the potential for new industries, supports affected regions, and protects ecosystems is not guaranteed – it is an outcome achievable in both Germany and Australia with effective policy.

Recent work on these issues is summarised in a series of papers. This report addresses some of the questions that arise in relation to the third point. Specifically, it covers carbon dioxide removal and utilisation.

SUMMARY

Carbon dioxide removal (CDR) technologies aim to suck carbon dioxide (CO_2) from the atmosphere. These technologies need to accompany rapid and sustained greenhouse gas (GHG) emission reductions to achieve net-zero emissions and keep global warming well below 2°C as agreed in the Paris Agreement. CDR technologies include relatively simple options like planting more trees, restoring forests, or crushing rocks that naturally absorb CO_2 and spreading them on soils so that they remove CO_2 more rapidly. Other technological options include using chemicals to absorb CO_2 directly from the air (DACCS), or burning plants for energy and capturing the CO_2 (BECCS). Any captured CO_2 has to be stored over long timescales in soils, trees, geological reservoirs, oceans or mineral rocks.

A broad scientific assessment of CDR in climate change mitigation is emerging, even though some land-based options such as afforestation, reforestation or soil carbon sequestration have been discussed for many years. Hub research has made important contributions to developing such an understanding by comprehensively synthesising insights from more than 2,000 individual studies and by closing key knowledge gaps. These scientific contributions have had a significant impact on global and national climate policy assessments. With dedicated engagement efforts, the Hub has successfully informed research, policy and broader societal discourses on CDR in Germany and Australia. Important insights have emerged from this first phase of Hub research:

- **Paris climate goals depend on the availability of CDR**: Limiting warming to 1.5°C depends on large-scale CDR, as does the 2°C goal, unless there is a significant increase in mitigation action before 2030.
- **Most CDR options show the potential for large-scale deployment, but all have limits**: The technical feasibility and viability of large-scale CCU and CCS is unclear. Land-based CDR must not compromise achievement of ecological and agricultural productivity benefits or the sustainable development goals (SDGs).
- **There is an innovation gap for CDR**: Key technologies are still in the early stage of development, but modelling shows substantial deployment is already needed between 2030 and 2050. The urgency of the need for R&D and commercialisation of CDR is not widely appreciated.
- **CCU can deliver new opportunities for climate policy and innovation**: CCU could accelerate the maturing of CO_2 capture technologies by providing new niche markets and new business opportunities, possibly reduce net costs of emission reduction, and help to decarbonise sectors with few other options. Several technology pathways could deliver significant amounts of CO_2 utilisation and storage.
- **CDR presents opportunities for both Australia and Germany**: Australia could be a significant source of land-based CDR using nature-based solutions. This can deliver co-benefits for biodiversity, ecosystem services, and agricultural productivity. Australia could also be major supplier of DACCS or BECCS. The need for accelerated development of CDR and CCU technologies could be an opportunity for an innovation country like Germany. Having played a key role in developing sound knowledge of the role of CDR in climate change mitigation, future Hub research could provide tailored information for guiding national CDR efforts in Australia and Germany.

The role of CDR in limiting warming to 1.5°C and 2°C

Substantial amounts of CDR will be needed to complement rapid and sustained emission reduction efforts to limit global warming to well below 2°C (*Fuss et al., 2018; IPCC, 2018; Minx et al., 2018; Strefler et al., 2018*). The underlying reason is the limited remaining CO2 budget for achieving the Paris climate goals. To stay within the carbon budget, emissions will have to reach net zero (*IPCC, 2013; Meinshausen et al., 2009*). As not all global emissions can be avoided, CDR will be required to compensate for the residual GHG emissions that are too difficult to mitigate (*Kriegler et al., 2018; Luderer et al., 2018*). Examples of such residual emissions are some from aviation or heavy industry, nitrous oxide emissions from fertilizer application and methane emissions from cattle ranching. CDR might also be required because global efforts to curb GHG emissions have been insufficient so far. The transition towards a net-zero carbon society may therefore involve temporarily exceeding the remaining carbon budget to limit global warming to well below CO2. As with a bank loan, these emissions need to be paid back in the future by going beyond net zero towards net atmospheric CO2 removal. These key tasks of CDR in climate change mitigation are illustrated in Figure 1 (*Fuss et al., 2018; Minx et al., 2018*).

