Swiss Re Institute

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The insurance rationale for carbon removal solutions

Executive summary

Carbon removal is required to achieve net-zero emissions by 2050 and net-negative emissions long thereafter.

Carbon removal is the capture and permanent storage of carbon dioxide (CO_2) from the atmosphere. To limit global warming to 2015 Paris Accord levels, the world's net emissions of greenhouse gases need to drop to zero by 2050. Thereafter, there will still be work to do to sustain net-negative emissions through the second half of the century. Zero emissions is far from reality. Even with actions to transition to a low-carbon economy, global emissions are still rising, and it may take many decades to fully decarbonise some sectors. Therefore balancing residual and reversing historical emissions will require billions of tonnes of negative emissions up to and after 2050.

For net-zero, emissions need to be reduced and residuals removed.

In this context, scaling the deployment of carbon removal technologies and activities will be central to keeping global warming at safe levels over the long term. "Net-zero emissions" has become common parlance in the public and private sectors, an acknowledgment of the need to: 1) double-down on emission reduction efforts; and 2) build a carbon removal industry capable of delivering negative emissions at the speed (within three decades) and scale (10–20 billion tonnes per year) that climate science says will be required to enable sustainable living for future generations.

Without carbon pricing or policy mandates, carbon removal has lacked a business case. Nevertheless, the industry is now gaining a foothold.

The main barrier to deployment of carbon removal is lack of business case. In the absence of carbon pricing in many parts of the world, society disposes of carbon into the atmosphere at will. A sufficiently high fee on emissions would internalise expected negative externalities, and foster low-carbon decision making in production and consumption. In the absence of a fee and policy mandates, there is little incentive to cut, let alone collect and store emissions. That said, recent years have seen the emergence of first commercial providers of carbon removal services and also marketplace initiatives to commoditise carbon removal outcomes.

Nature-based solutions make use of scarce land resources, but come with many co-benefits.

Carbon in the atmosphere can be captured and stored through different means. The least cost-intensive involves sequestering carbon in forests, wetlands, oceans and soil. When executed properly, these so-called nature-based solutions address multiple sustainability goals, including adaptation to climate change and preserving the integrity of ecosystems and biodiversity. But there can be opportunity costs, such as afforestation projects competing with agriculture for land resources. Moreover, nature-based solutions are susceptible to reversal through catastrophe events like fires and floods, and/or man-made threats (eg, deforestation).

Technical solutions for carbon removal carry higher costs, but the risk of storage reversal is lower.

There are also technological solutions for removal. Carbon can be filtered from the atmosphere and used as commercial goods in long-lived products like concrete. CO_2 can also be contained and mineralised in underground rock layers, for instance in depleted oil and gas reservoirs. The implementation costs of these solutions are higher than for nature-based approaches, and existing solutions are under-deployed and new ones under-developed. Importantly, however, the risk of reversal is lower.

Re/insurers can support the carbon removal industry developments by taking on some of the associated risks,…

The re/insurance industry can assist with scaling-up of the carbon removal industry in three ways. First, re/insurers can improve the bankability of carbon removal projects by providing compensation for losses in the case of adverse events. Standard engineering policies (eg, contractors all risk policies) can cover the construction, operation and deconstruction risks of carbon removal facilities (for air filters, CO_2 pipelines, or injection rigs among others). And standard property insurance, including for losses resulting from natural disasters, can cover technology infrastructure and natural assets like forests. More challenging are potential long-term liability exposures arising from the risk of carbon storage reversal.

…by making long-term investments in removal projects and infrastructure, and by buying carbon removal services

Second, as institutional investors re/insurers can provide financing for removal projects and infrastructure. Carbon removal is a long-term investment opportunity through which re/insurers can balance their long-term liabilities, and run a net-zero emissions asset portfolio strategy. And third, re/insurers can be early buyers of carbon removal certificates to balance their own operational footprint in pursuit of net-zero emissions. That footprint is small relative to other sectors, making first-mover removal projects more affordable. By entering long-term offtake agreements and guaranteeing future revenues, re/insurers can be strong partners for the carbon removal industry, while also gaining access to its new risk pools and asset classes.

The case for carbon removal

A warming world

Carbon emissions have caused global temperatures to rise by 1.0°C already.

Rising temperatures are causing climate change effects of increasing visibility, frequency and severity. The increase in global temperatures is due to anthropogenic (man-made) greenhouse gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC), human activity has caused approximately 1.0°C of global warming from pre-industrial levels.[1] Since the beginning of the industrial revolution, humans have released 2 200 billion tonnes of carbon dioxide (CO_2) into the atmosphere,[2] half of it during the last three decades alone.[3] Currently, the world emits around 40 billion tonnes of CO_2 annually. Unabated, this emission rate would see the +1.5°C warming limit of the Paris target reached in 10 years, and the +2°C limit in 30 years.[4] By the end of the century, temperatures would rise by between 3.7°C and 4.8°C.[5] Even if all emissions are halted immediately, GHGs will remain in the atmosphere for many centuries, exacerbating the impacts of climate change.[6]

The effects of climate change are far reaching and will impact nature, humans, and the global economy.

Climate change is a systemic threat, with far-reaching consequences for the world and life as we know it. Increasing temperatures are melting the planet's ice reservoirs and warming the oceans. Together these are leading to rising sea levels, and an increase in the frequency and severity of extreme weather events such as droughts, hurricanes or torrential rains. Beyond lasting implications on natural ecosystems – with climate change seen as one of the most important drivers for future biodiversity loss and ecosystem degradation – these physical changes will likely cause increased mortality and damage to human health, food and water scarcity, disease spread and more damage to and devaluation of property assets.[7] From a broad economic perspective, a recent Swiss Re Institute report estimates that unabated from today, the physical effects of warming temperatures could result in an 18% loss to global gross domestic product by mid-century, relative to a world of no climate change.[8]

A call by climate science

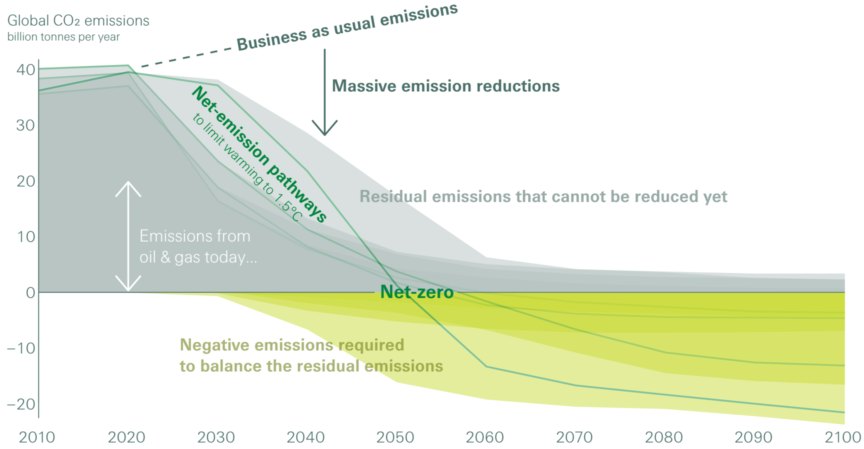
Limiting global warming to 1.5°C requires emission cuts of 50% by 2030, net-zero emissions by 2050, and net-negative emissions thereafter.

The global target of the Paris Agreement of 2015 is to limit global warming to well below 2°C, and preferably to 1.5°C. This is the cap that scientists say can still prevent the worst impacts of climate change. The IPCC says that limiting global warming to 1.5°C will require GHG emission cuts of 50% by 2030, and net-zero emissions by 2050.[9] For net-zero, any residual emissions would have to be balanced by the same amount of negative emissions, in other words, permanent removal and storage of carbon from the atmosphere. This process is known as Carbon Dioxide Removal (CDR), or carbon removal. The IPCC further predicts that global emission levels would be required to stay net-negative (negative emissions > residual gross emissions) throughout the second half of the current century. By the year 2100, depending on how fast we start reducing emissions, the carbon removal industry will have to deliver cumulatively up to 1 000 billion tonnes of negative emissions. For context of scale, that is almost half of all that already has been emitted since pre-industrial times.[10] Figure 1 shows four emission scenarios modelled by the IPCC that would allow limiting global warming to 1.5°C. Three

1 *Global Warming of 1.5°C*, IPCC, 2018.
2 Ibid.
3 *More than half of all CO_2 emissions since 1751 emitted in the last 30 years, Institute for European Environmental Policy, 29 April 2020.*
4 J. Rockström, et al., "The world's biggest gamble", *Earth's Future*, vol 4, 2016.
5 See "Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change", in *Climate Change 2014: Synthesis Report*, IPCC, 2014.
6 CO_2 emissions stay in the atmosphere for decades to centuries. It is estimated that even after 1 000 years, 15–40% of the anthropogenic CO_2 emissions remain in the atmosphere. Other GHG have shorter residence times in the atmosphere (eg, methane 12 years; NOx ~100 years) but exhibit a stronger greenhouse effect (eg, methane 25 times stronger radiative forcing than CO_2; NOx ~300 times stronger). See *Die Treibhausgase*, German Environment Agency, 2020.
7 E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors), *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, IPBES, 2019.
8 *The economics of climate change: no action not an option*, Swiss Re Institute, April 2021
9 IPCC, 2018, op. cit.
10 1750–2017: 2 200 billion tonnes CO_2. See Ibid.

scenarios assume more or less stringent emission cuts starting immediately. Another assumes an initial high-emissions lifestyle (essentially current business-as-usual) that would, in turn, require even larger amounts of negative emissions later.

Figure 1
Net-emission pathways to limit global warming to 1.5°C



Source: Swiss Re, based on *Global Warming of 1.5°C*, IPCC, 2018 (overlap of the scenarios P1-4).

Even with best efforts to reduce GHG emissions, there will be residual carbon release into the atmosphere.

The scenario illustrates three important findings. First, it will require deep emission cuts to follow the 1.5°C net-emission pathway, and the longer we wait, the steeper the reduction path will need to be. Second, even with best efforts to reduce emissions, there will be residual carbon release, meaning that emissions will not reach absolute zero this century.

So much so that to hit Paris Agreement targets, carbon removal will need to reach a double-digit billion tonne scale.

Third, the challenge is huge. In 2050, society must have the capacity to remove up to 10 billion tonnes of CO_2 from the atmosphere every year: that's a quarter of what is emitted each year today. It will take time to build that capacity, and work needs to start today, parallel to (not instead of) stringent emission reduction efforts. Later this century, it will take up to 20 billion tonnes of negative emissions each year to stay on track with the 1.5°C global warming target. As an analogy, 20 billion tonnes corresponds to today's emissions generated by human consumption of all oil and gas products in one year: if it takes a trillion-dollar industry to provide for all the oil and gas that causes 20 billion tonnes of emissions today,[11] it will take the next trillion-dollar industry to remove that same amount from the atmosphere in 2050+.[12]

Not all emissions can be readily reduced. Hence the need for negative emissions.

Certain hard-to-abate industries are more difficult and more expensive to decarbonise. Table 1 outlines how each sector contributes to GHG emissions. It shows current absolute and relative emissions alongside sector-specific reduction measures and key mitigation challenges. These help explain and reaffirm why negative emissions are a necessity if the world is to limit temperature rise to 1.5°C.[13]

[11] The top 20 global oil and gas companies together had cumulative revenues of USD 3.4 trillion in 2020. See *Global 500*, Fortune, accessed on 8 February 2021.

[12] An analogy shared in other publications. For example, *An investor guide to negative emission technologies and the importance of land use*, Vivid Economics, 2020; *Global Climate Restoration for People, Prosperity and Planet*, Arizona State University, 2020; "Occidental to Strip Carbon From the Air and Use It to Pump Crude", *Bloomberg Businessweek*, accessed 13 January 2021.

[13] For further reading, see "Special feature: Moving to a low-carbon future," *SONAR*, Swiss Re, 2020.

Table 1
Emissions, reduction measures and mitigation challenges, by sector[14]

Sector	Absolute (relative) emissions in billion tonnes CO_2eq per year	Key reduction measures[15] (excluding general, cross-sectorial policy measures like carbon pricing, carbon-intensity mandates, etc)
Energy	17 $GtCO_2$ (34.6%)	– make global electricity production wholly renewable – reappraise energy infrastructure: add electricity storage capacity; build robust and fast transmission/distribution lines, and smart, local grids. – fuel switch (green/blue H2 and synthetic-/bio-methane) and fuel efficiency for back-up plants
Agriculture, forestry and other land use	11.8 $GtCO_2$ (24%)	– decrease number of methane-producing livestock: change to plant-rich diets, and diversify protein consumption away from meat – reduce waste/loss of crop and food – optimise fertiliser use (precision farming, nitrification inhibitors, biochar) – conserve existing and restore carbon pools (soils, forests) through improved land management, agricultural practices and fire prevention
Industry	10.3 $GtCO_2$ (21%)	– increase energy and materials efficiency in manufacturing and construction – improve product design to lower embodied carbon and increase circularity (facilitate dismantling, sorting, re-using, re-cycling, product longevity) – substitute raw materials with low carbon alternatives (eg, mass timber, carbon-fixing concrete) – electrify production processes – switch to renewable heat/process fuels and reactants (blue/green hydrogen) – carbon capture (utilisation) and storage to decarbonise heavy industry, in particular cement and chemicals works
Transport	6.9 $GtCO_2$ (14%)	– electrify light-duty road transport, mostly through battery electric vehicles – modal shifts (increase public transport, more efficient modes for logistics) – fuel switch (biofuels, hydrogen/ammonia, synthetic fuels) in heavy-duty road transport, shipping and aviation – improve fuel efficiency – substitute and optimise travel (remote collaboration, longer/less trips, etc.)
Buildings (operations only)	3.1 $GtCO_2$ (6.4%)	– improve buildings' energy efficiency technology (appliances, heating etc) – advance building automation and control systems/meters (smart building) – building construction: replace fossil-fuelled building technology with low-carbon alternatives (rooftop solar, heat pumps, biofuels, district heating/cooling)

Source: Swiss Re Institute

14 Table is built on the Fifth Assessment Report by the IPCC (2014) and amended based on authors' judgement and further literature as indicated separately: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2014. For further reference, other sources used were Climate Engineering: Risks, Challenges, Opportunities? German Research Foundation, January 2019; and CO_2-neutral bis 2035: Eckpunkte eines deutschen Beitrags zur Einhaltung der 1,5-°C-Grenze, Wuppertal Institute, 2020.
15 See also *SONAR* 2020, Swiss Re, op. cit.

Key sector specific mitigation challenges[16]
(excluding general, more broadly applicable challenges like lack of regulation, consumer preferences, economical/structural impediments, etc)

- fossil fuel subsidies of USD 333 billion per year (USD 5.3 trillion per year if the value of combustion-related externalities is included), creating a negative carbon price at production and consumption side[17]
- lack of seasonal storage options/capacity
- new renewable energy infrastructure competes for other land-use purposes, and may compromise habitat and biodiversity protection.
- energy security: increased demand for electricity outweighs addition of new renewable capacity, and old fossil power plants remain operational
- long investment cycles in energy infrastructure, causing a lock-in of emissions
- lack of de-risking for renewable energy investments in developing countries (reducing the cost of capital that weighs heavy on renewable assets)[18]

- population growth (food security)
- subsidies for unsustainable farming practices, with less than 5% of USD 600 billion in global agriculture subsidies going to conservation efforts[19]
- increasing share of meat in average diet
- higher land use per yield
- technical, economic, educational, cultural impediments to new (less intensive) agricultural or forestry practices
- lack of valuation of positive externalities from climate/biodiversity friendly agriculture and forestry (improved local air, soil, and water quality)
- unmitigated deforestation, including driven by land grab/speculation[20]
- increased frequency and severity of natural hazards (wildfire, droughts, storms)
- counter-productive subsidies that do not reduce the global warming footprint of agriculture, nor the negative impacts on biodiversity[21]
- food waste due to inefficient harvesting, transport and storage capacities

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- compared to consumer-facing industries, hard-to-abate material producer sectors (cement, mining, textiles, chemicals, steel, aluminium) have the higher emission intensity (CO_2/product) but smaller margins (income/product), making affordability of emission reduction measures challenging[22]
- long investment cycles for heavy machinery/processing plants
- performance and concerns about cost/willingness to pay by clients/consumers
- intransparency of supply chains

- increased demand for mobility
- increase in global trade
- airplanes, trains and ships with increased longevity see total life-cycle adjusted usage cost decline, an argument to keep operating inefficient transport means/infrastructure
- lack of infrastructure prevents adoption at scale (eg, few supercharging stations for electric vehicles)
- transport infrastructure investments are long term and tie down capital.

