The **Keeping 1.5°C Alive** Series

Mind the Gap:

How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive

March 2022

Version 1.0

Energy Transitions Commission

Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive

The Energy Transitions Commission (ETC) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C.

Our Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. The ETC is chaired by Lord Adair Turner and who works with the ETC team, led by Faustine Delasalle (Director) and Ita Kettleborough (Deputy Director). Our Commissioners are listed on the next page.

Mind the Gap: How CDR can Complement Deep Decarbonisation in Keeping 1.5°C Alive was developed by the Commissioners with the support of the ETC Secretariat, provided by SYSTEMIQ. This briefing paper has also been developed in close consultation with experts from companies, industry initiatives, international organisations, non-governmental organisations and academia. We warmly thank our knowledge partners and contributors for their inputs. The ETC also gratefully acknowledges the financial support from We Mean Business which supported the consultation process and ensuing report, upon which this report is based on.

This report constitutes a collective view of the Energy Transitions Commission. Members of the ETC endorse the general thrust of the arguments made in this publication but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse this briefing paper.

The ETC Commissioners not only agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by mid-century, but also share a broad vision of how the transition can be achieved. The fact that this agreement is possible between leaders from companies and organisations with different perspectives on and interests in the energy system should give decision makers across the world confidence that it is possible simultaneously to grow the global economy and to limit global warming to well below 2°C. Many of the key actions to achieve these goals are clear and can be pursued without delay.

Learn more at:

www.energy-transitions.org

www.linkedin.com/company/energy-transitions-commission

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Ms. Cathy Zoi,
President – EVgo

Contents

Major ETC reports and working papers

Global Reports

Mission Possible (2018) outlined pathways to reach net-zero emissions from the harder-to-abate sectors in heavy industry (cement, steel, plastics) and heavy-duty transport (trucking, shipping, aviation).

Making Mission Possible (2020) showed that a net-zero global economy is technically and economically possible by mid-century and will require a profound transformation of the global energy system.

Making Mission Possible Series (2021) – a series of reports outlining how to scale up clean energy provision to achieve a net-zero emissions economy by mid-century. The reports set out specific actions in the 2020s to put this net-zero by 2050 target within reach.

Keeping 1.5°C Alive (2021): COP26 special report outlining actions and agreements required in the 2020s to keep 1.5°C in reach.

Sectoral and cross-sectoral focuses

Sectoral focuses provided detailed decarbonisation analyses on each on the six harder-to-abate sectors after the publication of the Mission Possible report (2019).

Our latest focus on building heating (2020) details decarbonisation pathways and costs for building heating, and implications for energy systems.

As a core partner of the Mission Possible Partnership, the ETC also completes analysis to support a range of sectoral decarbonisation initiatives:

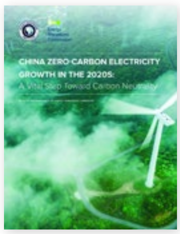
In October 2020, the corporate members of the Clean Skies for Tomorrow initiative (CST) developed a **Joint Policy Proposal to Accelerate the Deployment of Sustainable Aviation Fuels in Europe.**

Produced for the Getting to Zero Coalition, **"The First Wave – A blueprint for commercial-scale zero-emission shipping pilots"** (2020) highlights five key actions that first movers can take to make tangible progress towards zero emission pilots over the next three to four years.

Steeling Demand: Mobilising buyers to bring net-zero steel to market before 2030 demonstrates that demand signals from steel buyers to steel manufacturers can help unlock investment and breakthrough technologies needed for net-zero primary steel.

Geographical focuses

China 2050: A Fully Developed Rich Zero-carbon Economy described the possible evolution of China's energy demand sector by sector, analysing energy sources, technologies and policy interventions required to reach net-zero carbon emissions by 2050.



China Zero Carbon Electricity Growth in the 2020s: A Vital Step Toward Carbon Neutrality (January 2021). Following the announcement of China's aim to achieve carbon neutrality before 2060 and peak emissions before 2030. This report examines what action is required by 2030 aligned with what is needed to fully decarbonise China's power sector by 2050.

A series of reports on the Indian power system and outlining decarbonisation roadmaps for Indian industry (2019-2020) described how India could rapidly expand electricity supply without building more coal-fired power stations, and how India can industrialise whilst decarbonising heavy industry sectors.

Setting Up Industry for Net-Zero (June 2021) explores the state of play in Australia and opportunities for transition to net-zero emissions in five supply chains – steel, aluminium, liquified natural gas, other metals and chemicals.

Introduction

Global warming poses severe risks to communities and ecosystems this century – the first impacts are already noticeable. To have a 50:50 chance of limiting global heating to 1.5°C, the world must reduce CO_2 emissions to around net-zero by mid-century, with a decline of around 40-50% achieved by 2030.[1] Understanding this, many countries and companies are now committed to achieving net-zero by 2050.

At COP26 in the Glasgow Climate Pact the parties to the Paris Climate Agreement resolved to achieve more rapid reductions during the 2020s than currently included within country commitments.[2] Recognising the urgency, many businesses and organisations have made similar pledges to strive for 'net-zero'.

The Energy Transitions Commission (ETC) has demonstrated that it is possible to achieve more rapid reductions in gross emissions than seemed feasible a decade ago, including in harder-to-abate sectors. The IEA's 2021 roadmap *Net Zero by 2050* reinforces this message.[3] Massive clean electrification must be at the core of decarbonisation pathways, combined with the deployment of a range of complementary technologies, including clean hydrogen, carbon capture, utilisation and storage (CCUS) and prioritised use of sustainable bioenergy.[4]

However, even with the most ambitious possible reduction in gross emissions, it is almost certain that cumulative CO_2 emissions between now and 2050 will exceed the "carbon budget" consistent with a 1.5°C climate objective. The IPCC estimates that carbon budget at about 500 Gt CO_2, but two ETC scenarios that we describe in this report suggest cumulative emissions from energy, waste, agriculture and land use change of between 725 Gt CO_2 (under a fairly ambitious reduction scenario) and 570 Gt CO_2 (if gross emission reductions are in line with our maximum feasible case - Exhibit 1).

In addition, even the most ambitious decarbonisation strategies will not be able to reduce gross emissions to absolute zero by 2050, with a low level of CO_2, N_2O and CH_4 residual emissions likely continuing beyond mid-century.

In addition to dramatic decarbonisation to meet the 1.5°C climate objective a significant volume of carbon dioxide removals (CDR) will therefore be required, to achieve two objectives:

- To neutralize the impact of the likely carbon budget overshoot ahead of mid-century. Our scenarios suggest a need for at least 70-225 Gt CO_2 of cumulative removals between now and 2050.
- To neutralize continuing residual emissions after mid-century of both CO_2 and N_2O, which might run at about 3-5 Gt CO_2e /year.

It may also be necessary to generate sufficient net negative emissions in the second half of the 21st-century to reverse the climate-warming effect of an overshoot of the cumulative budget. However any strategy which relies on removing CO_2 after the 'budget' has already been overshoot carries a danger of triggering earth system tipping points and self-reinforcing

1 IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report*.
2 UNFCCC (2021), *Glasgow Climate Pact*.
3 IEA (2021), *Net Zero by 2050*.
4 ETC (2020-2022), *Making Mission Possible series*. ETC (2020), *Making Mission Possible: Delivering a Net-Zero Economy*; ETC (2021), *Making Clean Electrification Possible*; ETC (2021), *Making the Hydrogen Economy Possible*; ETC (2021), *Bioresources within a Net-Zero Emissions Economy*; ETC (Upcoming, 2022), *Carbon Capture Utilisation and Storage*.

feedback loops that are potentially irreversible.[5] This outcome could result in devastating losses, especially for vulnerable countries (e.g., small states with low-lying islands).

During 2021 the ETC analysed the potential for different forms of carbon dioxide removal and their role in climate mitigation strategies. This report summarises the insights from this analysis, following a consultation process that started in May 2021.[6] It describes how ambitious development of a portfolio of CDR solutions, combined with ambitious decarbonisation, could prevent 'overshoot' of the 1.5°C carbon budget by 2050. The portfolio includes a range of so called Natural Climate Solutions (NCS), engineered solutions which rely on geological storage, and a number of hybrid options, also referred to as Biomass with carbon removal and storage (BiCRS). The report discusses the risks presented by these approaches, their potential, and how they might be financed by either countries or companies.

The central message is that carbon removals must play a role in climate change mitigation strategies, in addition to, not instead of, rapid decarbonisation efforts, starting today.

The report covers in turn:

1. Climate targets and implications for carbon budgets.
2. Emission reduction scenarios and the size of the gap.
3. Types of carbon dioxide removal and their feasible scale by 2050.
4. The risks involved in different types of CDR and how to manage them.
5. Who should pay for removals: countries and/or companies? Including how the purchase of removals fits into the wider debate about carbon markets.
6. The actions needed in the 2020s to ensure subsequent removals occur at sufficient scale.

This report draws on past ETC analysis on decarbonisation solutions such as clean power, clean hydrogen, and the sustainable bioeconomy.[7] A forthcoming ETC report will explore in detail the role of carbon capture, utilisation and storage (CCUS) technologies.

ETC decarbonisation scenarios compared with 'no-overshoot' of the 1.5°C target

ETC decarbonisation reduction scenarios versus IPCC 'no overshoot' 1.5°C pathway for net emissions

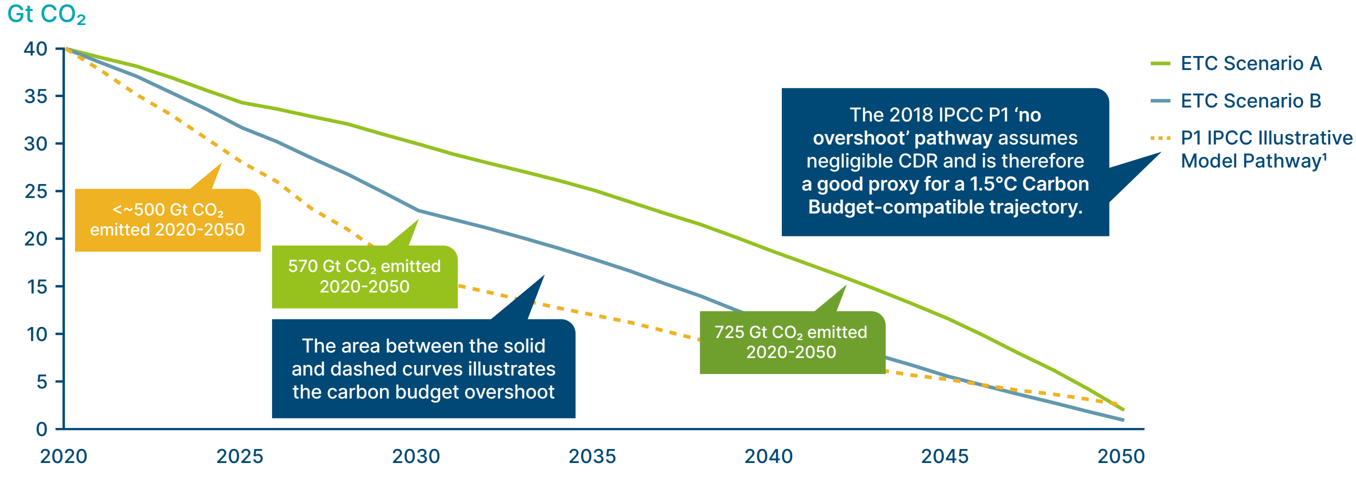


Exhibit 1

NOTE: [1] P1= an ambitious scenario which assumes social and technical innovation drive rapid decarbonization through low energy demand assumptions and investment in afforestation, cited in the IPCC (2018) Special Report. IPCC (2021) AR6 did not include a no-overshoot scenario in its illustrative pathways.

SOURCE: SYSTEMIQ analysis for the ETC based on: IEA (2017), *Energy Technology Perspectives;* IEA (2020), *Energy Technology Perspectives;* IPCC (2018), *Global Warming of 1.5°C; IIASA SSP Public Database, Version 2.0 (Accessed 2021)*

5 In reference to emissions overshoot this is cumulative overshoot by 2050. In addition, it is possible that beyond some thresholds or "tipping points" positive climate feedback loops could become so strong as to trigger highly non-linear and irreversible climate change. How near we are to such "tipping points" is debated, and the IPCC carbon budgets do not explicitly model their potential impact. IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report.*

6 ETC(2021), *Consultation Paper, Reaching climate objectives: the role of carbon dioxide removals.*

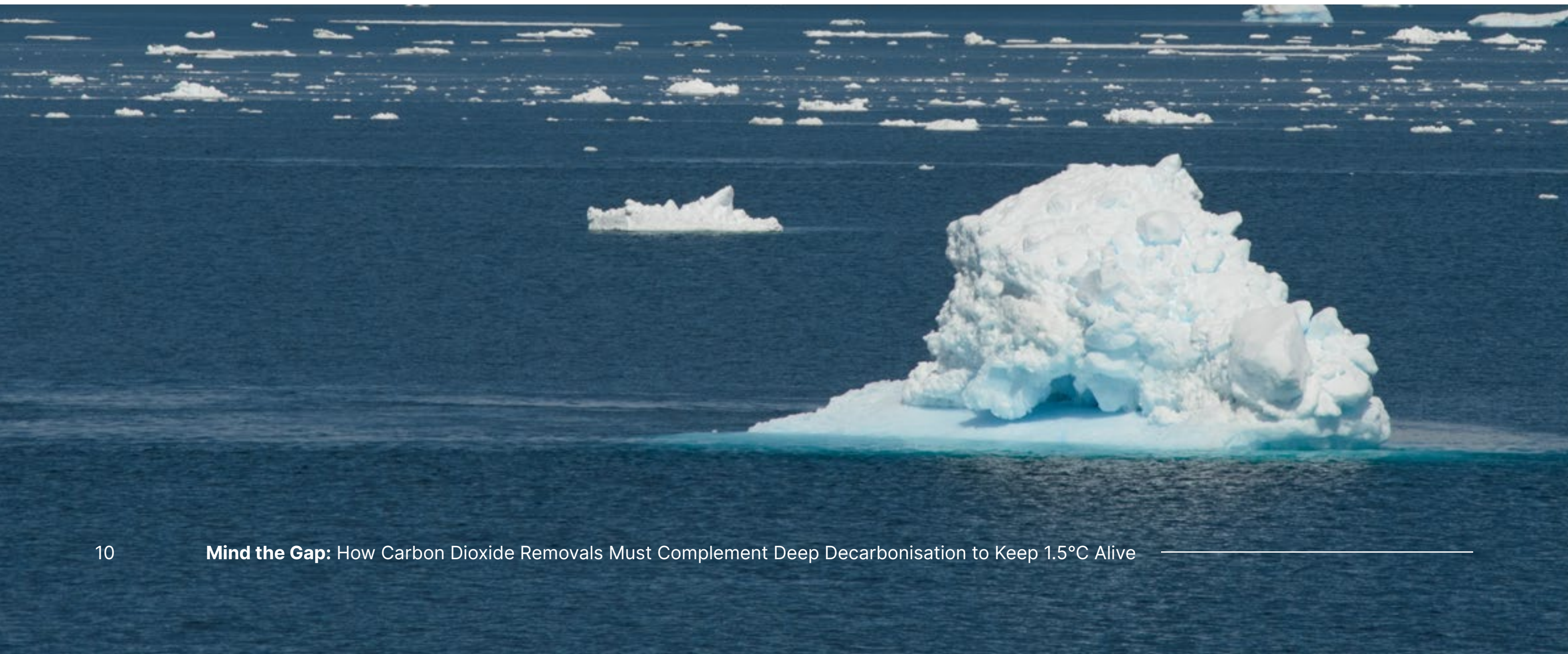
7 ETC (2021), *Making Clean Electrification Possible*; ETC (2021), *Making the Hydrogen Economy Possible*; ETC (2021), *Bioresources within a Net-Zero Emissions Economy.*

Box A: Definition of Terms

Definition of terms: There is no definitively correct use of terms, but for the purposes of this report we use them as follows:

- "EBIT sectors" are the energy, buildings, industry and transport sectors.
- "AFOLU sector" represents agriculture, forestry and other land use change activities.
- "Net-zero" a balance between sources of emissions and removals of emissions that results in zero additional emissions being released to the atmosphere. (For specific definitions of how this term should be used in corporate claims, see Chapter 5.2).
- "Net emissions" for the EBIT sector means emissions after the application of CCS in energy production and industry but before the purchase of carbon credits to offset emissions.
- "Negative emissions" is used for the case where the combination of all sector CO_2 emissions plus carbon removals results in an absolute negative (and thus a reduction in the stock of atmospheric CO_2).
- "Carbon dioxide removals" (CDR), sometimes shortened to "carbon removals", refers to actions that can result in a net removal of CO_2 from the atmosphere.
- "Carbon budget" refers to the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given probability, taking into account the effect of other greenhouse gas reductions. The remaining carbon budget indicates how much CO_2 could still be emitted while keeping warming below a specific temperature level.
- "Nature-based Solutions" (NBS) are activities that harness the power of nature to deliver services for adaptation, resilience, biodiversity, and human well-being, including reducing the accumulation of greenhouse gases (GHGs) in the atmosphere. "Natural Climate Solutions (NCS)" can be considered as a subset of NBS with a specific focus on addressing climate change. NCS has been defined as 'conservation, restoration, and/or improved land management actions to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, agricultural lands, and oceans'.[8] In this report, NCS refers specifically to solutions which remove CO_2 from the atmosphere.
- "Carbon capture and storage" (CCS) refers to technology which can capture CO_2 from a gas stream and turn it into a medium which is able to be permanently stored, typically in geological formations underground. Such point-source CCS is considered a reduction in emissions. CCS can also be combined with technologies which capture carbon from the atmosphere rather than a point-source, consequently achieving net CDR. Typical examples include "Direct Air Capture and CCS" (DACCS) or "Bioenergy with CCS" (BECCS).
- "Biomass with Carbon Removal and Storage" (BiCRS) is an umbrella term for hybrid CDR solutions which combine photosynthesis with technology specifically to achieve carbon removal.

8 Griscom et al. (2017), *Natural Climate Solutions*.



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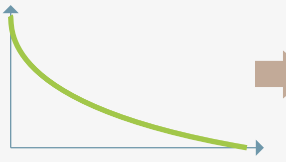
MIND THE GAP: CARBON DIOXIDE REMOVAL (CDR)

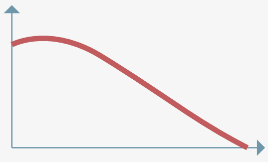
CDR is needed in addition to deep and rapid decarbonisation

THE WORLD HAS A LIMITED AND DECLINING CARBON BUDGET FOR 1.5°C

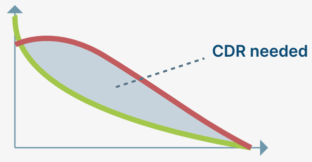
The 1.5°C aligned carbon budget emissions trajectory looks a bit like this:



But even ambitious decarbonisation scenarios look a bit like this:



The carbon budget 'overshoot gap' – the amount of CDR needed to stay within the 1.5°C carbon budget – looks like this:



What will it take to scale CDR to keep 1.5˚C alive?

A PORTFOLIO OF SOLUTIONS...

	NATURAL CLIMATE SOLUTIONS		HYBRID / BIOMASS WITH CARBON REMOVAL STORAGE		ENGINEERED SOLUTIONS
	'RESTORE'	'MANAGE'	BIOCHAR	BECCS	DACCS
WHAT?	Restore natural ecosystems (e.g. forests, peatlands)	Better manage current use of land	Burn biomass in absence of oxygen to slow decomposition	Produce energy from biomass then capture CO_2 produced	Capture CO_2 direct from air and store underground
RISKS	Permanence: carbon stored in biosphere is short-term	Permanence: improved practices are not maintained	Feedstock: biomass feedstock not sourced sustainably	Feedstock: biomass feedstock not sourced sustainably	Moral Hazard, Clean power: insufficiently available
CO-BENEFITS*	Biodiversity, Clean water, Community economic return	Biodiversity, Clean water, Community economic return, Soil health	Clean water, Soil health	Fossil free energy generation	Skilled jobs

CO-BENEFITS*
- Biodiversity
- Clean water
- Community economic return
- Soil health
- Fossil free energy generation
- Skilled jobs

...SCALED RAPIDLY TO CUMULATIVELY REMOVE 165GT CO_2 BY 2050

CDR POTENTIAL 2020-2050

58 Gt CO_2 + 60 Gt CO_2 + 6 Gt CO_2 + 13 Gt CO_2 + 27 Gt CO_2 = 165 Gt CO_2

Deploying portfolio of removals solutions at maximum speed could remove around **165 Gt CO_2 by 2050**

IN ADDITION

ACCELERATE CDR INNOVATION, E.G. ROCK WEATHERING, OCEAN ALKALINITY AND FERTILISATION, MICRO-ALGAE

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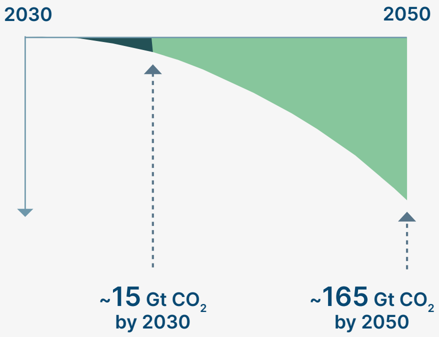
CLOSING THE CDR FUNDING GAP

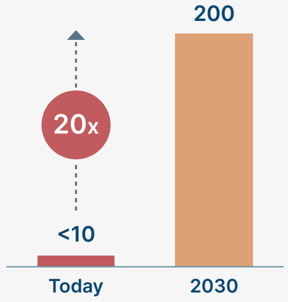
A MASSIVE SCALE UP OF CDR STARTING TODAY

Cumulative CDR



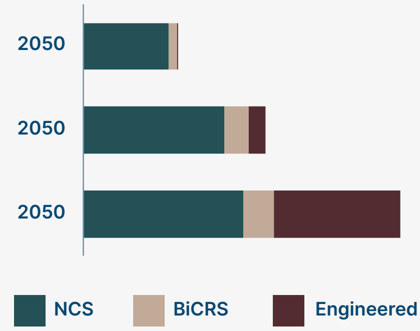
REQUIRING A 20X INCREASE IN FUNDING BY 2030

USD $bn/year



DELIVERING AN EVOLVING PORTFOLIO OF CDR SOLUTIONS

Gt CO_2/yr removed



Who should pay for removals?

GOVERNMENTS, VIA:

- Direct finance & purchase of removals
- Enhancing and creating compliance markets with a limited quantity of removals
- Reforming existing policy and subsidy regimes

+

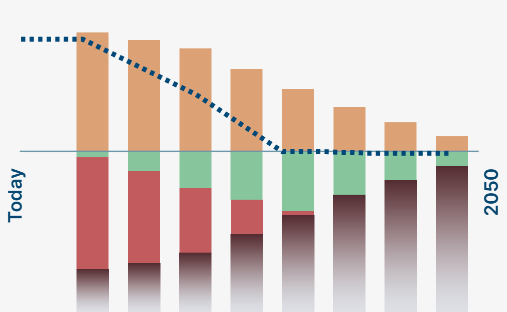
CORPORATES, VIA:

- Meeting obligations in compliance markets (e.g., EU ETS)
- Committing to net-zero decarbonisation pathways...
- ...neutralising any remaining emissions with carbon removal credits in the voluntary market.

How do removals fit into government and corporate responsibilities?

- High-additionality credits can play a role as long as they don't delay rapid decarbonisation
- Credits purchased should shift away from today's focus on emissions reductions, towards removals

Net CO_2 emissions



PRIORITIES	
1 Reduce gross emissions	Deep and rapid decarbonisation
2a Carbon removal	Offset remaining emissions via removal credits to close the overshoot gap
2b Reduction credits to end deforestation and exit coal ASAP	High-additionality reduction credits for a tightly defined transitional period
Funding further action	Additional finance for clean tech ambition

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CARBON DIOXIDE REMOVAL (CDR) IN THE 2020S

2030 TARGETS:

3.6 Gt CO_2 CDR per year

$200 bn/yr for CDR

NATURAL CLIMATE SOLUTIONS		HYBRID / BIOMASS WITH CARBON REMOVAL STORAGE		ENGINEERED SOLUTIONS
'RESTORE'	MANAGE	BIOCHAR	BECCS	DACCS
1.6 Gt CO_2 per year	1.6 Gt CO_2 per year	0.1 Gt CO_2 per year	0.2 Gt CO_2 per year	0.1 Gt CO_2 per year
300 Mha marginal degraded land (tropics) planted	500 Mha (~12-15 %) of forest under improved management	2-5 EJ of sustainable crop residue biomass	~4 EJ of sustainable biomass from residues and dedicated energy crops	235 TWh Of clean power, <10% of 2050 supply
7 Mha of mangroves restored	400 Mha (12 %) of cultivated land under improved management	40 Mha of biochar applied to farmland	~170 BECCS 1 $MtCO_2$ /yr scale facilities	~80 DACCS facilities
13 Mha of peatland recovered				

NINE ACTIONS TO SCALE CDR IN THE 2020s

In addition to rapid and critical decarbonisation action

	#	Action	CORPORATES	GOVERNMENTS & REGULATORS	BROKERS/ EXCHANGES	STANDARD SETTERS*	PROJECT DEVELOPERS
CLOSE THE FUNDING GAP	1	Scale up voluntary carbon markets by pursuing high-ambition corporate action.	✓			✓	
	2	Establish compliance carbon markets and include a limited quantity of removals.	✓	✓			
	3	Direct government funding for carbon removal, via project funding or credit purchase.		✓			
	4	Indirect government support for carbon removal, via policy shift and subsidies.		✓			
MANAGE PROJECT RISK	5	Address risks around permanence and additionality for CDR solutions (e.g. improved monitoring and verification).		✓	✓	✓	✓
	6	Ensure carbon credits are of the highest possible integrity, via improved standards.	✓	✓		✓	
CREATE ENABLING CONDITIONS	7	Build associated supporting infrastructure (e.g., clean power, CCS).	✓	✓			✓
	8	Public education and training to implement CDR solutions (e.g., farming practices).		✓			✓
	9	Accelerate CDR innovation via research and development grant funding.	✓	✓			

* 'Standard Setters' include voluntary bodies setting standards for corporate action and credits, credit standard setters are often closely associated with brokers and exchanges

Climate targets and carbon budgets

- To have a 50% chance of limiting global warming to 1.5°C (and an approximately 90% chance of limiting it to 2°C), cumulative CO_2 emissions between 2020 and mid-century must be limited to a "carbon budget" of 500 gigatons (Gt) CO_2.
- This budget assumes a concurrent reduction of around 50-55% in annual methane (CH_4) emissions and 30% in annual nitrous oxide (N_2O) emissions by mid-century.

1.1 Temperature targets for limiting global warming

Human-induced emissions of greenhouse gases are causing significant global warming. The current concentration of CO_2 in the atmosphere is approximately 417 ppm,[9] versus about 280 ppm in the pre-industrial age,[10] while CH_4 concentrations have increased from 770 ppb to 1890 ppb.[11] To date this has resulted in global warming of ~1.1°C above preindustrial levels.[12] This level of global warming already has serious adverse effects in many countries, and the IPCC described in 2018 and 2022 how those consequences would increase as temperatures rise further with particularly severe effects if warming exceeds 1.5°C.[13]

Climate change science provides probability distributions of possible temperature increases from a given flow of GHG emissions. Temperature targets, therefore, have to be set in probabilistic terms. The ETC believes that to meet the objectives of the Paris Agreement the world should set emissions targets which will give *at least* a 50:50 chance of limiting global warming to 1.5°C and a 90% chance of limiting it to 2°C. As described by the IPCC, missing the 1.5°C target and instead aiming for 2°C of warming will have significant adverse consequences for threatened natural ecosystems such as the Arctic region, extreme weather events such as coastal flooding and other climate-risks such as low crop yields and heat-related deaths.[14]

Under IPCC pathways for low/no 1.5°C overshoot, methane emissions must decline by at least ~35% by 2030 and ~50-55% by 2050

Methane

Methane in IPCC SR 1.5 Low Overshoot Pathways

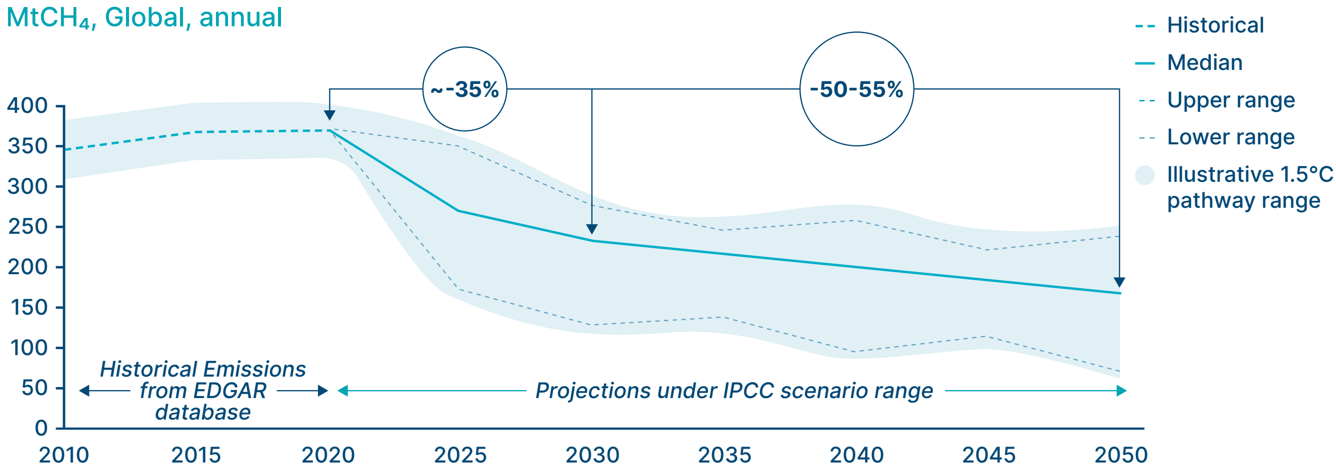


Exhibit 2

NOTE: Historical values for methane emissions have a very high range of uncertainty.

SOURCE: EDGAR database, IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report,* as referenced in IPCC (2021), *6th Assessment Report.*

9 Betts, R. (2021), "Met Office: Atmospheric CO_2 now hitting 50% higher than pre-industrial levels," Carbon Brief.
10 Pre-industrial atmospheric concentrations assumed to be 278ppm. Betts, R. (2021), "Met Office: Atmospheric CO2 now hitting 50% higher than pre-industrial levels", Carbon Brief.
11 Methanelevels.org (accessed 19th April 2021), assuming pre-industrial era began 1850.
12 IPCC (2021), *Climate Change 2021: The Physical Science Basis. Summary for Policy Makers.*
13 IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report.* IPCC (2022) *Climate Change 2022: Impacts, Adaptation and Vulnerability.*
14 IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report. Summary for Policy Makers.*

It is worth acknowledging that although the IPCC assigns a probability to a given temperature determined by global policy objectives, others such as the Climate Crisis Advisory Group suggest that this approach pays insufficient attention to the adverse consequences already triggered by global emissions to date. As a result, they argue against a purely carbon budget-focused approach, but instead call to focus on targets to reduce overall atmospheric concentrations of CO_2 to ~350ppm by 2100.[15]

1.2 Different GHG gases: lifetimes, stocks and flows

The main gases responsible for global warming are CO_2, N_2O, CH_4 and fluorinated gases (the latter we exclude in the remainder of our analyses).[16] In each case, the "forcing effect" which induces global warming is a function of the atmospheric concentration of the given greenhouse gas at any time. However, differences in the average lifetime of the gases have implications for whether emission objectives should focus on the stocks or flows:

- CO_2 and N_2O are both long-lived gases, which once accumulated in the atmosphere take many decades or indeed centuries to dissipate. As a result, annual flows must be reduced to net-zero to prevent further increases in atmospheric concentrations and thus temperature. It is possible to express N_2O emissions on a carbon equivalent basis (with one tonne of N_2O having an equivalent forcing effect of ~265 tonnes of CO_2).[17] To estimate the carbon budget, the IPCC first develops estimates of the likely evolution of N_2O emissions and then calculates a "carbon budget" for acceptable cumulative emissions of CO_2 alone.

- By comparison, CH_4 is a relatively short-lived gas with a half-life in the atmosphere of about 10-12 years.[18] This indicates that the concentration of methane produced by a one-off emission (or 'pulse') takes around 10 years to halve, as methane is converted (via a complex set of oxidization reactions) into CO_2 and H_2O, eventually leaving around 2.75 tonnes of CO_2 per tonne of methane emitted.[19] Estimates suggest that increasing concentrations of CH_4 have been responsible for about 0.5°C out of the ~1.1°C of global warming so far.[20] Given the short-lived nature of methane, methane concentrations and the associated forcing effect would stabilise if the flow of new methane emissions ceased to rise. But this does not mean, as some interest groups suggest, that the appropriate objective should be simply to stabilise rather than reduce methane emissions for two reasons. First, (i) because of the ongoing effect of high CO_2 concentrations, which will continue for as long as net CO_2 flows are above zero,[21] (ii) and second, because the very fact of methane's high but short-lived global warming potential (GWP) (see Exhibit 3) means that reducing methane emissions is the most powerful lever to limit short-term temperature forcing, and thus reduce the risk that feedback loops will take the climate beyond potential tipping points (discussed below). Objectives for CH_4 emissions are therefore expressed in terms of how fast annual flows should fall over time. [22,23]

- Given the different nature of the long-lived gases (CO_2 and N_2O) and short-lived CH_4, estimates of the "carbon equivalent" effect of CH_4 emissions depends on the timescale assumed. Over a 100-year period, a tonne of CH_4 emitted today has a forcing effect (and therefore impact on average temperature over the period) about 27-30 times more than a tonne of CO_2 emitted today. Viewed over a 20-year period, though, CH_4's impact is 81-83 times greater

15 Climate Crisis Advisory Group (2021), *The Global Climate Crisis and the Action Needed.*

16 For simplicity, fluorinated gasses are not discussed in this consultation paper. IPCC Integrated Assessment pathways consistent with 1.5°C reduce emissions of fluorinated gases in by roughly 75–80% relative to 2010 levels in 2050 with no clear differences between the classes. IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report.*

17 Over a 100-year time scale.

18 Saunois, M. et al. (2020), *The Global Carbon Budget 2000-2017.*

19 As methane in the atmosphere degrades into carbon.

20 IPCC, (2021), *Climate Change 2021: The Physical Science Basis.*

21 Referring to CO_2 only, not CO_2 equivalent emissions.

22 Saunois, M. et al. (2020), *The Global Methane Budget 2000-2017.*

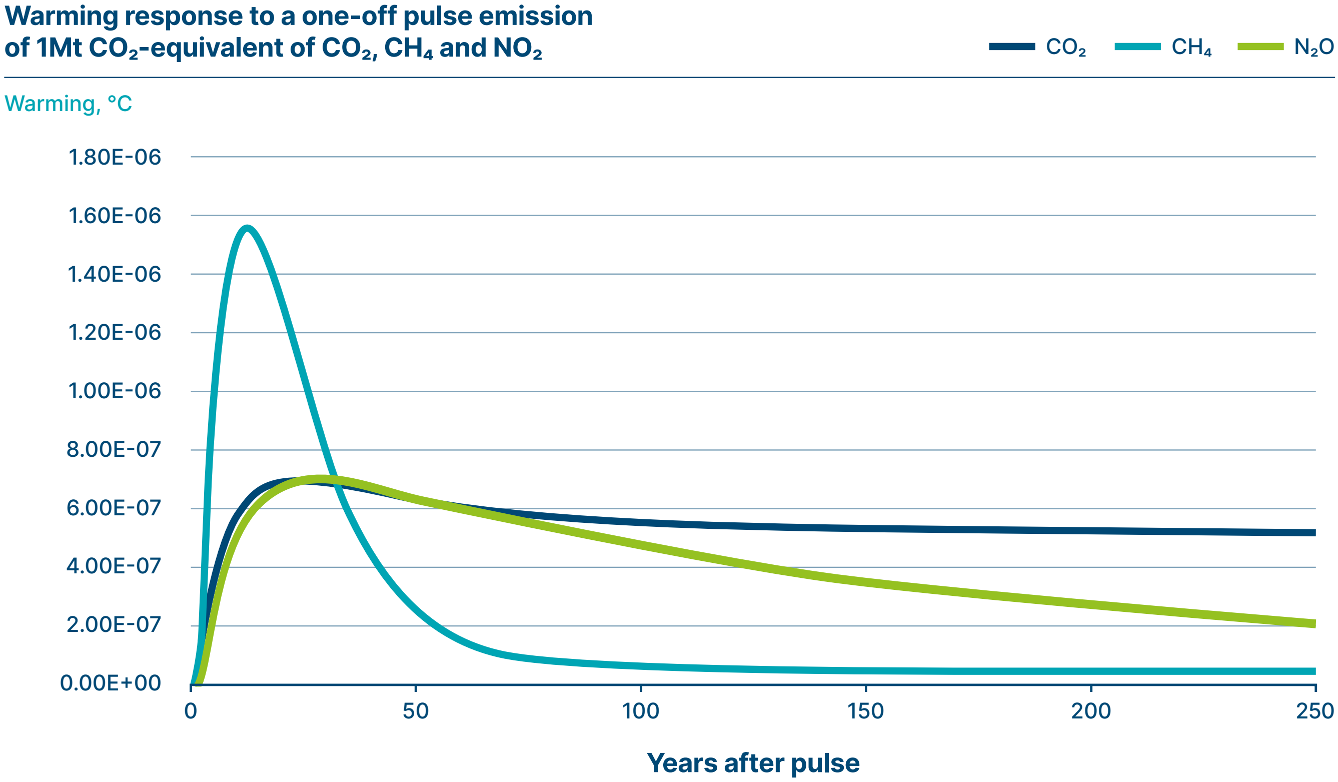
23 It is assumed that IPCC carbon budgets take the long-lasting products of tropospheric oxidation of CH_4 into account; "Collins, M. et al. (2018), applied a process-based approach to assess the importance of CH_4 reductions for the 1.5°C target. Their modelling approach included indirect effects of CH4 on tropospheric ozone, stratospheric water vapour and the carbon cycle." IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report.*

per tonne emitted.[24] Neither measure is, in absolute terms, the correct one, but the potential for climate feedback loops means that the 20-year calculation is arguably a better measure of the impact of CH_4 in today's specific circumstances.