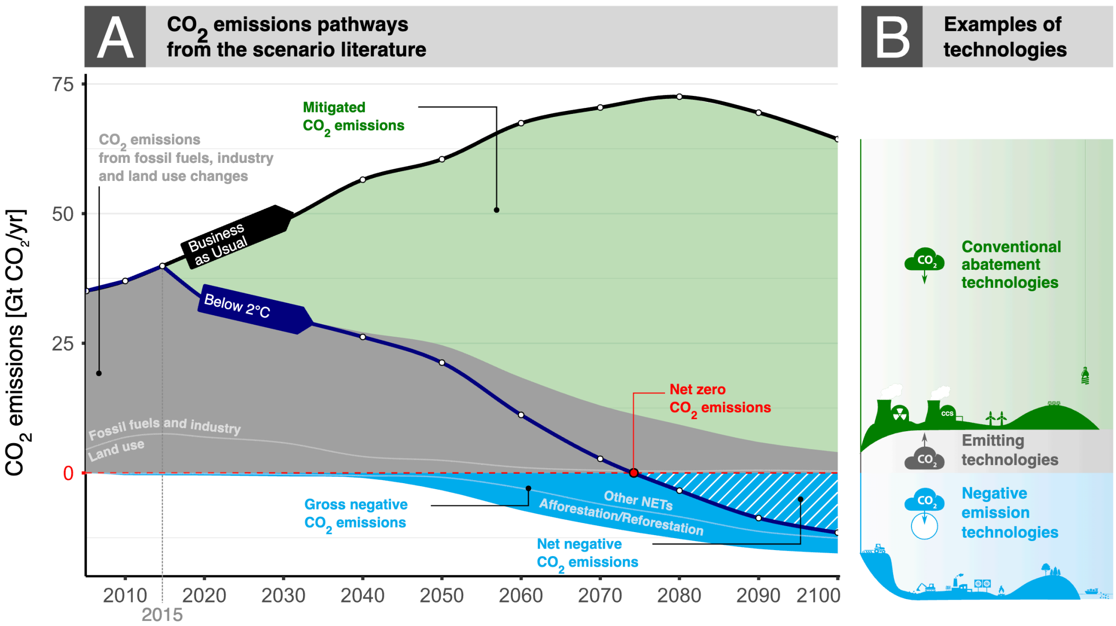

Figure 1: *The role of CDR in a scenario consistent with a 66 percent chance of keeping warming below 2°C relative to a baseline scenario.*
CDR can: 1. Help reduce net emissions faster (between 2040 and 2075 in this scenario);
2. Compensate for residual emissions to enable a zero-carbon economy; and
3. Compensate for earlier carbon budget overshoot (hatched blue area).
Cumulative gross CDR is represented by the entire blue area. Source: Fuss et al., (2018)

Hub research has played a crucial role in developing a robust understanding of the role of CDR in climate change mitigation. Hub research has made the largest contribution to date in synthesising and reconciling knowledge on the state of CDR (*Fuss et al., 2018; Hilaire et al., 2019; Minx et al., 2018; Nemet et al., 2018; Smith et al., 2019*). This research highlights that keeping warming below 1.5°C requires large-scale deployment of CDR, but this dependence can still be kept to a minimum for the 2°C warming limit if there are immediate, sustained and rapid emissions reductions (*Fuss et al., 2018; Minx et al., 2018*).

Hub research has also closed important knowledge gaps. For example, Hub researchers show that the amount of CDR needed depends crucially on the level of short-term ambition. If the levels of ambition of nationally determined emissions reduction targets are not increased before 2030, even the 2°C limit can no longer be achieved without substantial amounts of CDR (*Strefler et al., 2018*). Also, the CDR discussion was expanded to include a dedicated energy systems perspective by bringing in a focus on integration aspects for large-scale adoption of BECCS and DACCS (see Box) respectively (*Creutzig et al., 2019*).