- slow renovation/renewal cycle for buildings (and energy intensive appliances)
- concerns over higher investment outweighs benefits from lower running cost[23]
- lack of access to financing

16 Engström et al., "Carbon pricing and planetary boundaries", Nature Communications vol. 11, 2020
17 *Measuring Fossil Fuel Subsidies in the Context of the Sustainable Development Goals.* UNEP, OECD and IISD, 2019.
18 *Derisking renewable energy investment. A Framework to Support Policymakers in Selecting Public Instruments to Promote Renewable Energy Investment in Developing Countries*. UNDP, 2013.
19 *Redirecting Agricultural Subsidies for a Sustainable Food Future*, World Resources Group, 21 July 2020.
20 "Curb land gabbing to save the Amazon", Nature Ecology & Evolution, vol 3, 2019.
21 L. Gubler, S.A. Ismail, I. Seidl, *Biodiversity damaging subsidies in Switzerland, Swiss Academies Factsheet 15, 2020; and The Economics of Biodiversity: The Dasgupta Review*, UK Treasury, 2021
22 *Net-Zero Challenge: The supply chain opportunity* World Economic Forum and Boston Consulting Group, 2021.
23 Energy savings can relatively quickly cover investment costs. See Global Energy Assessment. Cambridge University Press, 2012. The report estimates a USD 24 billion total investment need to realize ambitious climate goals for buildings, in contrast to cumulated USD 65 billion energy savings by 2050, induced by these investments.

A new industry taking shape

The need for carbon removal is clear but the business case is still unfolding.

To limit global warming to the Paris Agreement target, the case for carbon removal is clear, but the commercial rationale is still unfolding. Some carbon removal solutions are well established but have not yet been widely deployed. Others have not yet moved beyond early research stage. In the absence of universal carbon pricing policies and associated fees (polluter-pays-principle comparable to a municipal waste collection fee), polluters have little economic incentive to cut, collect and dispose of emissions. In other words, carbon removal still lacks a business case.

The industry is gaining a foothold...

This situation has been changing since 2019, after the IPCC (at the request of the parties to the Paris Agreement) published its special report assessing what it will take to limit global warming to 1.5°C.[24] The number of agents/companies developing carbon removal technologies, practices and services has increased notably since then.[25] The scale-up plans reach from a few 10 000 tonnes removal today to hundreds of millions of tonnes by the end of the decade. The frontrunners are attracting investor interest, including those developing the least mature and most expensive solutions.[26]

...and the private sector is the main driver.

The private sector is the main driver of current momentum. Since early 2020, increasing numbers of companies have pledged to achieve net-zero emissions from their own operations, at times incorporating their supply and/or entire value chains. Some have pledged to reverse historic emissions altogether.[27] Many (but not all) of the commitments acknowledge the need to balance unavoided emissions via carbon removal and some firms, including Swiss Re, have already bought first removal services.[28, 29] Buyers require attestation that the service captures and stores a certain amount of carbon from the atmosphere. The attestation is usually in the form of a carbon certificate per tonne removed. The price of the certificate is the price a buyer is willing to pay voluntarily to compensate for unavoidable emissions. Thus the first business cases for carbon removal services are being built on the sales of carbon removal certificates, and 2019 saw the first market trading of such certificates.[30]

24 IPCC, 2018, op. cit.
25 See, for example "Remove carbon. Restore Forests", *pachama.com*; "Enable removal of CO_2 from the air", *climeworks.com*, both accessed on 8 February 2021.
26 See, for example, "Pledge by Amazon: The Right Now Climate Fund", *us.1t.org;* "Swiss Carbon Capture Startup Raises USD76m in Funding Round", *bloomberg.com*, 2 June 2020; "Blamed for Climate Change, Oil Companies Invest in Carbon Removal", *The New York Times*, 7 April 2019.
27 See, for example, *Carbon Removal Coprorate Action Tracker*, Institute of Carbon Removal Law & Policy, 7 May 2020; *Net-zero emissions: do our best, remove the rest*, Swiss Re, 12 April 2020.
28 "Swiss-Re backed carbon removal market targets gigaton scale-up", *theenergyst.com*, June 2020.
29 See, for example, R. Orbuch, "Stripe's first carbon removal purchases", *stripe.com*, 18 May 2020; "Fighting for the Future: Shopify Invests $5M in Breakthrough Sustainability Technologies", *shopify.com*, 15 September 2020; *Microsoft Carbon Removal – Lessons from an early corporate purchase*, Microsoft, 2021.
30 For example, "Carbon removal starts here: The world's first B2B marketplace, standard and registry focused solely on carbon removals", *puro.earth*; "The Nori Carbon Removal Marketplace", *nori.com*, both accessed on 8 February 2021.

The barriers to development of carbon removal span supply, marketplace and demand.

All told, the carbon removal industry is still in early stages of development. There is a long way to go and little time to reach the billion-tonnes scale of removals. Barriers to deployment exist along the entire value chain. Key constraints on the supply side include high cost and resource requirements, lack of economic incentives, lack of knowhow, resistance to change, as well as competition for land-use and uncertainties regarding the permanence of storage. On the demand side, first movers are inclined to wait and see in view of high initial prices (free-rider problem). Other demand-side constraints include lack of market access, lack of regulatory requirements, and the perception that supporting carbon removal may deter action to reduce emissions in the first place (moral hazard). Supply and demand equilibrium is being hampered by the lack of standardisation of carbon removal services, small transaction volumes, limited fungibility and lack of regulation of international transfers of removal outcomes.

The carbon removal industry has to scale at an unprecedented speed. This requires de-risking and access to capital.

All constraints aside, to answer the call of science and prevent the worst impacts of a warming world, the carbon removal industry will have to scale from some 10 000 tonnes of negative emissions today to around 10 billion tonnes by 2050. That's a factor increase of 1 million over a period of three decades, or a compound annual growth rate (CAGR) of close to 60%.[31] To reiterate, the task is massive. Once the industry has taken shape, further scaling will require de-risking and finance. This is where re/insurers with appetite for the journey can play to their strengths.

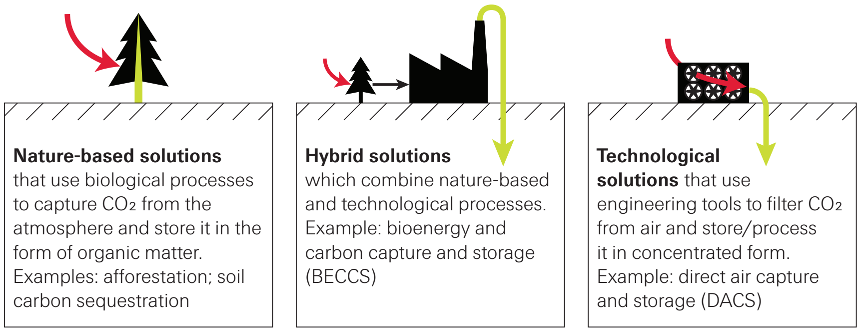
[31] Swiss Re estimates a CAGR of 58% to move from a few 10 kilotonnes of negative emissions services in 2020 to 10 gigatonnes by 2050. If onset of scaling up carbon removal services is delayed to 2025, the CAGR rises to 74%. Delay to 2030 = CAGR of 100%.

The removal industry landscape

Nature-based, technological and hybrid solutions are the three main categories of carbon removal.

Carbon removal solutions differ in how atmospheric CO_2 is captured, processed, transported and stored. They are often referred to as Negative Emissions Technologies (NETs), but not all rely on the deployment of technological means. There are three main categories of carbon removal solution (see Figure 2).

Figure 2
Three main categories of carbon removal solutions



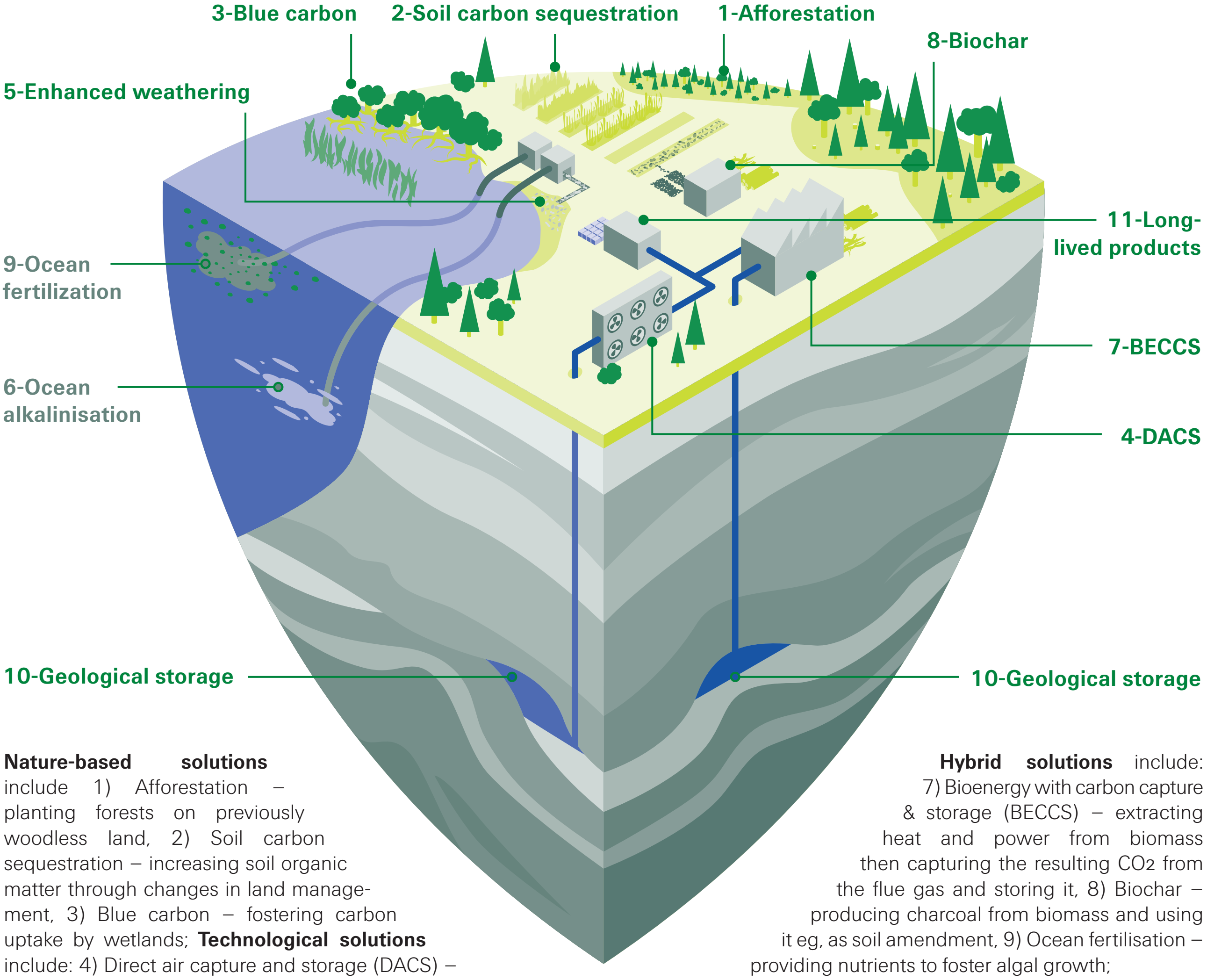
Source: Swiss Re

To meet the capacity required, carbon removal solutions need to developed in parallel.

Scientists agree that no single approach or solution has the scale potential to remove enough carbon to limit global warming to well below 2°C.[32] As with other climate change mitigation strategies, a portfolio approach that exploits niches and synergies, aligns to the varied needs of communities, landscapes and economic priorities, and follows risk diversification, is required. The purpose of this chapter is to provide a better understanding of the carbon removal landscape, illustrated in Figure 3. The value chain of each solution — from CO_2 capture from air, to processing, transport and permanent storage — is described. Thereafter, Table 2 provides an assessment of the solutions featuring key parameters such as cost, co-benefits and possible adverse effects.

[32] IPCC, 2018, op. cit.

Figure 3
Carbon removal landscape



Nature-based solutions include 1) Afforestation – planting forests on previously woodless land, 2) Soil carbon sequestration – increasing soil organic matter through changes in land management, 3) Blue carbon – fostering carbon uptake by wetlands; **Technological solutions** include: 4) Direct air capture and storage (DACS) – filtering CO_2 directly from air and storing it permanently, 5) Enhanced weathering – fostering the fixation of CO_2 through natural minerals, 6) Ocean alkalinisation – providing chemicals to ocean waters to foster the uptake of dissolved CO_2;

Hybrid solutions include: 7) Bioenergy with carbon capture & storage (BECCS) – extracting heat and power from biomass then capturing the resulting CO_2 from the flue gas and storing it, 8) Biochar – producing charcoal from biomass and using it eg, as soil amendment, 9) Ocean fertilisation – providing nutrients to foster algal growth;
Storage options for concentrated CO_2 from BECCS and DACS are 10) geological reservoirs similar to an oil filed (porous rock in great depth, sealed by impermeable caprock) or 11) long-lived products such as aggregates, carbon fibres, etc.

Source: Swiss Re

Nature-based solutions

Nature-based solutions use plants to capture CO2 from air. They can harness many co-benefits…

Plants remove CO_2 from the atmosphere through photosynthesis and use it as building blocks to produce their biomass (leaves, wood, roots), in which the carbon remains stored as long as the plant lives. Dead biomass decomposes and releases some carbon back to the atmosphere, and some is converted to humus or peat. Most nature-based solutions – like afforestation and practices to improve soil carbon sequestration are well-established and relatively inexpensive.[33, 34] Other areas of nature-based carbon removal activity like blue carbon remain less explored.[35] If undertaken correctly, nature-based solutions can yield co-benefits beyond carbon sequestration, including flood protection, drought resilience and other benefits like biodiversity conservation and the maintenance of essential ecosystem services.

.. but face limits of scalability. Results also take a long time to realise.

On the downside, nature-based solutions require land and water resources. They compete for land with food and fodder production, and other human activities, which sets a limit to their economic feasibility and scalability.[36] Moreover, they do not produce negative emissions instantaneously: it takes decades to grow a forest or accumulate humus.[37] Another risk is the durability of storage due to environmental and human impacts. Global warming and changing precipitation alter the ability of trees and vegetation to sequester carbon, and wildfires or changes in land management may quickly release the CO_2 back into the atmosphere. The three main nature-based solution types currently are afforestation and improved forest management, soil carbon sequestration and blue carbon.

Afforestation and improved forest management

Afforestation is the planting of new trees to increase the carbon stock of forests.

Afforestation is the planting of trees on previously woodless land. Improved forest management seeks to increase the carbon stock of an existing forest.[38]

- *Capture:* trees and undergrowth capture carbon from the atmosphere via photosynthesis.
- *Processing:* none.
- *Transport:* moving seedlings or saplings to final planting site.
- *Storage:* in the form of maturing and mature forests, including the living biomass and the carbon stored in forest soils. Note that the woody biomass may also be harvested and manufactured into long-lived construction materials like mass timber, which can remain (store carbon) in buildings for several decades.

[33] S. Fuss et al. "Negative emissions—Part 2: Costs, potentials and side effects", *Environmental Research Letters*, vol. 13, 2018.
[34] C. Beuttler, S. Keel, J. Leifeld, The Role of Atmospheric *Carbon Dioxide Removal in Swiss Climate Policy*, Federal Office for the Environment, October 2019.
[35] *Coastal Blue Carbon – methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows*, Conservation International, IOC-UNESCO and IUCN, 2014.
[36] P. Smith, et al., "Biophysical and economic limits to negative CO_2 emissions", *Nature Publishing Group, Nature Climate Change*, vol. 6, 2016.
[37] Depending on species and geography, on average, a grown-up tree can absorb roughly 22 kg CO_2 per year. See *Forests, health and climate change*, European Environment Agency, 2011. As a sapling, it will absorb much less. It takes a UK broadleaf tree its full lifetime of ~100 years to capture 1 tonne of CO_2. See *How much CO_2 can trees take up?* The Grantham Institute, 2015.
[38] Note that in the context of climate protection, forest management strategies can lead to: 1) emission avoidance: upholding the existing forest carbon stock, also known as avoided deforestation; 2) emission reversal: restoring the forest carbon stock of a recently degraded forest, also known as reforestation; or 3) negative emissions through afforestation or improved forest management. All three are important measures to mitigate climate change, but only afforestation and improved forest management should be counted as carbon removal. In practice, af- and reforestation are often used interchangeably, as there is no consensus on the time scale to be applied for defining "recently degraded" for "previously woodless". *The Economist Intelligence Unit* (2020) suggests that planting on land that has been woodless for at least 50 years qualifies as afforestation, and less than that as reforestation.