Exhibit 3

Global warming potential of different greenhouse gases varies over time

Warming response to a one-off pulse emission of 1Mt CO_2-equivalent of CO_2, CH_4 and NO_2



SOURCE: Food Climate Research Network (2020); defined using GWP100

1.3 Climate objectives and IPCC carbon budgets

The IPCC estimates the carbon budget compatible with different climate objectives by first assuming a feasible pace of CH_4 and other non-CO_2 GHG emission reductions and then estimating the cumulative emissions of CO_2, which are compatible with different probabilistic climate objectives.[25, 26] If those non-CO_2 emissions reductions are not achieved, then the CO_2 carbon budget would be reduced. The IPCC also explains that to limit the world to 1.5°C of warming, global "net-zero" must be achieved by 2050, therefore a carbon budget can be thought of as the remaining emissions which can occur prior to this date.

24 IPCC (2021), *Climate Change 2021: The Physical Science Basis;* carbon budget estimated from 2020. Range represents whether methane is of fossil or non-fossil origin.

25 Carbon Budgets provide directional insight only and remain highly uncertain. They relate only to anthropogenic emissions or emissions from natural sources arising because of human activity (e.g., land use change), and already allow for the significant carbon sequestration which naturally occurs in forests and oceans. This implies that (i) if standing natural sinks got smaller over time, the overall carbon budget would reduce; and (ii) that any carbon removals to close the gap between future anthropogenic emissions and the carbon budget must be in excess of the terrestrial sequestration already assumed.

26 IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report*; IPCC, (2021), *Climate Change 2021: The Physical Science Basis;* carbon budget estimated from 2020.

Exhibit 4 shows the results; if CH_4 emissions can be cut by around 50% and N_2O by around 30% by mid-century, then:

- A 500 Gt CO_2 "carbon budget" gives a 50% chance of limiting global warming to 1.5°C. A still lower limit of 340 Gt CO_2 would be compatible with a 67% probability of staying below 1.5°C. The underlying probability distribution suggests that a 500 Gt CO_2 budget would be broadly equivalent to a 90% chance of keeping global warming below 2°C.[27]

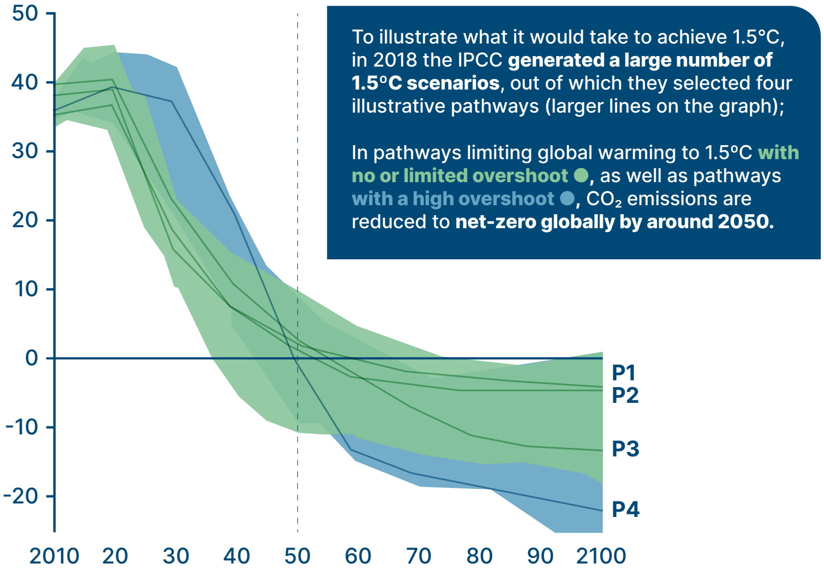
- A much larger 1420 Gt CO_2 budget gives a 50% chance of limiting warming to 2°C, while a 1090 Gt CO_2 tonne would give a 67% chance of this limit.[28] But this would leave the world almost certain to face severe impacts as warming goes above 1.5°C, and would expose the world to a non-trivial risk of even higher warming, with potentially catastrophic consequences.

These budgets relate only to anthropogenic emissions, including emissions from natural sources arising because of human activity (e.g., land-use change); they already allow for the significant carbon sequestration which naturally occurs in forests and oceans (see ***Box B***). This implies that; (i) if these standing natural sinks got smaller over time, the overall carbon budget would reduce; and (ii) that any carbon removals to close the gap between future anthropogenic emissions and the carbon budget must be in excess of the natural sequestration by the terrestrial sink already assumed in the IPCC carbon budget.[29]

Finally, it is important to consider the timing of emission reductions. The "carbon budgets" shown in Exhibit 4 are expressed in Gt of total cumulative emissions independent of the shape of reduction between now and mid-century. This makes the simplifying assumption that different specific reduction paths would result in the same temperature effect as long as the "area under the curve" is the same. But in fact, if emission reductions were significantly more delayed than some of the IPCC scenarios assume, feedback loops mean that the defined carbon budget could produce a larger temperature increase by 2050 (see next chapter). This reinforces the importance of early emissions reduction.

To have a 50% chance to remain <1.5 degree warming, IPCC estimates the remaining carbon budget to be around ~500 Gt CO_2 from 2020.

Global emissions pathway characteristics in the IPCC 1.5°C report
Gt CO_2/year



SOURCE: IPCC (2018), *Global Warming of 1.5°C*

Chosen carbon budget in this report

	50% chance	67% chance	~90% chance
<1.5°C	**500** Gt CO_2 from 2020	**400** Gt CO_2 from 2020	N/A
<1.7°C	**850** Gt CO_2 from 2020	**700** Gt CO_2 from 2020	N/A
<2°C	**1350** Gt CO_2 from 2020	**1150** Gt CO_2 from 2020	**500** Gt CO_2 from 2020

CH_4 and N_2O reductions corresponding to chosen carbon budget

CH_4 reduction by 2050	N_2O reduction by 2050
~50% (42%-76% range)	~30% (-25%-48% range)

SOURCE: IPCC (2021), *Climate Change 2021: The Physical Science Basis (AR6)*

Exhibit 4

NOTE: The IPCC 6th Assessment Report (2021) only illustrated one 1.5C 'low overshoot' compatible pathway, approximately represented by P2 above.

SOURCE: IPCC (2018), *Global Warming of 1.5°C*; IPCC (2021), *Climate Change 2021: The Physical Science Basis (AR6)*.

27 This estimation is derived by approximating the probability distribution for a carbon budget which would limit warming to below 2°C using a normal distribution.
28 IPCC (2021), *Climate Change 2021: The Physical Science Basis;* carbon budget estimated from 2020.
29 Net emissions from deforestation and land use change therefore consume the carbon budget the same way gross emissions from the EBIT sector do.

Feedback loops, tipping points, and implications

Concentrations of greenhouse gases in the atmosphere produce "radiative forcing effects" which increase atmospheric temperature.[30] But the impact of atmospheric GHG concentrations on global temperatures can be magnified by feedback loops which arise either because: (i) higher temperatures today generate higher temperatures in future, and do so even if forcing effects cease to increase (e.g., the loss of Arctic sea ice resulting in a diminishing albedo effect); or (ii) higher temperatures today generate increased local emissions (e.g., via CH_4 release from the thawing of Arctic permafrost).[31]

In addition, it is possible that, beyond some thresholds or "tipping points" – whether defined in terms of overall temperature or of local climate and physical effects, positive feedback loops could become so strong as to trigger highly non-linear and irreversible climate change. How near we are to such "tipping points" is unclear, however evidence is beginning to suggest we are close to several. For example, the Artic Circle region registered a more-than 3.5º C increase above pre-industrial temperatures in the summer of 2020.[32] The sixth assessment report of the IPCC included for the first time in carbon budget calculations an estimate of possible earth system feedback effects, for example, the impacts of permafrost thaw, dust, lightening and fires, reducing the carbon budget estimate by around 30 Gt CO_2.[33]

These possible feedback loops and tipping points carry three implications:

- There should be a strong focus on achieving GHG emissions reductions as early as possible – and in particular, reductions in CH_4.
- It is possible that the IPCC carbon budget referenced as a base case in this report overstates acceptable cumulative emissions and that further research about the power of feedback loops and the potential for tipping points could result in a tighter budget (the Climate Crisis Advisory Group have consequently argued for a shift towards atmospheric concentration-based targets).[34]
- Any strategies which accept a sizeable overshoot of the cumulative carbon budget and temperature target, with temperatures brought back to within the 1.5°C limit by assumed large net "negative emissions" beyond 2050, are unacceptably risky.

Considering all the risks of overshooting the carbon budget estimated by the IPCC, especially for the world's most vulnerable communities, the global goal should therefore be to limit cumulative CO_2 emissions between 2020-2050 to 500 Gt CO_2 while also cutting methane emissions by at least 50% and N_2O by at least 30%.

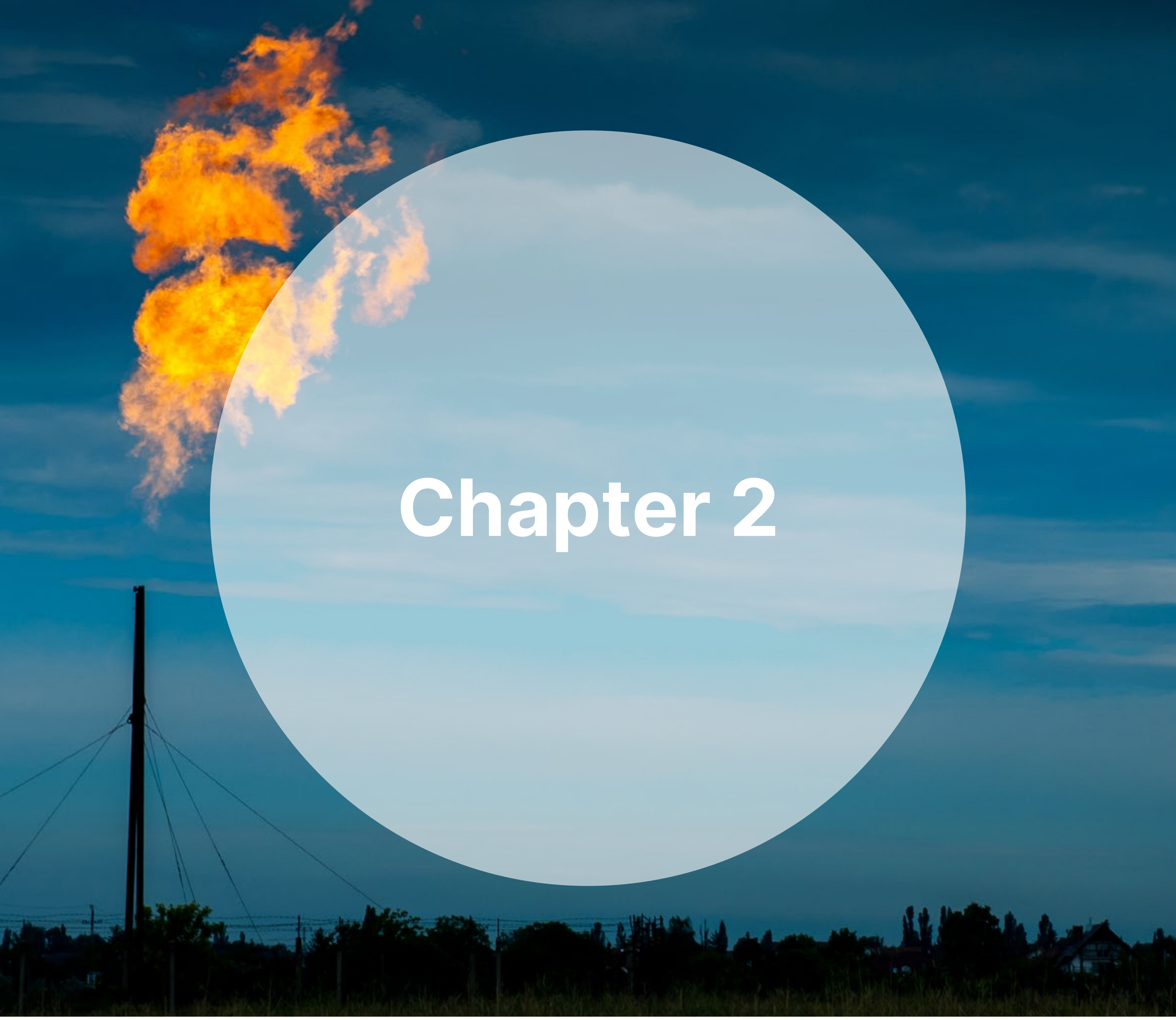
30 When the earth absorbs more energy from the sun than it emits to space it causes warming, this difference between incoming and outgoing radiation is known as 'radiative forcing'. Greenhouse gasses can exacerbate this warming effect, which is known as the 'radiative forcing effect'.

31 The 'albedo effect' refers to how light surfaces reflect more heat than dark surfaces.

32 Climate Crisis Advisory Group (2021), *Extreme Weather Events in the Artic and Beyond: A Global State of Emergency*.

33 With a significant uncertainty range. IPCC (2021), *Climate Change 2021: The Physical Science Basis,* carbon budget estimated from 2020.

34 Indeed the whole concept of whether there remains any safe level of warming can be questioned, in line with arguments that global policy should shift focus towards reducing atmospheric concentrations of GHGs rather than limiting further increases in temperature. Proponents of this approach highlight the need to focus on reduction, removals and climate repair simultaneously. *Climate Crisis Advisory Group (2021), The Global Climate Crisis and the Action Needed*.



Emissions reduction scenarios and the overshoot gap

Today's annual anthropogenic emissions are approx. 40 Gt CO_2, 3.3 Gt CO_2e of N_2O, and 375 Mt of CH_4. The critical question is how fast these emissions can be reduced over time.

We consider two scenarios for the pace of CO_2 reduction:

- In Scenario A, CO_2 emissions could be reduced to around 2 Gt by 2050 but would fall only to 30 Gt by 2030.
- Scenario B – which reflects the ETC's autumn 2021 report on "***Keeping 1.5°C Alive***" - would see still lower 2050 emissions at 1.2 Gt, but more importantly, a faster reduction in the 2020s, reaching 23 Gt by 2030.

Comparing these CO_2 reduction scenarios with the remaining carbon budget suggests a need for 70 to 225 Gt of carbon removal between now and 2050.

In addition, the world would need to maintain carbon removal at around 3-5 Gt per annum after 2050 to neutralize residual CO_2 emissions plus remaining N_2O and methane emissions.

2.1 The starting point – current emissions

In 2020, global anthropogenic emissions were approximately 40 Gt CO_2, 3.3 Gt CO_2e of N_2O, and 375 Mt methane (CH_4), as shown in Exhibit 5.[35]

In the energy, buildings, industry, and transport (EBIT) sectors, CO_2 and N_2O emissions can be estimated reasonably precisely since they primarily result from the burning of known quantities of fossil fuels and standard processes of transforming fossil fuel into products. Methane emission estimates are less precise due to uncertainties about the sectoral origin, location, and timing of methane leakage. Detection and quantification technologies are improving, and standards for reporting methane emissions are being developed, but methane estimates will continue to be less certain than for other gases.[36]

Estimates for emissions from agriculture, forestry, and other land use change (AFOLU) (whether CO_2, N_2O or CH_4) are inherently less certain than for EBIT. AFOLU CO_2 emissions primarily result from land-use change (a net ~6 Gt CO_2 emissions) rather than fossil fuel use (about 1.6 Gt CO_2), and the emissions which result when a hectare of forest is cut down or burnt vary significantly depending on specific local circumstances. Total estimates for CH_4 and N_2O emissions from ruminant animals (e.g., cattle), rice paddies, and agricultural manure are subject to significant uncertainties. Finally, it should be noted that estimates of agriculture-related land-use change depend on the robustness of tracking mechanisms and on government self-reporting, which may in aggregate produce a bias towards lower estimates than the underlying reality.[37]

It is also important to understand the precise meaning of the ~6 Gt CO_2 net emissions from deforestation and other land-use change in the AFOLU sector today. In particular:

- Overall net anthropogenic emissions – i.e., the amount that results from human-induced land-use change (sometimes referred to as LULUCF)[38] - result from a combination of gross emissions, which average around 16 Gt CO_2, and gross removals (estimated to average around 10 Gt CO_2) (see **Box B** below). Humans are thus simultaneously driving gross emissions via deforestation and other land-use changes, while also managing land areas where tree growth is absorbing CO_2. Unfortunately, emissions from land degradation are increasing faster than removals from forest regrowth, resulting in net emissions increasing over time, in addition to other environmental impacts such as biodiversity loss.[39]
- In addition to the impact of human-induced land use change, significant carbon removals occur as natural terrestrial sinks absorb CO_2 in pristine natural ecosystems. In particular, primary tropical forests absorb a considerable amount of CO_2 each year, which is why ending deforestation remains a critical action.[40]

35 Baseline is not COVID-19 adjusted and developed from a range of sources, including: European Commission, Emissions Database for Global Atmospheric Research (EDGAR), release EDGAR v5.0 (1970 - 2015) of November 2019; IPCC (2019), *Special Report on Climate Change and Land;* IEA (2020), *Energy Transitions Pathway;* IEA (2020), *Cement Analysis.*

36 Examples including: Methane Intelligence (miq.org) and the IEA (2020), *Methane Tracker.*

37 Harris et al. (2021), *Global maps of twenty-first century forest carbon fluxes.*

38 Sometimes referred to as LULUCF – *Land Use, Land Use Change and Forestry*.

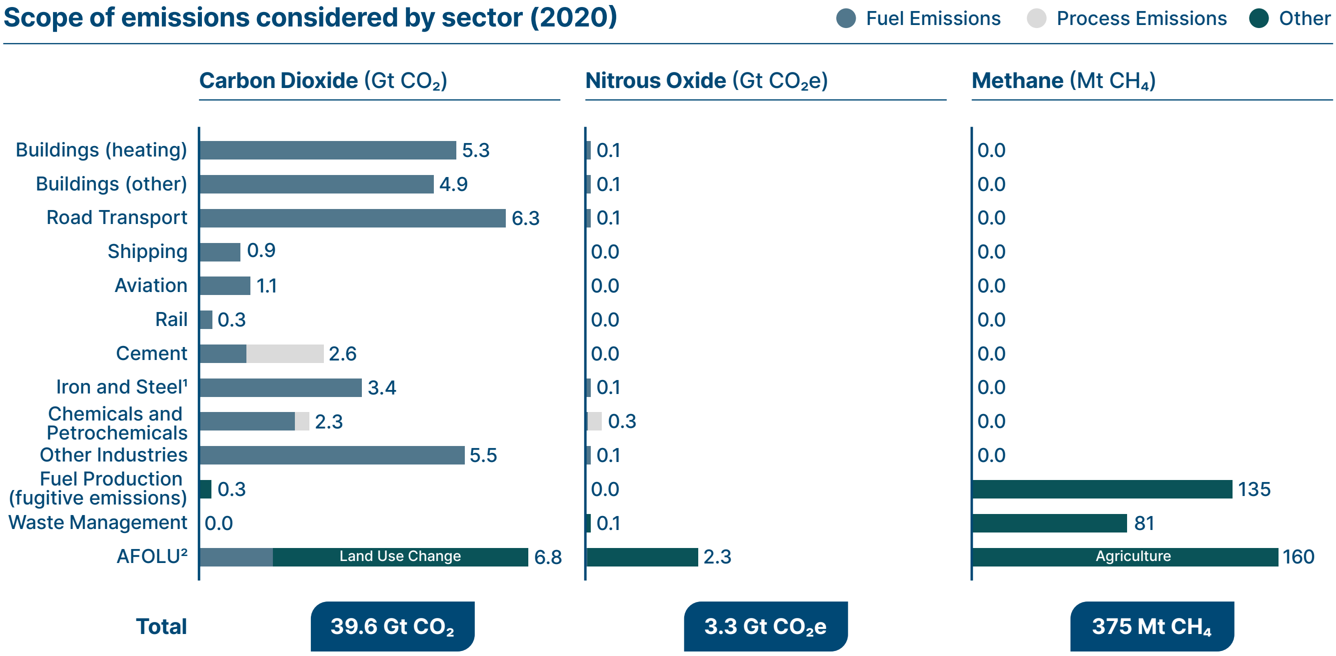
39 Forest regrowth is also often of a lesser quality forest than that which is degraded, resulting in degradation of biodiversity and soils. Freidlingstein et al. (2020), *Global Carbon Budget 2020.*

40 Oceans represent the other major natural CO_2 sink. As the CO_2 concentration in the atmosphere increases the amount absorbed by the oceans also increases. However, this leads to greater concentrations of carbonic acid in oceans, resulting in small yet impactful decreases in ocean pH – the phenomenon known as ocean acidification.

Assumptions about gross removals from the forestry and land-use change sector, as well as these terrestrial sinks, are already taken into account in IPCC estimates of the available carbon budget. Therefore, existing natural sinks cannot be seen as a solution to close any GHG emissions overshoot gap. Additionally, in the carbon budget, these numbers are assumed to be relatively constant over time, whereas in reality, warming and ongoing land-use change might decrease the size of these natural sinks.[41]

In 2020 the energy, buildings, industry and transport sectors (EBIT), waste and AFOLU emitted 40 Gt of CO_2, 3.3 Gt CO_2e of N_2O and 375 Mt of CH_4

Scope of emissions considered by sector (2020)



[1] Due to the production process, process emissions and fuel emissions are typically not separated for iron and steel
[2] AFOLU emissions include ~0.7Gt CO2 emissions from power used in agriculture, this is reflected in energy part of EBIT

NOTE: Estimates of global greenhouse gas emissions in 2020 range widely as a result of varying assumptions, including different assumptions on GWP of methane. The values have not been adjusted for COVID-19 effects. Emissions from electricity generation are allocated to sectors based on their estimated electricity consumption. "Other" includes non-fuel emissions such as methane flaring, landfill & agricultural production. Numbers do not add perfectly due to rounding.

SOURCE: SYSTEMIQ analysis for the ETC based on: IEA (2020), *Energy Technology Perspectives;* EDGAR database; IIASA SSP Public Database, Version 2.0 (Accessed 2021); IEA (2020), Methane Tracker

Exhibit 5

41 Recent research suggests rising temperatures could lead to near-halving of the terrestrial sink due to reduced photosynthesis by 2040. Duffy et al. (2021), *How close are we to the temperature tipping point of the terrestrial biosphere?*

Box B: Global Carbon Sinks

For millennia the Earth's carbon dioxide cycle has been balanced by cycles of carbon between geological formations, the biosphere, the oceans, and the atmosphere. Since the industrial revolution, however, gross emissions have increased dramatically as a result of fossil fuel combustion, alongside the destruction of ancient forest carbon stocks. Net anthropogenic emissions have therefore grown from only about 3 Gt CO_2 per annum in 1860 to around 40 Gt CO_2 in 2000 (Exhibit 6).

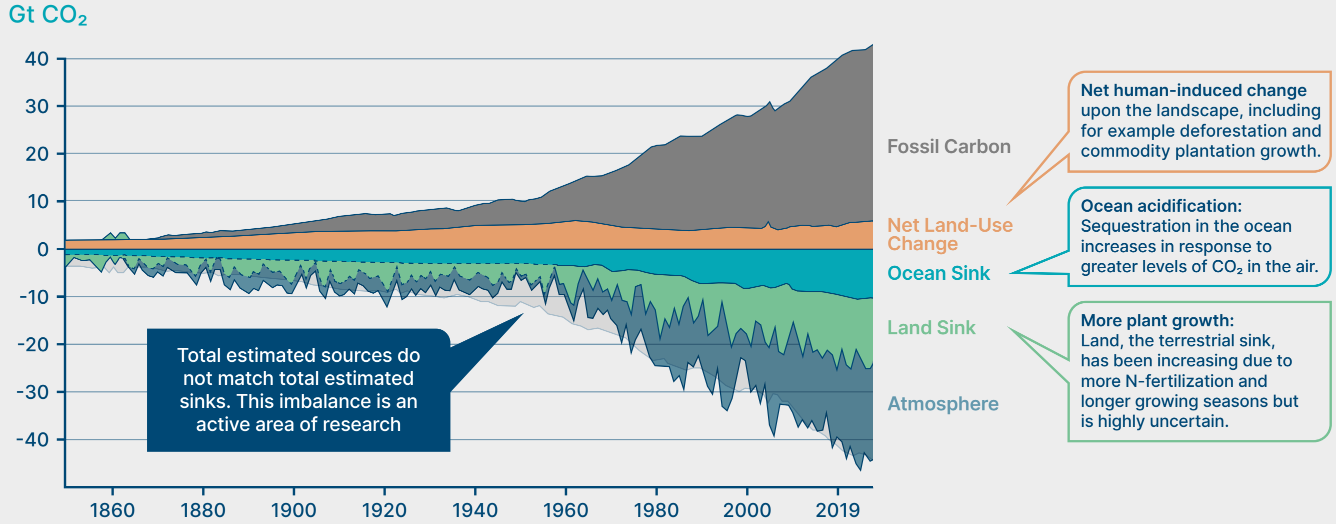
Part of these increased emissions have been absorbed by an increased uptake in terrestrial and ocean sinks since higher concentrations of CO_2 in the atmosphere automatically generate greater CO_2 uptake in forests and seas (which can also have negative impacts such as driving ocean acidification). But the net effect is still a large increase in CO_2 atmospheric emissions, currently ~19 Gt CO_2 per annum, driving a relentless increase in the stock of atmospheric CO_2.

Exhibit 7 shows the average annual flows between 2010-19 with anthropogenic flows about 50 Gt CO_2 on a gross basis, but 40 Gt CO_2 net, with terrestrial and ocean sinks removing a combined 22 Gt CO_2 per annum.

As global CO_2 emissions have increased so too has sequestration in land and ocean sinks, alongside a gradual increase in the atmospheric concentration of CO_2

Balance of sources and sinks

CO_2 only



NOTE: Fossil Carbon includes carbonation sink (sequestration in concrete).

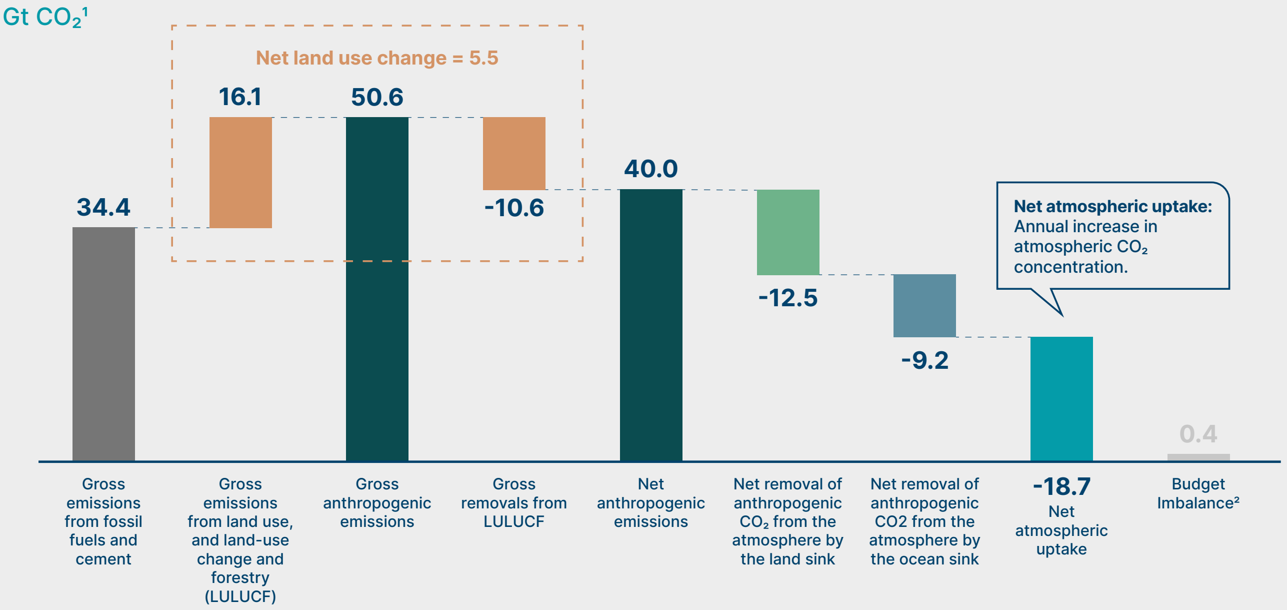
SOURCE: Global Carbon Project (2020).

Exhibit 6

The AFOLU sector both emits and sequesters carbon dioxide, making accounting complex

CO₂ only

Average annual carbon dioxide fluxes 2010-19



[1] Friedlingstein, P. et al. (2020): Global Carbon Budget (2020).
[2] Budget Imbalance = The carbon left after adding independent estimates for total emissions, minus the annual increase in atmospheric CO2 concentrations and estimates for land and ocean carbon sinks using models constrained by observations. It represents the flux uncertainties.

NOTE: Slight rounding uncertainties.

SOURCE: Adapted from FOLU (2021) *Why Nature, Why Now.*

Box B

Exhibit 7

2.2 Emissions reduction scenarios and comparison with the carbon budget

We consider two scenarios for how rapidly anthropogenic emissions could fall towards net-zero over the next 30 years and beyond. These are built up from a detailed analysis of opportunities for CO_2 emissions reductions in every sector in the economy based on five years of ETC analysis, with more broad-brush indicative assumptions for N_2O and CH_4.

- Scenario A builds on the ETC's *Making Mission Possible* (2020) analysis, which set out to demonstrate the feasibility of achieving net-zero emissions by taking ambitious action across the global economy. It reflects primarily supply-side decarbonisation action and assumes only limited progress in improving energy efficiency.[42]

- Scenario B reflects the ETC analysis in *Keeping 1.5°C Alive*, published in 2021 in the run-up to COP 26. This scenario reflects increased ambition and described opportunities for "Keeping 1.5°C Alive". In particular, it highlights the additional carbon reductions that could be achieved through early coal closure and ending deforestation by 2030 and includes more significant improvements to energy productivity that lower overall energy demand. Commitments made at COP 26 represented a step forward towards this scenario but would still not deliver as rapid a reduction as it illustrates.[43,44]

Box C shows key assumptions by sector for the two scenarios and Exhibit 8 shows the resulting trend in CO_2 emissions from the EBIT sectors.

42 Particularly slower progress on power system decarbonisation.
43 ETC (2021), *Keeping 1.5°C Alive: Closing the gap in the 2020s.*
44 The ETC briefing paper *Assessing the achievements at COP26*, issued just after COP26, describes our assessment of what the country and company COP26 commitments might imply for the pace of emissions reduction if fully delivered.

Each scenario represents a different emissions reduction pathway:[45]

- In Scenario A, CO_2 emissions from these EBIT sectors fall from 33.6 Gt CO_2 in 2020 to 1.9 Gt CO_2 in 2050, but with only a 17% reduction to 27.7 Gt CO_2 achieved during the 2020s.

- Scenario B sees still lower emissions of 0.8 Gt CO_2 in 2050, but crucially also a faster pace of decline in the 2020s, with 2030 emissions reaching 22.0 Gt CO_2.

As for the AFOLU sector, the urgency of ending deforestation has long been recognised. This key action plays a pivotal role in reducing emissions and keeping 1.5°C alive. By 2030, almost 10% of global annual emissions (3.6 Gt CO_2) could be eliminated if deforestation reduced by 70%. Simply put - if deforestation is not rapidly brought to a halt within the next decade, global climate goals will become impossible to achieve.

In both scenarios, we assume that CO_2 emissions from the AFOLU sector are reduced from 6.1 Gt CO_2 to less 0.4 Gt CO_2 by 2050.[46] In Scenario A most of this reduction is achieved by 2040, in Scenario B, by 2030. This would be the case if the commitments made at COP26 to end deforestation by 2030 were delivered.[47] However although these commitments hold the right ambition, they are currently underfunded. Furthermore, a similar pledge was also put forward in 2014, signed by 37 countries, and deforestation rates have since increased. Success will depend on:

- Increased flows of finance. Currently committed finance is less than $20bn, spread over the next four years, far below the possible $200bn/year of finance that could be required.[48]

- Jurisdictional approaches to land management coupled with forest-friendly economic development opportunities at a regional or national level, that ensure emissions are genuinely reduced, rather than simply displaced.

- Widespread changes in consumer behaviour to accelerate a shift from meat-heavy to more plant-based diets.

These scenarios for CO_2 reductions, covering both the EBIT and AFOLU sectors and therefore starting at 39.6 Gt CO_2, are compared with the estimated remaining CO_2 budget in Exhibit 9.

- In Scenario B, cumulative emissions over the next three decades (the area under the curve) would amount to 570 Gt CO_2, exceeding the estimated carbon budget by 70 Gt CO_2.

- In Scenario A, the cumulative CO_2 emissions would be 155 Gt CO_2 higher at 725 Gt CO_2 and would exceed the carbon budget by 225 Gt CO_2.

This illustrates that, even with the ambitious reductions envisaged in Scenarios A and B, at least 70 to 225 Gt CO_2 of carbon removal are required between now and 2050 to deliver a 50% chance of limiting global warming to 1.5°C.