Box: What is Carbon Dioxide Removal?

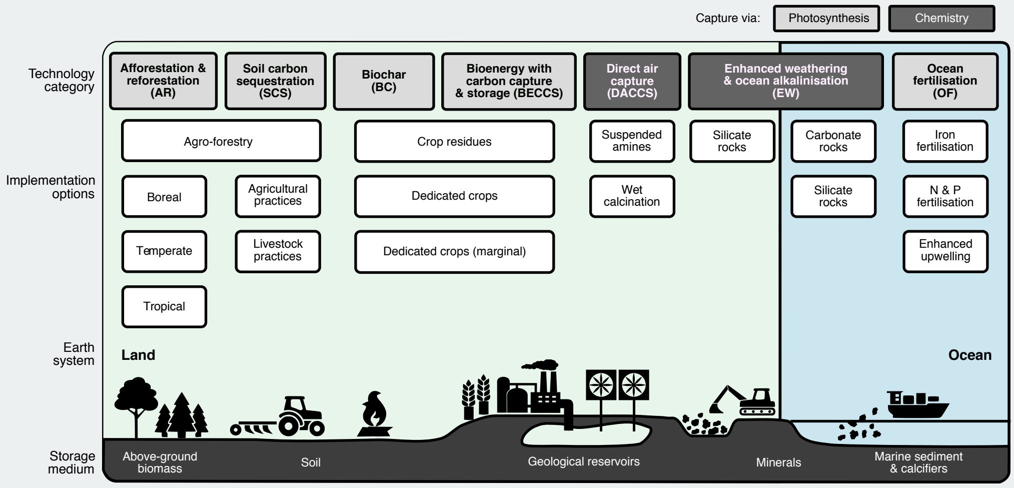

Figure 2 – A taxonomy of carbon dioxide removal technologies (Source: Minx et al., 2018)

CDR is an intentional human effort to remove CO_2 from the atmosphere. CDR technologies can be distinguished by their capture process, the earth system in which they operate, and the storage medium, as shown (Figure 2). Major CDR options include:

- **Afforestation and reforestation (AR):** Additional trees are planted, capturing CO_2 from the atmosphere as they grow. The CO_2 is then stored in living biomass.
- **Biochar (BC):** BC is created by pyrolysis of biomass, making it resistant to decomposition; it is then added to soil to store the embedded CO_2.
- **Soil carbon sequestration (SCS):** SCS stores additional atmospheric carbon in soils by increasing inputs or reducing losses e.g. through enhanced agricultural practices such as conservation tillage, soil fertility optimisation or improved crop residue management.
- **Ocean fertilisation (OF):** Iron or other nutrients are added to the ocean, stimulating phytoplankton growth and increasing CO_2 absorption. When the plankton dies, it sinks to the deep ocean and permanently sequesters carbon.
- **Bioenergy with carbon capture and storage (BECCS):** Plants turn CO_2 into biomass, which is then combusted in power plants, a process that is ideally CO_2 neutral. If CCS is then applied, CO_2 is removed from the atmosphere.
- **Enhanced weathering and ocean alkalinisation (EW):** Minerals that naturally absorb CO_2 are crushed and spread on fields or the ocean; this increases their surface area so that CO_2 is absorbed more rapidly.
- **Direct air capture and storage (DACCS):** Chemicals are used to absorb CO_2 directly from the atmosphere; this is then stored in geological reservoirs.

Technical feasibility and viability of CDR options

Hub research has looked at the potential of individual technologies. Within the range of CDR technologies (see Box) most have substantial potential for removing atmospheric CO_2 at the gigatonne-scale, except ocean fertilisation. Yet, all these technologies have limits and scale-dependent risks. There is no silver-bullet technology. However, it is not yet clear which CDR approaches and technologies will be the most viable and effective in the timeframes and conditions required to support achievement of the Paris Agreement goals without undermining other social and ecological objectives (*Fuss et al., 2018; Minx et al., 2018*).