Regenerative agricultural practices increase the carbon stock in soils.

Soil carbon sequestration

Through regenerative agricultural practices, soils accumulate organic matter in the form of sub-surface biomass and humus. The aim of soil carbon sequestration is to deploy land management practices that either increase the carbon input to soils (through cover crops, crop rotations, manure/compost/residue addition, improved grazing management) or decrease the carbon loss from soils (no-/low-tillage, switch from annual to perennial crops and grasses).[39]

- *Capture:* via plant biomass growth and decomposition, atmospheric CO_2 ends up in soils.
- *Storage:* in the form of soil organic matter.

Restoration and conservation of coastal zones and wetlands increase the carbon stock in these ecosystems.

Blue carbon

This is the conservation and restoration of coastal wetlands (mangroves, seagrass meadows, salt marshes, macroalgae) and freshwater peatlands, which can sequester more carbon faster than any other ecosystem.[40, 41] However, there are gaps in the understanding of sequestration rates and how humans can optimally (or negatively) influence them.[42]

- *Capture:* via plant biomass growth and decomposition, atmospheric CO_2 ends up in wetland ecosystems.
- *Transport:* moving seeds and saplings to planting sites.
- *Storage:* in the form of the living biomass, soil carbon, peat and sediments that accumulate in wetlands.

[39] K. Paustian, E. Larson, J. Kent, E. Marx, A. Swan, *Soil carbon sequestration as a biological negative emission strategy.* Frontiers in Climate, 16 October 2019.
[40] D. Herr et al., *Coastal "blue" carbon.* International Union for Conservation of Nature and Natural Resources, 2015.
[41] D. Gordon, B.C. Murray, L Pendleton and B. Victor, *Financing Options for Blue Carbon: Opportunities and Lessons from the REDD+ Experience.* Nicholas Institute for Environmental Policy Solutions, Duke University, 2011.
[42] Conservation International, IOC-UNESCO, and IUCN, 2014, op. cit. These bodies classify five areas in which further research is still needed: geography, sequestration and storage, emissions and removals, human drivers of ecosystem degradation, and coastal erosion.

Technological solutions

Technological solutions use engineering tools to remove carbon, and require lots of renewable energy.

Technological solutions use industrial processes to remove atmospheric CO_2 for capturing, storage or both. They rely on machinery, processing or storage infrastructure, as well as logistics to transport the captured concentrated CO_2 products. The steps are energy intensive. The energy used should be from renewable sources to prevent putting new CO_2 into the atmosphere while removing what is already there. For example, to capture one tonne of CO_2 directly from the air using current filter technologies requires 2 300 kWh of energy, equivalent to the energy content in 0.2 tonnes of oil.[43] Producing, transporting and burning 0.2 tonnes of oil releases roughly 0.6 tonnes of CO_2. If the energy to capture 1 tonne of CO_2 from air came from oil, the net benefit would be just 0.4 tonnes of CO_2 capture.[44]

Technological solutions are still at an early stage of development.

Technological solutions are more capital- and operating-expenditure intensive than nature-based alternatives. Also, the co-benefits involved are fewer and less obvious (eg, job creation, re-purposing of stranded infrastructure,[45] innovation spill-over).[46] This helps explain why technological solutions are still at an early stage of development and deployment. In the absence of stringent carbon pricing, mandates or voluntary buyers, there has been little business justification to develop expensive equipment to clean the air of CO_2. On the upside, land requirements are small and the storage in chemical or geological systems is more durable than the storage potential of biological systems. The two main technological solutions are currently direct air capture and storage, and enhanced weathering.

Direct air capture and storage (DACS)

DACS deploys filter machines to capture CO_2 directly from air.

CO_2 is filtered directly from ambient air, compressed and then injected into geological formations deep underground for permanent storage.

- *Capture*: through chemical filters in air processing units, CO_2 is brought from only 0.04% concentration in the air to close to 100% concentration in the resulting gas product. This separation task requires electricity to drive sufficient amounts of air through the unit (10–20% of total energy), and heat to regenerate the filters (80–90% of total energy).[47]
- *Processing*: after capture, the concentrated CO_2 stream is liquified in compressors (>65 bar at ambient temperature).
- *Transport*: air capture units are ideally co-located at a renewable energy source or a storage site or both, so that air capture can take place anywhere (independent from a CO_2 point source). Therefore, only limited or no CO_2 transport infrastructure – such as long-distance pipelines – is required.
- *Storage*: the compressed, liquified CO_2 is pumped through an injection well into geological structures, usually at 800 (minimum) to 2 500 (maximum) metres depth. Like oil or gas fields, these structures consist of porous rock topped by a layer of dense caprock. Once injected at a pressure slightly above the reservoir pressure (minimum 80 bar, well below fracturing pressure), physical and chemical processes stabilise the CO_2 over time.[48] A benefit of storing CO_2 geologically is that existing depleted oil and gas fields can be re-filled using old infrastructure.

[43] Energy consumption of direct air capture technology is ~200 tonnes oil equivalent (toe) per tonne CO_2 captured. Burning a tonne of oil roughly emits ~3 tonnes of CO_2. See *Direct Air Capture – more efforts needed*, International Energy Agency (IEA), June 2020.
[44] Ibid.
[45] "Stranded infrastructure" are infrastructure assets that seen premature write-down due to economic or unexpected regulatory reasons. For example, fossil energy infrastructure like an oil pipeline may be re-purposed to serve for CO_2 transport.
[46] J. Minx et al "Negative emissions – Part 1: Research landscape and synthesis", *Environmental Research Letters*, vol 13, 2018.
[47] IEA, June 2020, op. cit.
[48] Within the storage reservoir, the CO_2: 1) is trapped physically beneath the cap rock (structural trapping, immediately effective): 2) gets immobilized in the form of trillions of tiny bubbles behind pore necks (residual trapping, immediately effective); then 3) starts dissolving in the pore fluid and sinks to the bottom (dissolution trapping, takes years to centuries); and later 4) reacts with the rock to form stable mineral carbonates (mineral trapping, takes decades to millennia). Over time, these four sequential trapping mechanisms transform CO_2 into ever more durable forms of storage. See Special Report on Carbon Capture and Storage, IPCC, 2005.

In concentrated form, the CO_2 can be stored in geological formations…

In North America, CO_2 injection into maturing oil fields through one well is practiced to produce more oil in another well nearby. This is known as Enhanced Oil Recovery (EOR). In theory, more CO_2 can be injected and sequestered than that emitted through downstream oil usage. Another special case for geological CO_2 storage has been demonstrated in Iceland, where captured CO_2 is pre-dissolved in water and then injected into basalts, a type of rock that react with the CO_2 to form stable minerals.[49]

…and also in long-lived products.

Air captured CO_2 can be processed into long-lived products like carbon fibre, aggregates and other building blocks for concrete and precipitated calcium carbonate. This is referred to as 'carbontech', or carbon capture, utilisation and storage (CCUS). Currently, carbontech makes use of just some 200 $MtCO_2$ per annum, including CO_2 used for EOR and short-lived products such as synthetic fuels or plastics (= carbon capture and utilisation, CCU), meaning it plays/will likely play just a small role in the global quest to deliver gigatons of negative emissions (see also *Carbon removal vs. carbon capture and storage: what are the differences?* on p15).

Enhanced weathering accelerates the natural process by which minerals can bind CO_2 dissolved in water.

Enhanced weathering

Chemical weathering is the natural process by which rock surface gets attacked when exposed to atmospheric CO_2 dissolved in water. This process can be enhanced by enlarging the surface area of suitable rocks and optimally exposing them to rain- or ocean water.[50]

- *Capture:* alkaline rock such as olivine is mined and finely ground to increase surface area before being spread evenly over soil or beaches. CO_2 in water forms carbonic acid that attacks and dissolves the rock grains, thereby forming a stable mineral/bicarbonate solution. Enhanced weathering can also be carried out in an engineered reactor where temperature, pressure and pH conditions can be varied to increase the speed of reactions (mineral carbonation, or mineralisation).[51]
- *Processing:* mining and grinding rock.
- *Transport:* from the mine/grinder to the weathering sites using trucks, trains and ships.
- *Storage:* chemically fixed as bicarbonate solution (pore-, surface-, ocean water) and eventually precipitated as carbonate minerals.

[49] See, for example, the Carbfix project in Iceland.

[50] R. D Schuiling, P. Krijgsman, "Enhanced Weathering: An Effective and Cheap Tool to Sequester CO_2", *Climatic change*, vol 74, 2006. See also D.J. Beerling, E.P. Kantzas, et al., "Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature, vol 583, 2020.

[51] K. Lackner et al., "Carbon dioxide disposal in carbonate minerals", *Energy*, vol 20,1995.

Hybrid solutions

Hybrid solutions combine nature-based and technological solutions.

Hybrid solutions seek to combine and reap the benefits of different features of nature-based and technological approaches. What nature does best is sun-powered air capture through photosynthesis. Technology, on the other hand, is better at converting CO_2 into durable forms of storage.

Bioenergy with carbon capture and storage (BECCS)

BECCS converts biomass to energy, and captures and stores the resulting biogenic CO_2 from the flue gas.

Biomass is converted to heat and power in a power plant or to energy carriers like ethanol, methanol or biogas in an industrial facility. The conversion results in biogenic CO_2 that is separated from the off-gas through conventional point source carbon capture methods. The concentrated CO_2 can be sent for geological storage or processed into long-lived products. The "CCS" part of BECCS is the same as the conventional carbon capture and storage value chain to decarbonise large point sources of CO_2 such as coal fired power plants (see also *Carbon removal vs. carbon capture and storage: what are the differences?* below)[52]

- *Capture:* the first step of capturing of CO_2 from the air is through photosynthesis in plants.
- *Processing:* plant biomass is harvested and burned, or converted to biofuels and other chemicals. The resulting biogenic CO_2 can be then stripped relatively easily from the flue gas/process gas using conventional CO_2 capture methods (eg, amine scrubbing).[53] This is the second capture step in BECCS. The concentrated CO_2 is then compressed and sent for storage.
- *Transport:* two main steps: 1) moving biomass from the field/forest to the processing plants: and 2) from there, moving compressed or liquified CO_2 in pipelines (typically at 100 bar pressure, ambient temperature) or using trucks/ trains (~20 bar, –20°C) or ships (at 7 bar, –50°C) to a storage site. Ideally biomass source and storage sites are in close proximity to keep transport costs to a minimum.[54]
- *Storage:* the storage options are the same as for DACS.

Biochar

Heating biomass under lack of oxygen produces biochar that is more durable than the original biomass.

Biochar results from heating biomass under lack of oxygen (pyrolysis). It consists of carbon black which decomposes very slowly under natural conditions, rendering biochar a more durable carbon storage form than the original biomass. It is usually added to degraded topsoil to improve soil fertility.

- *Capture:* plant growth captures carbon from the atmosphere through photosynthesis.
- *Processing:* the plant biomass is converted into biochar in a pyrolysis plant. Pyrolysis produces a methane and hydrogen rich off-gas (syngas) that can be used to power the pyrolysis process or be upgraded to synthetic biofuels.
- *Transport:* biomass is moved from the field/forest to the pyrolysis plant, and the biochar from that plant to its place of use.[55]
- *Storage:* in the form of carbon black, which is stable over decades when used as building blocks in the construction or chemical industries,[56] and can also be used for soil amelioration.[57]

[52] IPCC, 2005, op. cit.
[53] Note that conventional CO_2 capture from a flue gas containing 4–25% CO_2 requires much less energy than direct capture from air containing only 0.04% CO_2. As a rule of thumb, cost of capture scales linearly with dilution (Sherwood's Rule).
[54] IPCC, 2005, op. cit.
[55] Mobile pyrolysis units could be used to process the biomass and return the biochar on field site. See "Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs – a preliminary assessment," *Biomass and Bioenergy*, vol 30, 2006.
[56] "Application of the biochar-based technologies as the way of realization of the sustainable development strategy", *Economic and Environmental Studies*, Opole University, vol. 17, 2017
[57] J. Lehmann, S. Joseph, *Biochar for environmental management, first edition*. Earthscan, 2009.

Other solutions

Other approaches to carbon removal are less developed...

Other less-developed carbon removal solutions include ocean fertilisation and alkalinisation. These accelerate the natural carbon cycle by modifying ocean chemistry towards a higher CO_2 uptake rate.

- **Ocean fertilisation** provides the missing nutrient – mostly iron – that controls algal growth directly in the surface water at high sea. Algae (phytoplankton) grows and absorbs CO_2 through photosynthesis. It then dies and sinks, creating a carbon flux to the ocean floor.
- **Ocean alkalinisation** provides alkaline brines directly to oceans to raise the pH of the water and allow more uptake of atmospheric CO_2. The alkalinity is derived from minerals (silicates, limestone) or industrial by-products (ashes, desalination brines).

...and entail many unknowns.

There is still much uncertainty with respect to the effectiveness and adverse impacts on ocean ecology of these solutions, which merits further research before considering large-scale deployment.[58]

[58] *Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments,* Energy Futures Initiative, 2020.

The value chains of BECCS, DACS and CCS overlap.

Carbon removal vs. carbon capture and storage: what are the differences?
The terms carbon removal and carbon capture and storage (CCS, or simply carbon capture) are often used interchangeably, but there are important differences. Carbon removal is the capture and storage of CO_2 from the atmosphere for the sake of producing negative emissions. CCS is the capture and storage of CO_2 from the flue gas of large industrial point sources for the sake of reducing emissions from fossil fuel use.[59] There are overlaps in the CCS value chain, and that of BECCS and DACS, which all provide concentrated atmospheric CO_2 post capture. The three processes can share the same CO_2 transport and storage infrastructure. In the case of BECCS and CCS, the point source capture technology is the same.

CCUS produces long-lived products that effectively store CO_2. CCU produces short-lived products that don't store CO_2.

Another area of confusion is the fate of the CO_2 once captured, in particular when it comes to carbon balance. CO_2 can be stored geologically as in the original CCS value chain. It can be converted to short-lived products that will release the captured CO_2 upon consumption, known as carbon capture and utilisation (CCU), or it can be converted to long-lived products that hold CO_2 for a long time, called carbon capture, utilisation and storage (CCUS). Depending on the origin of the CO_2 (fossil derived or biogenic/directly from air), the three routes lead to a carbon balance that is positive (more emissions), neutral (emissions are avoided) or negative (carbon is removed).

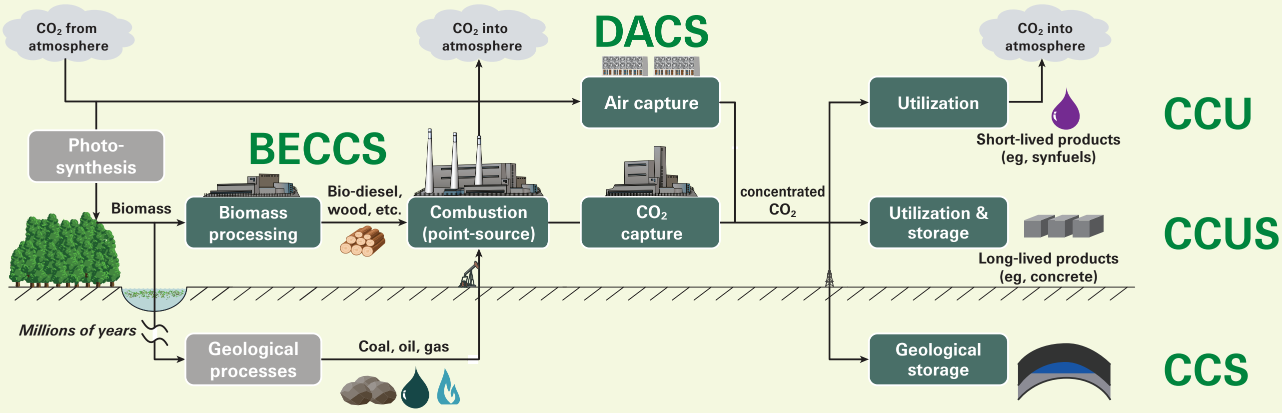
CCUS is limited in storage capacity. The bulk of the concentrated CO_2 has to go to geological storage.