In addition, however, there will be a need for some level of continuing negative emissions beyond 2050, for at least three reasons:

- First, to neutralize the residual CO_2 emissions illustrated in Exhibit 8, which together with remaining net AFOLU emissions would be around 1 to 3 Gt CO_2 per annum, even if the world achieved maximum feasible decarbonisation by 2050.

- Second, while the ETC believes that it is possible for the whole world to reach net-zero GHG emissions by 2050, several countries including China and India currently have net-zero targets beyond this date. I Even with these beyond 2050 net-zero commitments, CO_2 emissions will be very significantly reduced by 2050, but some allowance must be made for some additional residual CO_2 emissions for a decade or two after 2050.

- Third, it is unlikely that N_2O emissions can be reduced to absolute zero by 2050 or indeed ever. Our base case assumption is that N_2O emissions are cut from today's 3.3Gt CO_2e to around 1.5 Gt CO_2e by 2050, continuing at around that level thereafter.[49]

45 As these are bottom-up scenarios, although both scenarios reach (close to) net-zero by 2050, they are not necessarily 1.5°C aligned as they were not modelled with that earth-system constraint.

46 Note: In Exhibit 5 the AFOLU sector emissions include ~0.7Gt emissions from power used in agriculture, this is accounted for in the EBIT trajectory.

47 COP26 saw policy-makers from more than 130 countries – including countries with large forest areas such as Brazil and Indonesia – sign up to the Leaders declaration on Food and Land Use (FLU), which pledged to end deforestation by 2030, accounting for ~85% of the world's forests. This was supported by a FACT dialogue statement signed by multiple countries supporting increased supply chain transparency, with a view to avoiding deforestation, as well as the LEAF Initiative. Funding was also dedicated towards supporting Indigenous peoples and local communities, and advancing their land tenure rights.

48 ETC (2021), *Keeping 1.5°C Alive: Closing the gap in the 2020s*.

49 Methane emissions in the ETC's scenarios reduce by around 55% to 2050. Given the short half-life of methane emissions in the atmosphere, as long as methane emissions decrease in concurrence with the IPCC illustrative pathway range (Exhibit 1), then do not increase after 2050, then the overall effect of methane on global temperatures will be neutral or cooling. Therefore no ongoing removals will be required to offset methane emissions.

In total, these factors may imply a need for ongoing negative CO_2 emissions beyond 2050 of around 3 to 5 Gt CO_2 per annum, aiming to keep temperatures at around 1.5°C. Additional ongoing removals could be required if the global temperature goal were to reach below 1.5°C by aiming for net-negative emissions.[50]

While estimates are inherently uncertain and will continue to evolve in light of both climate science insights and changing assessments of feasible emissions reductions, our current assessment is, therefore, that to have a 50:50 chance of limiting global warming to 1.5°C, the world will need to achieve:

- Around 70-225 Gt CO_2 of cumulative negative emissions over the next 30 years.
- An ongoing rate of 3-5 Gt CO_2 per annum after 2050.

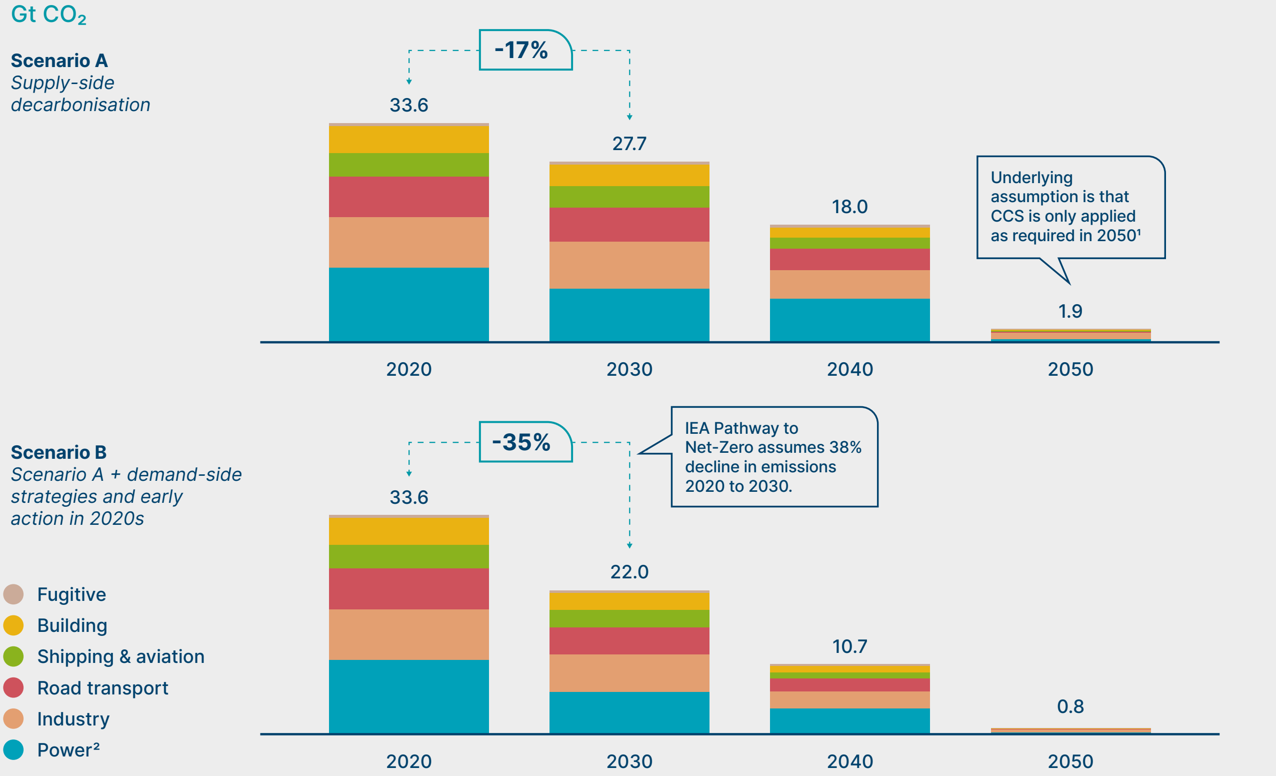
50 While the current global policy target is to reduce overshoot of the 1.5C carbon budget by mitigating on-going emissions, slowing (and eventually halting) the accumulation of CO_2 in the atmosphere, a tonne of CDR is approximately equal to a tonne of avoided emissions. However if the policy target shifts to reducing the absolute stock of CO2 in the atmosphere via net-negative emissions (for example beyond reaching net-zero in 2050), out-gassing effects from current sinks will mean that more than a tonne of CDR will be needed for every tonne reduced in the atmospheric stock.

Box C: Two decarbonisation scenarios described in this briefing

The Energy Transitions Commission has developed two scenarios that show what the pathway to net-zero could look like. The scenarios were initially developed for the Making Mission Possible report and have since been refined with updates from the ETC's sectoral work. It is important to note that both scenarios are primarily based on a bottom-up analysis of energy demand in future years and how this demand can be fulfilled by a growing share of low- and zero-carbon energy instead of fossil-based supply. Scenario A builds on increased energy efficiency and supply-side decarbonisation. In contrast, Scenario B assumes further efficiency improvements and more accelerated action in the 2020s by incorporating feasible actions from the recent ETC report *Keeping 1.5°C Alive*.

The energy, buildings, industry and transport sectors could reach 1-2 Gt CO_2 of residual emissions by 2050

Annual global EBIT emissions after CCS



[1] Assumes CCS is only applied if still required in 2050 based on the long lifetimes of CCS, the lead times of 5+ years and the limited CCS capacity to date.
[2] Power emissions include ~0.7Gt emissions used in agriculture, reflected here rather than the AFOLU trajectory.

NOTE: In Scenario B CCS is assumed to be adopted more quickly by the power sector, but lower absolute value required because of faster decarbonisation overall.

SOURCE: SYSTEMIQ analysis for the ETC based on: IEA (2017), *Energy Technology Perspectives;* IEA (2020), *Energy Technology Perspectives;* Previous analyses of the Energy Transitions Commission, drawing on data from BloombergNEF.

Exhibit 9

The recent ETC report on *Keeping 1.5°C Alive* sets out six categories of action that could bring emissions closer to the 1.5°C pathway. These actions deliver significant emissions cuts by 2030: methane by ~40% and carbon dioxide by 40-50%. Actions include accelerated closure of existing coal power generation, significantly reduced deforestation, and accelerated progress on road transport electrification, alongside decarbonisation of heavy industry and energy efficiency improvements.

Two decarbonisation scenarios described in this briefing

<table>
<tr><th></th><th>'Scenario A'
Scenario A considers more limited energy productivity improvements, with total final energy demand in 2050 15% greater than today, and slower progress in the 2020s.</th><th>'Scenario B'
Scenario B assumes further efficiency and materials circularity improvements by 2050 (total energy demand 15% lower than today) and accelerated action in the 2020s, as recommended in ETC (2021) Keeping 1.5°C Alive: Closing the Gap in the 2020s</th></tr>
<tr><td>Gross CO_2 emissions (compared to 2020)</td><td>• 25% by 2030
• 95% by 2050</td><td>• 45% by 2030
• 98% by 2050</td></tr>
<tr><td rowspan="2">AFOLU</td><td colspan="2">Forests: Rapidly reduced emissions from deforestation and degradation
Agriculture: Reduced process emissions from agriculture up to ~65% by 2030, and then up to 90% by 2050
Diets: 2050: Shift to plant-based diets reducing emissions up to 50%</td></tr>
<tr><td>• Forests: Emissions from deforestation and degradation down 70% by 2030, 95% in 2050.</td><td>• Forests: Emissions from deforestation and degradation down 90% by 2030, 95% in 2050.</td></tr>
<tr><td rowspan="2">POWER</td><td colspan="2">Coal: No new coal, with a full coal phase out globally by 2050.
Renewables: Rapid replacement of fossil fuel generation by renewables, wind and solar reach 40% of generation by 2030 from 20% today.
Full power decarbonization by mid-2040s at the latest, with developed economies leading the way.
Large growth in power system (to 3-5x today's level) to support electrification, and clean hydrogen production.</td></tr>
<tr><td>Global power decarbonization by 2040, incl.:
• Coal fully phased out by 2045/50.
• Developed economies achieve almost complete decarbonisation by mid-2030s.
• 60% of generation low-carbon by 2030: Wind and solar ~40% of generation, another 20% of generation from nuclear, hydro, other renewables.
• CCS*: 1.5 Gt CO_2/year of CCS on power by 2050.</td><td>Global power decarbonization by 2040, incl.:
• Coal fully phased out in OECD countries by 2030, and all countries by 2040.
• 70% of generation low-carbon by 2030: Wind and solar ~40% of generation, another 30% of generation from nuclear, hydro, other renewables.
• CCS*: ~0.5 Gt CO_2/year of CCS on power by 2050.</td></tr>
<tr><td rowspan="2">BUILDINGS</td><td colspan="2">A shift to electrification and improved energy productivity in buildings, leading to full electrification of buildings except for heat by 2030, with 80% of building heating electrified by 2050.</td></tr>
<tr><td>• 2050: Building heating 80% electrified via increased adoption of heat pumps; Bioenergy and H2 used in last 20%. Some efficiency improvements.</td><td>• 2050: Total building power demand 15% less via early adoption of efficiency improvements.</td></tr>
<tr><td rowspan="2">INDUSTRY</td><td colspan="2">Cement: Direct electrification of cement kilns from 2035 onwards, and increased use of biofuels and hydrogen to supply high-temperature heat, displacing fossil fuels from mid-2030s.
CCS on process emissions ramping up from mid-2030s.
Iron & steel: Hydrogen displaces a significant share of primary production from 2030. Coal-based production continues to play a role with CCS ramping up in the mid-2030s. All secondary production is electrified.
Chemicals & petrochemicals: Direct electrification and use of hydrogen as both fuel and feedstock in plastic + chemicals production. Significant share of energy and feedstock still supplied by fossil (with some CCS ramping up from the 2030s).</td></tr>
<tr><td>• Limited improvements in industry energy consumption
• CCS*: ~0.5 Gt CO_2/year point-source CCS in 2030, up to ~3.5 Gt CO_2/year in 2050 (for industrial sectors (cement, iron & steel, chemicals, and blue hydrogen).</td><td>• Improved energy productivity: Industry energy consumption ~15% less in 2030 compared to scenario A; 35% less in 2050.
• Cement: Demand ~35% less in 2050 through increased recycling and reuse and efficient use.
• Iron & steel: Faster adoption of green steel, and energy demand in iron and steel ~40% less in 2050 through increased recycling and electrification.
• Chemicals & petrochemicals: Plastics recycling reduces demand by ~55% in 2050.
• CCS*: ~0.5 Gt CO_2/year point-source CCS in 2030, ~2.5 Gt/year in 2050.</td></tr>
<tr><td rowspan="2">TRANSPORT</td><td colspan="2">Road: Rapid growth in the share of new auto sales accounted for by battery electric vehicles. Continued fuel economy improvements in light and heavy duty vehicles.
Shipping & aviation: near complete decarbonisation by 2045/2050 (shipping primarily via green ammonia; aviation using biofuels or synthetic fuels).
Rail: increased electrification, completely electrified by 2040.</td></tr>
<tr><td>• Road: Ban on ICE** sales in some developed countries from 2030.</td><td>• Road: Global ban on light vehicle ICE** sales by mid-2030s at latest. Continued fuel economy improvements. Lower travel demand (e.g., via shared use models).
• Shipping & aviation: Total demand is ~30% less in 2050 through increased efficiency.
• Rail: 15% greater demand for rail transport over Scenario A.</td></tr>
</table>

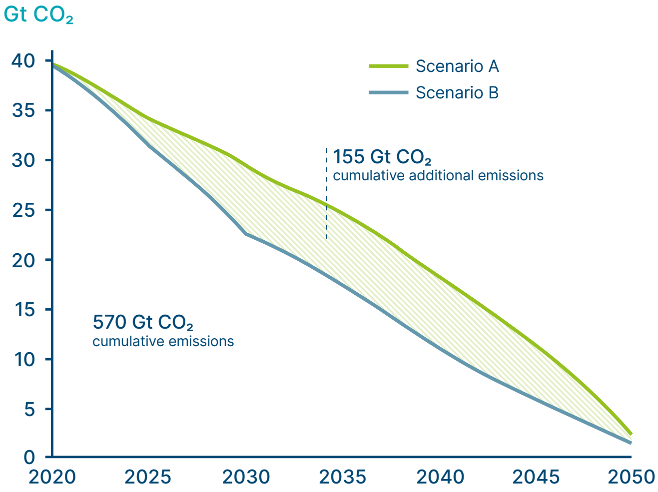
NOTES: * CCS = Carbon Capture and Storage

** ICE = Internal Combustion Engine

Box C

In Scenario A cumulative emissions overshoot the carbon budget by 225 Gt CO_2, accelerated emissions reduction in Scenario B limits this to 70 Gt CO_2

Global annual gross emissions in two ETC scenarios



Cumulative emissions and carbon budget

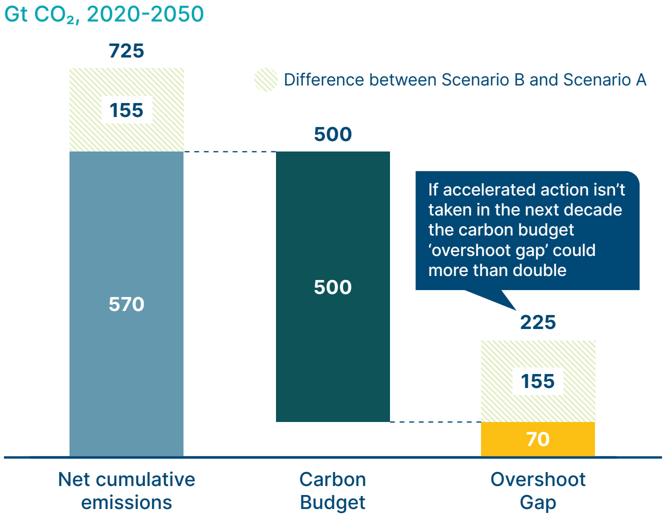


Exhibit 9

NOTE: Point-source CCS assumed as part of within-sector decarbonization for EBIT sectors for gross emissions.

SOURCES: SYSTEMIQ analysis for the ETC based on: IEA (2017), *Energy Technology Perspectives;* IEA (2020), *Energy Technology Perspectives;* IPCC (2021) *Climate Change 2021: The Physical Science Basis*

Both Scenarios A and B overshoot 1.5°C warming trajectories

Total annual gross emissions across sectors[3], shown in contrast with IPCC limited overshoot 1.5°C pathways for net emissions

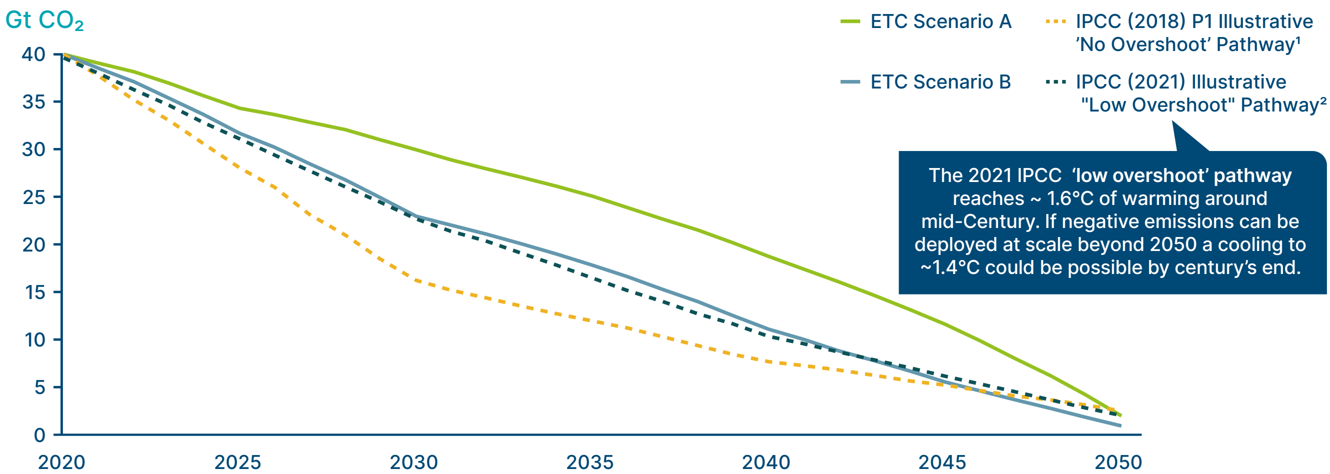
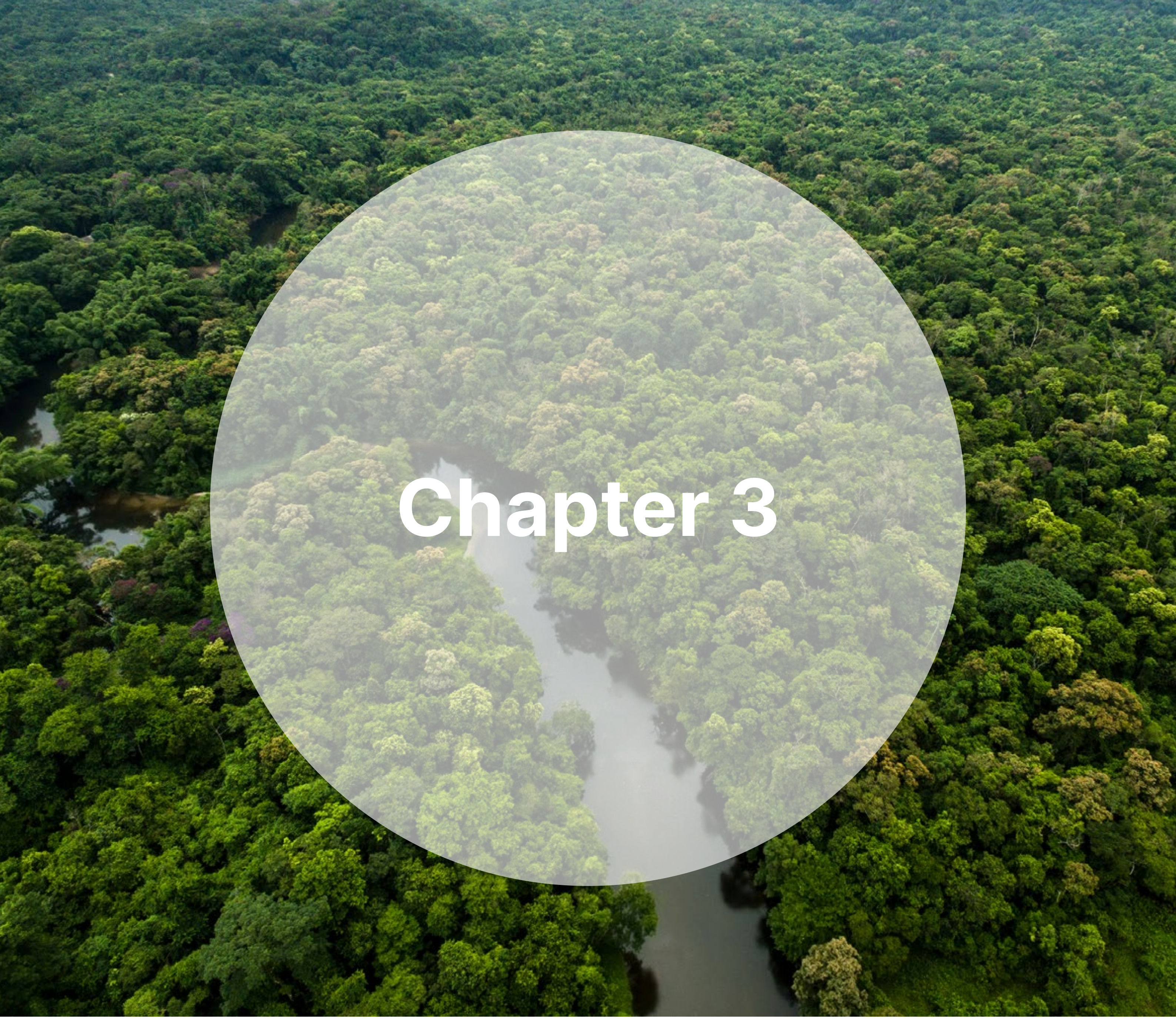


Exhibit 10

NOTE: : IPCC Integrated Assessment Models modelled 42 scenarios for <1.5C, typically draws on multiple data sources and forward projections, meaning that some variation in starting points is expected.;
[1] P1= an ambitious scenario which assumes social and technical innovation drive rapid decarbonization through low energy demand assumptions and investment in afforestation, cited in the IPCC (2018) Special Report, and achieves no overshoot of 1.5C;
[2] SSP1-1.9 the only illustrative pathway in the IPCC (2021) AR6 report which limits warming to <1.5C by the end of the century, after a slight overshoot to 1.6C by mid-century. However mid-century warming has a very likely range of 1.2-2.0 C, still posing significant risk;
[3] Point-source CCS assumed as part of within-sector decarbonization for EBIT sectors.

SOURCE: SYSTEMIQ analysis for the ETC based on: IEA (2017), *Energy Technology Perspectives;* IEA (2020), *Energy Technology Perspectives;* IPCC (2018), *Global Warming of 1.5°C; IIASA SSP Public Database, Version 2.0 (Accessed 2021)*



A typology of carbon dioxide removals, and their potential scale

- Carbon Dioxide Removal (CDR) refers to active interventions that can result in a net removal of CO_2 from the atmosphere.

- Technically feasible options for carbon dioxide removal can be grouped into three broad categories: Natural Climate Solutions (NCS), engineered solutions such as Direct Air Carbon Capture and Storage (DACCS), and hybrid solutions (sometimes known as Biomass with Carbon Removal and Storage (BiCRS)), which includes Bio-Energy with Carbon Capture and Storage (BECCS).

- Combined, these could cumulatively sequester ~165 Gt CO_2 in the next 30 years, reaching about 12 Gt CO_2/yr in 2050.

Exhibit 11 sets out a wide range of potential CDR solutions. Each involves a process for removing CO_2 from the atmosphere and placing it in permanent storage.[51] Additionally, some but not all require the transport of CO_2 from one location to another. The main options which already demonstrate potential to be feasible at scale can be considered in three categories (Exhibit 12):[52]

- **Natural Climate Solutions (NCS)**, [53] which apply natural photosynthesis processes to capture CO_2 from the air, and store CO_2 in the biosphere either above or below ground.

- **Engineered solutions**, and in particular DACCS, which uses direct air capture to remove CO_2 from the atmosphere and then stores the CO_2 in geological formations.[54]

- **Hybrid solutions** which bridge natural and engineered approaches, such as Biomass with Carbon Removal and Storage (BiCRS), use photosynthesis to capture the CO_2 but technological intervention to store it, for example in mineral or geological forms. These include BECCS and Biochar.

In addition there are a range of more speculative options – e.g., enhanced weathering, ocean mineralisation and ocean fertilisation, which are currently at earlier stages of development and come with greater uncertainty about the environmental and social impacts of application at scale. These are described further in Chapter 3.4, but we do not assess them in detail in this report nor assume any significant application before 2050.

For each of the options in Exhibit 12, we describe below:

- What the option entails, possible costs and technological readiness.[55]

- The feasible annual potential by 2050 and the implications for land or other resource requirements.[56]

- Sequestration time profile – i.e., how the annual flow and cumulative stock of CO_2 removed by specific project builds up over time.

- A scenario for total annual flows and cumulative sequestration.

We then compare the combined potential sequestration with the need for negative emissions described in Chapter 2.

51 Permanent is defined as several decades to 1000s of years. Storage is in durable materials, geological storage, or living biomass. Technologies which capture CO_2 from sources other than the atmosphere (e.g., point-source exhaust streams) are not considered carbon removal.

52 Furthermore, the environmental impacts of these CDR solutions are well-understood.

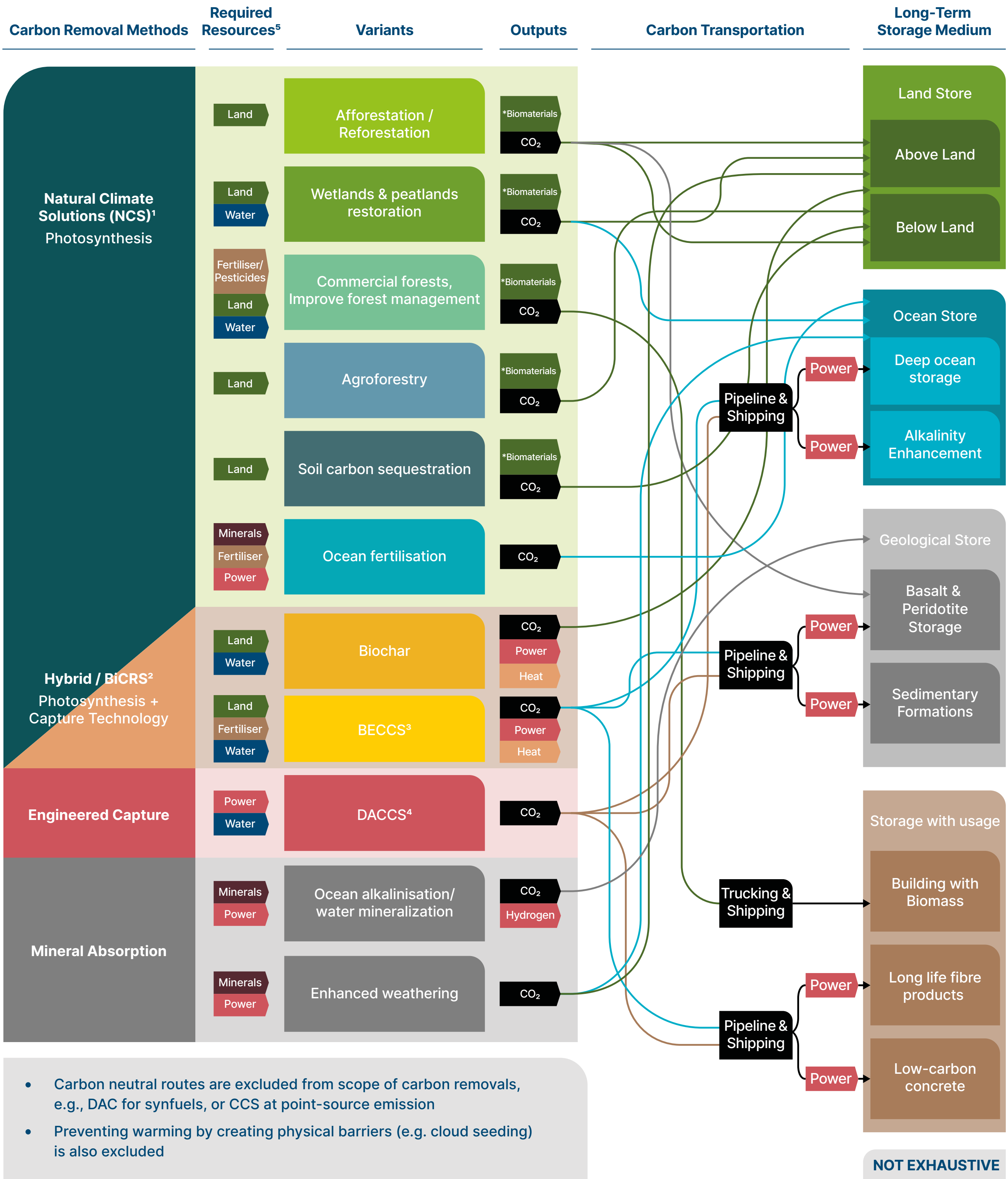
53 Nature-based Solutions (NBS) are activities that harness the power of nature to deliver services for adaptation, resilience, biodiversity, and human well-being, including reducing the accumulation of greenhouse gases (GHGs) in the atmosphere. Natural Climate Solutions (NCS) can be considered as a subset of NBS with a specific focus on addressing climate change. NCS has been defined as 'conservation, restoration, and/or improved land management actions to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, agricultural lands, and oceans' (Griscom et al. (2017), *Natural Climate Solutions*).

54 In addition, there may be opportunities to store CO_2 in very durable materials, e.g., in concrete via fly-ash additives or aggregate.

55 Technological readiness assessed via a literature review and consultation process.

56 Feasible potential assessed by considering maximum technical potential and adjusting for cost-effectiveness, sustainability, and other feasibility criteria.

The options for achieving carbon removal are various and complex



- Carbon neutral routes are excluded from scope of carbon removals, e.g., DAC for synfuels, or CCS at point-source emission
- Preventing warming by creating physical barriers (e.g. cloud seeding) is also excluded

NOT EXHAUSTIVE

NOTE: List of removal and storage options not exhaustive. *If done with limited sustainable forestry within an intact forest landscape. Biomaterials include food, feed, fuel and fiber.
[1] Natural Climate Solutions (NCS) are activities that harness the power of nature to reduce the accumulation of greenhouse gases (GHGs) in the atmosphere and provide benefits for biodiversity and human well-being;
[2] Biomass with Carbon Removal and Storage (BiCRS). These can be coupled with climate smart technology to secure long-term storage of carbon;
[3] BECCS: Bioenergy with Carbon Capture and Storage;
[4] DACCS: Direct Air Capture with Carbon Storage;
[5] Artificially added resources, (e.g., natural afforestation doesn't require fertilizer).

SOURCE: SYSTEMIQ analysis for the ETC.

Exhibit 11

Exhibit 12

Summary of CDR solutions considered for deployment at scale by 2050

NCS	RESTORE	1. Restore Forests	Afforestation / Reforestation
NCS	RESTORE	2. Restore Other Ecosystems	Restore peatlands
NCS	RESTORE	2. Restore Other Ecosystems	Restore Blue Carbon (including mangroves, coastal wetlands, marshes)
NCS	MANAGE	3. Agroforestry	Agroforestry; *e.g., integrating trees into agricultural land*
NCS	MANAGE	4. Improved Forest Management	Improved Forest Management; *e.g., reduced-impact logging, extended harvest rotation and designated protection*
NCS	MANAGE	5. Enhance Soil Carbon Sequestration	Enhance soil carbon sequestration in degraded grazing lands; *e.g., lessening grazing pressure*
NCS	MANAGE	5. Enhance Soil Carbon Sequestration	Enhance soil carbon sequestration in degraded croplands; *e.g., no-till management and cover cropping*
BiCRS / HYBRIDS	MANAGE	6. Biochar From crop residues	Thermal decomposition of biomass in the absence of oxygen into a form more resistant to decomposition
BiCRS / HYBRIDS		7. BECCS From forest residues and dedicated energy crops	Combustion of biomass to produce energy. CO_2 is captured and placed in geological storage
ENGINEERED		8. DACCS	Direct Air Capture and geological storage of CO_2

NOTE: List of removal and storage options not exhaustive. Solutions assessed to have uncertain environmental impacts not included in this assessment. NCS: Natural Climate Solutions; BiCRS: Biomass with Carbon Removal and Storage.; BECCS: Bioenergy with Carbon Capture and Storage; DACCS: Direct Air Capture with Carbon Storage.

3.1 CDR solutions

3.1.1 Natural Climate Solutions (NCS)

Natural climate solutions for carbon removal use natural photosynthetic processes to capture carbon dioxide from the air and store it in the biosphere above ground, below ground, and in the oceans.[57]

They can be divided into two sub-categories:

- **'Restore' solutions** involve changing the current pattern of land use, for instance by reforesting currently degraded or abandoned land, or land currently used for agriculture. This typically entails converting land back to a pre-existing natural ecosystem, but might involve afforestation of land which has not been forested for centuries.[58]

- **'Manage' solutions** improve how land is managed to increase carbon sequestration, without changing the current primary use of the land.

'Restore' solutions

These include restoring forests and other ecosystems, such as peatlands or ocean-margin ecosystems such as mangroves, tidal marshes and seagrasses (sometimes referred to as 'Blue Carbon'). [59,60] Exhibit 15 and Exhibit 16 set out what this CDR option might entail.

57 Nature-based Solutions (NBS) are activities that harness the power of nature to reduce the accumulation of greenhouse gases (GHGs) in the atmosphere and provide benefits for adaptation, biodiversity, and human well-being. Natural Climate Solutions (NCS) can be considered as a subset of NBS with a specific focus on addressing climate change. NCS has been defined as 'conservation, restoration, and/or improved land management actions to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands' (Griscom et al., (2017), *Natural Climate Solutions*).

58 Reforestation is always prioritised over afforestation for the best ecosystem outcomes. In some cases lack of historical data makes it difficult to assess the character of natural-ecosystems which were present in a land area prior to human activity.

59 Peatlands are organic-rich partially decomposed soils in high groundwater levels. They are extremely carbon rich, 44% of the world's carbon soil organic carbon stocks are estimated to be stored in peatlands, which is made vulnerable to atmospheric release when drained for agriculture.

60 *Macroalgae, or seaweed, has too large knowledge gaps for inclusion at this stage.* Hoegh-Guldberg. O. et al. (2019), *The Ocean as a Solution to Climate Change: Five Opportunities for Action.*

These options often involve returning land to a previous natural state in which its primary use is no longer to produce a commodity of economic value, but to sequester carbon (though it may also benefit from other revenue streams, see Box E below). But implementing these options requires human intervention and economic investment in the form of, for instance, tree planting and actions to re-wet peatlands (e.g., removing drainage systems). In these cases, best-practices such as stand diversity are important to ensure positive outcomes for biodiversity as well as climate. Ongoing monitoring and management costs are also entailed (see Chapter 4 for further discussion). In addition there can be an opportunity cost of removing the land from its existing economic function, which may be reflected in a land acquisition cost.