Risks associated with increasing reliance on CDR deployment to achieve the Paris Agreement goals include (*Fuss et al., 2018; Minx et al., 2018; Smith et al., 2019*):

- Ecological risks, e.g. large bioenergy plantations could result in biodiversity loss, enhanced nitrogen pollution, and enhanced water scarcity – these risks are particularly relevant to AR and BECCS.
- Technological risks relate to technical feasibility and readiness, carbon removal potential, and the ability to deliver CDR at the scale required in the modelled pathways consistent with Paris Agreement goals – these risks are most relevant to CCS and CCU.
- Institutional risks relate to financing large amounts of net-negative emissions – these risks are relevant to all forms of CDR in different ways.

The risks and the ethics of alternative approaches to large-scale CDR need to be carefully evaluated. This point is prominently highlighted by Hub researchers in a paper in the scientific journal *Nature* (*Lenzi et al., 2018*). As risks tend to scale with deployment level, it seems most plausible to develop portfolios of multiple CDR technologies that can hedge the various scale-dependent risks (*Minx et al., 2018*). These findings are complemented by further work from Hub researchers who argue that there is a need to consider communication and engagement around CDR carefully to avoid the political polarisation that has constrained conventional climate action (*Colvin et al., 2019*).

State of innovation in CDR

Hub research has also identified a large innovation gap in CDR that jeopardises the availability of relevant technologies at the scales required to keep global warming well below 2°C. Climate change mitigation scenarios highlight that although CDR technologies play a key role in the second half of the 21st century for 1.5°C and 2°C scenarios, the major period of new CDR deployment is between 2030 and 2050. The broader innovation literature consistently finds long time periods involved in scaling up and deploying novel technologies. The urgency to developing CDR technologies is not widely appreciated and is not reflected in scientific nor policy discussions (*Nemet et al., 2018*).

State of innovation in CDR

Consider the experience of arguably the most dynamic low-carbon innovation so far: solar photovoltaic (PV) panels (Figure 3). It took 60 years after the first commercial use, the Vanguard-1 satellite in 1957, to reach the current state in which solar PV is lower cost than coal and gas in sunny places. By 2030 solar is expected to be widely adopted and could - with coordinated advances in multiple components of the energy system - supply 30 to 50 percent of electricity in competitive markets in the long-run (*Creutzig et al., 2017*). The first commercial direct CO_2 air capture system came online last year. If air capture is to follow a similar timeline to solar, it will become low-cost in 2077 and attain widespread adoption by 2100. Climate change mitigation scenarios show that this would be far too late.

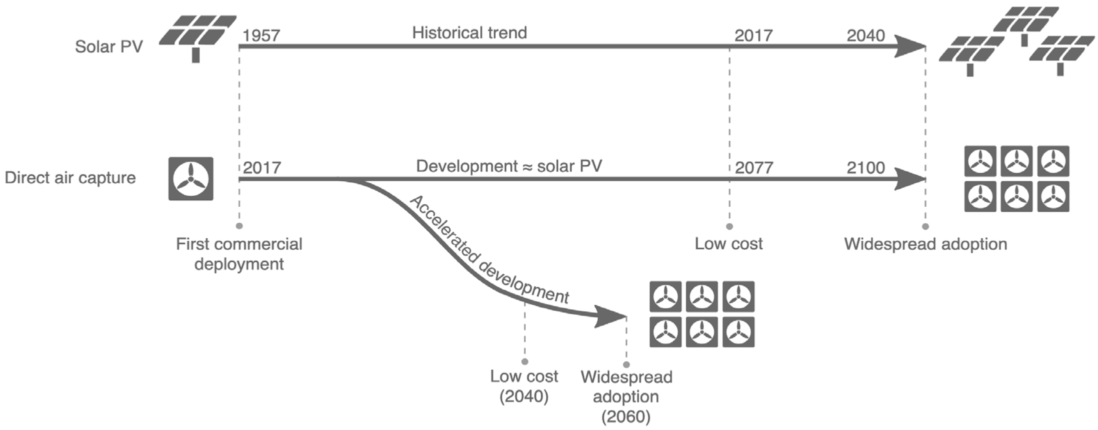

Figure 3 *– Learning on CDR needs to be much faster than for solar PV, which is a prominent example for rapid development. If air capture follows a similar timeline to solar, it will not be low-cost until 2077 or attain widespread adoption until 2100. Policies and institutions for accelerated learning are required. Source: William Lamb, MCC*