The CCUS route is preferable over geological storage, because it gives value to rather than disposing of CO_2 emissions as a waste product. However, the bulk market currently open to receive CO_2 from an external source is just some 40 million tonnes/year,[60] and most of that takes the CCU rather than CCUS route. This is well short of the need for many billion tonnes of emissions to be sequestered to balance residual and legacy emissions in line with the 1.5°C warming limit. That is why most of the concentrated CO_2 coming from BECCS and DACS plants will eventually have to take the geological storage route.

59 Twenty years ago, CCS emerged as a means to decarbonise coal- and gas-fired power plants at a time when new renewables were still prohibitively expensive. Today, utility-scale wind and solar are the cheapest energy source in many parts of the world, thus the role of CCS in the power sector will likely be limited. CCS remains, however, a solution to decarbonise hard-to-abate industrial sectors like cement.

60 Total bulk CO_2 market is 230 $MtCO_2$/year (Putting CO_2 to use, IEA,2019). Of this 130Mt/yr are for urea production and stem mostly from the process itself (CO_2 from methane reforming to produce ammonia), and 70–80 Mt/yr are used for EOR, where to date only ~20% stem from anthropogenic sources, the rest being deliberately produced from natural CO_2 reservoirs in deep geological formations. See *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*, National Academy of Science, 2015.

Figure 4
Overlap between carbon removal and CCS value chains



	Today	CCS	BECCS	DACS	CCU	CCUS
Main input	Fossil fuels	more fuel	Biomass (land, water, fertilizer)	Heat/power from renewables	Heat/power (from renewables)	Heat/power (from renewables)
Output	Heat/power, industrial products	Heat/power, industrial products	Heat/power, industrial products	–	Short-lived products	Long-lived products
CO_2 balance	Positive	Neutral	Negative	Negative	Positive for fossil CO_2 Neutral for bio/air CO_2	Neutral for fossil CO_2 Negative for bio/air CO_2

Source: Swiss Re

Table 2
Carbon removal solutions: literature-based assessment[61]

Method	Readiness[62]	Cost today USD/tCO_2[63]	Energy requirement GJ/tCO_2	Land requirement ha/tCO_2/yr	Scalability[64]
Nature-based solutions					
Afforestation (AF), improved forest management (IMF)	**Mature** Available at large scale	1–100	–[65]	0.03 – 0.7[66]	**Low** Barriers to upscaling: – land requirement creates competition with crop and fodder production, and conservational goals – full removal potential unfolds over several decades, for as long as a forest grows. A fully-grown forest cannot remove more carbon – concerns about permanence – lack of incentives/valuation of ecosystem/climate services – lack of demand for wood in most markets
Soil carbon sequestration (SCS)	**Early adoption – mature** – mostly available at large scale (a few practices such as perennialisation are still pre-mature)	0–40[67]	–[68]	–[69]	**Low** Barriers to upscaling: – lack of incentives for widespread adoption, including challenges for farmers when subsidy systems are tied to high yield of monocultural commodity crops – resistance to change of established practices – risks associated with transitioning of practices, such as impact on yield and labour in the farming practice transition phase – competing land uses – time taken for soil carbon to build up – difficulties/uncertainties in measuring soil carbon – concerns about permanence
Blue carbon (BC)	**Prototype – mature** from prototypes (eg, marine permaculture) to available at large scale (eg, mangrove restoration)	10–100[70]	–[71]	0.2[72]	**Low**[73] Barriers to upscaling: – conflicts of use in coastal zones – lack of incentives for conservation and restoration – water pollution – concerns about permanence – negative public perception of mangroves and wetlands

[61] The editorial deadline to compile this table was 28 February 2021.
[62] *Innovation needs in the Sustainable Development Scenario – Clean Energy Innovation Flagship Report:* IEA, 2020. Prototype = TRL 4–6, Demonstration = TRL 7–8, Early adoption = TRL 9–10 (TRL 10 defined by IEA as "Solution is commercial and competitive but needs further integration efforts"), Mature = TRL 11, defined by IEA as "Proof of stability reached, with predictable growth". Comments on the development status adapted from G. F. Nemet, et al. "Negative Emissions - Part 3: Innovation and upscaling", *Environmental research letters*, vol 13, 2018.
[63] Adapted from Fuss et al. 2018, op. cit.
[64] Categories defined based on average cumulative potential in GtCO_2 by the year 2100, complied from literature by Minx et al. 2018, op. cit., Table 2: Low = 0–150 Gt, medium = 151–300 Gt, high = >301GtCO_2. Note that the potential of the individual carbon removal solutions are not necessarily additive as solutions compete for limited land, biomass feedstock, and suitable geological storage capacity. Comments on the limitations status adapted from Nemet et al., 2018 op. cit.
[65] Af- and Reforestation, and Improved Forest Management have been found to require no additional energy input compared to conventional forest management. Numbers difficult to pinpoint
[66] *Land Use, Land-Use Change and Forestry*, IPCC, 2000.
[67] Informed by P. Smith, "Soil carbon sequestration and biochar as negative emissions technologies", *Global Change Biology*, vol 22, 2016, and current market intelligence.
[68] SCS has been found to require no additional energy input compared to conventional land management. Numbers difficult to pinpoint.
[69] SCS requires no additional land beyond what is already used for agriculture.
[70] Not assessed by Fuss et al. 2018, op. cit. Cost based on authors' judgement and *What is Blue Carbon?* American University
[71] No reliable calculations or estimations available
[72] Number refers only to specific mangrove plantations, other wetland ecosystems may be different. D. M. Alongi 2012, "Carbon sequestration in mangrove forests", *Carbon Management*, vol 3, 2012; O. J. Eeon, "Mangroves – a carbon source and sink", *Chemosphere* vol 27, 1993.
[73] Not assessed by Minx et al., 2018, op. cit. According to Griscom et al. in "Natural climate solutions", *PNAS*, 2017. Afforestation and improved forest management together have a yearly potential of 3.9 GtCO_2/year in 2030, whereas coastal wetland and peatland restoration together have 0.6 GtCO_2/year.

Permanence of storage[74]	Possible co-benefits[75]	Possible adverse effects[76]
Low[77] Risk of reversal from: – illegal and legal deforestation (policy changes) – slow degradation (global warming, pests) – natural hazards (wildfires, storms)	– protection and creation of habitats that conserve and enhance biodiversity – prevention of soil erosion – improved water quality/retention, local air quality and (micro-) climatic conditions – reversal of desertification – job creation in forestry and eco-tourism – revenue from sustainable timber	– ill-managed afforestation efforts (monoculture tree plantations, planting in species-rich ecosystems like savanna) can harm biodiversity and livelihood of local communities (displacement) – food security compromised – large water needs for projects in dry zones – tree coverage may reduce albedo (reflection of sunlight back into space), particularly in snow-rich regions, which may exacerbate global warming[78]
Low Risk of reversal from: – going back to original practices (eg, change of ownership of the land, policy changes, cease of incentives) – environmental changes and hazards (floods, droughts)	– improved crop yields after transition time with possible lower yields for a few years – lower expenses for fertiliser, irrigation and crop protection chemicals, which also reduce environmental impacts on soil, water, air, fauna and human health – increased soil resilience and microbial biodiversity – improved water retention (flood protection) – improved water quality due to lower fertiliser inputs and runoff, and less soil washing into waterways – significant reductions in other GHG emissions (eg, methane, N_2O)	– possible increase of other GHG emissions (N_2O) .
Low[79] Risk of reversal from: – land-use change/cease of conservation policies – coastal wetlands vulnerable to sea level rise and increased storm frequency/intensity	– intact coastal wetlands protect the coast and inland against storm surge and other storm-related impacts – increased biodiversity/restoring fish stock – improved water quality/ food security for local communities – job creation/protection (food, fishery, tourism)	– increased trace GHG emissions (CH_4, N_2O)

[74] Authors' judgment: low = decades, medium = centuries, high = millennia. Indication of risk of storage reversal adapted from Fuss et al., 2018 op. cit.
[75] Adapted from Fuss et al., 2018, op. cit.
[76] Ibid.
[77] C.f. 10–100 years contracted durability for forest projects, Microsoft, 2021 op. cit.
[78] C. A. Williams, et al., "Climate impacts of US forest loss span net warming to net cooling, "*Science Advances*, vol 7, 2021.
[79] Not assessed by Fuss et al. 2018, op. cit.. The permanence constraints with underlying risks of storage reversal are, however, not dissimilar from afforestation (eg, mangroves) and soil carbon sequestration (eg, salt marshes).

Method	Readiness[62]	Cost today USD/tCO_2[63]	Energy requirement GJ/tCO_2	Land requirement ha/tCO_2/yr	Scalability[64]
Technological solutions					
Direct air capture and storage (DACS)	**Prototype** Three front-running companies (Climeworks (CH), Carbon Engineering (CA), Global Thermostat (US)) run prototypes. Later in 2021, Climeworks will open the world's first pre-commercial demonstration[80]	600–1000[81]	6.7-12.3[82]	<0.001[83]	**High** Barriers to upscaling: – high cost (as a consequence of low technology readiness and resource/energy intensity due to physical/thermodynamic constraints) – high demand of (clean) energy – slow development of geological storage infrastructure, also due to lack of public acceptance (fear of leakage) – lack of consistent regulation and standards
Enhanced weathering (EC)	**Prototype** Early applications only[84]	50–200[85]	12.5[86]	<0.01[87]	**Medium** Barriers to upscaling: – fundamental understanding of impacts/ effectiveness – very slow sequestration rates – cost of transport of minerals
Hybrid solutions					
Bioenergy with carbon capture and storage (BECCS)	**Demonstration** Limited number of full-scale demonstration plants[88]	15–400	Energy production 0.8-10.9[89]	0.03 – 0.5[90]	**High** Barriers to upscaling: – cost of industrial capture and storage – availability/accessibility of biomass (competition with other uses, eg, biofuels) – competition for agricultural land if biomass stems from dedicated energy crops (if biomass stems from forests, more tonnes of CO_2 can be stored per land area with BECCS compared to AF/IMF, because the forest biomass can be harvested several times) – lack of consistent regulation and standards
Biochar	**Demonstration – early adoption** Available, but applied today only at small scale	20–120[91]	Energy production 0.1–5.1[92]	0 – 0.01[93]	**Medium** Barriers to upscaling: – cost of pyrolysis – constraints on resource availability as with BECCS – uncertainties in assessing the cumulative climate effects (including adverse) of biochar soil amendments

80 Climeworks' Orca plant, at the Carbfix storage site, Iceland (see https://www.carbfix.com/direct-air-capture)
81 Estimate includes publicly available price point (USD 775/tCO2, purchased by Stripe in May 2020) for Climeworks CDR services in Iceland.
82 Lower bound estimate based on International Energy Agency (IEA), 2020, op. cit. Upper bound based on P. Smith, S. Davis, F. Creutzig, et al., "Biophysical and economic limits to negative CO_2 emissions," *Nature Climate Change*, vol 6, 2015.
83 Ibid.
84 For example, *Project Vesta* and *Greensand*.
85 Adapted from Fuss et al. 2018, op. cit., and authors' judgment
86 P. Smith, S. Davis, F. Creutzig et al. 2015, op. cit.
87 Ibid.
88 For example, *DRAX, DPecatur, Illinois Industrial CCS facility*
89 P. Smith, S. Davis, F. Creutzig, et al. 2015, op. cit.
90 Ibid.
91 Adapted from Fuss et al. 2018, op. cit. and authors' judgment; *Greenhouse Gas Removal (GGR) policy options – Final Report*, Vivid Economics, 2019.
92 Between 13% and 47% of the energy in the source biomass is converted into a useful form such as syngas or bio-oil (K.Crombie and O.Mašek. "Pyrolysis biochar systems, balance between bioenergy and carbon sequestration." *Gcb Bioenergy*, 2015). These factors have been applied to the energy production from BECCS in reference [89].
93 Biochar can require no additional land beyond that used for agriculture/forestry if waste feedstocks are used. If dedicated crops are grown, there can be a land footprint. Upper bound from P. Smith, 2016, op. cit.

Permanence of storage[74]	Possible co-benefits[75]	Possible adverse effects[76]
High Risk of reversal from: – leakage along faulty/ abandoned wells – undiscovered caprock deficiencies – slow migration out of the storage reservoir together with formation fluids	– job creation/ preservation (for oil & gas industry transitioning to new business model; CO_2-as-a-service, "reverse the pump")[94] – repurposing of idle infrastructure – scientific insights and innovation spill-over benefits	– parasitic environmental impacts from DAC supply chain (metals, chemicals, other materials) and clean energy sources (and their supply chains) – induced seismicity during geological storage operation – in case of leakage: contamination of groundwater with displaced reservoir fluids, if CO_2 makes its way to surface (eg, along well casing), human health risk through asphyxiation (CO_2 is heavier than air and may accumulate in ditches, pits, etc.)
Low – high Risk of reversal from: – changes in water chemistry (eg, drainage from soils, external disturbances, including acid rain)	– adding certain minerals to leached soil improves soil fertility (nutrients, higher pH, nutrient retention capacity, moisture retention) and thus crop yields – job creation/ preservation in mining – repurposing of idle infrastructure	– potential heavy metal release – negative ecological/social impact of mineral extraction and transport – health risks related to fine-grain matter
High Risk of reversal same as for DACS (see above)	– biomass can substitute fossil fuels to produce baseload energy (covering production/ seasonal gaps of intermittent renewables) – energy independence if local biomass resources can replace imported fossil fuels – preservation of assets (retro-fitting of fossil fuel power plants) – undergrowth removed from forests and used for BECCS reduces the risk of severe wildfires – job creation (agro/ forestry) and preservation (power) – CCS retrofitted to waste-to-energy plants is partially BECCS, depending on the biogenic waste fraction	– similar potential adverse impacts as for nature-based solutions, in particular afforestation. Eg, negative ecological and social impact from land use change/monoculture tree plantations – growing dedicated energy crops compromises food/fodder security and bears risk of deforestation – same geological storage-related risks as for DACS (see above) – undergrowth removed from forests can diminish forest ecosystem integrity
Medium Risk of reversal from: – slow decay (mostly through microbial metabolism) depending on soil type, soil management and environmental conditions	– improved soil fertility (nutrient and moisture retention capacity) and thus crop yields[95] – reduced non-CO_2 GHG emissions from soils – renewable power from pyrolysis off gases – wildfire prevention like for BECCS – can also be applied to municipal waste (waste char) to reduce waste volume and prevent landfill gas emissions that have high global warming potential	– growing dedicated biochar crops compromises food/fodder security and risks deforestation – biochar amendment makes the soil darker (c.f. "terra preta"; "black soil"), which reduces albedo and leads to faster warming in spring – benefits to soil are not universal; sometimes biochar addition has led to decreased crop yields[96]

[94] The Rhodium Group (estimates that DAC at full scale in the US could generate 30 000 mostly high-wage jobs: See, *Capturing new jobs and new business: Growth opportunities from direct air capture scale-up*, Rhondium Group, 2020.

[95] Applying biochar to ameliorate soils is well-established by indigenous communities in the Amazon region (terra preta) and in regenerative agriculture. See "The bright prospect of biochar", *Nature Climate Change vol 1*, 2009.

[96] *Biochar: is there a dark side?*, ETH Zürich, April 2014.

The role of insurance

The insurance sector can support scaling up of the carbon removal industry.

The transition to net-zero emissions presents risks and opportunities for all sectors of the economy. Moving away from fossil fuels and polluting practices requires de-risking, financing and creation of a market for clean alternatives. The insurance sector is uniquely positioned to offer support on three fronts, by:

- providing risk management knowledge and transfer solutions, and insurance capacity for evolving risk pools;
- providing capital as an institutional, long-term investor; and
- stimulating the market as a buyer of green products and services to run own operations.