Technical and commercial readiness for these options is high with many projects already in place, and estimated costs per tonne of CO_2 saved are currently low e.g., in the range of $5 to $50 per tonne.[61] In addition such projects can deliver significant essential co-benefits via biodiversity recovery, improved freshwater supply, and economic opportunities for forest-based communities. Costs are however likely to trend upwards over time as the most favourable opportunities are exploited first.

Sequestration potential: Forests

Around 25% of the world's land area (3,700 out of 14,900 Mha) is currently covered by forests.[62] These forests form a major part of the "land sink" which, as described in Chapter 1, already removes around 6 Gt CO_2 from the atmosphere each year.[63]

Estimates for maximum technical additional sequestration suggest that devoting another 1,700 Mha to forest could deliver an average 8.5 Gt CO_2/yr over a 30 year period (with annual sequestration rates increasing over that period).[64] This is an area about five times the size of India. Competing demands for land are likely to make the feasible potential far less. In addition, forestation projects face reversal risks arising from wildfires, changes in government policy or economic incentives, and potentially climate change (see discussion of risks in Chapter 4). Taking these risks into account further reduces the cost-effective potential. Efforts should be focused on geographic areas such as the tropics, which have high sequestration density and low risk of wildfire, and where innovative technology, governance and financing can be used to reduce scaling challenges.[65]

61 Fuss et al. (2018), *Negative emissions—Part 2: Costs, potentials and side effects.* Global literature review of forest restoration costs.
62 FOLU (2019), *Growing Better*.
63 Global Carbon Project (2020), 2001-2019 average estimate. Note these are net land sink emissions, accounting for both anthropogenic land use change and natural terrestrial sinks. Gross sinks are larger.
64 Roe et al. (2021), Land-based measures to mitigate climate change: potential and feasibility by country.
65 Van Lierop et al. (2015), *Global forest area disturbance from fire, insect pests, diseases and severe weather events.* Between 2003 and 2012 approximately 38 Mha of forests were disturbed due to extreme weather, mostly in Asia.

This analysis therefore assumes a total ~300 Mha reforested on marginal degraded land – primarily in the tropics (Exhibit 18). To achieve maximum sequestration outcomes by mid-century, this area should be 'planted' or allowed to naturally re-grow over the next decade. The policy targets set by more than 70 countries under the Bonn Challenge equates to roughly 300 Mha of reforested land by 2030 (e.g., 8 Mha in the Democratic Republic of the Congo).[66,67] Delivering these targets would therefore see the ambition in this report achieved.

Estimates which assume that reforestation will be cost-effective below a carbon price of $100 per tonne, suggest a total potential flow of ~1.9 Gt CO_2 by 2050[68] cumulatively reaching 36 Gt CO_2 over that period (assuming forest restoration projects are begun on ~300 Mha in the next 10 years).[69] This assumes that, new forest can achieve an average stock "sequestration density" of 0.12 Gt CO_2 per Mha over 30 years (with ~8 Mha therefore required to sequester a stock of 1 Gt CO_2).[70]

Sequestration potential: Other ecosystems, including peatlands and blue carbon

The total land area of peatland and coastal ecosystems targeted for restoration is far smaller than that of forests. Estimates suggest that cost effective potential in these categories would mean restoring about 16 Mha for peatlands and 7 Mha for coastal wetlands.[71] But typical sequestration densities are much higher at around 1 Gt CO_2 / Mha. As a result, potential sequestration for these subcategories could be around a quarter of all the "Restore" potential in 2050, at around 0.7 Gt CO_2/yr, or 22 Gt CO_2 cumulative by 2050.[72]

Sequestration profiles over time

In assessing the potential for different categories of CDR to close the gap between emissions reductions in our scenario and what is required for 1.5°C, it is important to consider the build-up of sequestration volumes over time (the total carbon stock) as well as future annual sequestration by mid-century (the annual flow of sequestration). The aggregate cumulative sequestration is, in turn, the product of the sequestration profile for a specific project on a given area of land, and the area of land covered by each category project. Both annual and cumulative sequestration profiles vary by NCS type, as described in Box D.

In the case of "Restore" NCS projects (illustrated in Exhibit 15 and Exhibit 16) the annual removal flow tends to build up in an S-curve function, with only limited sequestration in early years, followed by several years of rapidly growing annual sequestration, then stabilisation and eventual decline in the very long term.[73] In stock terms, there is a gradual S-curve build-up to a maximum volume of sequestration which will be sustained thereafter as long as no disturbance occurs (Box D).

Scenario for total sequestration over time

Exhibit 17 sets out our scenario for total sequestration volume achieved from "Restore" NCS projects, with annual flows potentially reaching about 2.2 Gt CO_2 by 2030 and 2.8 Gt CO_2 by 2050,[74,75] and with total cumulative sequestration of about 60 gigatons by 2050 between restoration of forests, peatland and Blue Carbon ecosystems. These flows will eventually decline beyond 2050 as restored ecosystems mature.

This would require that reforestation projects be implemented on about 300 Mha of land in the next decade,[76] with 7 Mha of coastal land and 16 Mha of peatland also restored within that timeframe.[77] This is approximately 8% of standing forest area.

66 Lewis et al. (2019), "Restoring natural forests is the best way to remove atmospheric carbon", *Nature*.
67 Of this, 57 countries have made specific voluntary targets using an area metric, equating roughly 200Mha in restoration.
68 ETC Analysis based on Roe et al., (2021). Assumes a carbon stock accumulation curve based on sequestration flow rates and assumptions about rate of land conversion. Note the cost-effective sequestration potential from reforestation - defined as solutions available below a carbon price of $100/t CO_2e - is about ~14% of the average maximum technical potential. As restoration available at higher prices (above the cost-effective threshold) is likely on higher quality land, the average sequestration density is higher for the maximum technical potential. See technical annex for further details.
69 300 Mha is assumed here as a feasible target for reforestation efforts. Further reforestation beyond this target area not included in this analysis.
70 Averaged over the next three decades prior to 2050.
71 Roe et al. (2021), Cost-effective is defined as mitigation solutions up to a carbon price of $100/t CO_2e as it is in the middle of the range for carbon prices in 2030 for a 1.5°C pathway, and at the low end of the range in 2050.
72 Roe et al. (2021), *Land-based measures to mitigate climate change: potential and feasibility by country*. Note: based on analysis from average annualised estimates of sequestration potential 2020-2050 then adjusted for assumed scale up of solution over time.
73 Although sequestration rates will slow, healthy forests will continue to sequester per annum.
74 Roe et al. (2021), *Land-based measures to mitigate climate change: potential and feasibility by country*. Note: based on analysis from average annualised estimates of sequestration potential 2020-2050 then adjusted for assumed scale up of solution over time.
75 ETC Analysis based on Roe et al (2021), *High Level Panel for Oceans 2019*.
76 For comparison, approximately 60 Mha were restored globally 2000-2015 (an area the size of Madagascar). TrillionTrees.org (Accessed January 2022).
77 It is important to stress that sequestration via restoration must be in addition to reducing annual net AFOLU emissions by around 6 Gt CO_2 by 2050 - primarily achieved via avoiding deforestation in the first place (noting these are considered emission reductions, not removals). The ETC's recent *Keeping 1.5°C Alive* report highlighted the importance of, and required funding, of ending deforestation in the 2020s. Deforestation is the main source of CO_2 emissions from the Agriculture, Forestry & other Land Use (AFOLU) sector (not including other greenhouse gasses). Paying to 'avoid deforestation' is therefore the main CO_2 emissions reduction lever for that sector. ETC (2021), *Keeping 1.5 C Alive*.

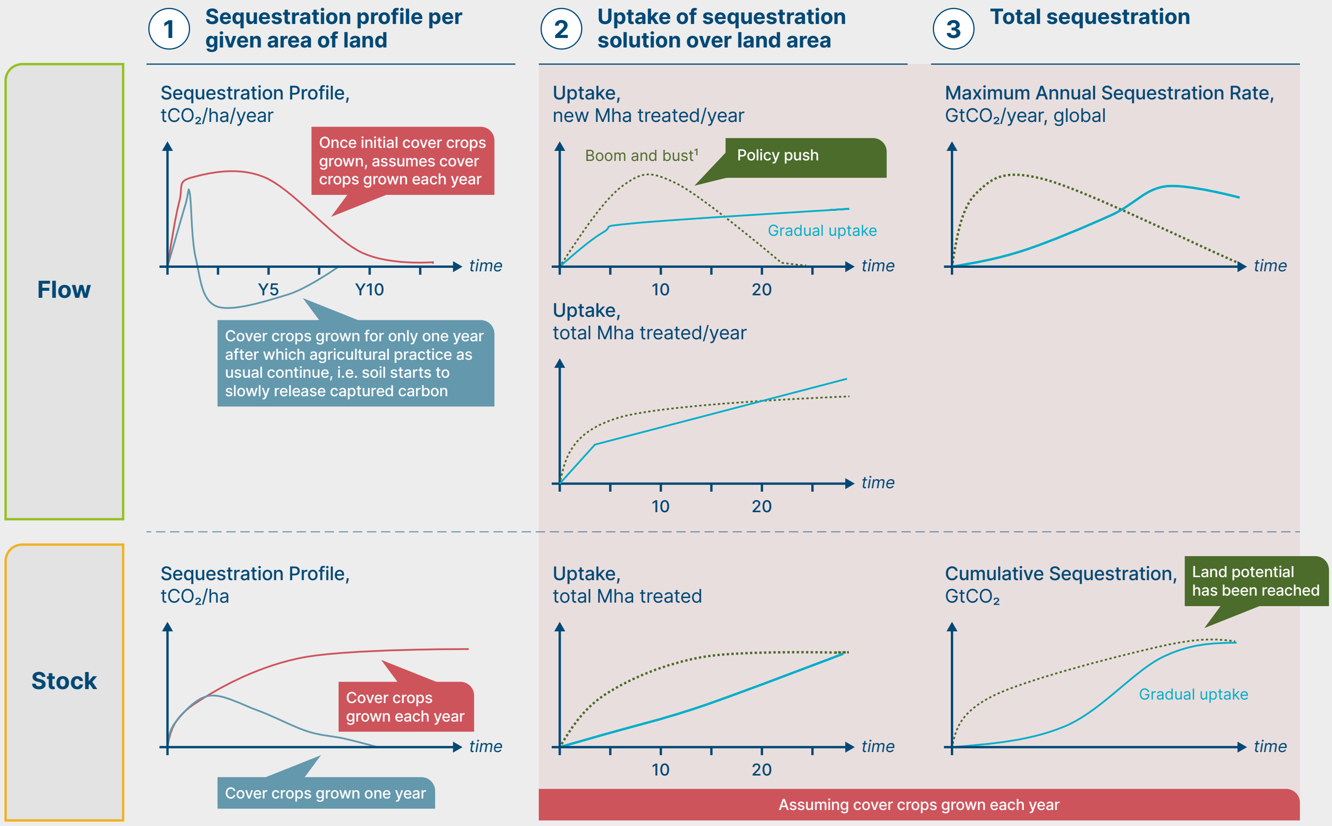
When thinking about total carbon sequestration over time in the biosphere there are several factors to take into account.

First is the annual flow rate at which carbon is absorbed out of the atmosphere and then stored in the biosphere for one unit of land; which can be thought of either in terms of an annual 'flow' or a cumulative 'stock' sequestered per unit of land. This differs depending on the biological and physical characteristics of the Natural Climate Solution in question. Above-ground biomass such as trees have a different sequestration profile to soil carbon, which has a tendency to reach 'saturation' sooner.[78]

Secondly is how that solution is scaled up over time to an increasingly greater area of land. As each new hectare of land is restored or brought into improved management, it begins its sequestration profile. This means that as annual sequestration rates in some areas of land are plateauing, others are just beginning to accelerate, at the steepest parts of their 's-curve'. Ultimately, land use profiles are a feature of policy choices. For example, a policy which subsidizes improved soil management techniques could cause a 'boom and bust' cycle in improved soil management, in contrast with a more gradual uptake of improved practices.

Total sequestration is therefore a factor of both the per unit sequestration profile and area of land to which the solution has been applied. Exhibit 13 and Exhibit 14 below illustrate these concepts. The sequestration profiles illustrated are then used to build up our estimates of aggregate potential CDR over time.

Illustrating the carbon flow and stock impacts of enhanced soil sequestration using cover crops



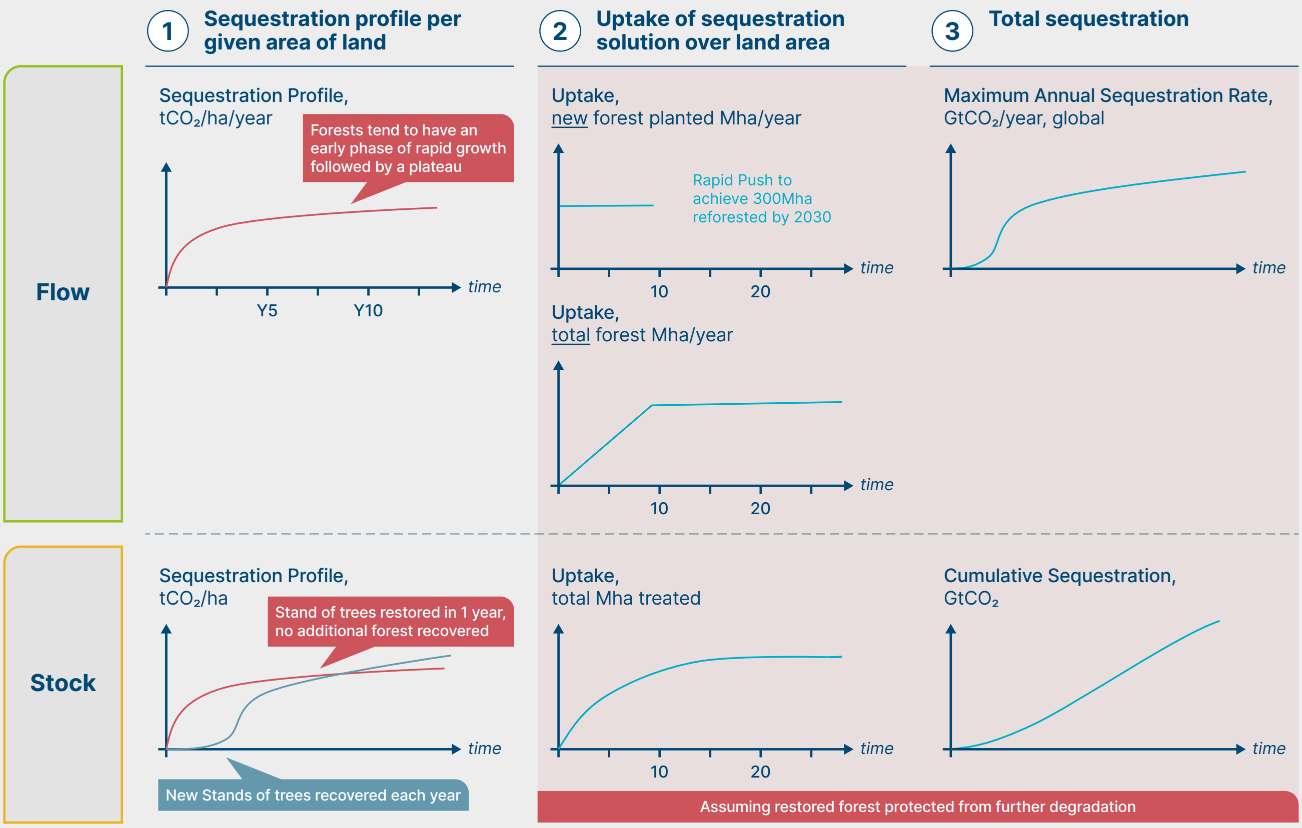
[1] 'Boom and bust' scenario provided for comparison. 'Gradual uptake' assumed in report analyses.

SOURCE: Jones, S., (2017) *Modelling Soil Carbon and Agriculture*, Climate Interactive

Exhibit 9

78 Climate Interactive (2017), *Modelling Soil Carbon and Agriculture.*

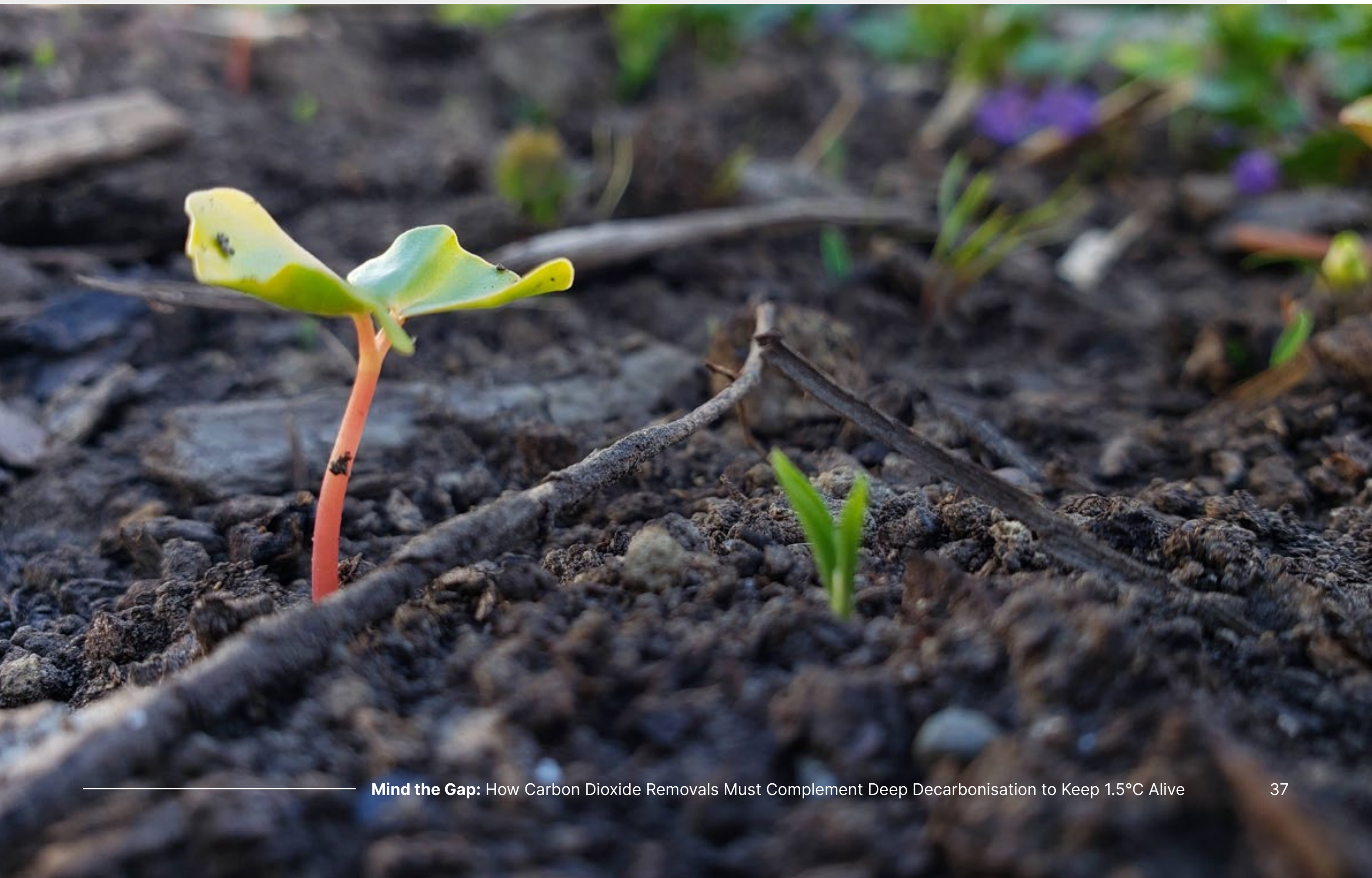
Illustrating the carbon flow and stock impacts of forest restoration



SOURCE: Cook-Patton et al., (2020)

Exhibit 14

Box D



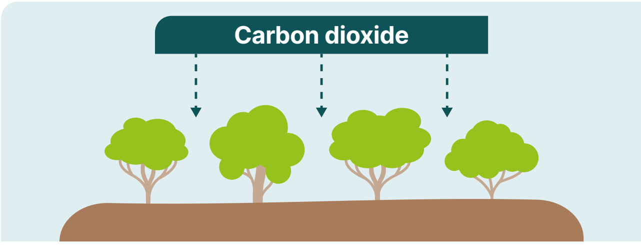
Restoring forests

Natural climate solutions

Nature restoration

What restoring forests entails

- **Forests which re-grow on degraded, abandoned or converted land** sequester carbon via photosynthesis both above ground into tree biomass and below ground into soils.
- This process **can be accelerated through active tree-planting** (and later monitoring, see Chapter 4), which requires labour, fertilizer and water resources.
- A typical reforestation project would take several months from inception to start of sequestration and **operates for about 20-45 years**.
- **Costs are typically in land acquisition and protection, planting**, and general labour, with as well as ongoing costs due to monitoring.
- **Costs are likely to rise as deployment increases**, due to the availability of low-cost projects.



Readiness to scale

Summary	Tree-planting is commonplace around the world. Around 50 Mt CO_2 of afforestation projects are currently issued on carbon markets.
Technological Readiness Level[2] (0-11)	**High (10-11);** well-designed projects can be executed at scale today.

When and how will carbon be removed

CO_2 Sequestration Profile	Carbon stocks **accumulate gradually, sequestration flows eventually plateauing at forest maturity** after many **decades**.

Costs & co-benefits

Costs	**Today:**[1] **$5-30** / tCO_2	**2050:**[1] **$15-50** / tCO_2
Co-Benefits	**Biodiversity recovery**, local area **freshwater** supply, economic support to forest-based communities.	
Other Challenges	**Additional sources of income** as well as policy support for **secure land tenure** may be required to ensure incentives to deforest are overcome. Possible **albedo effect** in certain geographies. Care must be taken to preserve indigenous land rights.	

Exhibit 15

NOTES AND SOURCES: [1] Restoration and afforestation costs vary significantly in methodology and considerations. Few cost studies exist for tropical countries in the past decade. Further assessments must include opportunity costs of land use. Have assumed costs move towards upper end of range by 2050. Fuss et al (2018);
[2] TRL adjusted from (0-9) *Royal Society* (2018) *Greenhouse Gas Removal Report* scale to (0-11) scale for comparison with other sources.
Graphic: Adapted from Royal Society (2018) *Greenhouse Gas Removal Report*

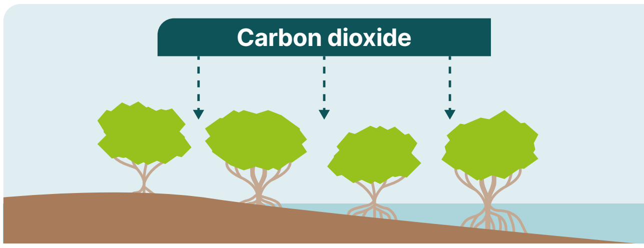
Restoring other ecosystems

Natural climate solutions

Nature restoration

What restoring peatlands and coastal lands entails

- Restoring peatlands and 'Blue Carbon' ecosystems is typically a **more labour-intensive process than forest restoration.**
  - **Peatland which have been drained must be re-wetted**, usually by removing the drain-works, to stop further oxidation. Depending on the geography, peat should be then replanted to restore the above-ground biomass layer (aiding sequestration).
  - **Peatland carbon typically remains 'stored' for very long periods of time** if conditions (high groundwater, primarily) are maintained.
  - **Mangrove restoration typically means planting seedlings in mudflats**
- Initial restoration costs are typically higher than for reforestation. Ongoing costs relate to monitoring and protection.



Readiness to scale

Summary	Pilot projects exist at a range of scales, but active commissioning of these projects is rare. <3% of NCS carbon credits issued today are for wetland restoration.[3]
Technological Readiness Level[2] (0-11)	**Medium-High (9-11);** well-designed projects can be executed at scale today.

When and how will carbon be removed

CO_2 Sequestration Profile	Carbon stocks **accumulate gradually, sequestration flows eventually plateauing at ecosystem maturity** after many **decades**.

Costs & co-benefits

Costs	**Today:**[1] **$10-100** / tCO_2	**2050:**[1] **$50-100** / tCO_2
Co-Benefits	**Biodiversity recovery**, local area **freshwater** supply, economic support to local communities, increased climate resilience, including storm protection.	
Other Challenges	Additional incentives are needed to ensure incentives to remove these ecosystems are overcome, in the long term.	

Exhibit 16

NOTES AND SOURCES: [1] Assume that restoration costs will move to the upper end of the range by 2050. Royal Society (2018) *Greenhouse Gas Removal Report*;
[2] TRL adjusted from (0-9) Royal Society (2018) Greenhouse Gas Removal Report scale to (0-11) scale for comparison with other sources.
[3] Climate Focus Voluntary Carbon Market Dashboard, Accessed 2021.
Graphic: Adapted from Royal Society (2018) *Greenhouse Gas Removal Report*

CO_2 sequestration for 'restoration' solutions (2020-2050)

Natural climate solutions

Nature restoration

CO_2 only

Potential ramp-up of CDR, $GtCO_2$/year, global

Cumulative CDR 2020-2030, $GtCO_2$, global

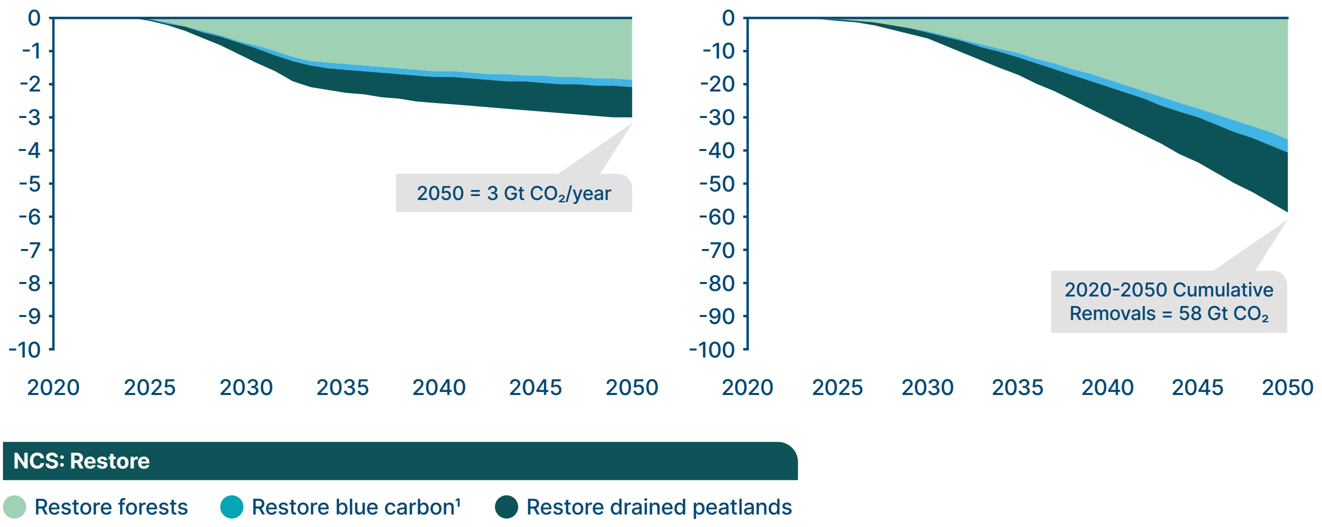


Exhibit 17

NOTES: The analysis was designed to avoid potential double-counting of emissions reductions, and is adjusted from annualised average potential estimates for 2020-2050 period. The models reflect land use changes, yet in some instances can also reflect demand-side effects from carbon prices, so may not be defined exclusively as 'supply-side'.
[1] 'Blue Carbon' is defined as ocean-based biomass sequestration including mangroves, seagrasses, and tidal marshes.

SOURCE: SYSTEMIQ analysis for the ETC, based on Roe et al. (2021), Griscom (2017), High Level Panel for Oceans (2020)

18% of global land surface would need to be engaged in CDR solutions to achieve our feasible sequestration potential by 2050

Total area targeted for cost-effective sequestration (2020-2050) Mha

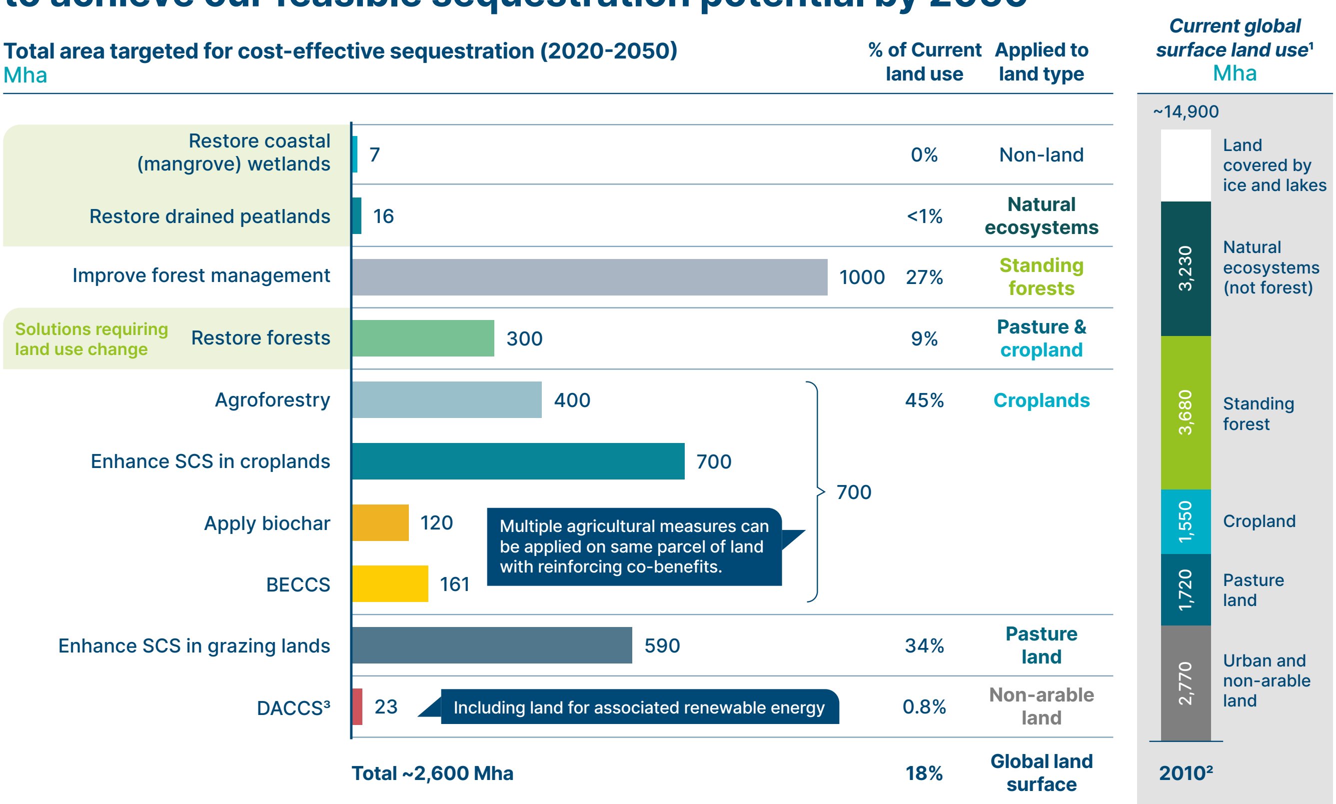


Exhibit 18

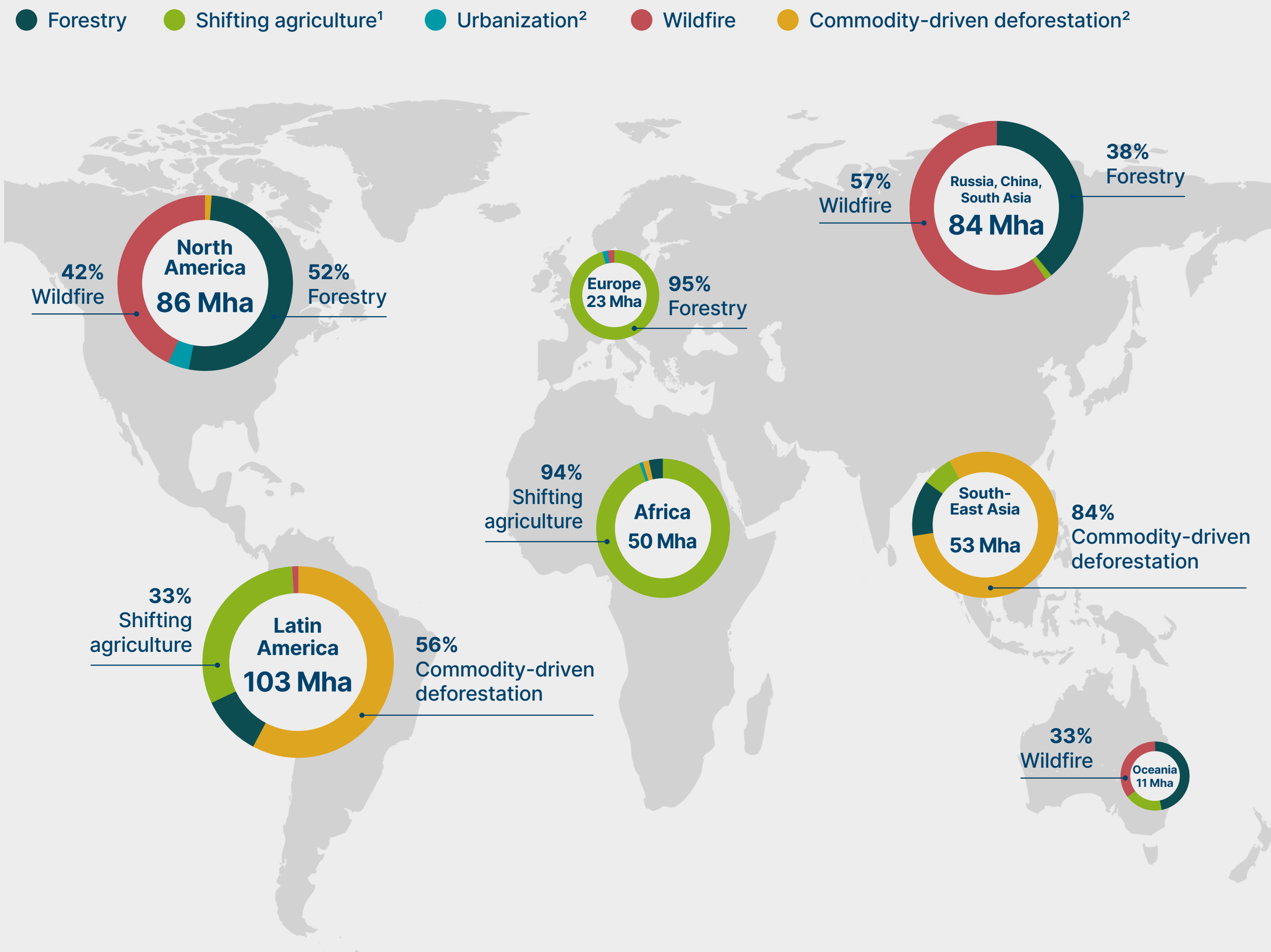
NOTE: [1] Global surface area excludes oceans. Land covered by lakes and ice (e.g., Antarctica) not available. Minor difference in totals and percentages due to rounding;
[2] Baseline data forecast from 2000.
[3] DACCS estimate assumed for 2050, this exhibit does not include land area for geological storage.

SOURCE: SYSTEMIQ analysis for the ETC: Roe et al (2021); IIASA GLOBIOM / FOLU *Growing Better* (2019); Ritchie et al., (2013); Land Use - OurWorldInData.org.