Closing the innovation gap in CDR is crucial for meeting the Paris climate goals. The innovation process for carbon removal must be accelerated to ensure that technologies are available in time at the scale needed. Innovation countries such as Germany play a key role; this is another avenue for opportunities to build a prosperous, competitive and climate-neutral economy.

If CDR technologies are to be deployed at the levels required to meet 1.5°C and 2°C targets, then important post-R&D issues will need to be addressed, including incentives for early deployment, niche markets, scale-up, demand, and—particularly if deployment is to be hastened—public acceptance (*Minx & Nemet, 2018*).

Hub Research at the Science-Society-Policy Interface

Even though CDR is important for reaching international climate goals and achieving net-zero emissions, the issue has only very slowly penetrated from science into policy and wider societal debates. Hub researchers have examined the dynamics of working across the climate science-policy interface, drawing lessons for effective and responsible knowledge sharing between domains (*Lacey, Howden, Cvitanovic, & Colvin, 2018*). On CDR, Hub activities have made important contributions in mainstreaming key scientific insights and stimulating a more informed debate at multiple levels.

Internationally, Hub research has delivered key inputs for important international climate policy assessments such as the IPCC Special Report on global warming of 1.5°C (*de Coninck et al., 2018; IPCC, 2018*), the IPCC Special Report on Climate Change and Land (*IPCC, 2019*) and the recent CDR assessment of National Academy of Sciences (*National Academy of Science, 2018*). This was followed by multiple contributions to discussions at COP24 in Katowice and written expert inputs into the UNFCCC process. An open access website on CDR brings together the state of knowledge on CDR technologies (https://co2removal.org/).

At the national level, the Hub has been instrumental in generating informed dialogue on CDR in Europe and Australia through:

- Organising four CDR roundtables in Germany over 2018 and 2019 with participants from the European Commission, several German government departments, environmental NGOs, and industry associations as well as unions;
- Organising the first Negative Emissions Conference in Australia (*Canberra, 2018*), and a subsequent roundtable focused on engineering aspects of negative emissions technologies (*Melbourne, 2019*);
- Translating key results in open editorials of newspapers, their online publications, and other media such as the Washington Post, CarbonBrief or Wirtschaftswoche; and
- Radio appearances in Germany and Australia.

Land-based CDR and natural climate solutions

The extensive land demand of afforestation and bioenergy for BECCS can amplify social risks if it displaces food production or is implemented in a form that negatively impacts ecosystems. These risks have been well documented, including by Hub researchers (*Dooley & Kartha, 2018; Smith et al., 2019*). CDR from nature-based solutions (NBS) could, however, support achievement of the SDGs and provide ecosystem services if implementation is well managed. Hub research comprehensively describes the link to ecosystem services, highlighting how climate protection could actively reduce hunger and poverty (*Smith et al., 2019*).

NBS come with significant co-benefits for biodiversity, ecosystem services, and local and indigenous communities. The global potential of NBS through four ecosystem-based land-management pathways was assessed by Hub researchers (*Meinshausen and Dooley, 2019*). A peak global CDR rate of 9 $GtCO_2$ per year from NBS, resulting in cumulative sequestration of 550 $GtCO_2$ by 2150, could be achievable after accounting for saturation times and maximum carbon density. This scale of CDR is equivalent to historical loss of carbon from the biosphere. The full sequestration potential would be required for 1.5°C compliant pathways (*Meinshausen & Dooley, 2019*).