... as a risk taker, investor and buyer, and with transparent reporting and planning of and advocating for climate action.

To give a practical example, an insurance company can drive energy transition by providing risk transfer solutions such as performance guarantees to solar PV plants, by investing in green bonds, the proceeds of which are used to finance wind farms, and by sourcing 100% of its own power consumption from renewable sources.[97] In addition, insurers can demonstrate leadership in mitigating climate change with transparency in reporting on all emission sources (own-operation and indirect emissions from insurance offerings and investments); by committing to net-zero emission strategies with separate targets for carbon reductions and removal; and by advocating for climate action and sharing of best practices. An example for such action is the UN-convened Net-Zero Insurance Alliance announced in April 2021, committing founding (including Swiss Re) and future signatories to achieve a net-zero underwriting portfolio by 2050.[98] The following explores how the re/insurance industry can engage in carbon removal along the three main transition levers: as risk taker and investor in, and as buyer of green products and services.

Understanding and insuring carbon removal risks

Carbon removal can profit from re/insurers risk assessment and management capabilities.

Re/insurers conduct assessment to select insurable risks, propose suitable pricing thereof, and provide risk management advice to insureds.[99] They also diversify selected risks based on lines of business, geography and time. These same risk management activities apply to understanding and insuring of carbon removal risks.

Many elements of the carbon removal value chain are already insurable. Some opportunities are novel or non-existing.

Already insurable risks: Many elements of the carbon removal value chain are familiar to insurers through existing activities, technologies and products in other sector value chains. The private insurance market has long been underwriting a suite of associated risks through Property & Casualty lines of business, including:

- Property traditional (includes property value and business interruption insurance). The main covers are for fire, explosion, malicious damage, strike, civil commotion and natural peril (eg, flood, windstorm, hail and earthquake) risks.

- Casualty traditional lines
  - General third-party and product liability
  - Employer's liability
  - Motor
  - Professional liability
  - Environmental liability

[97] All three examples are real engagements pursued by Swiss Re. See *Sustainability Report 2019*.
[98] *UN-convened Net-Zero Insurance Alliance,* 21 April 2021.
[99] There are four general criteria that insurance products need to conform to: 1) randomness of the peril (ie, no-one should be able to foresee the exact time of occurrence of an adverse event that has to be accidental and independent of the will of the insured); 2) quantification of the frequency and severity of the peril (insurers can model for the probability of occurrence and estimate the impact to the value at risk in case of occurrence of an adverse event); 3) affordability (the insurance premium must be affordable for the insured and adequately cover the financial risk carried by the insurer); and 4) reciprocity or mutuality (insurance portfolios must be sufficiently diverse to avoid systemic risk). See G. Heal, H. Kunreuther, *Environmental Assets & Liabilities: Dealing with catastrophic risks*, The Wharton School, November 2008, and P. Brahin et al., *The essential guide to reinsurance*. Swiss Re, 2015.

- Specialty lines (traditional and non-traditional)
  - Marine
  - Engineering
  - Agriculture (forestry, crop)
  - Political risk
  - Cyber
  - Credit & Surety

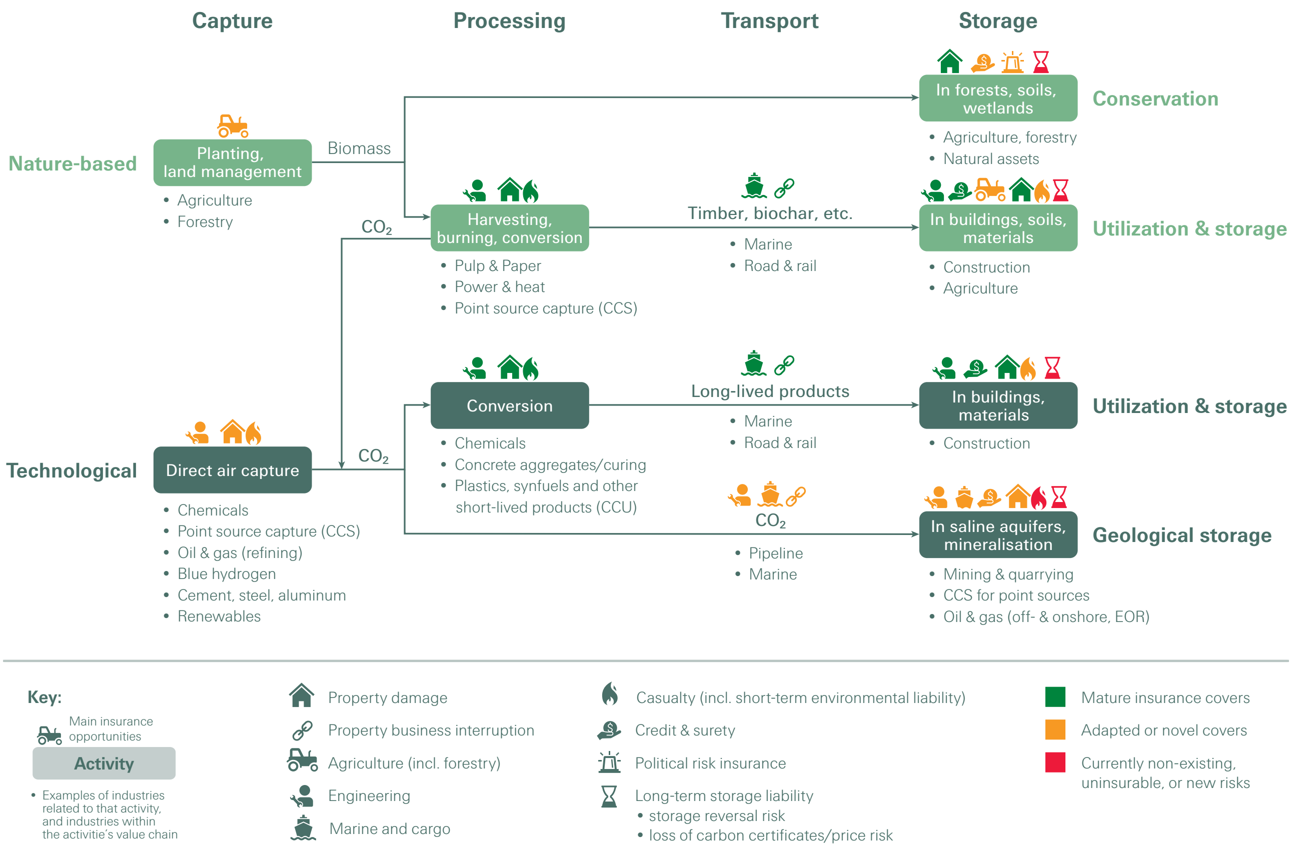
Multi-line insurance offerings for renewables is an example for the insurability of technology.

Take renewable energy as an example of insurable risks that can transfer to the carbon removal value chain. A developer of an offshore wind farm, for instance, would go to the traditional insurance market and seek multi-line covers across project phases: planning liability during the development phase; cargo all-risks and delay in start-up during the transport phase; erection all-risk, advance loss of profit and project liability products during the construction phase; and operational all-risk, business interruption and public- and product-liability covers, as well as environmental liability during the operational phase. Through Credit & Surety insurance, the developer and lenders may seek to protect their contracted services and financial interests.

The insurance opportunities along the carbon removal value chain are manifold.

Figure 4 shows the carbon removal value chain, with a simplified linkage of the four main stages: CO_2 capture from air, processing, transport, and storage. As indicated, each stage presents key insurance opportunities, accompanied by a non-exhaustive list of related industries with risk pools that underwriters are already familiar with. The pre-existing understanding can spur further development of insurance offerings for specific stages of the carbon removal value chain.

Figure 5
Insurance opportunities and related industries along the carbon removal value chain



Source: Swiss Re

Insurers are designing multi-line offerings for CCS. These will yield learnings for carbon removal.

A multi-line offering for a direct air capture project would look largely similar to the exposures covered in the offshore windfarm example. The risks during planning, transport, construction and operation are known and also insurable. Zurich Insurance, for instance, is currently "spear-heading a task force to conceptualise an insurance product to cover the physical and legal risks associated with CCS."[100] The first step is to package existing P&C products for CCS pilot and demonstration projects in the UK.[101] This will yield learnings for the carbon removal insurance more broadly, given significant overlap between the CCS and carbon removal value chains (eg, BECCS, and DACS).

More carbon removal projects are needed to solidify the risk knowledge and provide feasible insurance offerings.

Still present challenges to insurability: All told, with carbon removal processes still in early stages of development, the structuring and pricing of insurance offerings for the industry will remain challenging for some time. More projects, performance data and loss history are needed for insurers to build credible loss expectations. The Sleipner Vest field in Norway is an example of how to generate and understand performance data for a key element of carbon removal, namely geological CO_2 storage. Since 1996, some 19 million tonnes of CO_2 have been injected into the Sleipner reservoir, at a rate of 0.85 million tonnes per year. In a meta-analysis of more than 150 scientific papers, Furre et al. examined the extensive monitoring programme carried out at the Sleipner storage site, concluding that the CO_2 injected at the Sleipner site has remained contained since the start of operations.[102] The study also stressed the importance of case-specific, risk-based monitoring design (no one-size-fits-all)[103] and how, over time, the data feedback enabled improvement of reservoir models to render better, long-term predictions and thus risk knowledge.

Also challenging the insurability of carbon removal are the many process interdependencies and long time frames.

Other than lack of loss history, another challenge to the insurability of carbon removal is the complexity and interdependency of the value chains involved, especially for hybrid and technological solutions. Underperformance or failure of one of the chain links (eg, a faulty compressor unit, a shortage in transport capacity, a safety shut down of an injection pump, etc) will cause interruptions up- and downstream. These may lead to general underperformance and, in the worst case, to stranded assets.[104] Such chain integration risks hint at liability issues during the operational phase, which will require special attention. Furthermore, the liability question does not stop with the end of "operations", for example once a forest is fully grown, or CO_2 injection into a geological reservoir is complete. Unlike a wind farm that can be decommissioned and dismantled at its end of life, a properly regulated carbon removal project has long tail obligations: once the CO_2 is captured from the atmosphere and the store is created, it must be kept safely and *permanently* stored. Regulators usually put in place financial security obligations to ensure that operators set aside the means to observe storage integrity for as long as required as deemed necessary in a given jurisdiction.

Storage reversal is the main new risk inherent to carbon removal.

Still uninsurable risks: Carbon removal solutions come with varying degrees of risk of storage reversal. A wildfire destroying an afforestation project, the new owner of a farm abandoning carbon sequestering land-use practices, and a geological storage reservoir leaking through an old, insufficiently plugged well, are just some examples. For the climate system to stabilise, temporary storage is not an option. Nor is it for efficient functioning of a market in carbon removal certificates, the current means of monetising carbon removal. At some point, lawmakers may also mandate carbon removal for providers or consumers of carbon-intensive goods and services. Thus, in the event of storage reversal, contingency plans and financial securities that allow for the timely deployment of remedial measures to stop and undo any emission from the store must be in place. Insurance could be one instrument of such financial security.

100 F. Streidl, K. Sheppard, *Sustainability in Energy Insurance*, Zurich, December 2020.
101 Personal communication with K. Sheppard of Zurich UK Energy team, March 2021.
102 A. Furre et al., "20 years of monitoring CO_2-injection at Sleipner", *Energy Procedia*, vol 114, 2017.
103 Monitoring encompasses a combination of various geophysical methods and downhole sensors to follow and predict the movement of the CO_2 plume (conformance monitoring), to confirm that the CO_2 stays within the storage reservoir (containment monitoring), and – should leakage occur – to assess the effect of remedial measures (contingency monitoring).
104 W. Goldthorpe, L. Avignon, M. Repmann, J. Schwieger, *Enabling a Low-Carbon Economy via Hydrogen and CCS*, Elegancy, 2018.

To date, the insurance industry has shown little appetite to cover storage reversal risk.

The insurance industry is struggling with long-term liabilities related to carbon storage. Private insurers are not willing to take very long duration tail risks due to uncertainties in loss prediction. This has been clear from the early days of carbon storage in the context of CCS, originally conceived in the 2000s as a means to decarbonise fossil fuel-fired power plants. The "un-insurability of some liabilities" related to geological CO_2 storage has always been considered a "material barrier" to the deployment of CCS technologies.[105] In 2008/2009, Zurich Insurance was the first and to date only insurer to offer a liability cover for CCS, tailored to the US market. There is very little public information about that product.[106] Five years later in 2014, long-term liabilities related to CO_2 storage were again identified as "not insurable", according to the insurance plan for the Peterhead CCS project proposal under the UK CCS Commercialisation Programme, summarized in Table 3.[107]

Table 3
Insurance plan for the Peterhead CCS project proposal

Risk	Design and construction	Operations	Closure and de-commissioning	Post-closure
Liability				
3rd party liability	Y	Y	Y	Y
Seepage & pollution from reservoir	N	N	N	N
Automobile liability	Y	Y	Y	Y
Employer's liability	Y	Y	Y	Y
Professional liability	(N)	(N)	(N)	(N)
Sub-surface liabilities	N	N	N	N
Physical damage				
Damage to the works (construction all risk)	Y	n/a	Y	n/a
Damage to existing assets	Y	Y	Y	Y
Loss of well control	Y	Y	Y	Y
Automobile physical damage	(N)	(N)	(N)	(N)
Transit/cargo	Y	Y	Y	n/a
Other				
Loss of carbon credits	N	N	N	N
Business interruption due to physical damage	n/a	Y	n/a	n/a

Source: *Peterhead CCS Project: Insurance plan*, Shell, 2014; based on *Stage 1 Design Phase Risk and Insurance Report*, Marsh, 2014.

105 *Managing Liabilities of European Carbon Capture and Storage*, ClimateWise, 2012.
106 Personal communication with K. Sheppard of Zurich UK Energy team, March 2021.
107 *Peterhead CCS Project: Insurance plan*, Shell, 2014; based on *Stage 1 Design Phase Risk and Insurance Report*, March 2014. See also I. Havercroft et al., Lessons and perceptions. *Adopting a commercial approach to CCS liability*, Global CCS Institute, 2019.

Insurance could play a role when carbon certificates need to be replaced upon storage reversal.

The role of carbon certificates
Also listed as uninsurable in Table 3 are carbon certificates ("loss of carbon credits"). As aforementioned, in the context of carbon removal, a carbon certificate is the attestation that 1 tonne of CO_2 has been removed from the atmosphere and stored permanently. Voluntary buyers of carbon removal certificates use them to balance their residual emissions in line with a net-zero claim (net-zero flight, personal footprint, own operations, city, etc). In the case of storage reversal, the carbon removal certificates – and with them the climate claims they had supported – are annulled. The value at risk is given by the cost of replacing the lost certificates at current market prices. Due to market volatility, the replacement certificates could sell at a much higher price than what was originally paid.[108] As a remedy, the buyer could ask the seller to protect the validity of the certificates through some sort of product liability insurance, where the product to be covered is the negative emission service (in the form of the certificates) offered by the seller. Buyers may also decide to tender and purchase such a certificate insurance on their own to better control and optimally protect the integrity of their net-zero claim.

The emergence of a compliance carbon market for removal certificates may drive demand for such insurance offerings.

Interest for insurance offerings related to removal certificates may soon be amplified by the emergence of new compliance markets for carbon removal. There, regulators will require emitters to balance their emissions by purchasing removal certificates. To ensure compliance and avoid fines, regulated emitters may then also start to look for insured certificates or certificate insurance. Also, public sector buyers will likely add to this new demand for insurance. The Paris Agreement Article 6 for cooperative mechanisms will allow one country to sell emission reduction or negative emission services to another. The corresponding certificates are called Internationally Transferred Mitigation Outcomes (ITMOs).[109] As international climate negotiations about the rule book for such transfers are ongoing, first transactions are being piloted.[110] Pilot transactions usually take place via bilateral agreements between a developed country as buyer and a developing country as seller of ITMOs. In these cases, the insurance taker would typically be the buying country.

There is still some way to go to improve risk knowledge of storage reversal.