In addition to payments for carbon sequestration (carbon credits) there are many case studies of projects which leverage different business models or revenue streams to drive forest protection and recovery. The suitability of different project types depends on their location within the 'forest frontier' – the area on the edges of remaining primary forests most vulnerable to further degradation and encroachment. In the tropics, this is an estimated 600 MHa of land. The 'Forest Frontier' is vulnerable to different types of deforestation drivers (see Exhibit 19 below). Applying a combination of the business models described in Exhibit 20 below which address these different drivers could be a highly effective strategy to "seal off" the forest frontier and hence protect the primary forest lying behind it.[79] This could be particularly effective in areas where the primary driver of forest degradation has been shifting small-scale agriculture (the primary driver in Central Africa for example), which already provides poor returns.

Deforestation drivers in the tropics relate mostly to agriculture, whereas boreal and temperate regions experience more tree loss from forestry and wildfire

Drivers of tree cover loss by region (2001-2020)



[1] Shifting agriculture is defined as forest degradation and clearing for agriculture before often being temporarily abandoned again. Associated with many different types of smallholder farming practices.
[2] These practices result in permanent tree cover loss.

SOURCE: Adapted from WRI (2020) and Curtis et al., (2018)

Exhibit 19

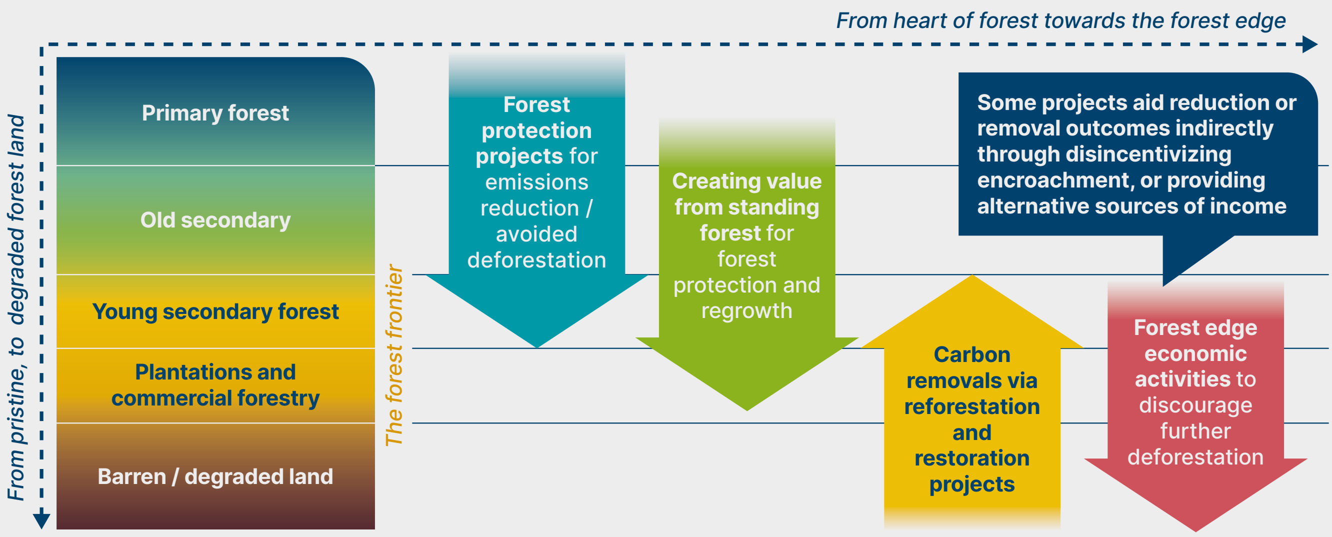
Box E: Forest Protection and Recovery Business Models

79 FOLU (2019), *Prosperous Forests.*

Projects which drive forest restoration and protection can be designed to draw upon various revenue streams

Drawing on over 40 case studies highlighting the work of Partnerships for forests (P4F) in the tropical region, which demonstrate real-life achievements in protecting the 600Mha region of the tropical forest frontier.

Business model categories for forest protection and restoration



Economic models for forest protection and recovery in and around the forest frontier:		Emissions reduction projects Is it protecting standing forests?	Carbon removal projects Is it driving forest regrowth?	Geographic zone
Grant-based revenue or government funding	**Blended Finance or development grants**			All
	Conservation / Protection Areas			All
Generates revenue from standing forests	**Ecotourism** Tourism revenue for pristine nature			All
	Reduced Impact Logging Selectively logging high-value timber to preserve majority of forest integrity			All
Generates revenue from forest regrowth	**Wild forest harvesting** Foraging for high value products e.g., açai berries, brazil nuts, truffles			All; Tropical / Sub-tropical a priority
	Payments for Ecosystem Services E.g. Carbon credits, biodiversity			Tropical / Sub-tropical
	Productive Forest Regrowth E.g. Planting of native species as commodities			All; Tropical / Sub-tropical a priority
Generates revenue from Agricultural production and forest protection	**Interim commodities to recover degraded land** E.g., high-value shade-crops			All
	Forest-edge agricultural commodities Highly productive and well-regulated commodities which discourage further encroachment at forest boundary			Tropical / Sub-tropical
	Sustainable Commercial Forestry / Tree Farming Sustainably managed timber / Timber plantations			All

How effectively project model delivers outcome — Highly effective ← N/A

SOURCE: Adapted from FOLU (2019), *Prosperous Forests.*

Box E

Exhibit 20

'Manage' solutions

Manage solutions include agroforestry, improved forest management techniques, and agricultural practices which enhance soil carbon sequestration on existing crop or pasture land. Exhibit 21 shows details of what improved forest management entails, while Exhibit 22 describes how increased soil carbon sequestration can be achieved.

These "Manage" options do not entail changing the primary economic use of land, and unlike "Restore" projects do not therefore typically entail an opportunity cost of economic output forgone, nor require the purchase of land to take it out of existing use. As a result, it is possible that some of these projects could be achieved at very low or even negative cost per tonne of CO_2 saved. Some of these projects could also deliver co-benefits of improved crop yields or water holding capacity.

All of these projects however require changes in established agricultural or forestry practices which may be difficult to achieve because of entrenched traditions (e.g., stopping tilling of soil before planting),[80] and must be maintained in perpetuity to prevent reversal of the carbon stock increase. As in the case of "Restore" projects, moreover, typical costs will tend to increase over time, as the most economic projects are likely to be implemented first and on-going management costs will continue.

Sequestration potential for managed solutions

Globally, there is approximately 3,300 million hectares of land cultivated for agriculture (around 22% of global land cover).[81] Forests cover an additional approximately 3,700 million hectares (25%). It is difficult to estimate the exact percentage of global forest land that is under management, but FAO estimates that approximately half of that area is under either heavy management or multiple uses including primary production for commodities such as timber.[82]

In principle improved practices could be applied to the vast majority of cultivated land. Published estimates indeed suggest that 90% of all crop and pasture land (i.e. around 3,000 Mha) and 60% of global forests (i.e. around 2,200 Mha of 3,700 Mha) could be covered by cost-effective forms of improved management.

But even if in principle improved techniques should be cost-effective, deploying them across the whole world would require changing the behaviour of hundreds of millions of small businesses and individuals; while 70% of world crop and pasture land is farmed by mid-to-large size operations (greater than >50 hectares per farm), the world has about 600 million farms in total.[83]

In our scenario we therefore assume that for "Manage" NCS solutions only 50% of the theoretically cost-effective potential could be achieved. Even this would mean about 11% of the entire global land area, and 33% of forest and agricultural land would be managed in a significantly different fashion to today.[84] This could result in carbon sequestration reaching 3.2 Gt CO_2 per annum by mid-century.[85]

Sequestration profile over time for "manage" solutions

Sequestration profiles over time for "Manage" projects vary by sub-category:

- Improved forest management or agroforestry will tend to produce profiles somewhat similar to forest restoration projects with a gradual build-up of sequestration flows and with stocks slowly growing to reach a maximum attainable level in several decades time.[86]

- Soil carbon sequestration projects by contrast (Exhibit 13) can produce a rapid build up to maximum annual sequestration flow – e.g., within just 2 to 3 years – with the annual flow then falling to zero within a decade, and the maximum stock effect by then achieved. Crucially too, this maximum stock effect will only be maintained if changed practices are continued in perpetuity, with any reversal of practice producing a rapid and much more certain reduction of the sequestered stock than is the case for forest-based projects.[87]

80 That being said, examples show that adoption of best practices can sometimes be rapid as farmers learn from peers and via robust networks.
81 FOLU (2019), *Growing Better,* IIASA Data from GLOBIOM 2019. Note: based on 2010 estimates, this includes both cropland and pasture or grazing lands. Total global land cover includes ice-covered or barren land.
82 FAO (2020), *Global Forest Report 2020*.
83 The Land Inequality Initiative (2020), *Uneven Ground.*
84 FOLU (2019), *Growing Better,* IIASA Data from GLOBIOM 2019.
85 Roe et al. (2021), Land-based *measures to mitigate climate change: potential and feasibility by country*. Note: based on analysis from average annualised estimates of sequestration potential 2020-2050 then adjusted for assumed scale up of solution over time.
86 A 'zoomed-in' view of year by year profile would should a fine 'saw-tooth' pattern representing regular forest harvesting practices.
87 Feasibility assessment includes political, socio-cultural, geophysical, environmental and economic factors, therefore incorporates consideration of risks of reversal.

Scenario for total sequestration potential for "Manage" solutions

Exhibit 23 sets out our scenario for the total sequestration achieved by "Manage" NCS projects in both annual flow and cumulative stock terms. After adjusting for cost-effective and feasibility criteria, we estimate annual rates of sequestration for improved forest management and agroforestry could reach ~0.7 Gt CO_2 by 2030 and ~1.7 Gt CO_2 by 2050, with further growth possible thereafter as trees continue to grow. Soil carbon sequestration could reach ~0.9 Gt CO_2 by 2030 and ~1.5 Gt CO_2 by 2050, but with limited – if any – opportunity for subsequent growth. Total cumulative sequestration could be ~6.5 Gt CO_2 between now and 2030, reaching 60 Gt CO_2 by 2050.[88]

This would require applying improved practices to ~1,000 Mha of managed forest and ~1,300 Mha of cropland and pasture, one-third of cultivated forest and agricultural land today (Exhibit 18).

Improving forest management

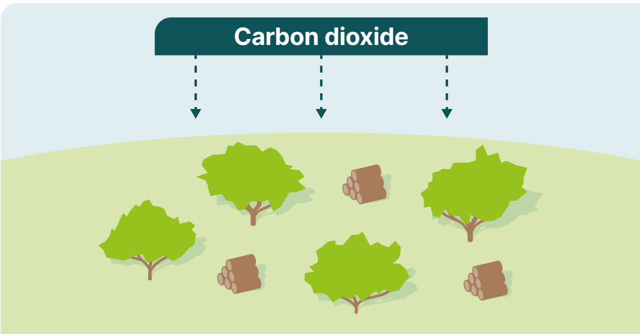
Natural climate solutions

Improved management

What improving forest management entails

Multiple variants for managed forestry projects, but one specific example for an existing forestry project would be:

- **Regular harvesting** of forest for use in timber, paper or pulp markets.
- **More optimised thinning** of forests, removing trees unfit for market, can enhance growth of other trees, improving sequestration. Thinned trees could be a source of sustainable bioenergy.
- **Improving the harvest rotations** to allow greater stand diversity.
- **Costs** are concentrated in increased maintenance and operational costs.



Readiness to scale

Summary	Active forest management occurs on around half of global forest land today, improving these techniques is an on-going trend.
Technological readiness level[2] (0-11)	**High (10-11);** could be executed at scale today for well-designed projects.

When and how will carbon be removed

CO_2 Sequestration Profile	Carbon stocks accumulate in a gradually increasing a 'sawtooth' pattern as biomass is routinely harvested.

Costs & co-benefits

Costs	**Today:**[1] **$5-30** / tCO_2	**2050:**[1] **$15-50** / tCO_2
Co-benefits	More sustainable forest management supports to a lesser extent **biodiversity recovery**, local area **freshwater** supply.	
Other challenges	Environmental impacts from timber industry, including fertilizer and pesticide use. **Albedo effect** means tropical reforestation is priority.	

Exhibit 21

NOTES AND SOURCES: [1] Royal Society (2018) *Greenhouse Gas Removal Report; Fuss et al.*, (2018). Have assumed costs move towards upper end of range by 2050;
[2] TRL adjusted from (0-9) *Royal Society* (2018) *Greenhouse Gas Removal Report* scale to (0-11) scale for comparison with other sources.
Graphic: Adapted from Royal Society (2018) *Greenhouse Gas Removal Report*

88 ETC Analysis based on Roe et al. (2021), Land-based measures to mitigate climate change.

Enhanced soil carbon sequestration

Natural climate solutions

Improved management

What enhancing soil carbon sequestration entails

Changing agricultural land management practices such as tillage or crop rotations **to increase the soil carbon content.**

This is achieved by **changing the balance of carbon inputs and carbon losses in soil** by:

On cropland:
- Use of 'cover crops'
- Improving crop diversity
- Reducing tillage intensity
- Residue retention
- Optimising fertilizer use

On grassland:
- More grass varieties with deeper roots
- Reducing animal stock density
- Fire management

Majority of costs are operational (e.g. annual cover cropping) and must be maintained even as carbon stocks plateau to avoid reversal.

Readiness to scale

Summary	Can be achieved via moderate widespread changes to common agricultural practices, but is difficult to measure.
Technological Readiness Level[2] (0-11)	**High (10-11);** Many practices already in use today and mostly do not require significant additional machinery or infrastructure.

When and how will carbon be removed

CO_2 sequestration Profile	Creates an initial spike of increased carbon captured, before plateauing and eventually declining after decades with little additional sequestration over time.

Costs & co-benefits

Costs	**Today:[1] ~$0-50** / tCO_2	**2050:[1] ~$0-100** / tCO_2
Co-benefits	**Increased crop yields** and **water holding** capacity. No impact on albedo. Some positive outcomes for biodiversity.	
Other challenges	Increasing soil organic matter could increase other GHGs, particularly organic nitrogen in the soil. Practices must be maintained to avoid losing carbon stored.	

Exhibit 22

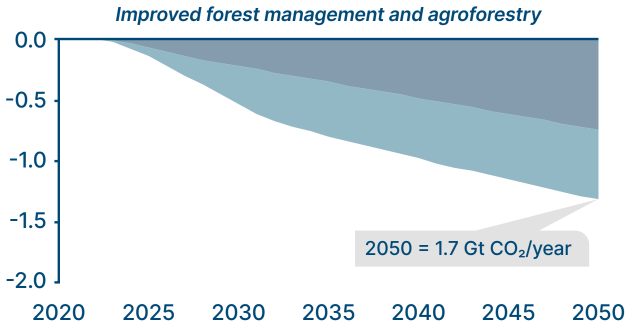
NOTES AND SOURCES: [1] Assume that costs will move to the upper end of the range by 2050. *Fuss et al (2018)*;
[2] TRL adjusted from (0-9) *Royal Society* (2018) *Greenhouse Gas Removal Report* scale to (0-11) scale for comparison with other sources. Image: *Royal Society* (2018) *Greenhouse Gas Removal Report*
Graphic: Adapted from Royal Society (2018) *Greenhouse Gas Removal Report*

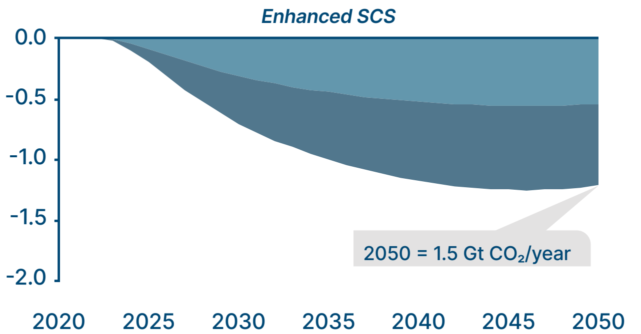
CO_2 sequestration for 'manage' solutions (2020-2050)

Natural climate solutions

Improved management

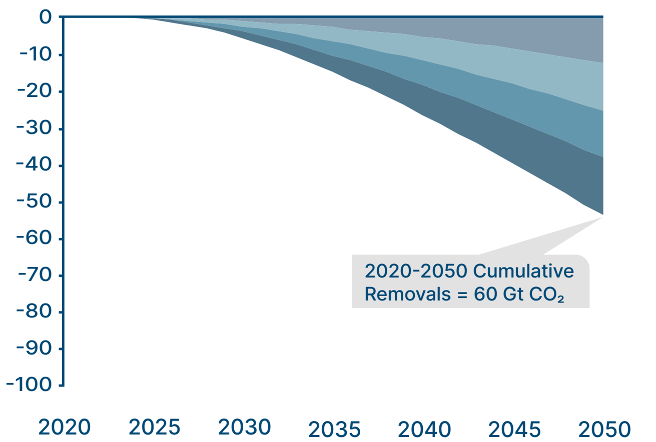
Potential ramp-up of CDR, $GtCO_2$/year, global





Cumulative CDR 2020-2050, $GtCO_2$, global

CO_2 only



NCS: Manage
- Improve forest management
- Agroforestry
- Enhance soil carbon sequestration in degraded croplands
- Enhance soil carbon sequestration in degraded grazing lands

Exhibit 23

NOTES: Improved management solutions have been adjusted for feasibility on a country-by-country basis. Overall average reduction is ~50%. The analysis was designed to avoid potential double-counting of emissions reductions, and is adjusted from annualised average potential estimates for 2020-2050 period. The models reflect land management improvements, yet in some instances can also reflect demand-side effects from carbon prices, so may not be defined exclusively as 'supply-side'.

SOURCE: SYSTEMIQ analysis for the ETC, based on Roe et al. (2021), Griscom (2017)

Box F: Recovering Degraded Land

Recovering degraded productive land is a win-win for climate and people

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) estimates that more than 75% of earth's land is degraded, meaning that human activity has caused a decline in natural productivity of that land.[89] It is identified by the reduction of biological productivity, ecological integrity, or value to humans. This includes marginal waste land that has low agricultural productivity, or high-intensity cultivated land which has degraded soil quality from decades of high-fertilizer use and tilling practices. For example, it is estimated that global cropland soils have lost 20-60% of their organic carbon content prior to cultivation and continue to be a source of emissions today.[90] Some degraded land has also been abandoned, but a significant proportion is still in some category of economic use (and often still being degraded).

Climate change and degraded land go hand in hand. Climate change exacerbates land degradation, and land degradation drives climate change via emissions (particularly deforestation) and reduced rates of carbon uptake.

The Natural Climate Solutions for CDR described in this report all aid the recovery of degraded land to varying degrees. For example, reforestation solutions over 300 MHa are targeted at degraded marginal land, primarily in the tropics. 'Manage' solutions have sequestration potential because of the widespread decline of soil carbon – returning this back up to baseline increases the inherent economic potential and longevity of this land.

Natural climate solutions which improve land management therefore present an opportunity to not only increase carbon sequestration but also recover its declining economic value. Improving soil health via better practices can both reduce costs (through saved time and reducing the use of fertilizer) and increase long-term yield. This is a critical development opportunity, providing resilience for communities and incentivizing those who work the land to continue to invest in its continued recovery. This, in turn, helps ensure on-going permanence of sequestered soil carbon. However financial structures must support these developments. Often the reasons these practices are not being applied already relate to long-term economic incentives.

3.1.2 Engineered solutions

Pure engineering CDR solutions do not rely either on photosynthesis for CO_2 capture nor on the biosphere for carbon storage. In future these could include enhanced weathering and ocean mineralisation options described in Chapter 3.4. But the most promising option today is Direct Air Carbon Capture and Storage (DACCS) in which chemical solvents are used to capture CO_2 directly from the air, requiring significant energy inputs, with the CO_2 then transported and stored long-term in geological formations (Exhibit 24).[91]

With small-scale projects already operating in several countries,[92] DACCS is clearly technically feasible but currently far more expensive than Natural climate solutions with costs in excess of $300 per tonne.[93] Estimates suggest that DACCS cost is likely to decline over time as the technology improves and renewable energy costs continue to fall, with DACCS possibly reaching $100 per tonne by 2050 or earlier.[94]

DACCS projects will not deliver the essential co-benefits that some NCS projects could achieve in terms of biodiversity or local environmental impacts. But they are also less vulnerable to reversal risks than either Restore or Manage NCS projects. And unlike with "Manage" NCS projects, which often require significant and widespread behavioural change, investment to build DACCS projects will be driven by large profit maximising companies who will make investments if and when DACCS projects become economic.[95]

Sequestration potential for engineered solutions: DACCS

DACCS does not raise the same issues of land availability or competing land uses that apply to NCS.[96] Direct air capture plants capable of capturing 4.5 Gt CO_2[97] would use only ~6,750 Km^2 of land (0.7 Mha, less than 1% of the area of degraded land targeted for reforestation efforts), which can be located anywhere reasonably close to geological storage, and does not need to be fertile.

89 IPBES (2018), *Assessment Report on Land Degradation and Restoration*.
90 IPCC (2019), *Climate Change and Land*. An IPCC Special Report.
91 Note: Long-term storage could also take-place in long-lived building materials. This possibility is discussed in Chapter 4.1.
92 In 2021 the world's largest DAC plant began operation in Iceland, with a capture capacity of 4 Mt CO_2/yr. (2022), Climeworks.
93 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal.*
94 Fuss et al., (2018), *Negative emissions—Part 2: Costs, potentials and side effects*
95 Although technically not a form of CDR, demand for production of synthetic fuels from DAC will also support technology development.
96 Specifically, NCS "Restore" Solutions. NCS "Manage" Solutions provide carbon sequestration in addition in the primary economic use of that land.
97 Socolow et al., *Direct Air Capture with Chemicals* (2011). Assumes that to remove 1 Mt CO_2/yr from the atmosphere using absorbers that remove 20 t CO_2/yr from each square meter of frontal area, a facility with a total area of 50,000 m^2 facing the incoming air would be required.

DACCS will, however, require very large inputs of zero-carbon electricity (for use as electricity and process heat); 4.5 Gt CO_2 of DACCS in 2050 would for instance require 13,500 TW hours per annum, which is equivalent to one half of today's total global electricity generation.[98] While the ETC *Making Mission Possible* series demonstrates that this level of clean power is possible,[99] large challenges must be overcome if capacity is to grow fast enough to support the decarbonisation pathways described in Chapter 2. If this electricity came from solar PV farms, it would require 15 Mha of land (0.1% of global land) which, while significant, is still trivial compared with the land areas involved in NCS solutions (~320 Mha of restored land and ~2,300 Mha of cultivated land under improved management).

Evidence from naturally occurring CO_2 stores suggests leakage rates are very low and very slow. The IPCC considers it likely that 99% or more of injected CO_2 will be retained for 1000 years.[100] Furthermore, technical storage volume capacity will also not be a significant constraint on DACCS volumes in the long-term. Theoretically available storage has been quantified at >10,000 Gt CO_2 globally, which would be enough to store today's total annual CO_2 emissions (ca. 40 Gt) each year for >250 years.[101] However just 0.2 Gt CO_2 storage capacity has been classified as 'injection-ready' to date, falling far below future volumes of potential DACCS (~4.5 Gt CO_2 by 2050), BECCS or point-source CCS projects.[102] The crucial issue is therefore the pace at which the required capacity could be developed, including the necessary transport and storage infrastructure. Thus the potential constraint arising from storage capacity is not geological but economic: rapid and widespread subsurface appraisal is necessary to de-risk investment and develop injection-ready storage capacity.

Sequestration profile for engineered solutions: DACCS

For any given DACCS project, there are none of the sequestration profile complexities which need to be considered in the case of NCS. Once a DAC plant, a transport system, and appropriate storage facility has been constructed, annual flows will be constant at the capacity of the DAC plant (assuming constant energy prices), and cumulative sequestration will equal the annual flows times the number of years of plant operation. Metering requirements also mean that measuring that flow is simpler than for NCS projects (discussed further in Chapter 4.1).

The relevant issues relating to DACCS volumes over time are instead how fast DACCS costs will decline to reach commercial scalability, and the pace at which the infrastructure of DACCS plants, transport and storage facilities and the required zero carbon electricity capacity can be put in place.[103]

98 McKinsey, *The Case for Negative Emissions* (2019), SYSTEMIQ analysis for the ETC. Assumes 2 MWhptCO_2 by 2050. This implies ~13,500 TWh additional power.

99 ETC (2021), *Making Clean Electrification Possible*.

100 Alcalde et al., Nature Communications (2018), *Estimating geological CO_2 storage security to deliver on climate mitigation*.

101 Pale Blue Dot (2021), *CO_2 Storage Resource Catalogue – Cycle 2*; IEA (2020), *CCUS in the energy transition*.

102 ETC (Upcoming, 2022), *Carbon Capture Utilisation and Storage*.

103 Assumption is that most DACCS will be primarily powered by dedicated renewables. In the case of significant reliance on grid power, issues related to the level and the stability of clean power prices could arise.

Scenario for total sequestration for engineered solutions: DACCS

Exhibit 27 (which also shows the results for the hybrid solutions) shows our scenario for the total sequestration volume achieved, with annual flows from DACCS still minimal in 2030 but potentially reaching 4.5 Gt CO_2 by 2050, and with cumulative sequestration from DACCS potentially reaching around 30 Gt CO_2 by then.

Direct air capture with carbon capture & storage (DACCS)

Engineered and hybrid solutions

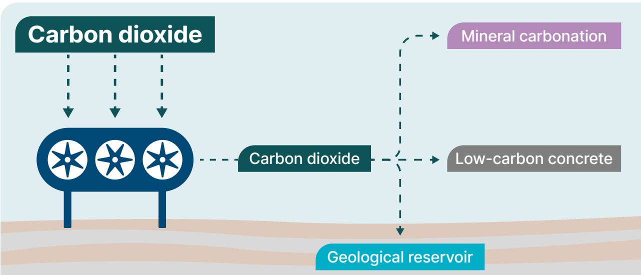
Engineered

What DACCS entails

Provider builds DAC plant plus infrastructure to transport CO_2 to storage which entail either:

- **Geological reservoir** (e.g., a depleted oil field) with CO_2 stored deep underground (usually 1 to 5 km depth).
- **Mineral carbonation** (accelerating silicate rock conversion).
- Or (probably in much smaller volumes) within long-life materials such as cement (with end-of-life recycling).

Costs include initial plant construction plus significant on-going costs for associated energy supply and chemicals.



Readiness to scale

Summary	Occurs at very small-scale today.
Technological readiness level[3] (0-11)	**Direct Air Capture: Medium (5-9) –** small-scale pilots in operation in EU and North America. **Geological storage: Medium (5-9) –** Largely at demonstration stage, examples in North America.

When and how will carbon be removed

CO_2 sequestration profile	Immediate sequestration.

Costs & co-benefits

Costs	**High cost today:[1] \$300-600/tCO_2**	**Expected to decline by 2050:[2] \$100-\$300 / tCO_2**
Co-bBenefits	Limited	
Other challenges	• Large demand for zero-carbon power • Long lead times for geological storage development at suitable sites.	

Exhibit 24

NOTES: [1] American Physical Society. (2011) *Direct Air Capture of CO_2 with Chemicals*;
[2] Fuss et al (2018);
[3] TRL adjusted from (0-9) *Royal Society* (2018) *Greenhouse Gas Removal Report* scale to (0-11) scale for comparison with other sources.

SOURCE: *Royal Society of Engineers*, "Carbon Dioxide Capture and Storage: A route to Net zero for power and industry".
Graphic: Adapted from Royal Society (2018) *Greenhouse Gas Removal Report*

3.1.3 Hybrid / Biomass with Carbon Removal (BiCRS) solutions[104, 105]

Biomass with Carbon Removal and Storage (BiCRS) is an umbrella term for hybrid solutions which combine photosynthesis with technology to achieve CDR. Common examples of these solutions include:

- Bioenergy with Carbon Capture and Storage (BECCS), in which biomass is used to produce power (or heat for industrial processes) with the resulting CO_2 then captured and stored in geological formations (Exhibit 25).[106]
- Biochar projects, in which biomass is converted via pyrolysis ('burned' in the absence of oxygen) into a more decomposition-resistant form of carbon which can be buried in soil or placed in long-term storage (Exhibit 26).

Biomass is already used widely for power and heat generation,[107] and carbon capture and storage is already deployed on a moderate scale. Biochar production and storage techniques are already in operation, but only on a small scale.[108]

104 Innovation for Cool Earth Forum (2021), *Biomass Carbon Removal and Storage Roadmap*. Another term for the hybrid use of biomass combined with CCS is 'BiCRS' (Biomass with Carbon Removal Storage), that does not prioritise energy generation, but describes a range of processes that use plants and algae to remove carbon dioxide (CO_2) from the atmosphere and store that CO_2 underground or in long-lived products. In theory, by excluding the energy generation step, a more efficient and effective processing of biomass and underground storage is possible, making it cost-effective and allowing for other applications of biomass.
105 WRI (2020), *Carbonshot: Federal Policy Options for Carbon Removal in the United States*.
106 Although its main purpose is energy production, BECCS qualifies as carbon removal because of the near-term absorption of CO_2 into biomass through forestry or energy crops which is then placed into permanent storage.
107 The ETC discusses the sustainable limits of biomass use for energy (e.g., providing reliable baseload) in a prior report. ETC (2021), *Bioresources within a Net-Zero Emissions Economy*.
108 Puro.Earth (2022), *Biochar Methodology*.

Estimates of the cost of BECCS relative to other CDR options need to take account of the economic value of the power or heat generated/used. However, generally speaking, the economic value of biomass use for energy is likely to be low in a number of sectors.[109] But even allowing for this, BECCS is currently much more expensive per tonne of CO_2 saved than many NCS solutions. These costs will fall over time as carbon capture and storage costs decline, but are still expected to exceed $100 per tonne in 2050.[110] Biochar project costs are estimated at about $30-$120 per tonne of CO_2 sequestered.[111]

Sequestration potential for hybrid / BiCRS solutions

Biomass used for variants of BiCRS could be derived either from forest or agricultural residues or from dedicated crops (in particular short-rotation crops). To assess total potential scale, we therefore need to assess agricultural and forest residue supply, and the amount of land which could be dedicated to crops. The latter will entail trade-offs between the use of land for bioenergy, food production, natural fibre commodities, biodiversity recovery, and to achieve carbon sequestration. Furthermore the use of residues for Hybrid/BiCRS could entail trade-offs with NCS "manage" carbon sequestration approaches.

The ETC's 2021 report on *Making a Sustainable Bioeconomy Possible*[112] considered these trade-offs and developed estimates of the maximum amount of biomass which could be utilised on a sustainable basis; this in turn carries implications for the total CO_2 which might be captured and stored when this biomass is burned.[113] Our overall conclusion was that in a prudent case 40 to 60 EJ per annum of biomass could be sustainably sourced and utilised for purposes beyond food and commodity production. For example, devoting all residual waste materials from agriculture and forestry production to BECCS might enable sequestration flows of 2 to 5 Gt CO_2 per annum. But given competing priority demands for limited sustainable biomass (e.g., bio-plastics or aviation biofuels, discussed in the ETC *Bioresources* report) the potential for sustainable biomass for CDR is considerably less.

For BiCRS/Hybrid CDR we therefore estimate that:

- For BECCS: Our illustrative supply-side CDR estimate assumes ~1 Gt CO_2/yr is sequestered by BECCS in 2050, delivered through a roughly even split of dedicated energy crops and forestry residues.[114]
    - Forest residues might provide ~5 EJ for BECCS energy production resulting in ~0.5 Gt CO_2 of carbon sequestration by 2050.[115]
    - In 2050 dedicated crops could account for 2-5 EJ of BECCS resulting in ~0.3 Gt CO_2 sequestration, utilising the small portion of land already dedicated to energy crop production today.[116]
- For Biochar: Our illustrative supply-side estimate assumes ~0.3 Gt CO_2 is sequestered utilising ~5 EJ of crop residues by 2050.[117]

In theory, the biomass feedstocks utilized by biochar or BECCS in our scenario above could be used for carbon removal without energy production via other BiCRS, such as Bio-oil.[118]

Finally, the scenarios above assume no conversion of current land uses for CDR. However, theoretically speaking, more sustainably sourced biomass could be made available if ambitious system change were achieved in food and agricultural sectors, freeing up land for dedicated biomass production. This would require significant food systems transition shifts in consumer behaviours and in technological innovation (examples include reducing food loss and waste by around 25 to 30%, continued improvements in global crop yields, and global shift towards a plant-rich diet, including reducing meat per capita consumption in Europe by two-thirds). With these types of changes it could be possible to free up approximately 1000 Mha of existing crop and pastureland for other uses (in addition to the marginal degraded land area targeted for

109 ETC (2021), *Bioresources within a Net-Zero Emissions Economy.*
110 Fuss et al., (2018), *Negative emissions—Part 2: Costs, potentials and side effects.*
111 Fuss et al., (2018), *Negative emissions—Part 2: Costs, potentials and side effects.*
112 ETC (2021), *Bioresources within a Net-Zero Emissions Economy*.
113 Or processed in other ways.
114 This is conservative in comparison with other published estimates, constrained by ETC perspectives on the limits of sustainable biomass supply. BECCS could be in theory be utilised for processes which produce power or biofuel.
115 ETC Analysis based on: ETC *Bioresources within a Net Zero Emissions Economy,* Roe et al., (2019), IIASA (2020) GLOBIOM.
116 ETC Analysis based on: ETC *Bioresources within a Net Zero Emissions Economy,* Roe et al., (2019), IIASA (2020) GLOBIOM.
117 Note: To avoid double counting, it was assumed that forest residues would be dedicated to BECCS and crop residues to Biochar.
118 Innovation for Cool Earth Forum (2021), *Biomass Carbon Removal and Storage Roadmap*. Another term for the hybrid use of biomass combined with CCS is 'BiCRS' (Biomass with Carbon Removal Storage), that does not prioritise energy generation, but describes a range of processes that use plants and algae to remove carbon dioxide (CO_2) from the atmosphere and store that CO_2 underground or in long-lived products. In theory, by excluding the energy generation step, a more efficient and effective processing of biomass and underground storage is possible, making it cost-effective and allowing for other applications of biomass.

NCS restoration solutions described above). Devoting it to energy crops would produce the most biomass for fuel and feedstocks, devoting it to rewilding would produce the most benefits to nature, while devoting it to managed forest will enhance the production of biomaterials. If 25% of this land was dedicated to energy crops (250 Mha), this could in theory deliver up to 5 Gt CO_2 of additional sequestration per annum (45 EJ).[119]

Sequestration profile over time for hybrid / BiCRS solutions

Neither the use of agricultural or forestry residues for bioenergy or biochar nor the use of short rotation energy crops raise the complex time profile issues considered in relation to NCS. As the biomass feedstock is available within short time frames (less than a year), annual sequestration flow rates are proportional to that feedstock supply.

Scenarios for total sequestration for hybrid / BiCRS solutions

Our scenario for annual flow and cumulative sequestration for the Hybrid/BiCRS options is shown on Exhibit 27 alongside the engineered (DACCS) scenario. Annual flows will initially grow slowly to ~0.3 Gt CO_2 by 2030 but could reach ~1.2 Gt CO_2 by 2050: total cumulative sequestration could therefore reach ~19 Gt CO_2 by 2050. This assumes that biochar potential is scaled up linearly between today and 2040 before levelling out, and that BECCS scales via an S-curve which begins its plateau around 2040.

This scenario implies that in total ~5-10 EJ of agricultural and forest residues would be utilised with less than 50 Mha dedicated to energy crops used specifically for BECCS or Biochar production.