Australia has significant potential for NBS, given its large land area and the extent of natural forest cover prior to land-clearing. Australian native forests contain some of the most carbon-dense forest ecosystems in the world. Specifying the potential for both natural ecosystems and agricultural landscapes to contribute to CDR in Australia is an important area for future Hub research. There is a range of cost-effective on-farm options for achieving net-negative emissions in the Australian agriculture sector (*Myer, n.d.*). The specific governance, technical and implementation requirements to support CDR through NBS requires additional work at both national and local scales.

There are benefits and risks from this magnitude of mitigation from nature-based terrestrial sinks. The benefits to biodiversity, ecosystem services, watershed protection, food security, agricultural productivity and resource dependent communities, are well documented (*Dooley & Kartha, 2018; Smith et al., 2019*). The key risk of NBS is sink reversal as a result of climate change. This risk is minimised when the focus is on restoration of ecosystems, which increases resilience to climate impacts compared to other terrestrial sinks such as afforestation resulting in large areas of plantations (*Dooley & Kartha, 2018*).

Carbon capture and storage

CCS could enable the mitigation of CO_2 from fossil fuel use and industrial processes that are difficult to avoid (*IPCC, 2005; Kriegler et al., 2014*). Two of the most prominent CDR technologies, DACCS and BECCS, rely on CCS (*Hilaire et al., 2019; Minx et al., 2018*). Australia has geological formations that may be suitable for large-scale CCS, land areas necessary for BECCS, and renewable energy resources needed for DACCS.

Several challenges still need to be addressed regarding CCS. First, it has been studied and successfully tested at small scale, but large-scale applications have not yet been seen. Second, widespread deployment would also require building a CO_2 transport infrastructure. This infrastructure may initially need public finance and, in the European case, could require a change in international law to enable transnational transportation. Finally, CCS may also face social acceptance problems, which have already hindered adoption in Germany and many other European countries. Governance and legal issues regarding transnational transportation, liability issues, and finance need to be clarified soon if CCS is to play a role consistent with the modelled pathways for limiting warming to 1.5°C or 2°C.

Carbon capture and utilisation

CCU-based synthetic fuels could be viable options for sectors and applications in which direct electrification is difficult due to technical, economic or behavioural barriers. These include some high-temperature industrial processes, aviation, and to some extent, freight transport.

Further work is needed to assess the likely role of CCU and to determine the viability and climate mitigation potential of different technologies. CCU is a term used to describe a wide variety of processes; consensus on a precise definition is yet to be achieved, adding confusion over its potential role in mitigation. The first systematic map of technologies defined as CCU, viability and constraints is being undertaken by Hub researchers (*Vicente Vicente, 2019*). Hub researchers also contributed to the first comprehensive assessment of ten different CCU options for the journal *Nature*, finding that all ten could scale to over 0.5 Gt CO_2 annually (*Hepburn et al., 2019*). Finally, in a third paper (*Ueckerdt et al., 2019*), Hub researchers analyse the potential role of different CCU conversion routes for climate change mitigation, which depend on two factors (illustrated in Figure 4):

1. The source of CO_2: whether it is from fossil fuels or the atmosphere. If synthetic fuels (e.g. renewable methane) re-use CO_2 of fossil origin (such as from a traditional coke-based steel plant) this still results in a net flow of CO_2 from geological reservoirs to the atmosphere. Double use of CO_2 can at best yield a halving of emissions, if efficiency losses and leakage are ignored. By contrast, if CO_2 from biomass or air capture is used instead, a large carbon cycle that includes the atmosphere can be closed, and synthetic fuels can become carbon neutral.
2. The type of usage and thus lifetime of a CCU product: whether the storage provided is short-term, as in synthetic fuels (energetic usage), medium-term, as in some plastics or polymers, or long-term, as in building materials (material usage).