Tackling the long-term liability challenges of carbon storage: To enable liability insurance solutions for storage reversal events, long-term environmental, property and health impacts must be clarified. Insurers need to be able to build reliable expectations about worst-case loss scenarios. Operational, managerial and regulatory responsibilities for damage must be clear, in line with the establishment of clear cause-effect analytics. The differentiation of storage reversal into gradual and abrupt, the type of value at risk through reversal, and the underlying type of carbon removal solution will determine the type of insurance cover needed. This could be environmental or product liability. Insurance solutions offered by the private sector would likely be limited to shorter-terms and with diverse exclusion clauses. Covering long-term liabilities would likely be left to public sector solutions, possibly in partnership with the private sector.

[108] Both voluntary and compliance carbon markets have seen significant price fluctuations in the past. For instance, an emission allowance unit under the world's largest compliance carbon market, the EU emission trading scheme, went from ~EUR 4 to ~EUR 40 in only 3 years from 2018 to 2021. See *eex*, accessed 23 April 2021
[109] *Paris Agreement*, United Nations Framework Convention on Climate Change (UNFCCC), 2015.
[110] S. Greiner, et al., *Article 6 Piloting: State of Play and Stakeholder Experiences*, Climate Finance Innovators, December 2020.

Open literature provides just a few hints on how to tackle the long-erm storage liability issue, among these using EOR as example, and public-sector underwriting.

The insurance of ITMO transactions or other future compliance carbon removal markets would open the door to public-private insurance partnership. This would require a dialogue with the regulator on the question of suitable risk sharing models for carbon removal, in particular the insurability of long-term storage liabilities. Some considerations and models described in open literature are:

- **Enhanced Oil Recovery (EOR) as comparative:** CO_2-EOR means injecting liquified CO_2 into mature oil fields to mobilise and extract more oil. At the end of the EOR operation, the injected CO_2 remains stored in the depleted oil reservoir. EOR has been practiced in North America since the 1970s.[111] A recent study featuring expert interviews on questions about CCS liabilities found respondents from the insurance industry assuming that analogues can be drawn between EOR and CCS.[112] The study, however, remains unclear whether this assumption also applies to the long-term liability of CO_2 storage (ie, the part of the CCS value chain most relevant in the context of carbon removal), or just the better-understood CO_2 capture, transport and injection phases.

  EOR presents the longest-standing record of practical experience with underground CO_2 injection for commercial reasons, yielding corresponding loss history. Furthermore, dedicated CO_2 storage benefits from technical as well as policy experience under the US oil and gas regulatory framework.[113]

- **Carbon allowance reimbursement insurance (CARI):** In 2012, the ClimateWise insurance industry group conceptualised the CARI policy to insure operators against the loss of carbon certificates under the EU Emission Trading Scheme.[114] The CARI policy is limited to the injection phase only, as post-closure, long-term storage liabilities are considered uninsurable. Policy terms foresee yearly renewal, a number of exclusions[115] and a deductible. Insurer and insured agree up-front on the expected maximum amount of CO_2 stored as well as on the price per certificate at which the policy would indemnify the insured upon storage reversal. Acknowledging price volatility in the certificates market, the suggestion is to limit the liability to a price cap, either fixed or based on the moving average certificate price from the previous few years.

  ClimateWise also addressed some challenges that would come with a CARI-type insurance cover: the annual renewability that creates cost and therefore investment uncertainty, aggregation risk with liabilities already covered or events affecting several operations simultaneously, as well as hindrance due to lack of insurance capacity, trigger definition (proximate cause versus a regulatory decision on the quantum of loss), and loss quantification. To date, the CARI policy model has not been operationalised nor put into practice.

111 See *Enhanced Oil Recovery,* Office of Fossil Energy, accessed 23 April 2021.
112 Havercroft, Ian et al., 2019, op. cit.
113 V. Nunez-Lopez, E. Moskal, *Potential of CO_2-EOR for Near-Term Decarbonization,* Frontiers in Climate, 27 September 2019.
114 The certificates under the EU Emission Trading Scheme (EU ETS) are called Emission Allowance Units (EUA). They allow an emitter under the ETS to release 1 tonne of CO_2 to the atmosphere. All emissions covered under the ETS are capped and all emitters receive a certain amount of EUAs according to industry benchmarks. EUAs can then be traded among emitters. If one emitter reduces emissions (eg, a cement plant through the installation of a CCS facility) it can sell the surplus EUAs to another cement plant that did not implement emission reduction measures itself.
115 Exclusions to CARI pay-outs: defects in design, plan, specification, materials or workmanship; normal wear and tear, gradual deterioration or normal corrosion; earthquake (can be included, but could give rise to aggregation risk depending on location); normal setting, normal shrinkage or normal expansion in land and/or caprock. Source: ClimateWise, 2012.

- **Public-sector underwriting for risk sharing:** As long as there is limited to no experience with long-term CO_2 storage, the private sector will consider the related risks as "unquantifiable" and shy away from full exposure. Risk sharing with governments will play an important role over the short to mid-term.[116] Governments or responsible public authorities may:
  - accept liability caps, including on the maximum cost for the replacement of lost carbon certificates;[117]
  - foster and/or administer a risk pooling approach like the Nuclear Risk Insurers Limited (NRI);[118]
  - establish a stand-alone agency (a "delivery company") to manage the full-chain risks of technology deployment;[119] and ultimately
  - accept the transfer of liability from the operator to the public sector after a clearly defined period post injection completion.[120]

Regulation can help governments manage their exposures.

By putting in place robust regulations with a diligent approach to permitting and reporting, governments will be able to manage their own exposure to risks acquired through sharing and transfer models.[121]

- **Buffer pools:** Most standards for nature-based solutions have applied buffer pools to address the risk that an emission reduction or carbon removal outcome is reversed as a result of a damaging event to the underlying natural asset (eg, from a wildfire, mismanagement, illegal deforestation, policy changes, etc). The idea is that projects subject to known non-permanence risks are assessed according to certain criteria to determine how many of the certificates issued by these projects cannot be sold, but instead need to be directed into a buffer pool.[122] From there, should a storage reversal event take place, replacement certificates can be released. The State of California's Low Carbon Fuel Standard (LCFS) applies the buffer-pool principal also to technological removals like DACS.[123] Project operators need to contribute up to 17% of the carbon certificates generated to a so-called "Buffer Account". The assessment of the buffer contribution is determined by onsite risk assessment, including of well integrity and site risks.[124] Table 4 shows the guide to a CCS project's risk rating that determines how much in certificate value the project needs to contribute to the LCFS buffer pool. If leakage from storage reservoir occurs during the first 50 years post injection, replacement certificates need to be drawn from the contributions to the Buffer Account from that very project. During the next 50 years, contributions made by all parties to the Buffer Account could be used to replace lost certificates. After 100 years, the post-injection monitoring obligation ends.

[116] W. Goldthorpe, L. Avignon, M. Repmann, J. Schwieger, 2018, op. cit.
[117] *Carbon capture and storage: the second competition for government support*, National Audit Office, January 2017.
[118] Other examples include the Oil Insurance Limited (OIL), Offshore Pollution Liability Agreement (OPOL), See W. Goldthorpe, L. Avignon, M. Repmann, J. Schwieger, 2018, op. cit
[119] R. Oxburgh, *Lowest Cost Decarbonisation for the UK. The critical role of CCS*, Report to the Secretary of State of Business, Energy and Industrial Strategy form the Parliamentary Advisory Group on CCS, 2016.
[120] In the EU and Australia, the post-closure time limit for transfer of (partial) liabilities is 20 years.
[121] W. Goldthorpe, L. Avignon, M. Repmann, J. Schwieger, 2018, op. cit.
[122] See Verified Carbon Standard, 2019. *AFOLU Non-Permanence Risk Tool*. Verified Carbon Standard, 2019, accessed 23 April 2021.
[123] See *California Air Resources Board*, accessed 21 April 2021.
[124] "Appendix G. Determination of a CCS Project's Risk Rating for Determining its Contribution to the LCFS Buffer Account", in *Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard*, California Air Resources Board, 6 March 2018.

Table 4
Guide to a CCS project's risk rating for determining its contribution to the LCFS Buffer Account

Risk type	Risk category	Risk rating contribution
Financial	Low financial risk: CCS project operators demonstrate their company has a Moody's rating of A or better; or an equivalent rating from Standard & Poor's and Fitch	0%
	Medium financial risk: CCS project operators that demonstrate their company hasa a Moody's rating of B or better; or an equivalent rating from Standard & Poor's and Fitch	1%
	High financial risk: CCS project operators cannot make one of the two demonstrations above	2%
Social	Low social risk: CCS projects located in countries or regions ranked among the top 20th percentile based on the World Justice Project Rule of Law Index	0%
	Medium social risk: CCS projects located in countries or regions ranked among the top 20th and 50th percentile based on the World Justice Project Rule of Law Index	1%
	High social risk: CCS projects located in countries or regions that are not ranked, or ranked below the 50th percentile based on the World Justice Project Rule of Law Index	3%
Management	Low management risk: demonstrated surface facility access control, (eg, injection site is fenced and well protected)	1%
	Higher management risk: poor or no surface facility access control (eg, injection site is open, or not fenced or protected)	2%
Site	Low site risk: selected site has more than two good quality confining layers above the sequestration zone, and a dissipation interval below the sequestration zone	1%
	Higher site risk: site meets the minimum selection criteria, but does not meet the above site criteria	2%
Well integrity	Low well integrity risk: all wells for the CCS project meet US Environmental Protection Agency (EPA) class VI well or equivalent requirements	1%
	Higher well integrity risk: the CCS project has wells that do not meet US EPA class VI well or equivalent requirements	3%

Source: *Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard*, California Air Resources Board, 6 March 2018. See Appendix G. Determination of a CCS Project's Risk Rating for Determining its Contribution to the LCFS Buffer Account

Investing in carbon removal solutions

Carbon removal solutions are high-risk investments.

Carbon removal solutions, in particular infrastructure-heavy technological and hybrid solutions, typically require substantial capital upfront, a long-term investment horizon, or both. The availability of specialised risk knowledge and inherent need to invest earned premiums over long periods of time to match assets and liabilities makes re/insurers well-positioned as partners for the carbon removal industry. However, most industry solutions are still immature, under-deployed and some under-developed, making existing carbon removal opportunities high-risk investments. As such, insurers need to hold significant levels of capital against such investments, not least to align with prudential and solvency rules.

The public sector and large industrial players are currently the main investors.

Currently, flagship carbon removal projects are mostly government-funded,[125, 126] and/or are supported by major industrial players, in particular from the oil and gas sector.[127, 128] Government and large industry are more able to take on the investment risk inherent in new technologies, which include:[129]

- Technical and physical risks, accentuated by immaturity of technologies/lack of performance data and uncertainties about the quality and availability of natural resources (eg, the performance of a natural carbon sink or geological storage reservoir, especially under climate change considerations which alter the bio-physical context).
- Market and commercial risks: high upfront costs, long investment horizons/payback periods, investor unfamiliarity with the new technology, and complexity of infrastructure investments.
- Political and social risks, such as the need to rely on public financial/institutional support, the long-term investment horizon (much longer than electoral policy cycles), and (potential) social resistance to the new technologies.

Policy asks for a robust investment environment are carbon pricing, subsidies, public/private risk sharing.

Project developers need to assess these risks and how to manage them. If they are to attract investors, they also need a business case that convincingly forecasts acceptable cash flows. Finally, a robust investment environment is required. To this end, the three most common policy asks are:[130]

- for policymakers to put a price on carbon that pays for reducing and removing emissions (including in the form of tax benefits);
- provision of seed money, for instance in the form of grants or guarantees to first-in-kind and early adopter projects; and
- fair allocation of risks across the public and private sectors, according to where comparative risk management advantages lie.

More public sector support is needed to attract private sector investors.

In summary, to accelerate the deployment of carbon removal and its popularity among investors, governments and policymakers need set in place more support and regulatory backing.

125 *£5m boost to scale up ground-breaking carbon capture pilot at Drax*, drax, 27 June 2019.
126 *Funding for Longship and Northern Lights approved*, Norwegian Government, 15 December 2020.
127 *The New York Times*, 7 April 2019, op. cit.
128 "Shell launches USD 300m forest plan to offset carbon emissions", *Financial Times*, 8 April 2019.
129 *Risk Gaps: A Map of Risk Mitigation Instruments for Clean Investments*. Climate Policy Initiative, January 2013.
130 *Special Report on Carbon Capture Utilisation and Storage – Energy Technology Perspectives*, IEA, 2020.

Investor initiatives and guidelines are still mostly bearish on the need for and potential of carbon removal.

The public sector and also private institutions/groups have launched several initiatives and guidelines on net-zero ambitions. Some remain silent on carbon removal. In ignoring the potential upside,[131, 132] they can also miss highlighting that to be able to claim a fully net-zero (as opposed to a low-carbon) portfolio, investors will inevitably have to fund negative emissions to balance any residual emissions from other assets in the portfolio.[133] Other initiatives and guidelines are essentially bearish in their outlook,[134] seeing "forest restoration as the earliest feasible investment opportunity," and BECCS and DACS not investible before 2030 and 2040, respectively (though the private sector has started investing in DACS[135]). Others see more promise. For example, in its recently published Inaugural 2025 Target Setting Protocol, the UN-convened Net-Zero Asset Owner Alliance, clearly defines "investments in economic activities [...] sequestering carbon dioxide already in the atmosphere" as "Climate Solution Investments".[136] The standard asks Alliance members to report on their invested/committed value in carbon dioxide removal investments.

Other than in forestry projects, investments in carbon removal projects remain scarce.

Given its still immaturity, investors – re/insurers included – have not yet had much opportunity to explore the carbon removal sector as a new asset class. This is with the exception of nature-based solutions, in particular forestry.[137]

Nature-based solutions are projected to generate substantial revenues in the next decades, also in view of an expected surge in carbon market volume.

Outlook on nature-based solutions as investment opportunities

According to Tobin-de la Puente and Mitchell, two thirds of countries are considering natural climate solutions as part of nationally-determined contributions to mitigate climate change under the Paris Agreement.[138] Yet, natural climate solutions currently receive only about 6% of total public funding on climate,[139] suggesting a large protection gap. Open literature does not yet provide long-term investment estimates. Using revenue figures as a proxy for investment size, Vivid Economics estimates that reforestation projects could generate up to USD 190 billion in revenue by 2050.[140] Short-term estimates exist: Deutz et al. assess current global private and public-private annual investment volume in natural climate solutions to be between USD 0.8–1.4 billion, and that this could increase to an estimated USD 25–40 billion per year by 2030.[141] These estimates include the transaction volume of carbon avoidance certificates from natural climate solutions traded on the voluntary market. This market reached an all-time high in 2019 and has continued to grow, despite the economic downturn under the COVID-19 pandemic.[142] Lately, buyers are explicitly soliciting carbon removal as opposed to the conventionally-bought carbon avoidance certificates.[143, 144] This is yet another indicator of a growing number of nature-based solution projects that will soon be on the lookout for finance.

131 *Net Zero Investment framework for Consultation,* Institutional Investors Group on Climate Change, 2020.
132 "The Oxford Martin Principles for Climate-Conscious Investments" in *Net Zero Carbon Investment Initiative,* Oxford Martin School, 2018.
133 There exists no truly zero-carbon asset today. For example, even renewables come with residual emissions (the aluminium and steel in the rotors of a wind farm, the bunker fuel from the cargo ship that brought the solar PV panels from China to Europe, etc).
134 *An investor guide to negative emission technologies and the importance of land use.* Vivid Economics, Inevitable Policy Response, 2020.
135 *bloomberg.com,* 2 June 2020; *The New York Times,* 7 April 2019, op. cit.
136 *Inaugural 2025 Target Setting Protocol, UN-Convened Net-Zero Asset Owner Alliance. Monitoring Reporting and Verification Track.* PRI, UNEPFI, 2021.
137 Vivid Economics, Inevitable Policy Response, 2020, op. cit.
138 The term "natural climate solutions" lumps together activities that either avoid emissions from landscapes and wetlands through conservation, or remove emissions through the nature-based solutions.
139 J. Tobin-de la Puente, A.W. Mitchell, *The Little Book of Investing in Nature,* Global Canopy, 2021.
140 Vivid Economics, Inevitable Policy Response, 2020, op. cit.
141 A. Deutz, G.M. Heal, R. Niu, E Swanson E. Townshend et al., *Financing Nature: Closing the biodiversity financing gap,* The Paulson Institute, The Nature Conservancy, the Cornell Atkinson Center for Sustainability, 2020.
142 "Carbon offset market progresses during coronavirus", *Financial Times,* 29 September 2020.
143 For an explanation of the difference between these two types of carbon certificates, see "Focus: Moving from carbon offsets to carbon removal", in *Sustainability Report 2019,* Swiss Re.
144 For example, *stripe.com* 18 May 2020; *shopify.com* 15 September 2020; Microsoft 2021, op. cit. and "Shopify Purchases More Direct Air Capture (DAC) Carbon Removal Than Any Other Company", *shopify.com,* 9 March 2021.