Bioenergy with carbon capture storage (BECCS)

Engineered and hybrid solutions

BiCRS / hybrid

What BECCS entails

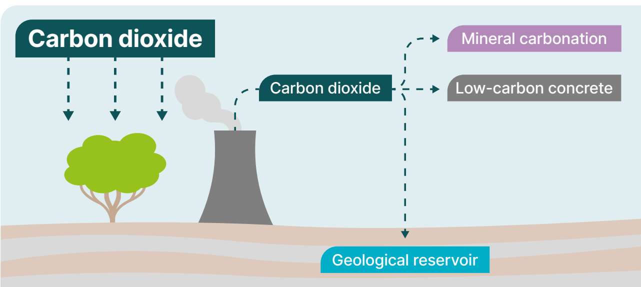
Biomass production and harvesting: forest residues or short rotation crops

- On-going costs from rotational planting and harvesting.
- Like NCS relies on natural processes (photosynthesis) but without biodiversity and ecosystem restoration benefits.

Carbon sequestration in growth = CO_2 production in combustion. Processing and transport CO_2 emissions must also be measured.

Carbon capture and storage;

- Capture stage similar to DACCS but with higher CO_2 concentration (decreasing costs).
- Transport and storage identical to DACCS.



Readiness to scale

Summary	Bioenergy projects exist at scale around the world today, but CCS has only been applied to small scale projects. Overall scale is limited by sustainable biomass supply.
Technological readiness Level[3] (0-11)	**Concentrated stream capture: Med-High (9-11) –** discrete exemplars in operation **Geological storage: Medium (5-9) –** Largely at demonstration stage, examples in North America.

When and how will carbon be removed

CO_2 sequestration Profile	Purchasers could buy on a year by year spot basis or long term contracts. Availability limited by supply of sustainable biomass

Costs & co-benefits

Costs	**Medium cost today:[1] \$100-\$300 / tCO_2**	**Some further decline by 2050:[2] \$100-\$200 / tCO_2**
Co-benefits	Energy generation (electricity or hydrogen, + heat).	
Other challenges	Bioenergy from energy crops could compete with food production for land & water or rewilding for nature & biodiversity. Biomass from waste limited in supply.	

Exhibit 25

NOTES AND SOURCES: [1] *Royal Society* (2018) *Greenhouse Gas Removal Report*;
[2] Fuss et al (2018);
[3] TRL adjusted from (0-9) *Royal Society* (2018) *Greenhouse Gas Removal Report* scale to (0-11) scale for comparison with other sources.
Graphic: Adapted from Royal Society (2018) *Greenhouse Gas Removal Report*

119 Note: in this hypothetical example area targeted for NCS Restoration would still be counted separately. See extended discussion of the trade-offs in ETC (2021), *Bioresources within a Net-Zero Emissions Economy*. In a hypothetical analysis comparing possible uses for freed-up former agricultural land BECCS from energy crops resulted in the most carbon storage and energy generation, but a significant amount of carbon was found to be held in biomass of afforested land and managed forests. The location and condition of the land and the desired outcomes – be they carbon sequestration, energy, materials, or benefits for biodiversity and nature – determine the most appropriate use of land. Managed commercial forests have lesser outcomes for biodiversity than re-wilding projects.

Biomass with carbon removal and storage – biochar and others

Engineered and hybrid solutions

BiCRS / hybrid

What Biochar stored in soils entails

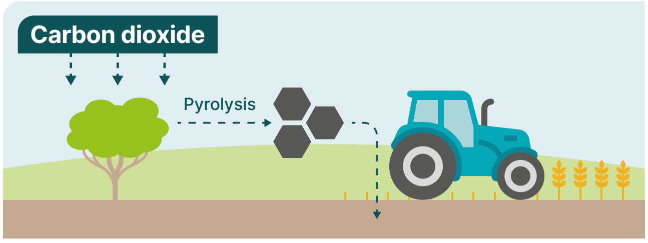
Biomass production and harvesting : forest residues or short rotation crops

- On-going costs from rotational planting and harvesting.
- Like NCS relies on natural processes (photosynthesis) but without biodiversity and ecosystem restoration benefits.

Pyrolysis of biomass: thermal decomposition of biomass in the absence of oxygen into a form more resistant to decomposition.

Storage of Biochar

- **Spread across soils;** stores carbon in soils in more stabilized form than ordinary soils and can enhance soil health. Minimal infrastructure.



Biochar stored underground: Hypothesis that biochar could be stored for longer durations if placed underground in 'artificial biochar mines' away from decomposition drivers such as moisture.

Readiness to scale

Summary	Biochar is an established process, but is not widely applied today due to costs and low availability of pyrolysis facilities.
Technological readiness Level[3] (0-11)	**Medium (4-8)**; established method but not demonstrated at scale.

When and how will carbon be removed

CO_2 sequestration Profile	Purchasers could buy on a year by year spot basis or long term contracts. **Availability limited** by supply of sustainable biomass.

Costs & co-benefits

Costs	**Today:**[1] **\$30-\$120 / tCO_2**	**2050:**[1] **\$30-\$120 / tCO_2**
Co-benefits	Improved soil health, including better water and nutrient retention, resulting in better crop yields.[2]	
Other challenges	Same as for BECCS. Albedo reductions due to soil darkening could dilute sequestration effect.	

Exhibit 26

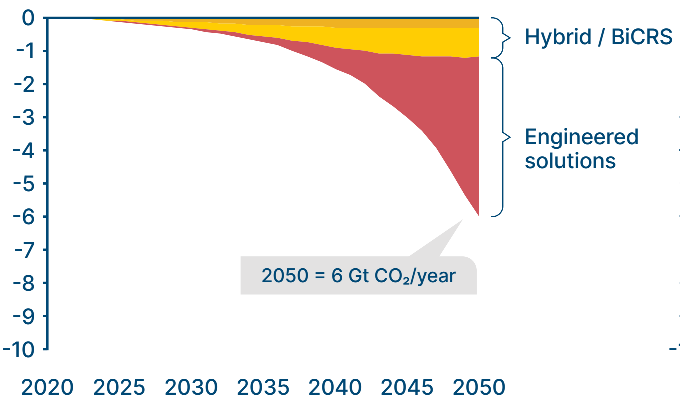
NOTES AND SOURCES: [1] Assumed here that costs are consistent over the next few decades. Fuss et al (2018);
[2] Thengane et al., (2020);
[3] TRL adjusted from (0-9) *Royal Society* (2018) *Greenhouse Gas Removal Report* scale to (0-11) scale for comparison with other sources.
Graphic: Adapted from Royal Society (2018) *Greenhouse Gas Removal Report*

CO_2 sequestration for hybrid / BiCRS and engineered solutions (2020-2050)

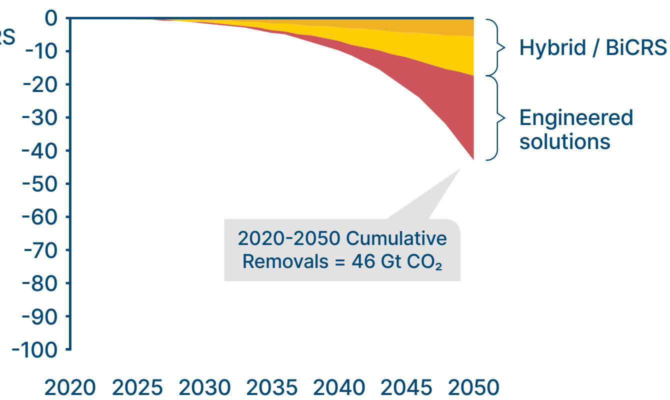
Engineered and hybrid solutions

CO_2 only

Potential ramp-up of CDR, $GtCO_2$/year, global



Cumulative CDR 2020-2050, $GtCO_2$, global



Hybrid and engineered approaches

Apply biochar BECCS DACCS

Exhibit 27

NOTES: The analysis was designed to avoid potential double-counting of emissions reductions, and is adjusted from annualised average potential estimates for 2020-2050 period.

SOURCE: SYSTEMIQ analysis for the ETC, based on Roe et al. (2021), Hannah et al. (2021), ETC (2021) *Bioresources for a Sustainable Net-Zero Economy*

3.2 What CDR is possible? Total potential sequestration and resource implications of CDR solutions

Combining our scenarios for all the CDR options, Exhibit 28 shows the possible sequestration flows and cumulative sequestration stock achieved by 2050,[120] with:

- Total annual removal flows reaching ~3.6 Gt CO_2 by 2030 and ~12 Gt CO_2 by 2050.
- Cumulative sequestration of 165 Gt CO_2 achieved by 2050.

This scenario suggests a different balance between the different categories over time, with:

- The NCS solutions developing more rapidly during the 2020s, reflecting their current, significantly lower costs.
- Engineering and hybrid solutions playing a smaller role in the 2020s but growing in importance during the 2030s and 40s, while both the "Restore" NCS solutions and the soil sequestration subcategory within "Manage" reach their stable maximum level.[121]
- Beyond 2050, the annual sequestration flow from NCS would stabilise and at some stage decline as opportunities for improved management are exhausted, and as eventually mature forests sequestration flow rates stabilise (with stocks continuing to grow slowly).
- By contrast, the maximum total potential for DACCS is theoretically very high, but total deployment will be constrained by zero-carbon power available, and the reduced demand for carbon removal in a world where gross emissions have been reduced close to zero, with technological progress making that possible at low cost.[122]

Exhibit 18 sums up the land resource implications of the different options, with total CDR solutions applied to approximately 18% of global land (2,700 Mha of 14,900 Mha):

- **NCS restore solutions** indicate that ~320 Mha of land must be returned to nature, in most cases by taking that land out of its current economic use.[123] This contrasted with current global totals of ~3,700 Mha of forest, 420 Mha of peatlands and 15 Mha of mangrove eco-systems across the world today.[124]
- **NCS manage options** imply that changed management practices must be applied to:
  - 1,000 Mha of forest which is currently managed for economic gain.[125]
  - ~ 700 Mha of land currently cultivated for crop (food and fibre) production, including changing approaches to agroforestry, improved soil carbon management on crop or pastureland or the use of agricultural and forest residues for BECCS or Biochar.[126] This is about 45% of the area in use for that purpose today.
    - Under this assumption no new land would be dedicated to crops specifically for **BECCS or other BiCRS** beyond what is currently dedicated to energy crop production (~25 Mha).
  - 600 Mha of current pasture land, to be managed for enhanced soil carbon sequestration on grazing lands (34% of pasture land today).
- **DACCS** will have a trivial impact on global land use (around 0.1%), but would require around 13,500 TWh per annum of zero carbon electricity supply by 2050.[127]

120 A supply-side estimate constrained by cost-effective, sustainability and feasibility criteria. Cost-effective is defined as mitigation solutions up to a carbon price of $100/t CO_2e as it is in the middle of the range for carbon prices in 2030 for a 1.5°C pathway, and at the low end of the range in 2050 (Rogelj et al., (2018); Roe et al. (2021)).
121 Assuming no further land returned to nature via greater behavioural change shift, etc.
122 ETC (2020), *Making Mission Possible: Delivering a Net-Zero Economy*.
123 Although other economic uses are possible, including eco-tourism and high-value forest products (see Box E).
124 Food and Agricultural Organization of the United States, (2007), The World's Mangroves; Xu et al., (2018), PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis.
125 Includes adjustment for feasibility rating, reducing on average by 50%.
126 As per Exhibit 16, these CDR applications could be considered over-lapping on croplands.
127 McKinsey, *The Case for Negative Emissions* (2019), SYSTEMIQ analysis for the ETC. Assumes 2 MWhptCO_2 by 2050.

3.3 Sequestration potential relative to need

Chapter 2 suggested that to ensure a 50:50 chance of limiting global warming to 1.5°C the world must aim to achieve:

- Between 70-225 Gt CO_2 of cumulative negative emissions between now and 2050, depending on how rapidly gross CO_2 emissions can be reduced (Scenario A or B).

- Ongoing negative emissions of ~3-5 Gt CO_2 per annum beyond 2050, to account for both small residual emissions from the harder-to-abate sectors and mitigating effects of other greenhouse gases such as N_2O.

In comparison shown in Exhibit 29, our analysis of what CDR is possible suggests that:

- Our feasibility assessment estimates that cumulative removals of 165 Gt CO_2 over the next 30 years could meet the carbon budget 'overshoot gap' if gross emissions are cut in line with Scenario B, but would be inadequate to close the gap left by Scenario A – missing the mark by ~60 Gt CO_2. This implies that the world must cut emissions significantly faster than Scenario A suggests, aiming to get as close as possible to Scenario B.

- Feasible ongoing negative CO_2 emissions beyond 2050, therefore, are likely to be more than essential to meet the ongoing need created by residual CO_2, N_2O and CH_4 for emissions.

- But potential for further removals beyond 2050 does not justify setting less ambitious objectives for either gross emissions reductions or removals between now and 2050, since that would entail accepting an overshoot of the temperature objective followed by subsequent reversal. Such a strategy would be excessively risky given the danger that temperature increases may themselves trigger self reinforcing effects.[128]

Beyond the range of CDR options described above, there are further, more speculative CDR solutions on the horizon. It would be a sensible insurance policy to explore these to their fullest potential to develop the full range of these solutions, once good understanding of their environmental impacts has been achieved. Further solutions on the horizon are described in Chapter 3.4.

128 See Chapter 1.3

An ambitious trajectory for CDR scale up to 2050 can deliver cumulative sequestration of ~165 $GtCO_2$ by 2050

Potential ramp-up of CDR | **Cumulative CDR 2020-2030** | **CO_2 only**

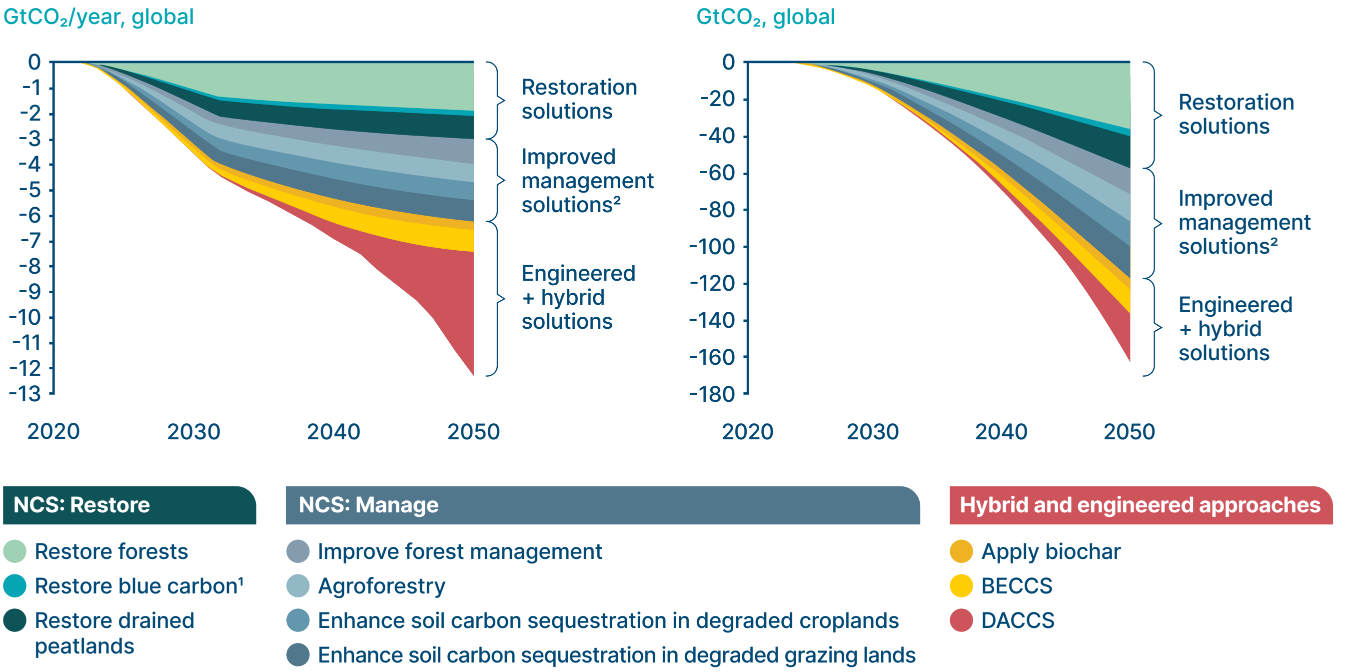


Exhibit 28

NOTES: The analysis was designed to avoid potential double-counting of emissions reductions, and is adjusted from annualised average potential estimates for 2020-2050 period. The models reflect land use & management changes, yet in some instances can also reflect demand-side effects from carbon prices, so may not be defined exclusively as 'supply-side'.

[1] 'Blue Carbon' is defined as ocean-based biomass sequestration including mangroves, seagrasses, and tidal marshes.

[2] Improved management solutions have been adjusted for feasibility on a country-by-country basis. Overall average reduction is ~50%.

SOURCE: SYSTEMIQ analysis for the ETC, based on Roe et al. (2021), Hannah et al. (2021), Griscom (2017), ETC (2021) *Bioresources for a Sustainable Net-Zero Economy*, High Level Panel for Oceans (2020).

Based on the CDR we think is plausible, rapid decarbonisation remains critical to keep 1.5C alive

Global cumulative emissions in Scenario A (Gt CO_2, 2020-2050) | **Global cumulative emissions in Scenario B (Gt CO_2, 2020-2050)**

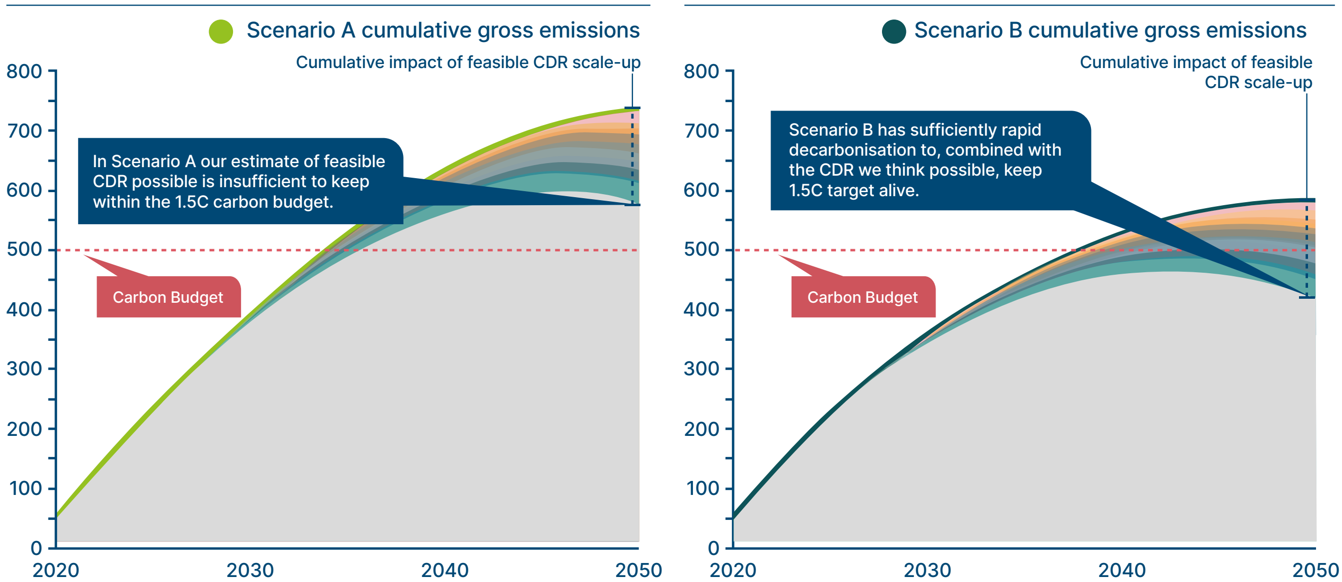


Exhibit 29

SOURCE: SYSTEMIQ Analysis for the ETC

3.4 Future possible CDR solutions

Many more CDR solutions exist at an earlier stage of research and development. These include CO_2 capture via mineral absorption or biogeochemical processes.[129] Mineral absorption solutions explore the chemical breakdown of rocks and minerals, while other solutions aim to enhance biological CO_2 uptake through enhancing photosynthesis. While these technologies are nascent, in some cases early estimates suggest a significant potential for CDR. They have been omitted from our estimate of feasible potential given the lack of available data for analysis and to demonstrate that there are no adverse effects on the environment.

Mineral absorption solutions include:

- **Enhanced weathering:**[130] Adding crushed carbonate and silicate rocks to accelerate geochemical processes on land which sequesters CO_2 from atmosphere. The process involves milling silicate rocks and spreading the dust over large areas of managed cropland, speeding up the weathering reaction from proximity to plant roots and increased surface area. This technology could technically be applied today, but its impact is uncertain and further research is needed. Estimates suggest that the annual waste from silicate mining and industrial processes could deliver an estimated sequestration of 0.7-1.2 Gt CO_2/yr. Cost estimates range from $50 to $200 per tonne of CO_2; these primarily arise from mineral processing and transport costs.

- **Ocean alkalinisation/sea water mineralisation:**[131] Increasing concentration of positive-ions such as calcium in the ocean to enhance the natural ability to remove CO_2 and reverse acidification.[132] This could be achieved by adding lime directly to seawater or reacting CO_2 gas and limestone with water and injecting it into the ocean. The chemical processes involved are well understood; however, application at scale has never been tested and the ecosystem impacts are not well-known. The full costs have been estimated at $15 to $500 per tonne of CO_2, but these are highly uncertain. Moreover, there remain concerns about the risk of unintended ecosystem effects.[133]

Other solutions applying biogeochemical processes include:

- **Ocean fertilisation**:[134] Enhancing open-ocean photosynthesis productivity by adding nutrients to increase CO_2 drawdown by phytoplankton, moving carbon into the deep ocean. The science of this carbon transfer is as-yet unproven and fertilisation nutrients (nitrates and phosphorous) are expensive, energy-intensive and (in the case of phosphorous) scarce. Some research has recently pointed to the remarkable role of global whale populations as a nature-based solution for ocean fertilisation enhanced by their excrement. An estimated 1% increase in phytoplankton activity as a result of recovered whale populations would "capture hundreds of millions of tons of additional CO_2 a year, equivalent to the sudden appearance of 2 billion trees."[135]

- **Micro-algae for BiCRS:**[136] Cultivated on land, in ponds or reactors, with high value -added products extracted and the remaining (wet) organic materail buried in solid form. Microalgae biomass is relatively expensive to cultivate however extremely efficient at converting sunlight into biomass.

Finally, in recent months the question of atmospheric methane capture and storage has also been raised, however it is not explored in this report for the following reasons:

- Methane, while a potent greenhouse gas, is short-lived (~12 years) and has the greatest global warming potential immediately after its initial release into the atmosphere (Exhibit 2). Therefore one could argue it is better to implement measures to avoid methane release in the first place, rather than remove it after the fact.

- There is also a significant lack of information about whether methane removal could be practically achieved. It is about 600 times more dilute in the atmosphere than carbon dioxide, and natural processes already serve to destroy about 10% of methane in the atmosphere every year.[137] While some researchers are calling for investment into better understanding of methane removal potential, insufficient information is available to be included in the discussion here.[138]

129 Note: this definition does not explore 'geo-engineering' solutions, which do not aim to increase carbon dioxide removal, but instead target changing earth system elements such as the earth's albedo.

130 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.

131 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.

132 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.

133 "Such Ocean CO2 storage would "represent an unprecedented ocean biogeochemistry perturbation with unknown ecological consequences" (Gonzales and Ilyina, 2016), *High Level Panel for Oceans*.

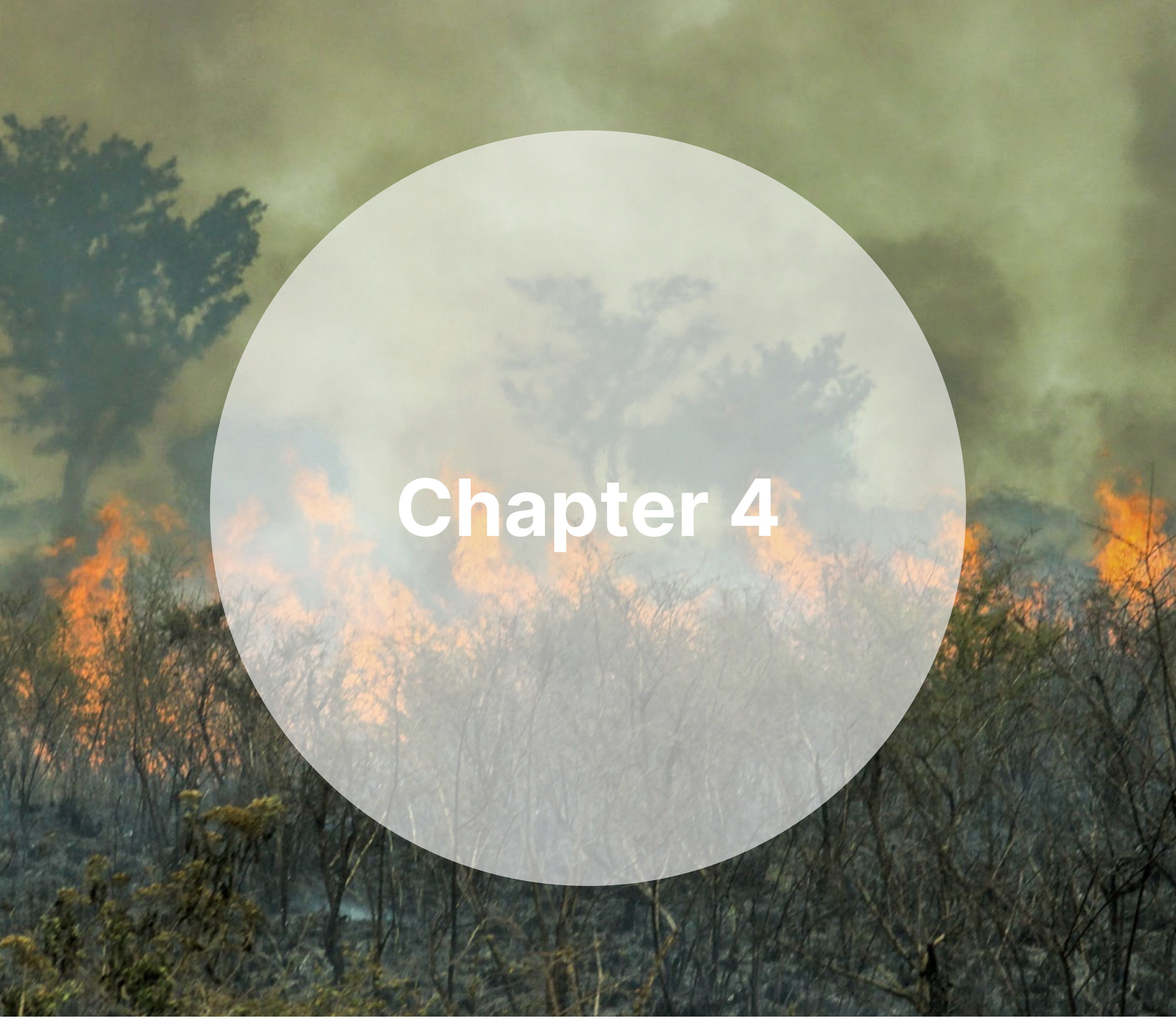
134 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.

135 Chami et al., (2019), "Nature's Solution to Climate Change", *Finance and Development*.

136 Innovation for Cool Earth Program, (2021), *BiCRS Roadmap*

137 Lackner, K.S (2020), Practical constraints on atmospheric methane removal.

138 Jackson, R.B. et al (2021), Atmospheric methane removal: a research agenda.



Risks of CDR solutions and how to manage them

- Natural climate solutions are currently much lower cost than engineered solutions, but tend to face higher risks to permanence.
- Risks facing all forms of removal option must be carefully managed, with robust monitoring and verification systems.
- Developing and investing in a portfolio of different removal types can reduce the overall risk for the planet's CO_2 trajectory.
- Overtime, the balance of costs and risks, which initially favors NCS, will shift to allow a bigger role for Engineered solutions.

The different categories of CDR solutions are characterised by a different balances of cost and risk:

Natural climate solutions currently entail lower estimated costs of abatement (e.g., $10-$100 per tonne) than the Engineered and BiCRS solutions and in addition provide improved outcomes for biodiversity, water supply, food security, and income to local communities. However, NCS assets have inherent risks with respect to:

- Accurate estimates of sequestration volumes.
- Timing - sequestration of carbon takes place gradually over a number of years.
- Permanence of sequestration, given the potential risks of sequestration being reversed e.g., through forest fires, insecure finance[139] and the return of deforestation drivers, including changing political interests.

Engineered solutions such as DACCS have much higher costs, and fewer co-benefits than NCS. They are more nascent but can offer lower risk as:

- The amount of CO_2 sequestered via storage can be fairly precisely defined, and can be managed on a year by year basis.
- Permanence in geological storage is inherently more straight-forward to ensure, provided robust project design, monitoring and verification systems are in place.[140]

Hybrid / BiCRS solutions must overcome risks around responsible sourcing of sustainable biomass for their respective uses.[141] Beyond that, BECCS and Biochar solutions there have different cost and risk profiles:

- BECCS: Has a similar risk profile to DACCS but currently lower costs.
- Biochar: Has a lower risk of reversal than Natural climate solutions but monitoring of stored carbon is challenging in soils.

This chapter considers the risks around ensuring CDR solutions deliver permanent sequestration, how these risks are managed today, and how risks can be better managed in the future.[142]

139 Insecure finance means that the economic incentives to exploit and degrade natural resources are likely to return.
140 IPCC (2005), *Carbon Dioxide Capture and Storage*. An IPCC Special Report.
141 See ETC (2021), *Bioresources within a Net-Zero Emissions Economy* report for further discussion on this topic.
142 Additional risks to be managed which should be kept in consideration include environmental impacts and societal impacts, such as ensuring the rights of indigenous communities are maintained and bolstered.

4.1 CDR risks: Storage options, permanence and monitoring

CO_2 removed from the atmosphere can stored in one of four ways – in the biosphere on land, in geological storage, in the biosphere in oceans, or in durable material products and buildings ("storage in use"). Of these, the first two are likely to be the most important for CDR. Each entail different resource demands and management challenges, and for each it is important to assess the permanence/duration of storage. No standardised approach to assessing that duration is yet in place.

- **Storage on land/the biosphere**[143] involves direct sequestration of carbon into plant biomass and soils and is clearly possible on a large scale. Natural climate solutions can store carbon over periods of decades to centuries (e.g., in standing forest) through to millennia (via peatland), but manmade (e.g., deforestation) and natural disturbances (e.g., wildfire) risk reversing carbon sequestration in some instances. Significant potential exists to store carbon in the biosphere, however ensuring its permanence requires monitoring that actions taken to increase carbon sequestration deliver and maintain that sequestration over time.
  - The duration of storage in land/biosphere could therefore range anywhere from less than 10 years (in the case of exogenous disturbance events such as extreme weather causing trees to fall)[144] to 1000+ years, in the case of ancient undisturbed peatlands.[145,146]
  - A longer term solution for storage in the biosphere is the use of biochar – produced by burning biomass in the absence of oxygen to produce a form of charcoal resistant to decomposition. Added to soils to improve soil quality, biochar can remain for a long time (1000+ years), especially if buried deep.
  - However during their lifetime both existing and newly restored natural climate solutions, which sequester carbon over long periods of time, face a range of threats that can destroy or damage an NCS project, or affect its growth. In particular:
    - Natural disturbances such as droughts, pests, diseases and wildfires, some of which could be exacerbated by a changing climate. For many of these risks mitigation measures can be taken, and incorporated into project design. Furthermore, tropical forests in particular, because of their natural humidity, have little risk for wildfire if well-managed for restoration; temperate forest may be more vulnerable.
    - Anthropogenic factors such as deforestation, often driven by the 'opportunity cost' of using the land affected for an alternative economic use.
  - Technologies for monitoring and verification of biosphere storage (e.g., tracking forest growth via satellites and LiDAR technology) are becoming increasingly effective, but in practice such technology-aided monitoring is not extensively in use. Continued improvement and expansion of high-quality monitoring and verification systems to ensure high-integrity credits is therefore a crucial priority. Of particular importance is monitoring of soil carbon, because current methodologies are primarily manual, and therefore laborious and expensive.
- **Geological storage** involves the sequestration of captured CO_2 underground, and is the end stage of both DACCS and BECCS solutions. Once captured, the CO_2 is then injected underground into saline aquifers or depleted oil and gas fields, typically either as a solution (mixed with water) or as "supercritical CO_2".[147] A combination of natural and manmade factors mean that once injected underground, storage of CO_2 is likely to be permanent, though ensuring this is the case will involve monitoring over time.[148]
  - **Underground storage of CO_2 is highly likely to be permanent.** Once CO_2 is injected, leakage rates from CO_2 stores are expected to be very low over periods of hundreds of years: the IPCC considers it likely (66–100% probability) that 99% or more of the injected CO_2 will be retained for 1000 years.[149] This is due to a combination of natural and manmade factors:
    - CO_2 is injected deep underground (at depths of ~1km), where it then lies under a natural 'cap-rock' which acts as a natural barrier to CO_2 rising to the surface.

143 Biosphere is defined as the regions of the surface and atmosphere of the earth occupied by living organisms, which includes vegetation and the top levels of the earth's soil strata.

144 Between 2003 and 2012 approximately 38 MHa of forests were disturbed due to extreme weather, mostly in temperate zones in Asia. Van Lierop et al (2015), *Global forest area disturbance from fire, insect pests, diseases and severe weather events.*

145 Treat et al. (2019), Widespread global peatland establishment and persistence over last 130,000 y.

146 In some cases storage in forms of biomass which have a shorter duration e.g., rapidly growing trees or plants, could be followed by conversion to biochar to deliver more permanent storage.

147 A supercritical fluid exists when any substance is pushed to a certain temperature and pressure beyond which distinct liquid and gas phases do not exist.

148 Note this definition does not include injecting CO2 for the purpose of Enhanced Fossil Fuel Recovery.

149 IPCC (2005), *Carbon Dioxide Capture and Storage*. An IPCC Special Report.

- Over time, CO_2 diffuses and is absorbed into the water or rock formations into which it is injected.
- Manmade concrete and steel plugs are also expected to be added to the equipment at the end of the injection period, ensuring CO_2 doesn't resurface. However over time these fail-safes are likely to erode and will need to be monitored and maintained.

- This is further reinforced by evidence from long lasting natural stores of CO_2, where leakage, where it has occurred, has been very low and occurred over periods of centuries or millennia.[150]

- **Significant capacities of low-cost underground CO_2 storage are available.** Theoretical storage capacity of CCS have been quantified at >10,000 Gt globally which would be enough to store today's total annual CO_2 emissions (~40 Gt) each year for >250 years. However just 0.2 Gt CO_2 storage capacity has been classified as 'injection-ready' to date, falling far below future volumes of potential DACCS, BECCS or point-source CCS use.[151] Developing more 'injection-ready' storage is a key barrier to CCS scale up.[152] Furthermore, studies or storage potential are not comprehensive, and further research is required to establish the potential volume of storage in India and Africa in particular.[153]

- **Monitoring and verification of geological storage is underdeveloped** and will be required to ensure that permanence is actually achieved, alongside clear definition of legal responsibility and of what forms of DACCS count as permanent storage. Under EU legislation, the operator is responsible for monitoring storage of CO_2 up to 20 years after the project closure and for contributing costs for additional monitoring thereafter, beyond which responsibility for CO_2 leakage would need to be taken by the Government.[154] In the US and Middle East, where CO_2 is often injected for Enhanced Oil Recovery (EOR),[155] monitoring and regulation of CO_2 storage is very limited. In practice this means that CO_2 may be subsequently emitted when oil is extracted and burnt.[156]

150 IPCC (2005), *Carbon Dioxide Capture and Storage*. An IPCC Special Report.
151 Pale Blue Dot (2021), CO2 Storage Resource Catalogue – Cycle 2.
152 See forthcoming ETC 2022 report on Carbon Capture and Storage for further information.
153 As understanding of the geological landscape is weaker in these regions than in the OECD and China.
154 The exact periods can be determined by individual member state authorities. Directive 2009/31/EC of the European Parliament and of the Council (2009), "On the geological storage of carbon dioxide."
155 Note that EOR is not considered a form of CDR.
156 Alcalde et al. (2018), Estimating geological CO2 storage security to deliver on climate mitigation, Nature Communications.