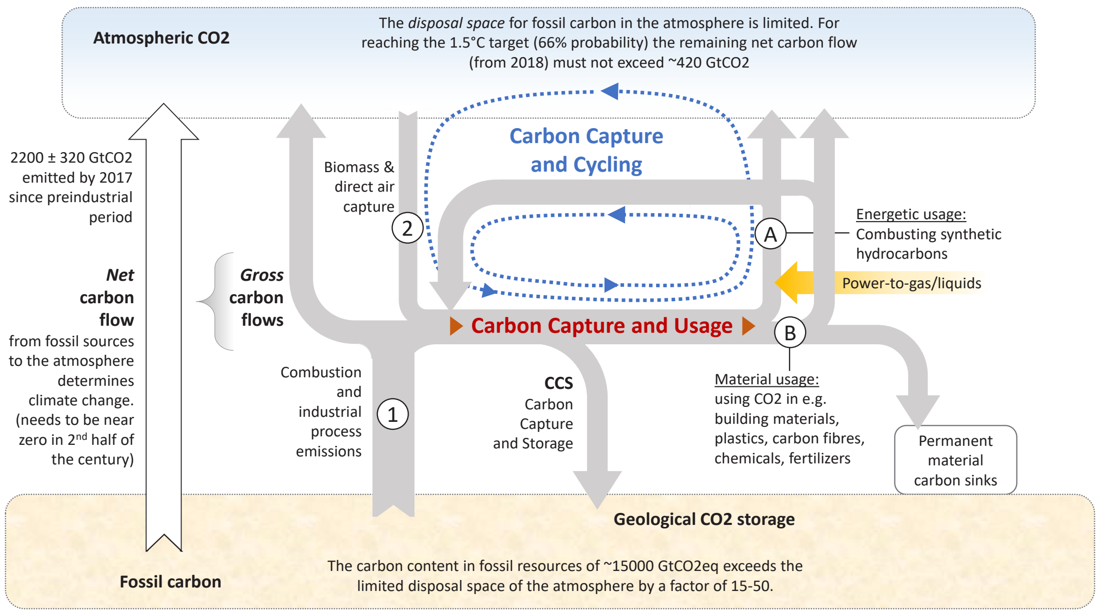

Figure 4: An integrated overview of energy and industry-related carbon flows illustrating established carbon management options and newly emerging CCU options, including carbon capture and cycling. The white arrow on the left shows the net carbon flow from fossil sources into the atmosphere as a result of the gross flows shown in grey on the right side. Source: Ueckerdt et al., 2019.

BIBLIOGRAPHY

Colvin, R. M., Kemp, L., Talberg, A., De Castella, C., Downie, C., Friel, S., … Platow, M. J. (2019). **Learning from the Climate Change Debate to Avoid Polarisation on Negative Emissions**. *Environmental Communication*. https://doi.org/10.1080/17524032.2019.1630463

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). **The underestimated potential of solar energy to mitigate climate change**. *Nature Energy*, 2, 17140.

Creutzig, F., Breyer, C., Hilaire, J., Minx, J., Peters, G. P., & Socolow, R. (2019). **The mutual dependence of negative emission technologies and energy systems**. *Energy and Environmental Science*. https://doi.org/10.1039/c8ee03682a

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., … Hourcade, J.-C. (2018). **Strengthening and implementing the global response**. In *Global Warming of 1.5 C an IPCC special report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.

Dooley, K., & Kartha, S. (2018). **Land-based negative emissions: Risks for climate mitigation and impacts on sustainable development**. *International Environmental Agreements: Politics, Law and Economics*. https://doi.org/10.1007/s10784-017-9382-9

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., … Minx, J. C. (2018). **Negative emissions—Part 2: Costs, potentials and side effects**. *Environmental Research Letters, 13(6), 063002*. https://doi.org/10.1088/1748-9326/aabf9f

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., … Williams, C. K. (2019). **The technological and economic prospects for CO_2 utilisation**. *Revised and Resubmitted*.

Hilaire, J., Minx, J. C., Callaghan, M. W., Edmonds, J. E., Nemet, G. F., Rogelj, J., & del Mar Zamora, M. (2019). **Negative emissions and international climate goals - learning from and about mitigation scenarios**. *Climatic Change, accepted*.