Long-term purchasing agreements of carbon certificates can support project finance.

Carbon removal certificates can also be used to structure new project finance mechanisms. A long-term contract called a Carbon Removal Purchase Agreement (CRPA) between a carbon removal project developer and certificate buyer can be used as security. The longer the contract term and higher the credit rating of the buyer, the more valuable the security (ie, the cheaper the capital cost for the developer). Revenues from certificate sales under the CRPA can be arranged to flow directly to the financing party. This mimics the Emission Reduction Purchase Agreement (ERPA) backed finance model.[145] Financiers with a need for certificates (eg, to compensate their unavoided operational emissions subject to a net-zero commitment) may also take (parts of) the project's certificates directly onto their book, in exchange for a corresponding reduction in the interest rate. Some of these types of financing mechanisms are explained in more detail in existing literature.[146]

Carbon-removal bonds could help make smaller projects also investible.

Another financing means could be carbon removal-type bonds, as a new sub-class of green bonds. These could be debt instruments to aggregate a pipeline of projects of various type and size. They would offer a new opportunity to diversify project risk and render smaller projects investible for a broader array of institutions, including insurers.

Blended finance is another key tool, particularly in emerging markets.

In developed markets, traditional financing mechanisms (project finance, public funding) will remain strong drivers for carbon removal projects. In developing markets, it is usually more difficult to attract capital. Currently blended finance – the mixing of public (eg, guarantees) and private (eg, equity) finance – is a clear signal to infrastructure investors to act under solid umbrellas and ratings from multilateral institutions, because it supports the de-risking of projects that are otherwise not interesting for investors. The Net-Zero Asset Owner Alliance calls on asset managers to support blended finance, because it allows "public financiers and other donors to use a small amount of their own resources as a first-loss to mobilize large amount of private capital".[147] The UN Environment Programme's Finance Initiative proposes blended finance as a tool to spur sustainable development projects in the field of blue carbon.[148] This may set a precedent that could be used to further expand the carbon removal investment space, especially as many nature-based solution opportunities are located in emerging markets.

Advancements in the understanding and monitoring of the solutions will continue to improve the attractiveness of nature-based solutions as an asset class.

Altogether, the above-listed trends and models indicate ample investment opportunities in natural assets that use vegetation or soils as carbon sinks. Vivid Economics concludes that "Negative Emission Technologies are the next investment frontier and offer trillion dollar upside opportunities".[149] Capital markets are familiar with investing in forests as natural assets and/or for timber. Forestry insurance, for example, against storms is a known field in underwriting as well.[150] Other parts of the nature-based solution space (eg, oceans) are less explored. Nevertheless, progress is being made to better understand, classify and standardise the climate services provided by all nature-based solutions.[151] For example, remote sensing in combination with machine learning capabilities can reduce the need for frequent field sampling of soils and vegetation to assess and monitor the carbon stock of natural assets.[152] This reduces management fees and improves risk management capabilities through more accurate data and more frequent reporting – also adding to the risk knowledge required for effective underwriting.

145 An ERPA is a long-term (usually 3–15 years) offtake agreement for conventional carbon avoidance certificates, usually at predefined volume and price. For ERPA-backed finance, see W. Goldthorpe et al. 2018, op. cit)
146 Vivid Economics, Inevitable Policy Response, 2020, op. cit.
147 *Net-zero asset owner alliance calls on asset managers to support blended finance*, UN Environment Programme (UNEP), 16 February 2021.
148 UN Environment Programme Finance Initiative, 2020. *A Blue Path to Recovery: The Power of Finance to Rebuild Ocean Health*, UNEP, 2020.
149 Vivid Economics, Inevitable Policy Response, 2020, op. cit.
150 *Forest Insurance: A largely untapped potential*. Swiss Re, 2015.
151 G. Somarakis, S. Stagakis, N. Chrysoulakis, *ThinkNature Nature-Based Solutions Handbook*, 2019.
152 See, for example, *Aspiring Universe*, *Pachama*, and *Siliviaterrra*. Currently ongoing is the *Sustaintech Xcelerator* supported by – among others – The World Bank, seeking to foster solutions to increase trust in nature-based solutions (eg, monitoring and verification technologies including remote sensing with AI and latest modelling advances, technologies to support ground sampling etc).

Estimates suggest annual revenues of technological removals will be between USD 500-625 billion by 2050.

Outlook on technological and hybrid solutions as investment opportunities
Robust, bottom-up estimates of the investment needs for the full BECCS and DACCS value chains are not yet available. Reasons include uncertainties about future cost, timing and extent of deployment, or difficulties in appropriating shared infrastructure like pipelines, storage infrastructure etc. Using again revenue estimates as a proxy for investment size, these figures are in the triple-digit billions. The US National Academy of Sciences, Engineering and Medicine stipulates that 5 billion tonnes of negative emission per year from technological removal solutions could generate an annual revenue of USD 500 billion.[153] Vivid Economics arrives at a figure of USD 625 billion per year by 2050.[154]

Current investments in CCS (for emission mitigation) are at USD 42 billion.

Taking CCS as a proxy for BECCS or DACCS (ie, reference of scale for investments in that type of infrastructure), one can appreciate how large investments in technological carbon removal infrastructure ultimately could be. The Energy Transition Commission estimates an investment need of USD 160–190 billion per year for CCS over the next 30 years (cumulatively USD 4.8–5.6 trillion) to mitigate 6–10 billion tonnes of CO_2 emissions over that period from power, hydrogen production and heavy industry.[155] Since 2010, globally USD 15 billion has been invested into 16 large-scale CCS projects.[156] Another 16 big projects in advanced planning stage today amount to another USD 27 billion of investments.[157] Private sector contributions have come mostly from oil & gas majors. During the same period, startups seeking to commercialise CO_2 utilisation routes have raised nearly USD 1 billion in private sector investment.[158] The handful of direct air capture (DAC) firms around today have raised some USD 200 million in private capital, and another USD 200 million in public research and development grants.[159] These are much smaller numbers than the level of capital that has already gone into large CCS, but are nonetheless notable for a technology long-considered economically unviable.

Government backing for technological carbon removal is increasing…

Government spending on technological carbon removal solutions is on the rise, too. In 2019, the US Congress allocated USD 60 million towards carbon removal.[160] A year later, USD 447 million of the second stimulus bill was earmarked for carbon removal R&D by 2025, starting with USD 175 million in 2021.[161] The EU Innovation Fund to support low-carbon technology is valued at EUR 10 billion.[162] Below are two examples of government-backed flagship projects, the British Acorn project and the Norwegian Longship project (see *Acorn and Northern Lights: two flagship CCUS projects).* Originally conceived as pure CCUS projects to decarbonise industry, both are now partnering with air capture and bioenergy companies, demonstrating the broader investment potential offered by the carbon removal value chain.

[153] *Negative Emissions Technologies and Reliable Sequestration – A Research Agenda*, The National Academies of Science Engineering Medicine, 2019.
[154] Vivid Economics, Inevitable Policy Response, 2020, op. cit.
[155] *Making Mission Possible – Delivering a net-zero economy*, The Energy Transition, 2020.
[156] IEA, 2020, op. cit.
[157] "Stored Carbon could morph into investment gold", *Reuters*, 20 October 2020.
[158] *Putting CO_2 to use*, IEA, 2019.
[159] Authors' estimate, informed by IEA's figures of USD 180 million in private capital and USD 170 million in public funds raised since 2019 (IEA, 2020, op. cit.)
[160] *US Government Allocates $60 Million to develop Carbon Removal Technology*, World Resources Institute, 2019.
[161] "Businesses Aim to Pull Greenhouse Gases from the Air: It's a Gamble", *The New York Times*, 18 January 2021.
[162] See "Innovation Fund" in *Climate Action*, European Commission.

...but more public sector backing could catalyse moree green finance.

The financing required for technological solutions is much greater than for nature-based solutions. To date, the main financing concern for full chain BECCS, DACS and CCUS is to secure the next R&D grant from government. Projects currently underway are heavily subsidised first-of-kind facilities. There is a long way to go before they become a readily investible asset class for the private sector. That said, "if governments make the first move, a wall of green finance could follow."[163] For its part, the oil and gas sector has been investing in these projects from the time that CCS became a topic, but much more is needed to embrace the inevitable transition from fossil-fuel providers to storage service providers. Further uptake of carbon-removal infrastructure investment could spur banks, insurers and others to follow suit.

Acorn and Northern Lights: two flagship CCUS projects

The UK government has pledged GBP 1 billion in investment for CCUS.

In spring 2020, the UK government announced a GBP-800-million infrastructure fund, subsequently topped up to GBP 1 billion, to support development of up to four industrial CCUS clusters.[164] This aligns with the UK's goal to become a world leader in carbon storage technologies, with a target to store 10 million tonnes of CO_2 by 2030.[165]

The Acorn project applies CCUS to a hydrogen production facility. A collaboration with a DAC firm will make Acorn a negative emissions pilot.

In September last year, Pale Blue Dot Energy and Carbon Engineering Canada announced a joint project.[166] Pale Blue Dot is an energy consultancy that leads the UK *Acorn* project in Eastern Scotland. Acorn is a flagship of the UK's CCUS programme, with a plan to capture in first phase 340 000 tonnes of CO_2 from the St. Fergus gas-fired power plant and later to also connect to a hydrogen production facility. The CO_2 will be compressed and sent through an existing natural gas pipeline to a geological storage site 100 km offshore.[167] With continued government and private sector support (Chrysaor, Shell and Total are project partners), the project could be commissioned in 2024. Investment needs are estimated at USD 270–550 million.[168] Carbon Engineering is one of the leading DAC companies from British Columbia in Canada. Carbon Engineering will install a DAC facility that connects to the Acorn transport and storage infrastructure. The DAC facility is expected to go live around two years after the Acorn project goes online.

The aim of Norway's Longship project is to create capacity to transport and store up to 5 million tonnes of CO_2 per year.

A further example where CCUS meets DACS is Norway's full-scale CCS project Longship. In phase 1, the project targets the capture of 0.7 and 1.1 million tonnes of CO_2 per year from a cement and a waste-to-energy plant near Oslo. Northern Lights, a joint venture between European oil majors Eqinor, Shell and Total, will take delivery of the concentrated liquified CO_2 from the two capture plants and ship it in tailor-made vessels to Bergen. There it will be unloaded and transported in a seafloor-mounted pipeline to a CO_2 storage site 2 600 meters underground. In Phase 2, capacity of the transport and storage will be increased to 5 million tonnes of CO_2 per year. Parts of the infrastructure for Phase 2 have already been built.

163 Reuters, 20 October 2020, op. cit.
164 *UK Government Set to Fund Four CCS Hubs and Clusters*, Global CCS Institute, 18 November 2020.
165 "PM outlines his Ten Point Plan for a Green Industrial Revolution for 25 000 jobs", *www.gov.uk*, 18 November 2020.
166 *Pale Blue Dot Energy and Carbon Engineering create partnership to deploy Direct Air Capture in the UK*, Pale Blue Dot, 17 September 2020.
167 See *Acorn*
168 *D16 Full Chain Development Plan and Budget*, Acorn, May 2018.

The storage capacity at the Longship site could cover 20 years of EU27 emissions.

Investment for the Longship Phase 1 pilot is USD 2.1 billion.[169] Two thirds is being funded by the Norwegian government, and the remainder by the capture operators and Northern Lights joint venture. Costs are currently estimated at more that USD 100 per tonne CO_2 stored.[170] Northern Lights foresees USD 400 million in annual revenue from its CO_2 storage service business during the whole Phase 2 (that adds 4 million tonnes of CO_2 per year in storage capacity). The total storage capacity of the Northern Lights injection site is estimated at 100 million tonnes, meaning that the injection well could be operated full capacity for 20 years before expansion is needed. The Storage Atlas of the Norwegian Continental Shelf concludes that storage capacity along the Norwegian West coast is sufficiently large that it could store more than 80 billion tonnes of CO_2.[171] This is equivalent to 1000 years of Norway's own current annual CO_2 emissions, or 20 years of all of the EU27 current annual emissions. These numbers demonstrate that carbon management, or "CO_2-as-a-service" could quickly turn into a business, catering a new export industry.[172]

Possibilities to expand the project to include biogenic or air-captured CO_2 are being explored.

In view of the growing interest in negative emissions, the Northern Lights joint venture has also started to look into sources of biogenic or air-captured CO_2. Stockholm Exergi plans to capture CO_2 from its biomass fuelled district heat and power plant Värtaverket, and ship it to the Northern Lights injection facility.[173] In March 2021, Northern Lights announced a partnership with Swiss air-capture pioneer Climeworks to explore a DACS project in Norway.[174]

Buying carbon removal services

Beyond reducing emissions, the financial industry is in prime position to act as early buyer of removal services.

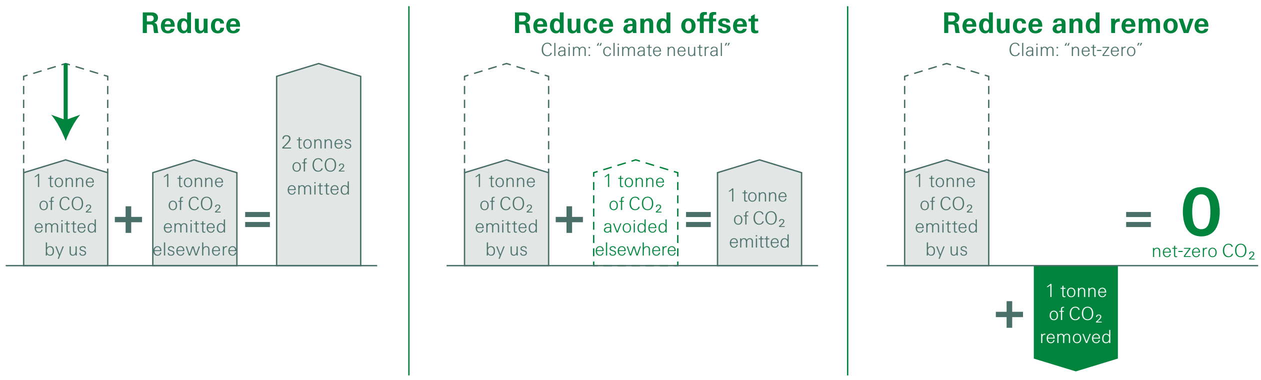
To achieve net zero emissions by 2050 or ideally earlier, companies should consider their sustainability strategy and business models. They first have to tackle those emissions for which they are directly responsible, in other words emissions from own operations. A robust net-zero strategy for operational emissions builds on separate targets for: 1) stringent emission reductions; and 2) balancing any emissions that cannot be avoided by an equivalent amount of negative emissions through carbon removal. The strategy should prioritise the former. Companies should seek to reduce emissions as fast and as much as possible in order to minimize the need for potentially very expensive negative emissions. Setting a separate target with interim milestones for carbon removal is important to alleviate the free-rider problem: if all firms were to wait until 2049 before removing unavoidable emissions in anticipation of falling prices in carbon removal technology, there would be a shortfall in know-how, capacity and affordability of removal services in 2050. Since early 2020, dozens of banks and insurers have committed to net-zero emissions in their own operations.[175] Achieving net-zero will be easier for the financial industry with higher net income per tonne of operational emissions than production industries such as mining, cement or textiles. Large banks and insurers, for example, have comparatively little in the way of direct emissions, and ample resources to deal with them. Customer-facing industries also tend to have larger financial means.[176]

169 *Funding for Longship and Northern Lights approved*, Norwegian government, 13 December 2020.
170 Reuters, 20 October 2020, op. cit.
171 See Norwegian Petroleum Directorate *website*, accessed 24 February 2021.
172 Reuters, 20 October 2020, op. cit.
173 *Stockholm plans world's first carbon-negative district heating*, Recharge, 28 January 2020.
174 *Climeworks and Northern Lights to jointly explore direct air capture and CO_2 storage in Norway* Northern Lights, 9 March 2021.
175 *Accelerating Net Zero – Exploring Cities, Regions, and Companies' Pledges to Decarbonise*, Data Driven EnviroLab, NewClimate Institute, September 2020.
176 *Net-Zero Challenge: The supply chain opportunity*, World Economic Forum in collaboration with Boston Consulting Group, January 2021.