- There could be significant potential for **storing carbon in the ocean biosphere.** This could be done via a number of ways, including increasing biomass growth in the oceans (e.g., plankton), or by increasing carbon stored in stable bicarbonates in ocean minerals and sediment. However, the technologies to achieve this (ocean fertilization and ocean alkalinisation) have unproven and uncertain environmental impacts on ocean ecosystems and more information is needed to understand the possible feedback effects.[157]

- **In addition some CO_2, whether captured via photosynthesis or through artificial capture, can be stored 'in use', for example in timber or concrete products**. Storage durations for these approaches could vary[158] from 50-200 years, but total potential capacity is small relative to need.[159] These "in use" options however, can still play a valuable role since the use of biomaterials typically substitutes for high-carbon alternatives (such as steel or conventional concrete in construction).

Exhibit 30 summarises the trade-offs between cost and risk involved in different categories of sequestration option. While details will vary by specific circumstance, in general:

- NCS solutions are more advanced in terms of technical readiness, and are currently at much lower costs than engineered solutions but tend to face higher uncertainty about sequestration volume achieved and higher risks to permanence.

- Engineered and hybrid/BiCRS solutions, and in particular DACCS, are at a nascent stage of development and face higher costs, though these will likely come down over time (while NCS solution costs are likely to rise slightly). In general they face lower volume uncertainty and risks to permanence.

A comparison of key characteristics and risks for selected CDR solutions

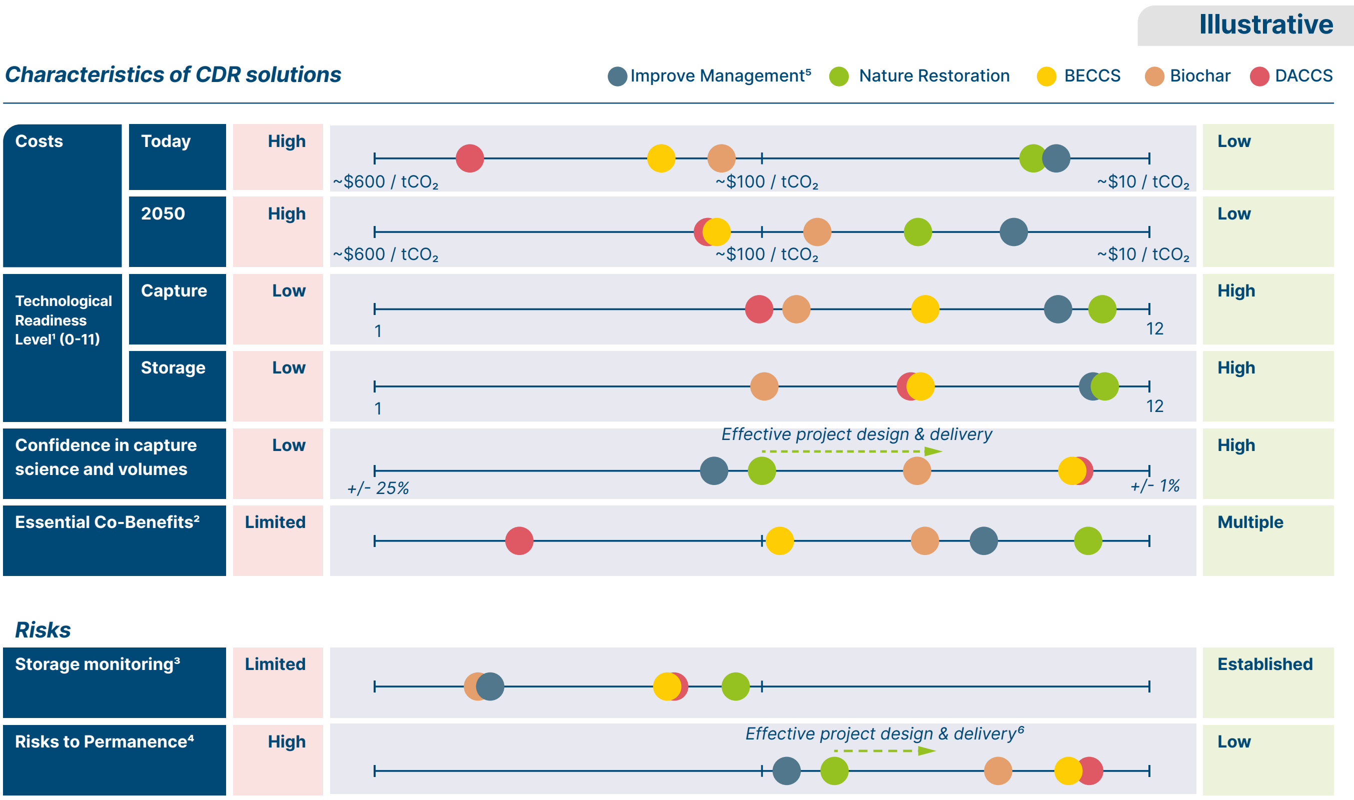


Exhibit 30

NOTES: [1] TRL based on literature review, some assessments adjusted from (0-9) scale to (0-11) scale for comparison with IEA;
[2] Biochar placement assumes biochar is spread on soils;
[3] Refers to ease of monitoring storage to ensure its permanence;
[4] Risks to permanence considered include economic, political and climate risks.
[5] Improved Management refers to both enhanced soils and forests.
[6] Effective project design means mitigating disturbance risk through community engagement, diverse revenue streams, etc.

SOURCE: Fuss et al. (2018) *Negative Emissions Part 2 – Cost, Potentials and Side Effects*; Royal Society (2018) *Greenhouse Gas Removal Report*

157 High Level Panel for Oceans (2020). Note that the risks of ocean fertilization and ocean alkalinisation differ.
158 This only considers long-term sequestration potential. Use of materials which have a 'short term' storage such as biofuels cannot be considered as carbon removals.
159 The ETC's upcoming report on CCS covers this in more detail, and notes that whilst storage of carbon in long-term products may be viable in niche locations and markets, mass storage of CO_2 is likely to be more cost-effective in underground sites.

4.2 Managing the risks

Careful risk management strategies are required to reduce the risks involved in all categories of CDR. For NCS in particular, projects should use deliberately conservative estimates of removals achieved, and in many cases are already being applied. For all types of credit, strong systems for monitoring and verifying removals achieved are essential.

4.2.1 Addressing risks in natural climate solutions

In most NCS projects the future scale of removals achieved is inherently uncertain and in some there is a significant risk of reversal. Well-designed contract structures can mitigate these risks using for instance:

- **Ex-post purchase of credits by brokers.** Brokers who sell NCS carbon credits for carbon reduction or removal are sold by brokers to end-purchasers after the carbon sequestration has taken place, avoiding the risk that credits that are sold rely on future sequestration.[160] Additionally, credits are listed on independently managed project registries (e.g., Verra, Gold Standard), which have developed methodologies against which evidence of sequestration is assessed, and independently audited. Where credits are purchased by brokers ex-ante, risks remain, but can be mitigated through other means (see below).

- **Buffer credits.** Given risks to future sequestration, project developers typically put aside an independently-managed, 'risk-adjusted' percentage of "buffer credits" for all land-based projects. If any sold credits are lost (e.g., through wildfire or future deforestation) then the equivalent number can be withdrawn from the 'buffer pool' to take their place.[161] Buffer pools of credits are typically ~5-25% of project size. This means making conservative estimates of the scale of sequestration which is expected to be achieved, or which actually has been achieved, to cover future adverse developments. Where projects have been affected, credits have been withdrawn from buffer pools to compensate for under-delivery of expected sequestration.
  - For example, Verra (the biggest standards body for certifying carbon credits) has today a global buffer pool of ~58 million credits out of ~130 million AFOLU issuances.[162] In 2019, during the unprecedented Brazilian Amazon fires, ~4.5-6 million credits were wiped from a buffer pool of then ~36 million credits (for context, ~70 million AFOLU credits were issued globally in 2019).[163]
  - Separately, the Art TREES standard ensures an additional up to 25% of a project's size is set aside in a buffer pool, but this percentage can be reduced upon demonstration of multiple factors that mitigate against future reversal (e.g., stable political environment).[164]

In addition to physical reversal risks (e.g., wildfires) some NCS projects face risks arising from future economic incentives, with, for instance, reforestation in one location offset by deforestation elsewhere, or reforestation projects themselves being reversed. These risks can be reduced via:

- **Jurisdictional approaches.** Often there is a risk that restoring ecosystems in one area simply displaces the drivers of land use change (e.g., for deforestation) elsewhere nearby. Ensuring that NCS projects – and in particular those which are at risk of the return of deforestation drivers – are embedded within wider national strategies for land use over time can avoid these risks. Such "jurisdictional approaches" will also often be essential to ensure the permanence of avoided deforestation projects.[165] Nesting project-based credits within jurisdictional approaches is a possible 'best-in-class' approach to NCS project governance. Exhibit 31 demonstrates how this approach is beginning to be applied across provinces in Indonesia, showing the possibilities at scale. Jurisdictional approaches are beginning to become adopted in the common standards, including recently in CORSIA.[166]

- **Building resilient business cases with multiple revenue streams.** For many removal projects the marginal value of NCS for carbon removal may only be slightly greater than the value of using that land for another purpose. This is often referred to as the 'opportunity cost of land'. Layering together multiple revenue streams, such as carbon payments, payments for co-benefits such as ecosystem services, and other high-value native forest products (e.g., Brazil nuts) can increase revenue certainty to landholders and reduce land use change incentives (See Box E). Additionally,

160 Verra, for example, requires planted trees to stand for 5 years before credits are issued. Verra (2021), *Methodology for ARR and Module for Estimating Leakage from ARR Activities: Consultation.*

161 Vertree (2021), *Compensation and Neutralisation*, Verra (2019), *Not the Full Story*.

162 Verra (2022), Buffer contributions can be viewed on the online database.

163 Verra.org, (2019), *Fires in the Brazilian Amazon — A Case in Point for Forest Carbon Projects.*

164 TREES: The REDD+ Environmental Excellence Standard (Accessed February 2022).

165 Avoided deforestation projects do not deliver CO_2 removal , but may be a particularly important sort of CO_2 "reduction" project, as discussed in Chapter 5. World Resources Institute (2020), *4 Reasons Why a Jurisdictional Approach for REDD+ Crediting Is Superior to a Project-Based Approach.*

166 ART (2020), "ART Approved to Supply Credits for Global Aviation's Carbon Market".

scaling up blended-finance mechanisms which create stable and secure financial flows for projects, alongside expanding business models which create value from protecting forests can support long-term project stability for local communities.[167] Similarly, early local and indigenous engagement in project development, including transparency and early resolution of land-tenure uncertainties, is shown to result in more resilient and stable business cases.

- **Monitoring of projects** to ensure that estimates of sequestration are fully delivered. Although semi-regular auditing of NCS projects takes place, in practice the quality of audits vary (suggestions on how this can be improved are covered in chapter 4.2.3). Improved monitoring (e.g., through satellite monitoring) can increase transparency and trust, mitigating risk.

Indonesian jurisdictional approach initiatives underway

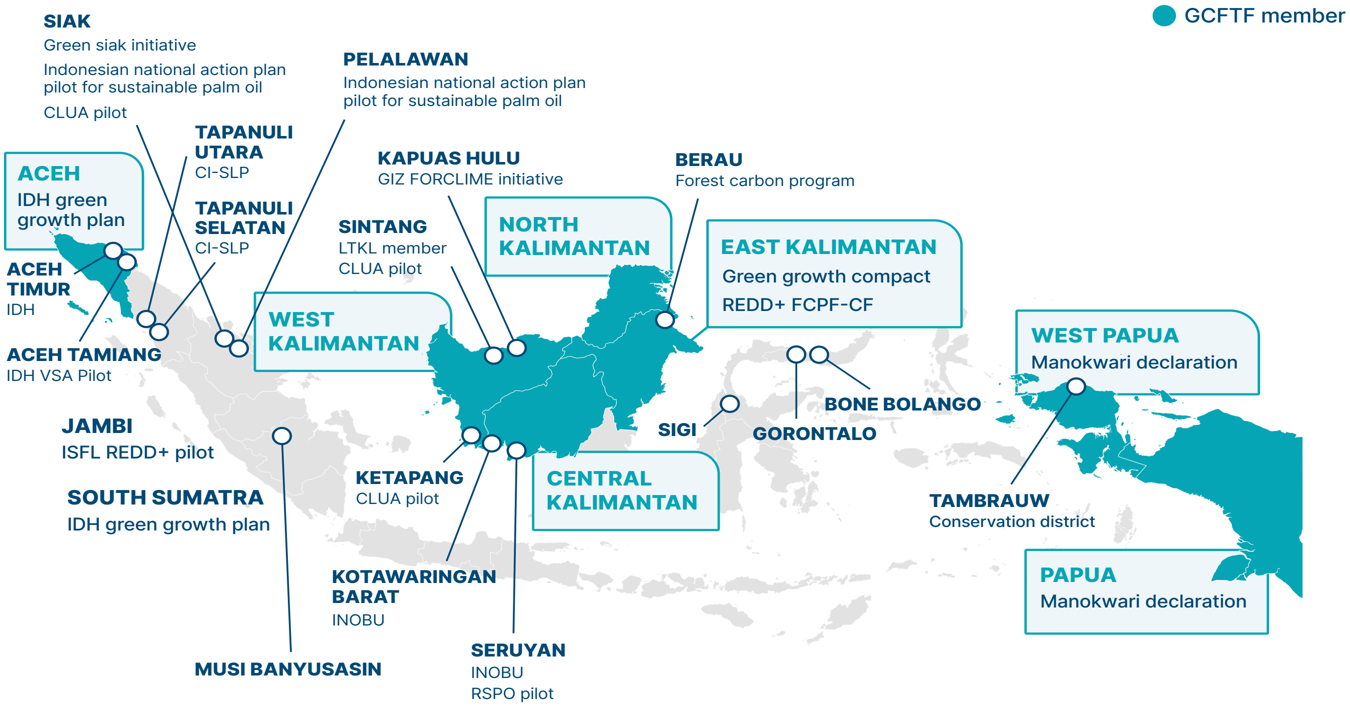


Exhibit 31

NOTES: GCFTF = Governor's Climate and Forest Task Force. It provided assistance and training to government officials in member provinces in areas such as measurement, reporting, and verification (MRV) of forest-based emission reductions in order to qualify for REDD+ finance, as well as more general support for transitioning to low-emissions development pathway.

SOURCE: Seymour et al., (2020) *The Jurisdictional Approach in Indonesia: Incentives, Actions, and Facilitating Connections*

167 FOLU (2019), Prosperous Forests.

Box G: Reduced Emissions from Deforestation and forest Degradation (REDD+)

Challenges in implementing REDD+

Global primary forests are in precipitous decline – at risk of deforestation and degradation from several drivers. These drivers include the expansion of commodity-supply chains, wildfire, forestry, urbanisation and shifting agriculture. Over the last 20 years, the majority of global forest carbon stock loss has been in the tropics, primarily from commodity supply chains, such as soya feedstock and palm oil (in Brazil and Indonesia), and shifting agricultural trends (in central Africa).[168]

One approach to mitigate these emissions has been to develop the REDD+ programme in order to encourage payments for 'avoided emissions'. REDD+ was devised as a programme that would facilitate results-based finance for 'Reduced Emissions from Deforestation and forest Degradation (REDD)' as well as the role of conservation, sustainable forest management and enhancement of forest carbon stocks in developing countries (+).

Some 600+ REDD+ projects have been initiated to date, and some 400 are still active, mostly implemented by NGOs or for-profit developers,[169] financed by more than $10 billion in donor funds from more than 65 countries.[170] CORSIA also recently approved use of REDD+ credits – a world first.[171]

Originally, implementation was intended to be at jurisdictional scale in order to provide a certain level of regional oversight, but in practice jurisdictional approaches have struggled to get off the ground (some head-way is being made in Indonesia and other places (see Exhibit 31)). Results-based payments for jurisdictional REDD+ programmes have to date been limited to a few bilateral and multi-lateral initiatives, such as Norway's International Climate and Forest Initiative (NICFI).

Four fundamental challenges have dogged the REDD+ framework, and apply also to carbon credits for NCS removals. They include:

1. Leakage: the risk of displacing deforestation activity to a nearby local area.
2. Additionality: Predicting what would have happened in the absence of a REDD project.
3. Permanence: Difficulty of long-term storage assurance.
4. Measurement: Difficulty accurately counting carbon stored.

4.2.2 Addressing risks in engineered and hybrid solutions

For BiCRS (Hybrid) solutions, it is essential to ensure that utilizing harvested biomass from crops or residues does not compete with biodiversity, food production, or the use of land for other carbon sequestration purposes. This requires a cautious approach to the role of bioresource exploitation which we discussed in our 2021 ETC report on *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.*

For both Engineered and Hybrid solutions, it is inherently more straightforward to measure how much CO_2 has been stored than for most NCS projects, and there is a lower risk that stored carbon will be released. But strong independent regulation of technical storage, monitoring and verification standards will be needed to ensure that the technical possibility of lower risk is actually achieved in practice. In many countries such regulations are not yet in place but in others they are beginning to emerge, with required buffer stocks also being used to cover uncertain future developments. For example, California's Low Carbon Fuel Standard (LCFS) provides incentives for engineered removals such as DACCS, and project operators are required to contribute up to 17% of the carbon certificates generated into a buffer pool.[172]

Regulations will need to be developed that ensure the operator takes liability for any leakage of CO_2 from storage sites during, and for a long, but ultimately time-limited, period beyond, operation, and monitoring of leakage is independently

168 Curtis et al., (2018), "Classifying drivers of global forest loss", Science. Note: Shifting agriculture is defined as defined as small- to medium-scale forest and shrubland conversion for agriculture that is later abandoned.
169 Yeung, P. (2021), "As COP26 looms and tropical deforestation soars, REDD+ debate roars on", *Mongabay*.
170 Yeung, P. (2021), "As COP26 looms and tropical deforestation soars, REDD+ debate roars on", *Mongabay*.
171 ART (2020), "ART Approved to Supply Credits for Global Aviation's Carbon Market".
172 The percentage required to be set aside is determined by assessing which mitigating factors are in place, in a similar manner to how some NCS buffer pools operate. If leakage from storage reservoir occurs during the first 100 years post injection, replacement certificates need to be drawn from the buffer pool. After 100 years, the post-injection monitoring obligation ends. Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard, California Air Resources Board, 6 March 2018.

verified.[173] In the long term, risks will need to be absorbed by Government, and the appropriate regulations (and if needed, institutions) will need to be set up. This type of regulatory framework can be challenging to establish and maintain, as the nuclear industry has demonstrated in regards to long term management of waste.

4.2.3 Standardising the standards: Addressing risks relating to carbon markets

All types of removal credit – NCS, hybrid or fully engineered - could be originated, bought and traded in the complex emerging 'Carbon Credit' ecosystem. The details of this system, which can involve both "compliance" and "voluntary" variants, are discussed in Chapter 5. For such a complex system to work well, it is essential to develop standards which provide assurance that a credit purchase results in removals equal to the stated quantity of that credit. A range of different voluntary carbon market standards has therefore emerged to provide this assurance (Box I), in addition to some government-regulated standards (e.g., in California, China and Australia). This multiplicity of standards creates a risk of confusion and/or "standard arbitrage" with some market participants potentially favouring the weakest standard.

There may therefore be a necessary role for financial regulators or accounting standard setters to ensure high quality standard and verification processes, in a manner analogous to the regulation of credit rating agencies introduced after the global financial crisis of 2008. The newly constituted Integrity Council for Voluntary Carbon Markets (IC-VCM), launched by the TSVCM, may be a good candidate to serve this role. In addition, a high level of quality assurance on the suitability of offset methodologies will soon be provided by the Paris Agreement's Article 6.4 Supervisory Board.

Box H: How carbon offsets are purchased today in the voluntary carbon market

The 'voluntary carbon market' is a carbon credits ecosystem though which carbon reduction and removal projects are developed, with the sequestration associated with these projects sold to credit buyers, often in support of corporate climate claims (*Exhibit 32*). This typically works as follows:

- Project developers develop reduction or removal projects. Projects that meet specific quality criteria (e.g., on measurement, community engagement, biodiversity) are then verified by independent standards setters (such as Verra and Gold Standard – see Box I for more detail). Independent auditors regularly vet projects over the project lifetime to ensure that these standards are upheld.

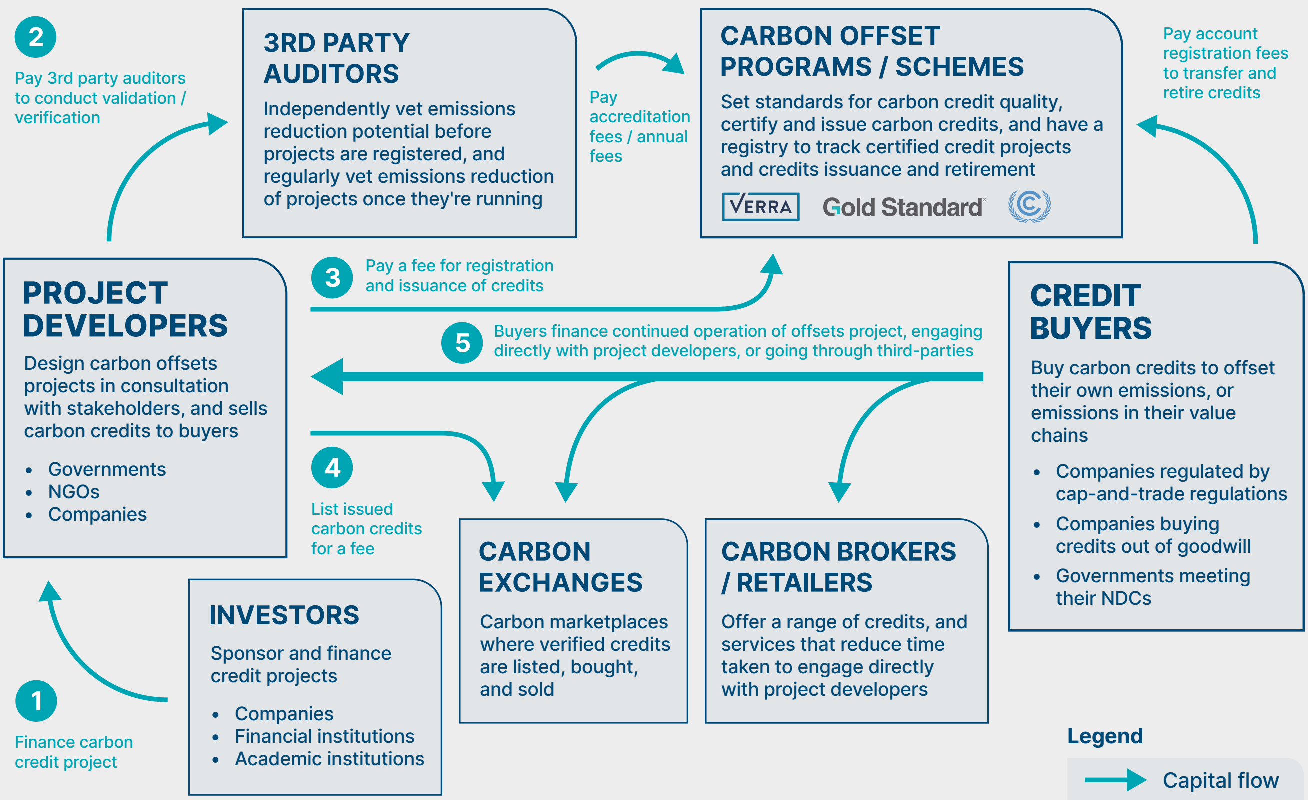
- Credit buyers – such as corporates or individuals – then purchase credits from established projects from carbon brokers/retailers, carbon exchanges or from project developers directly (either in single transactions, or in longer-term purchase agreements).[174]

Project developers might typically favour longer-term off-take contracts, which would reduce the risk (and cost) of developing their project, and guarantee future revenue streams. However for many credit buyers, who may prefer to buy ad-hoc credits based on demonstrated sequestration, long-term contracts may not be preferable. Carbon brokers/retailers and exchanges can help to bridge this divide by providing longer-term contracts (through which they would absorb some risk of non-delivery) and enabling buyers to purchase a portfolio of CDR solutions from a range of projects (Exhibit 32 above). Additionally, volume certainty will be key to incentivising investment in removals – both governments and corporate buyers have a key role to play here.

173 For example, in some jurisdictions nuclear operators must set aside a proportion of revenues to deal with long term plant decommissioning and waste management. Add reference (e.g., Hinkley Point UK).

174 Paia (2021), "Carbon Offsets and Credits, Explained"

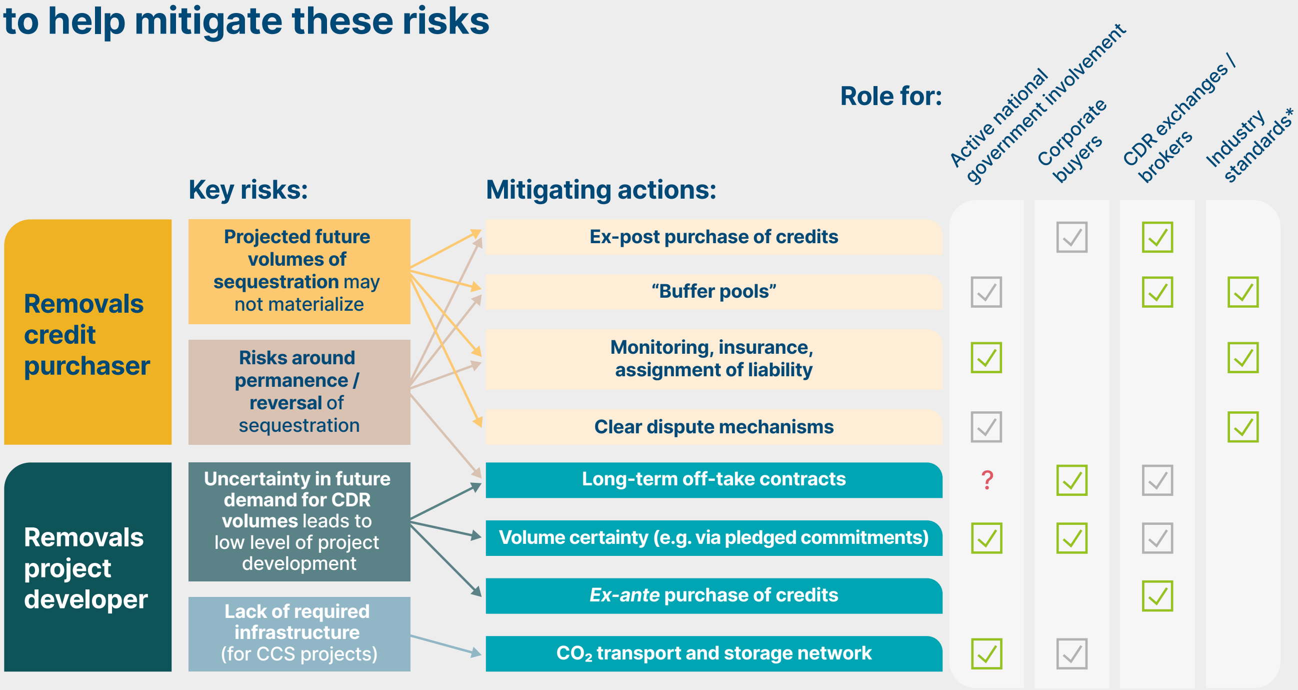
How carbon credits are purchased today



SOURCE: Paia Consulting (2021)

Exhibit 32

Risks faced by actors across the CDR value chain are fundamentally different, key roles for exchanges / brokers and industry standards to help mitigate these risks



*Backed by auditing, and potentially regulation

Leading role — Supporting role

Exhibit 33

Box H

Box I: Current Voluntary Carbon Market Standards and proposals for reform

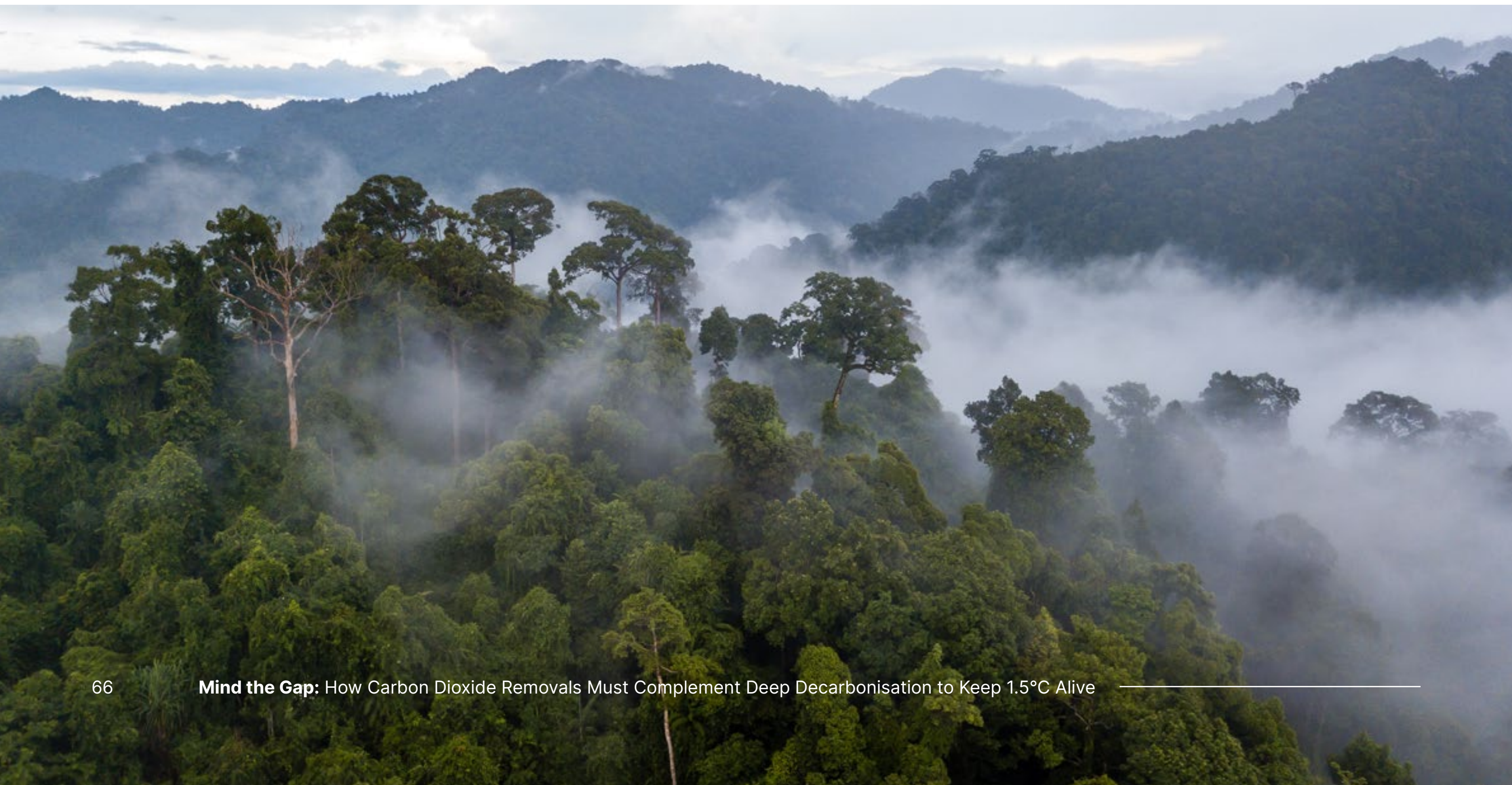
The majority of credits in the voluntary market are issued by private standards (e.g., VCS, Gold Standard, ACR, and CAR (see Exhibit 34)). Some compliance schemes also allow the use of private standard credits, an example being the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Standard setting/carbon crediting bodies include mechanisms for grievances to be raised and resolve (in line with International Standards Organization (ISO) requirements).

Several voluntary carbon market standards exist which vary in approach and scope

Standards	Origins	Scope	Information on type of credits
American Carbon Registry	The American Carbon Registry (ACR), a non-profit enterprise, founded in 1996 as the first private voluntary greenhouse gas registry in the world.	**Registration and verification of carbon offset projects issued on a transparent registry.**	Accepts permanent ex-post credits and there are no location restrictions on credits issued. Most project types allowable and **also includes a nested REDD Standard. ACR issues early Action Offset Credits (EAOCs) for the California Cap-and-Trade program.**
Climate Action Reserve	The Climate Action Reserve (CAR) began as the California Climate Action Registry and was created by the State of California in 2001 to address climate change through voluntary calculation and public reporting of emissions.	**Establishes high quality carbon offset standards, oversees independent third-party verification bodies, issues carbon credits and tracks credit transactions.**	California's Air Resources Board, responsible for the California cap-and-trade programme, has adapted CAR's Forest Project Protocol to create a Compliance Offset Protocol for US Forest Projects. **CAR credits from certain domestic forestry projects are also eligible for early action crediting under California's cap-and-trade programme.** CAR is working with partners in Mexico to create a new protocol for forest projects in Mexico.
Gold Standard®	Developed in 2003 by the World Wide Fund for Nature (WWF) and other partners. Today, the standard is administered by the Gold Standard Foundation, a non-profit foundation in Switzerland.	**A best practice standard for projects to quantify, certify and verify credible climate initiatives.**	Minimum social requirements to be met such as a stakeholder consultation process, a 'do-no-harm' assessment as well as a Free, Prior and Informed (FPIC) process. **The Gold Standard to afforestation, reforestation and natural re-vegetation and agroforestry projects.**
VERRA	Initially developed in 2005 by the World Economic Forum (WEF), The Climate Group and the International Emissions Trading Association (IETA).	**A best practice standard, incorporating independent assessment, accounting and registry of climate projects.**	Over time **has grown to incorporate and/or develop most of the relevant land-use standards** i.e. the Climate, Community & Biodiversity (CCB) Program and the VCS Jurisdictional and Nested REDD+ (JNR) Framework.

SOURCE: ACR, CAR, Gold Standard, Verra

Exhibit 34



These various standards provide a level of transparency on the criteria carbon credit projects need to meet in order to be considered eligible. However divergence across the standards limits comparability, and makes a truly independent assessment of the market difficult.

In recent years, multiple proposals for reform have been put forward, that seek to address several systemic failures in current voluntary carbon markets, with a view to scaling these markets substantially in the 2020s. Current shortcomings include ensuring projects protect indigenous rights and biodiversity whilst delivery emissions savings, ensuring projects deliver truly 'additional' savings (i.e. the project wouldn't have occurred without a carbon credit) as well as ensuring transparency and credibility in the market. Key proposals for reform include:

- The **Integrity Council for the Voluntary Carbon Market (IC-VCM):**[175]
    - IC-VCM argues for the introduction of a new set of standards, managed by an independent third party organisation, based on a set of Core Carbon Principles that set quality criteria for a verified tonne of carbon (or carbon equivalent) avoided/reduced or removed/sequestered, ensuring that credits adhere to the highest level of environmental and market integrity.
    - The same new entity should also establish a taxonomy of additional attributes (e.g., project vintage, project type (i.e., reduction vs. removal), co-benefits, impact on sustainable development goals (SDGs), location, and inclusion of corresponding adjustments (for any Article 6 trading).
    - The same body could provide regular audits and spot checks of existing standards organisations to ensure rigorous adherence to the Core Carbon Principles.
- The **Voluntary Carbon Market Integrity Initiative (VCMI)**[176] is considering a range of proposals for increased integrity assurance of carbon credits, aiming to recommend a way forward in 2022. Current options under consideration include:
    - A *principles-based model* which would see existing standards sign up to an agreed set of criteria.
    - A *'centralised' model* which would introduce a new common standard (similar to the TSVCM proposal).
    - A *hybrid model* whereby principles and criteria are further refined via a code of best practice (possibly including independent third party verification of claims).