IPCC. (2005). **IPCC special report on carbon dioxide capture and storage**. Prepared by working group III of the Intergovernmental Panel on Climate Change. In *IPCC Special Report on Carbon Dioxide Capture and Storage*. https://doi.org/10.1002/anie.201000431

IPCC. (2013). **Climate Change 2013: The Physical Science Basis**. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, … P. M. Midgley, Eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324

IPCC. (2018). **Global Warming of 1.5 °C** *an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.* Retrieved from http://www.ipcc.ch/report/sr15/

IPCC. (2019). **Special Report on Climate Change and Land**. Geneva. Retrieved from https://www.ipcc.ch/report/srccl/

Kriegler, E., Luderer, G., Bauer, N., Baumstark, L., Fujimori, S., Popp, A., … Van Vuuren, D. P. (2018). **Pathways limiting warming to 1.5°C: A tale of turning around in no time?** *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.* https://doi.org/10.1098/rsta.2016.0457

Kriegler, E., Weyant, J. P., Blanford, G. J., Krey, V., Clarke, L., Edmonds, J., … Vuuren, D. P. Van. (2014). **The role of technology for achieving climate policy objectives : overview of the EMF 27 study on global technology and climate policy strategies**, 353–367. https://doi.org/10.1007/s10584-013-0953-7

Lacey, J., Howden, M., Cvitanovic, C., & Colvin, R. M. (2018). **Understanding and managing trust at the climate science-policy interface**. *Nature Climate Change*. https://doi.org/10.1038/s41558-017-0010-z

Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., & Minx, J. C. (2018). **Don't deploy negative emissions technologies without ethical analysis**. *Nature, 561(7723),* 303–305. https://doi.org/10.1038/d41586-018-06695-5

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., … Kriegler, E. (2018). **Residual fossil CO 2 emissions in 1.5-2 °C pathways**. *Nature Climate Change*. https://doi.org/10.1038/s41558-018-0198-6

Meinshausen, M., & Dooley, K. (2019). **Mitigation scenarios for non-energy GHG**. In *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5C and +2C*. https://doi.org/10.1007/978-3-030-05843-2_4

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., … Allen, M. R. (2009). **Greenhouse-gas emission targets for limiting global warming to 2°C**. *Nature, 458(7242),* 1158–1162. Retrieved from http://dx.doi.org/10.1038/nature08017

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., … del Mar Zamora Dominguez, M. (2018). **Negative emissions—Part 1: Research landscape and synthesis**. *Environmental Research Letters, 13(6),* 063001. https://doi.org/10.1088/1748-9326/aabf9b

Minx, J. C., & Nemet, G. F. (2018). **The inconvenient truth about carbon capture**. *Washington Post*. Retrieved from The inconvenient truth about carbon capture

Myer, R. (n.d.). **The challenge of achieving net negative emissions in a productive Australian agricultural sector: a review of emission sources and the potential of mitigation options**.

National Academy of Science. (2018). *Negative Emissions Technologies and Reliable Sequestration: a Research Agenda. National Academies Press.*

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., … Smith, P. (2018). **Negative emissions—Part 3: Innovation and upscaling**. *Environmental Research Letters, 13(6),* 063003. https://doi.org/10.1088/1748-9326/aabff4

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., … Keesstra, S. (2019). **Impacts of Land-Based Greenhouse Gas Removal Options on Ecosystem Services and the United Nations Sustainable Development Goals**. *Annual Review of Environment and Resources*. https://doi.org/10.1146/annurev-environ-101718-033129

Strefler, J., Bauer, N., Kriegler, E., Popp, A., Giannousakis, A., & Edenhofer, O. (2018). **Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs**. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/aab2ba

Ueckerdt, et al. (2019). **Carbon capture and utilization (CCU) for climate change mitigation – silver bullet or placebo**? *Manuscript in Preparation*.

Vicente Vicente, et al. (2019). **A systematic map of carbon capture and utilization.** *Manuscript in Preparation*.