To date, purchasing carbon offsets has been the status quo of compensating operational emissions.

The most material direct emission sources of an insurer are business travel, data centres, office space and commuting. Net-zero targets must trigger serious actions:[177] lean travel policies, 100% renewable power including for data centres, and green buildings, topped by the setting of an internal price on carbon that presents a challenge. The UN Global Compact calls on firms to set a minimum internal carbon price of USD 100 per tonne of emissions.[178] Until now, companies have compensated unavoided emissions through conventional carbon avoidance certificates (carbon offsets). Through these, an emitter pays third parties to avoid an equivalent amount of emissions to those the emitter itself cannot avoid, as illustrated in Figure 6. This type of CO_2 compensation qualifies for the claim "climate neutral" operations. It does not meet the requirements for a net-zero target, whereby an emitter has to buy a certificate from a carbon removal project, proving that unavoided emissions have been balanced through an equivalent amount of negative emissions.

Figure 6
Strategies to manage operational emissions and resulting claims



Source: Swiss Re

Higher prices for carbon certificates from technological solutions drives businesses towards nature-based solutions.

The market for conventional carbon offsets is fully established, with prices per tonne of CO_2 typically ranging from less than USD 1 to a maximum USD 20. A market for carbon removal certificates has yet to be established. First marketplace initiatives have emerged, but the few experiences of larger removal service purchases by corporates included an arduous tendering, selection and contracting process (eg, Stripe,[179] Shopify,[180] and Microsoft[181]). Essentially, removals lack international standardisation, are difficult to find, and their price can be significantly higher than that for carbon offsets. Prices range from USD 5–10 per tonne of CO_2 for some already existing projects in the nature-based solutions space, to several hundreds of USD per tonne for less developed, technological solutions. The world's first certificates for DACS in Iceland are currently available over the counter for more than USD 1000 per tonne of CO_2,[182] and wholesale for around USD 700–800.[183] In this environment, business instinct is to favour the cheaper nature-based solutions, in particular certificates from forest projects. Over the long run, however, nature-based solutions alone may not be sufficient to achieve the goal of limiting global warming to well below 2°C (see *Why companies should support more than forests* below).

[177] A. Pineda, A. Chang, et al. *Foundations for science-based net-zero target setting in the corporate sector – V1.0.* Science Based Target Initiative, Data Driven EnviroLab, NewClimate Institute, 2020.
[178] *Put a price on carbon,* UN Global Compact, accessed 28 February 2021.
[179] *stripe.com,* 18 May 2020, op. cit.
[180] shopify.com 15 September 2020, op. cit.
[181] Microsoft 2021, op. cit.
[182] See *Climeworks webshop,* accessed 28 February 2021.
[183] *stripe.com,* 18 May 2020, op. cit.

Nature-based solutions, in particular forest projects, are important…

Why companies should support more than forests

Currently, most implementation plans behind corporate net-zero pledges favour cheaper and more accessible nature-based solution certificates. Forest projects dominate corporate purchases of carbon removals services, followed by soil carbon sequestration and blue carbon initiatives, in particular mangroves.[184] Sustainably run forest projects are key to solving the climate issue, and come with a wealth of co-benefits. However, new forests conflict with other land-use needs like farming or ecosystem conservation. Their upper limit removal potential falls short of the amount of negative emissions that science predicts will be necessary to hit the 1.5°C global warming target: as already stated, the 1.5°C limit requires cumulatively up to 1 000 billion tonnes of negative emission by 2100, equivalent to around a yearly need of 10–20 billion tonnes throughout the second half of the century.

…but fall short in delivering the amount of negative emissions required to meet the 1.5°C global temperature rise target.

Minx et al. reviewed estimates for the removal potential of forest projects and found that existing and new forests will cumulatively be able to store 135 billion tonnes of CO_2 by the end of the century.[185] The yearly potential was assessed at 0.5–3.6 billion tonnes, with a caveat that such rates could only be sustained in the mid-term (until ~2050), and only if no other land-use based carbon removal solutions run in parallel. This is due to "bio-physical and socio-economic limits" and "rapid sink saturation".[186] Such shortcomings underline that corporates should – in parallel to investing in nature-based solutions – start supporting the development and scaling of less mature, more expensive but more scalable technological solutions.

A heavy focus on nature-based solutions now will inevitably drive up the price and will make it harder for the world as a whole to reach net-zero by 2050.

A second issue is what type of removals should balance what sources of residual emissions. If today's climate pioneers put all their CO_2 compensation money exclusively into forest projects, they would essentially buy up all readily available land. Then, as land becomes scarce, prices will rise and carbon removal – on average – will become more expensive for all, including for less developed markets and for industries with hard-to-abate footprints.

Paying higher prices now for hybrid and technological solutions will see prices decrease in the future when the world needs them at scale.

If instead companies signal their willingness to pay the first-mover price of more scalable and/but more expensive hybrid and technological solutions, the market will translate that signal into supply. The immature hybrid and technological solutions will start to scale, and prices will come down. This way, the average carbon removal certificates will become cheaper for all – hopefully on time for when the world needs them at the gigatonne-scale.

Buyers of carbon removal services can choose from three sourcing options for removal certificates.

The only way to grow the carbon removal industry to the required scale is by creating demand: voluntary buyers who act now and can afford the first-mover price, and/or lawmakers enforcing compliance markets at the right price point globally. The latter seems less realistic than the former. The question is how well-resourced private sector institutions like banks and insurers that are able to fund the full portfolio of carbon removal solutions, can engage and create demand in the most impactful manner. In most cases, buyers of carbon removal services require an attestation of their engagement in the form of certificates.[187] In most cases, buyers of carbon removal services require an attestation of their engagement in the form of certificates.[188] There are three sourcing options for carbon removal certificates.

[184] Swiss Re keeps its own database of corporate net-zero pledges, a less detailed public database is published by the *American University* of Washington DC, accessed 28 February 2021.
[185] J. Minx, et al., 2018, op. cit.
[186] S. Fuss, et al., 2018, op. cit.
[187] Other than through-purchasing removal certificates, companies could also realise negative emissions inside their value chain (= "insetting": Eg, a chocolate manufacturer sponsors the switch to agroforestry and a biochar plant for their cacao farmers), where they may or may not register their action under a standard that issues certificates. Furthermore, some stakeholders advocate for contributional claims, where companies become climate financiers without insisting on a tonne-by-tonne accounting, but some other forms of payment and reporting terms.
[188] Other than through-purchasing removal certificates, companies could also realise negative emissions inside their value chain (= "insetting": Eg, a chocolate manufacturer sponsors the switch to agroforestry and a biochar plant for their cacao farmers), where they may or may not register their action under a standard that issues certificates. Furthermore, some stakeholders advocate for contributional claims, where companies become climate financiers without insisting on a tonne-by-tonne accounting, but some other forms of payment and reporting terms.

These come with decreasing levels of commitment and thus impact, but also with decreasing level of buyer-vendor interaction, and thus less transactional effort:

- **Carbon Removal Purchasing Agreements (CRPA)** are long-term offtake agreements with bespoke volume and price over several years. They are like an ERPA for carbon offsets, or a power purchase agreement (PPA) for green electricity. The transactional effort is high, but standard contracts where only the confirmation and schedule have to be negotiated are likely at some point in time. The CRPA guarantees future revenue to the carbon removal service provider, which renders the underlying project bankable. Therefore, the CRPA brings new removal projects online, making it an impactful sourcing option.

- **Carbon removal purchasing facility (CRPF):** A CRPF matches the aggregated demand of several buyers with the aggregated supply from a project pipeline according to pre-defined participation rules and project criteria.[189] For the buyer, the transactional effort is lower than for CRPAs because the facility is managed by a trustee that administers all contracts, and builds the project pipeline (sourcing, due diligence, contracting, registration under a standard if necessary, verification oversight). The trustee is paid for these efforts directly from the facility. The strength of a CRPF as a market catalyst is that the trustee can use funds from the facility to create the project pipeline and provide limited financial support until the project can start issuing certificates. After that point, further payments are subject to the delivery of certificates. In other words, the facility can to some limited extent provide up-front finance, ahead of the bulk result-based payments. This allows realisation of projects with promising, but less-proven technologies that would otherwise struggle to secure up-front finance from traditional lenders.

- **One-off purchases (over-the-counter):** Buyers who do not want to commit long-term can cover their certificates demand year-by-year through one-off purchases over-the-counter, via brokers/intermediaries, or through (Dutch) auctions. In the absence of established market structures or marketplace initiatives, companies may organise their own tender process to directly solicit offers from carbon removal providers. While the transactional efforts are limited for one-off purchases (with the exception of own tenders), they are also not the most impactful. The market risk remains with the seller who may have difficulty to scale production in the absence of a bankable contract. Also, certificates sourced in this manner stem from existing projects, some of which can be quite old (as in the case of forest projects). Buyers whose goal is to bring new, additional removal projects online should consider other sourcing options.

Direct engagement with suppliers via purchase agreements can open doors for insurers to new business opportunities.

With transactional effort comes chance for direct engagement with a counterparty. Today, given the immaturity of the market, the limited number of counterparties can automatically be considered the world's leading carbon removal service providers. If an insurer demonstrates willingness to take risks by entering a long-term offtake agreement, that firm may be perceived as a credible partner for other risks, and as an investor of choice. To this end, buying removals to compensate operational emissions can also be a door opener to new insurance business opportunities.

To reach net-zero, massive emission reductions *and* carbon removal at the gigatonne scale are needed.

The science is clear: carbon removal is a necessity for net-zero, on top of massive emission reduction efforts. Beyond 2050, the world must be able to tackle historic emissions and remain net-negative. The scale of the problem is daunting: by 2050, a new industry must have capacity to remove the same amount of emissions from the atmosphere as coming from humanity's use of oil and gas today.

[189] The single volumes of each buyer are usually small, and they cannot enter CRPAs with sufficiently large (and thus economical) projects on their own. Alternatively, the aggregation serves to share the burden of the first-mover price, where buyers – for cost control reasons – only want to commit smaller volumes on a particular set of removal solutions covered by the facility.

Conclusion

The industry needs to grow quickly, and the many barriers along the carbon removal value chain need be overcome.

The carbon removal industry is in its infancy and needs to develop quickly. Existing barriers standing in the way of market growth need to be overcome. Each stage of the value chain faces challenges. Supply-side restrictions such as cost, lack of knowledge and resistance to change may slowly progress, but the technological learning curve may help alleviate these issues as solutions become more mature and efficient. Adding to the difficulty in getting what is still a low-volume industry up and running is an undefined and unregulated marketplace and lack of uniform standards.

Figure 7
Selected barriers to growth in the carbon removal value chain

Source: Swiss Re

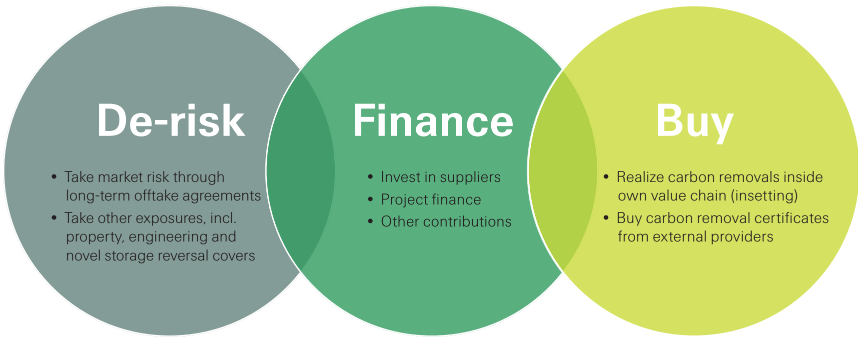
Those able and willing to pay the high first-mover price, and stringent support policies, are vital for sector development.

A particular hindrance to scaling-up is the first-mover problem. Today the most scalable carbon removal solutions are also the most expensive. First-movers will bear the high cost of getting the industry to critical mass, while free-riders remain on the side lines waiting for prices to fall. Further, there is no business case without carbon pricing. The scale-up of carbon removal relies on the existence of stringent climate policies, currently absent in most jurisdictions.

The insurance industry can facilitate growth of carbon removal via de-risking, financing and buying.

Such issues are typical of an untapped market on the cusp of explosive growth. The private sector can leverage and accelerate the deployment of the carbon removal industry. Figure 8 illustrates how those with the funds to do so could realise meaningful gains by stepping in to de-risk carbon removal services, finance developers and projects, and create demand through purchasing carbon removal certificates to balance their own operational footprint. The insurance industry is well-positioned on all three fronts. Re/insurers' risk knowledge and transfer capabilities, paired with their long-term investment horizon and a high net income per tonne of operational emissions, make for ideal carbon removal project partners.

Figure 8
How insurers can contribute



Source: Swiss Re

There are clear links between carbon removal and insurance business cases.

For insurers, most carbon removal solutions have clear links to different lines of business. For example, soil carbon sequestration and biochar link directly to the future of agribusiness; afforestation builds a market for new insurance products to replace inefficient storage reversal safeguards from fires and disasters; blue carbon products naturally fit within the realm of disaster insurance while also decreasing future costs from flooding; and geological CO_2 storage opens up new opportunities to cover the risk of leakage or induced seismicity via earthquake insurance. For classical engineering covers and well-established forest covers, the case for insurability is much clearer than for liability questions.

Experts call on the insurance industry to get involved in improving the bankability of carbon removal projects.

In general, the insurability of carbon removal, in particular the storage liabilities, strongly depends on a robust legal and regulatory framework that governs financial security obligations and eventually the transfer of liabilities to the public sector.[190] Currently, this is yet to be developed for most carbon removal solutions. Even the standard bodies of the voluntary carbon market (Verra, GoldStandard, ACR, etc) have not yet come up with methodologies for all types of removals – in particular the technological solutions – that would address questions about the risk of storage reversal. Altogether, an insurance market for carbon removal solutions has not yet taken off. Often voiced is the need for the insurance industry to participate proactively in the dialogue between regulators and project developers, or standard bodies and project developers. The call is to bring in the risk assessment perspective, and clarity as to under which conditions the private insurance industry can engage more actively in carbon removal as a risk taker.

Investments side-by-side with bigger players can lower the barriers for asset management.

The asset management, investor side of insurance faces barriers to entering the carbon removal market. This is due to the still immaturity of the market, and the lack of insurance offerings and institutional support that would alleviate some of the investment risks. It is unlikely that any potential insurer or other investor would go into carbon removal alone. Instead, investors look for opportunities for sidecar investments, for instance alongside the oil & gas majors already investing in the transition to net-zero. This could smooth initial fears about the maturity of the market. Ultimately, the growing momentum of shareholder pressure, tightening climate policies, investors' own net-zero commitments, and rapidly improving technology of carbon removal solutions, will attract investors. The question is "how soon?"

Impactful purchases of carbon removal services may enable further business.

As a buyer of carbon removal services, insurers have the possibility to help create a market that will open avenues to new business related to the upcoming carbon removal risk pools and asset classes. To this end, their carbon removal purchasing strategies need to look ahead and value quality and impact over least-cost options.

Early engagement of insurers in the carbon removal market will reap a series of benefits as the market develops.

Insurers that take the risk and engage early in carbon removal may find investments well-rewarded. At first, they may increase their understanding of the new carbon removal risk landscape by offering standard products for the easy-to-cover exposures, by investing at a small scale, and by entering long-term offtake agreements with select carbon removal providers. Then, as the market matures and the risk knowledge consolidates, liability covers for carbon removal services – currently considered uninsurable by many – may also become standard business. At that point, the front-runners among insurers will profit from the on-the-ground experience already gathered. They will be seen as credible insurance partners and investors of choice. Eventually, once the carbon removal market reaches its perceived trillion-dollar status, there will be a whole lot to insure and to invest in.

[190] This is not dissimilar to the insurability of nuclear waste repositories, where the regulator defines the level and period of financial securities, as well as the monitoring and verification obligations, before accepting the passing of any remaining liabilities from the operator to the public sector in form of a suitable governmental body.

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