Box I

4.3 Risk-adjusted costs over time

In general NCS projects today have a much lower cost per tonne of expected CO_2 sequestered. But there is often high uncertainty about how much CO_2 has been sequestered, and greater risk that sequestration might be reversed. As a result there is greater variance in estimates of the future stream of sequestration over time. In addition there are likely to be higher monitoring and verification costs than required in engineered solutions.

But the higher risks can be managed via explicit use of buffer credits, and even after allowing for the cost of buffer credits and for intense monitoring and verification, NCS projects will often be far cheaper than engineering solutions today. Over time however the relative risk adjusted costs are likely to change as indicated using illustrative numbers in Exhibit 35:

- Thus, if an NCS credit today had a cost of abatement per mean expected tonne of CO_2 sequestered of $20, adding a 25% buffer stock (i.e., $5 per tonne) and another $5 to cover monitoring and verification costs, would still leave the total cost of $30 per tonne, far below today's available engineering solutions.

175 TSVCM (2020), *Taskforce on scaling voluntary carbon markets*, consultation document.
176 VCMI (2021), *Aligning Voluntary Carbon Markets with the 1.5°C Paris Agreement Ambition.*

- Over time however, the cost of NCS solutions is likely to rise as the most economic projects are implemented first, while the cost of DACCS is likely to decline as a result of economy of scale and learning curve effects, with costs potentially reaching around $100 per tonne by or before 2050, with further falls possible thereafter. If, for example, marginal NCS costs rose above $60 per tonne and DACCS reached $80 per tonne, DACCS could become cost competitive with NCS on a risk-adjusted basis.

Two implications follow:

- There should continue to be a demand for NCS solutions even with conservative approaches to buffer stocks and investments in high quality monitoring and verification. Responsible corporate buyers should concentrate on buying high quality credits for all removals from verified reputable standards which already account for buffer stocks and robust monitoring to ensure the removal has actually taken place rather than minimising the purchase cost (at the expense of reduced certainty about future sequestration volumes).

- Even though higher cost today, DACCS and other engineering solutions should be developed given their potential to deliver moderate cost and lower risk solutions in the future. Private and Government actors have an interest in funding the development of these technologies.[177]

Appraisal of the risks of different CDR options is likely to shift the relative costs towards engineered solutions over time

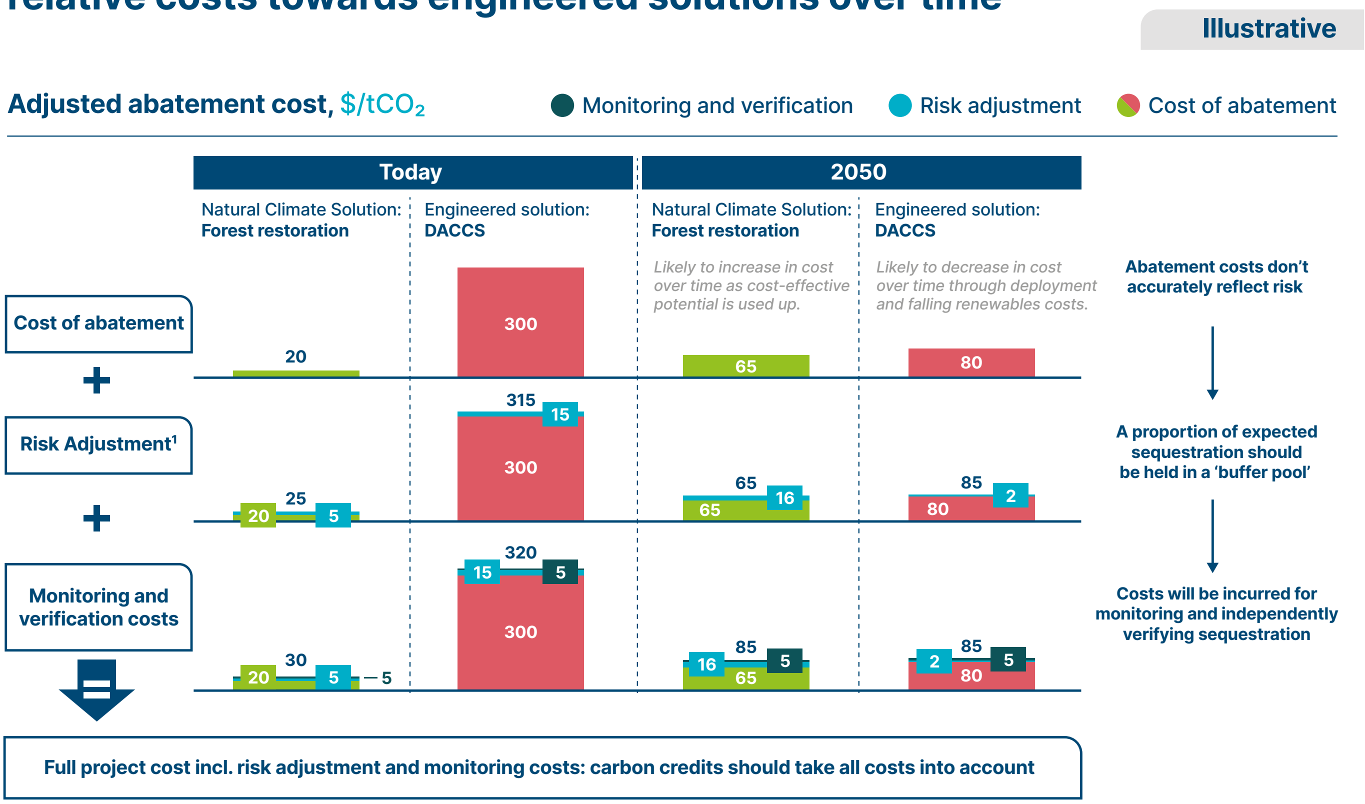


Exhibit 35

NOTE: [1] Reflecting the risk of future CO_2 sequestration materialising or being reversed/non-permanent.

177 See for example investments by SwissRe, Stripe, and Microsoft.

Chapter 5

Funding removals

- Removals will only occur at the required scale with much greater funding than currently delivered by compliance or voluntary carbon markets.

- Corporate purchases of removal credits in compliance or voluntary carbon markets could play a significant role, but must be as well as - and not instead of - strong targets to reduce companies' own emissions as rapidly as possible to net-zero.

- Governments will have to play a significant role in delivering sufficient removals, both as direct providers of funding, and by creating the policy frameworks which can ensure that NCS removals are permanent.

5.1 Funding requirements

Removals will only occur if someone pays for them. There needs to be an annual flow of money from purchasers of removals to providers; and in some cases providers will have to make significant initial investments to make subsequent flows of removals over time possible. This will require a view of future market size, supported by long-term contracts.

Exhibit 36 provides an illustration of the possible annual flows required to support removals at the scale illustrated in Exhibit 28 in Chapter 3, rising to equal 3.6 Gt CO_2/yr by 2030 and 12 Gt CO_2/yr by 2050, with a cumulative total of 165 Gt CO_2 over the next three decades. The estimate presented here assumes that all removals are purchased on an annual basis at the costs illustrated, with NCS costs in a range of $5 to $50 per tonne but rising over time, while the costs of Engineered removals are initially around $300-600/ t$CO_2$ per tonne but fall to around $100 over time.[178] To support the growth in CDR shown on Exhibit 28, annual CDR payments could reach over $200 billion / year by 2030. Over the whole period to 2050 sequestering 165 Gt CO_2 could require payments of around $15 trillion over the next three decades, equivalent to around 0.25% of projected global GDP over this period. In contrast required investment in clean power is around 1.5% of GDP over the same period. This is a substantial increase on the estimated less than $10bn/yr of funding flowing into these sectors today.[179] However this comes with a huge range of uncertainty by mid-century driven by both; (i) uncertainty about the future costs of engineering solutions; (ii) uncertainty about the volume which would be economic given the alternative cost of reducing gross emissions even closer to zero.

Exhibit 37 illustrates the possible profile of investment needs over time, with a very different profile for:

- **NCS solutions**, where large investments are required during the 2020s (e.g., to pay for land acquisition or for labour and equipment for ground preparation and tree planting) in order to make possible future rising volumes of sequestration.

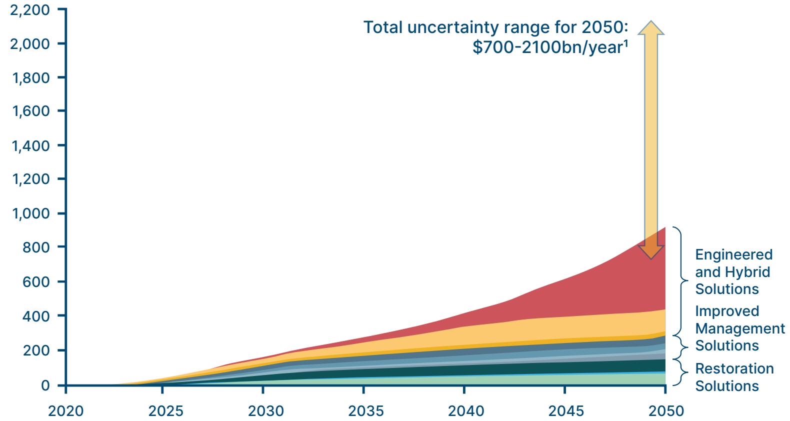
- **Engineered and hybrid solutions**, where Exhibit 37 shows the significant buildup of investments in DAC plant capacity needed to support flows of carbon capture potentially reaching 4.5 Gt CO_2 per year by 2050, but with investment than falling off once the capacity is in place. A similar profile, at a smaller scale, applies to BECCS. The costs shown cover the direct investment in DAC plant: in addition a similar order of magnitude investment would be required in zero carbon electricity capacity, which is not included in the illustration in Exhibit 37, but the annualized cost of producing that electricity is included in (and is the largest element of) the annual costs of removal shown in Exhibit 36.

178 Costs for hybrid solutions such as BECCS are also expected to fall over time, from around $140-270/t$CO_2$ today to $100-200/t$CO_2$.
179 SYSTEMIQ analysis for the ETC; Coalition for Negative Emissions (2021) *The Case for Negative Emissions*.

Exhibit 36

Total market for CDR could reach \$200bn/year by 2030; \$1000bn/year by 2050

Expected annual cost of CDR solutions
USD bn/year, global



	Cost estimate (Today)	Cost estimate (2050)	Cumulative potential (2020-2050)
Engineered and Hybrid/BiCRS solutions	\$~600/t CO_2	\$100-300/t CO_2	45 Gt CO_2
NCS: Improved management solutions	\$0-100/t CO_2	\$0-100/t CO_2	60 Gt CO_2
NCS: Restoration solutions	\$5-100/t CO_2	\$25-100/t CO_2	60 GtCO_2
TOTAL			165 Gt CO_2

NCS: Restore
- Restore forests
- Restore blue carbon
- Restore drained peatlands

NCS: Manage
- Improve forest management
- Agroforestry
- Enhance soil carbon sequestration in degraded croplands
- Enhance soil carbon sequestration in degraded grazing lands

Hybrid and engineered approaches
- Apply biochar
- BECCS
- DACCS

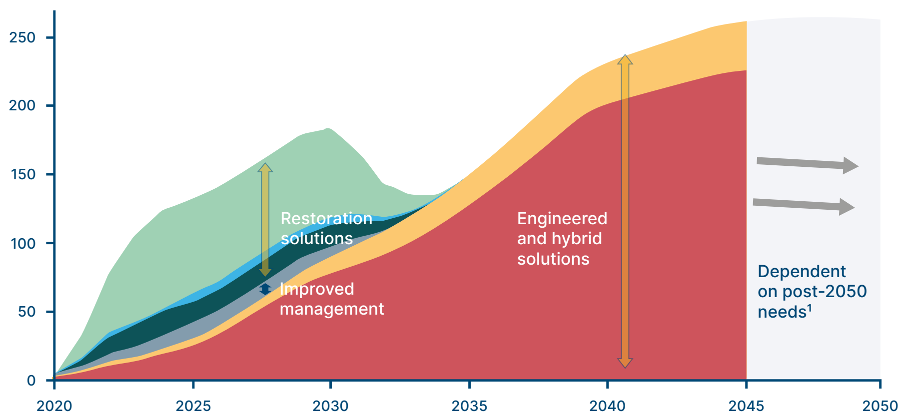
NOTE: [1] Cost estimates for different solutions vary significantly, chart shows the weighted average between the low and high estimates, uncertainty range based on high estimates and low estimates for all solutions. Current funding for removals estimated to be less than \$10bn/year. Additional funding would be required for emissions reductions (e.g., avoided deforestation)

SOURCE: ETC analysis based on Fuss et al. (2018) *Negative Emissions Part 2 – Cost, Potentials and Side Effects;* Royal Society (2018) *Greenhouse Gas Removal Report; Direct Air Capture of CO_2 with Chemicals* (APS, 2011); Roe et al. (2021) *Land-based measures to mitigate climate change.*

Exhibit 37

Capital investment for CDR averages c. \$100bn/year over next 3 decades; significant investment in nature restoration required in 2020s, alongside scaling DACCS

Expected annual capital investment for CDR solutions
USD bn/year, global



	Annual average investment	Cumulative investment (2020-2050)
Engineered and Hybrid/BiCRS solutions	\$100 bn	\$3,000 bn
NCS: Improved management solutions	\$7 bn	\$200 bn
NCS: Restoration solutions	\$25 bn	\$700 bn
TOTAL	~\$130 bn	~\$4,000 bn

NCS: Restore
- Restore forests
- Restore blue carbon
- Restore drained peatlands

NCS: Manage
- Improve forest management
- Agroforestry
- Enhance soil carbon sequestration in degraded croplands
- Enhance soil carbon sequestration in degraded grazing lands

Hybrid and engineered approaches
- Apply biochar
- BECCS
- DACCS

NOTE: CAPEX estimates for individual CDR solutions based on case study analysis and academic literature reviews.

SOURCE: SYSTEMIQ Analysis for the ETC, based on Coalition for Negative Emissions (2021) *Case for Negative Emissions;* BEIS (2018) *Call for CCUS Innovation: literature review, benchmarking report and calculator;* Economics for the Environment Consultancy (2015) - *The Economic Case for Investment in Natural Capital in England;* Brown, T., Wright, M., and Brown, R (2011) *Estimating Profitability of Two Biochar Production Scenarios: Slow Pyrolysis vs. Fast Pyrolysis.*

5.2 Who could pay and how – carbon markets and direct payments

The financial flows described above will only occur if someone pays for them. This could entail either corporate or government funding, and payments could occur in a number of forms, some of which involve organized carbon markets, and some not. Exhibit 38 describes the range of possibilities.

How, and who, to pay for CDR scale up?

Primary mechanism for organising payment?	Companies pay	Governments pay
Traded carbon markets	**Compliance markets** (e.g., EU ETS, CORSIA)	~~*International purchase under Article 6 transfer (included in NDC accounting)*~~
	Voluntary markets (e.g., Verra, Gold Standard)	**International purchase under Article 6 transfer (beyond NDC accounting)**
Beyond markets	**Action on removals within value chains** (e.g., better practices in FMCG supply chains)	**Direct finance of removals** ***And/or purchase*** [1]
	Other CSR / charitable contributions *(e.g., funding a re-wilding project)*	**Reforming existing subsidies mechanisms to incentivise CDR** (e.g., agricultural policy, innovation and R&D)

Recommend against   Critical lever

Exhibit 38

NOTE: [1] Only to be included in NDC accounting if within own country, except for a small subset of removals required to offset residual gross emissions to zero by mid-century. 'Included' and 'Beyond' in reference to NDC accounting here refer to the purchasing country. The selling country would need to make a corresponding adjustment to ensure that the removal is not counted towards its own NDC (avoiding double-counting).

Companies - Companies could pay either via:

- **Compliance markets.** Companies are obliged to purchase carbon credits in certain carbon markets such as the EU ETS, CORSIA or equivalent mechanisms. Today, removals are either excluded from these markets, or limited in scale. Over time removal credits could be introduced into these markets, with removal projects – either within or outside of the geographic coverage of the market – receiving the monetary benefit of the carbon credit.

- **Voluntary markets** where companies have no legal obligations, but choose to purchase carbon credits (e.g., in line with Net Zero strategies, or to offset legacy emissions).

In addition where companies have value chains that involve direct involvement in land use – e.g., food and fibre related companies – they may get directly involved in actions which drive removals rather than paying somebody else do it.

Governments - Even when companies are making the payments, governments will play a crucial role in setting the rules and motivations. For example:

- Setting the rules for compliance markets – including the types of sectors and companies that are obliged to purchase credits, the total quantities of credits and whether or not removals are allowed (and whether these removals need to occur within the geographic coverage of the scheme).

- Creating reporting requirements for companies and other forms of encouragement which stimulate voluntary markets.

- Applying regulations to supply chains could encourage/force major companies to take direct actions: for example changes to agricultural policy could have an impact on forest management, or soil carbon sequestration.

But governments can also be buyers of removals themselves in a number of ways, both internationally or domestically:

- **Internationally**: this could be within the context of Article 6, paying for removals which they then count towards domestic targets. Finalisation of the Article 6 rule book at COP26 could facilitate such arrangements (though we suggest below that they should not play a significant role). But they could also simply make international payments (e.g., via climate finance) without any implications for the domestic carbon account.

- **Domestically**: Governments could also make payments or directly fund projects to deliver removals within their own country.

5.3 Current funding flows are insufficient

Total funding flows of all possible types are currently insufficient to meet the need for removals which we have identified:

Corporate. Neither compliance nor voluntary markets are currently on target to deliver the scale of removals needed:

- Compliance markets cover over 10% of global emissions but few if any allow removals.

- The scale of the voluntary market is currently around 100 Mt CO_2e/yr (around 0.2% of global emissions) and a majority of these are Reductions not Removals. Furthermore, the scale of the voluntary market, though increasing, will eventually reduce over time as companies reduce gross emissions (assuming companies pay for offsets in relation to their ongoing carbon footprint).

This limited development in part reflects past concerns about quality and true additionality:

- Large schemes to incentivise cross-border trade in emissions reductions, such as the Clean Development Mechanism, have been criticised for not delivering significant emissions reductions beyond what was already occurring.

- Nature based solutions such as avoided deforestation where the counterfactual of intervening can be hard to prove, have also sometimes struggled to prove additionality, as well as other quality issues.

Governments. Flows of climate finance from richer to poorer nations have increased to around $100bn/yr, however the majority of this funding is currently committed to emissions mitigation and adaptation, rather than removals.[180] Furthermore, a lack of clarity exists about how much is truly grant rather than debt finance. Additionally, although actions are underway to change some wider government policies towards incentivising removals, the scale of removals likely to result from these interventions is currently low.

5.3.1 Corporate actions

Compliance markets

Compliance markets are growing in scope geographically, with over 10% of global emissions currently covered by emissions trading schemes, however although in principle perfectly possible, inclusion of emissions removals within these markets is currently very limited.[181]

Voluntary markets

Today's financial flows from voluntary markets represent a small fraction of the forecasted quantum required, and most of these are focused on various forms of "reduction offset" credits, as opposed to actual removals (Exhibit 40). Total removals in the voluntary carbon market are less than 10 Mt CO_2/yr – 0.3% of the volume required by 2030.[182]

Moreover, forecasted demand for growth in the voluntary carbon market isn't anticipated to ramp up sufficiently to meet the required volume of carbon dioxide removals to address the carbon budget overshoot (Exhibit 39). Even under the most ambitious projections of the voluntary carbon market, total market size reaches 1 Gt CO_2/yr by 2030, representing just 30% of the required emissions removals in our pathway.

180 By 2023. UK COP26 Presidency (2021) *Climate Finance Delivery Plan.*
181 World Bank (2021) *State and Trends of Carbon Pricing 2021.*
182 Trove Intelligence Research (2021), Future Demand, Supply and Prices for Voluntary Carbon Credits.

Furthermore, if we assume that companies in the voluntary carbon market pay for offsets in proportion to their carbon footprints, the need to pay for offsets will also decrease as companies' emissions decline towards net-zero over time.

Willingness to pay: Corporate demand for voluntary credits forecast to scale up to 2050, yet still falls far short of finance needed to support feasible scale up scenario

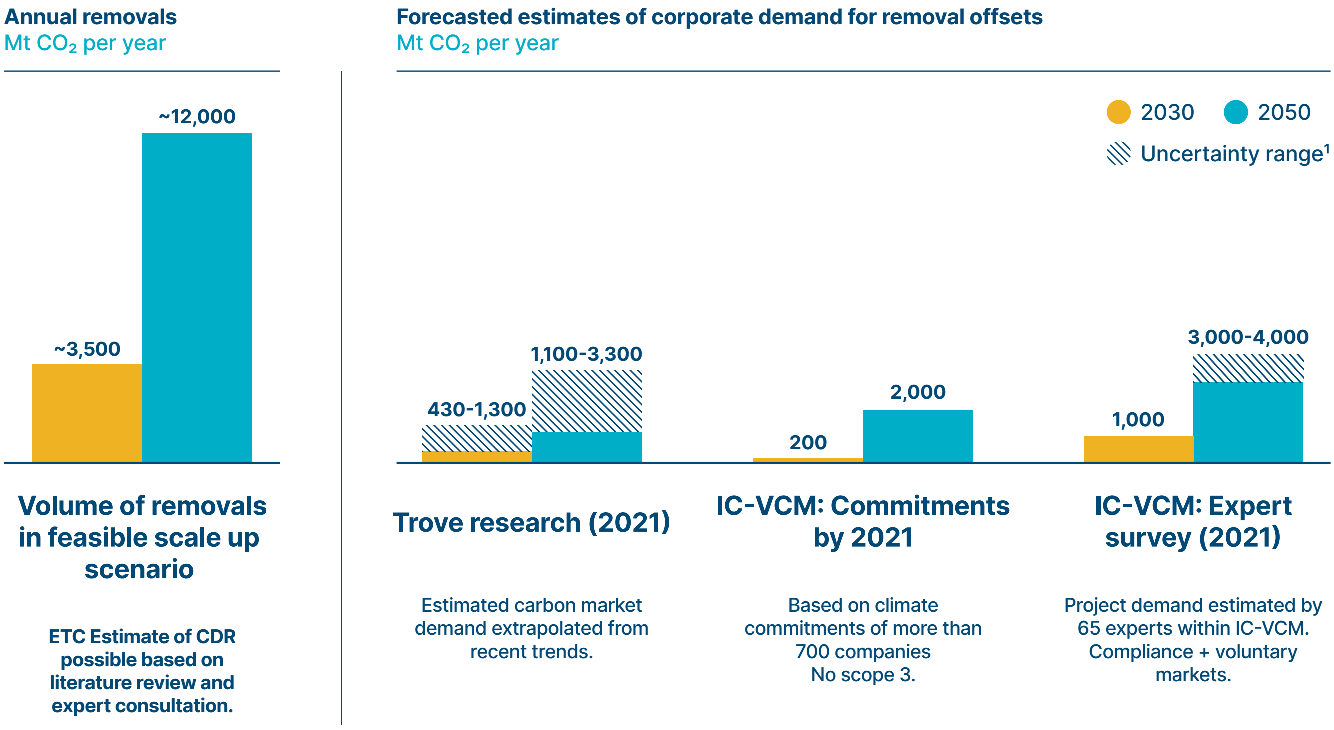


Exhibit 39

[1] Uncertainty range defined by source material

NOTE: IC-VCM = Integrity Council for Voluntary Carbon Markets; NZ = Net-Zero;

SOURCE: SYSTEMIQ Analysis for the ETC; Trove Intelligence Research (2021) *Future Demand, Supply and Prices for Voluntary Carbon Credits – Keeping the Balance*

Reduction versus removals

Historically, many credits in both the voluntary and compliance markets have been of poor quality. In recent years however the market has developed substantially, and over time many poor quality and cheaper credits have been retired or removed from circulation in the market. Today, the majority of credits available are energy-based engineered 'reduction' credits (Exhibit 40), which have been criticized as not being truly additional, failing to drive real acceleration of reduction strategies such as renewable power. For example, a review of the Clean Development Mechanism – a legacy carbon crediting scheme – found that up to 85% of the projects analysed, covering 73% of potential issuance between 2013 and 2020, were found to be non-additional.[183] Nature-based reduction credits, such as those supported by REDD+ projects for avoided deforestation have also struggled to ensure consistent high-quality, as well as facing the inevitable challenge of proving additionality – that without income from carbon credits, the forest would have been cut down (Box G).

183 Pineda, A. and Faria, P (2019), Towards a science-based approach to climate neutrality in the corporate sector, SBTI, CDP.

Exhibit 40

When buying ‘offsets’ there are two main categories of carbon credits available for purchase

REDUCTION:
Projects that indirectly reduce emissions from entering the atmosphere outside of the buyer’s value-chain. Also referred to as mitigating ‘Beyond Value Chain Emissions’ (BVCM)

Nature-Based Solutions

Avoided Deforestation: Reducing Emissions from Deforestation & forest Degradation (REDD) by developing projects which protect and secure existing forest ecosystems.

Energy-based solutions

E.g., Supporting the installation of **renewable electricity generation** or methane capture & utilisation (landfills, wastewater, mines etc.) in low income countries.

REMOVAL:
Projects that remove carbon from the atmosphere, and therefore ‘neutralize’ emissions.

Nature-Based Solutions

Use photosynthesis to capture CO_2 from the air and store it in the biosphere above ground, below ground, and in the oceans.

E.g., Restoration solutions such as **afforestation / reforestation**, and peatland restoration, or **Improved Management** solutions such as enhancing soil carbon sequestration.

Engineered/Hybrid solutions

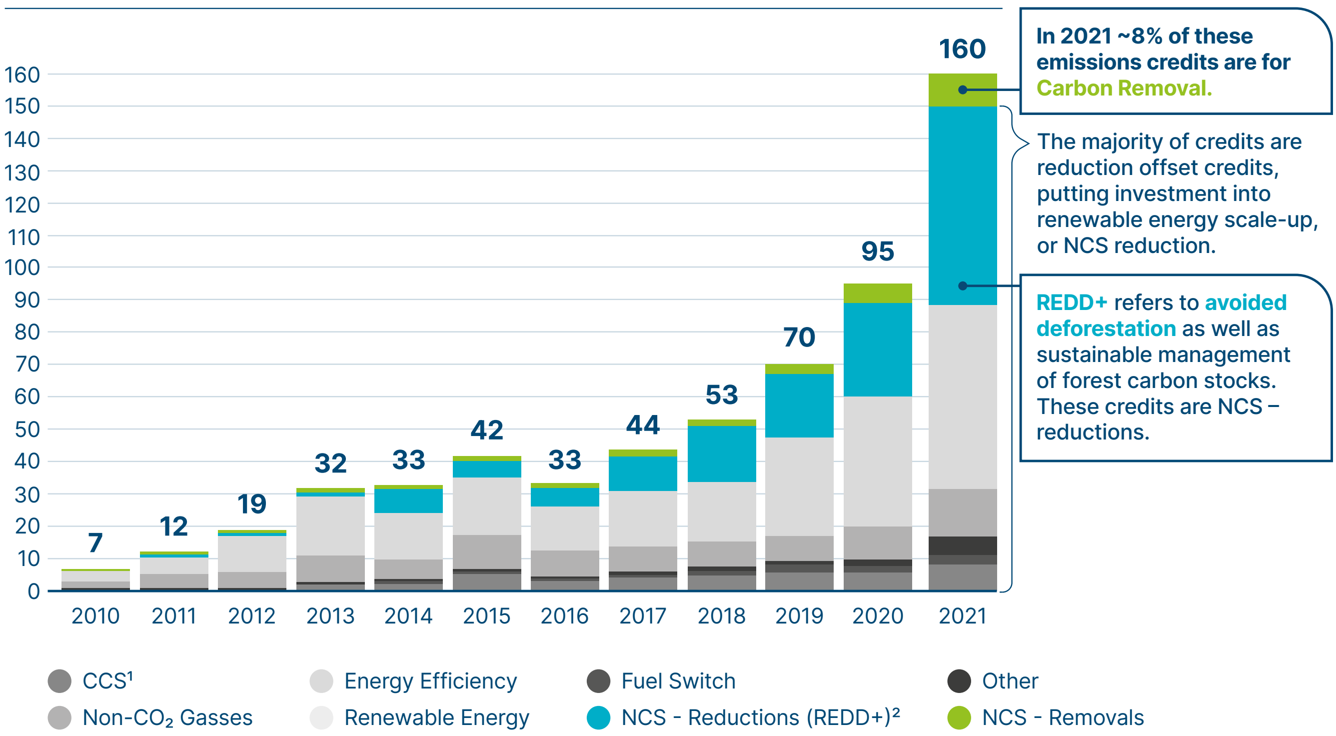
Energy-consuming technologies are used to capture CO_2 from the atmosphere.

E.g., **Direct air capture** (DAC); where chemical solvents are used to capture CO_2 directly from the air then transport and store it in geological formations, or BECCS; where bioenergy production is combined with carbon capture and storage.

Exhibit 41

The vast majority of voluntary carbon credits purchased today are ‘reduction’ credits, not ‘removals/neutralisation’

Demand for voluntary carbon credits 2010-2020
Mt CO_2e



NOTE: [1] Assumed that the vast majority of CCS credits are for point-source CCS, and therefore a reduction credit.
[2] REDD+ refers to Reduced Emissions from avoided Deforestation and forest Degradation, as well as the sustainable management and enhancement of forest carbon stocks

SOURCE: Trove Intelligence Research (2021) *Future Demand, Supply and Prices for Voluntary Carbon Credits – Keeping the Balance.*
2021 data sourced from Climate Focus (2022),”*Voluntary Carbon Market Dashboard.*

5.3.2 Government actions

Government finance of removals (whether within own country or in others) are currently also very small. In total we estimate that no more than $10 billion per annum is currently supporting removals across all possible funding mechanisms.[184] As configured, no combination of current funding mechanisms will deliver removals at the scale we need in the 2020s, or by 2050.

- Even if all of the $100bn/yr of climate finance were directed towards removals, this alone is unlikely to be enough. In practice, this finance is directed towards emissions mitigation and climate adaptation efforts.

- Other possible incentive mechanisms are also limited in scope and scale. Direct incentives for removals are under development in certain geographies, but are early stage and currently not delivering removals at scale. Other mechanisms such as agricultural policy and/or subsidies could be oriented towards incentivizing removals (indeed some funding is available under the EU's Common Agricultural Policy), but are likely to only deliver a subset of the overall removals required.

5.3.3 The overall gap in funding

A massive increase in financing flows to support removals is therefore required [Exhibit 39] in order to:

- Grow overall market size from close to zero today, to around $200bn/yr by 2030 - a scale sufficient to deliver the removals envisaged in our pathway.

- Ensure sufficient long-term demand for removals to give investors the confidence to develop removals projects in anticipation of future revenues from removals; from close to zero today, this investment needs to rise to around $130bn/yr by 2030.

5.4 Who should pay for removals

As section 5.2 described, carbon removals could be paid for by governments or by companies: and companies might be motivated to buy credits either to meet compliance market requirements or to meet voluntarily adopted net-zero or other targets.

However, credits sold in carbon markets (whether compliance or voluntary) might also be used to drive a reduction in existing emissions (sometimes called a "reduction offset")[185] rather than true removals. To decide the appropriate role of carbon market "removal credits" we therefore need to consider the wider issue of what role credits of any sort should play in emissions reductions.

5.4.1 The role of carbon markets: a shift from reductions to removals over time

In principle, trade in carbon credits could reduce the global cost of achieving emissions reductions, with countries or companies which face high marginal costs to abate emissions paying to achieve emission reductions (or removals) elsewhere. Moreover, large financial flows are required to support decarbonisation in many developing countries: purchases of reduction credits could be one source of such finance. But there are also strong arguments for limiting company or country reliance on credits to achieve emissions reductions, and for ensuring a focus on specific categories of offset credit;

1. The latest climate science shows that we need to reduce global emissions to net-zero by mid-century. Net-zero is only achievable if residual gross emissions are fully offset by carbon dioxide removals. The potential role for any reduction credits must therefore decline towards zero over time, with mid-century markets focused almost entirely on removals.

2. When countries, companies, or sectors set ambitious targets to reduce their own emissions, this drives technological progress and cost reductions, reducing future abatement costs. Purchases of credits (whether reductions or removals) should therefore be on top of, not instead of, strong targets for reductions of countries' and companies' gross emissions.

184 SYSTEMIQ analysis for the ETC, and Coalition for Negative Emissions (2021), *The case for Negative Emissions*.
185 Credits which avoid or reduce emissions are interchangeably called reduction or compensation credits. This report uses the term 'reduction' credits.

3. Technological progress and cost reductions (e.g., in renewable energy) in turn mean that many projects which purchased credits might support would be likely to occur in any case, either immediately or in a few years' time. It is essential to ensure that any reduction actions financed by credit purchase are truly additional to what would be likely to occur in any case. Major concerns have been raised about the true additionality of several categories of reduction credit sold in some compliance or voluntary markets.

These factors argue strongly for countries, companies, and sectors setting as strong as possible targets for emission reductions *within themselves*, reaching close to zero gross emissions by 2050, rather than overly depending on the purchase of any form of offset credit.

For private sector actors, the Science-Based Target initiative (SBTi), has sought to enforce this maximum internal action principle by requiring that companies seeking accreditation commit to reducing their gross emissions by at least 80 to 98% (depending on sector), with only 2 to 20% of emissions covered eventually by the purchase of permanent removal credits.[186] Complementing this, the Mission Possible Partnership is now developing sector by sector pathways for all the harder to abate sectors to the economy.[187] Together these demonstrate that deep decarbonisation is possible in all sectors of the economy, and countries and companies should seek to decarbonise their emissions in line with these pathways.

However, provided that company purchase of credits is in addition to strong internal action, it can play a useful role, particularly if focused on actions which are most likely to be additional to a business as usual scenario. This will most likely be the case for:

- Many categories of removals, most of which will only occur if someone pays for them. For instance, no one would perform a DACCS operation except if paid to do so, and many reforestation projects will only occur if someone pays the provider to implement them.

- Some specific categories of reductions where it is clear that there is not yet a low/zero cost route to emission reduction and where crucially important emissions reductions will only occur if supported by a financial flow from developed to developing countries. In particular, the ETC's recent report on *Keeping 1.5°C Alive,* shows that in the next decade the world must both reduce deforestation and accelerate the closure of existing coal power plants before the end of their useful life to make a 1.5°C pathway attainable by 2030. [188] It is likely neither will occur without a flow of compensation towards low-income countries. Given the additional cost, accelerating actions in these two categories (e.g., by bringing forward the closure of an existing coal plant to 2030 or earlier), if time-limited, are more likely to be additional than many other forms of emission reduction.[189]

The challenge is therefore to design a set of rules, norms and guidelines which does not remove pressure on companies (or countries) to achieve maximum possible internal emissions reductions, but which also encourages credit purchasewhere

186 SBTi (2021), *The SBTi Net-Zero Manual & Criteria Version 1.0*. SBTi recommends most companies to make emission reductions of at least 90% to reach net-zero, leaving only a maximum of 10% of a company's base year emissions to be addressed through permanent removals. Under the SBTi NZ standard, companies in the AFOLU sector are expected to take a different approach to achieving their science-based targets – one that includes both emission reductions and removals.

187 Mission Possible Partnership (2021), "Mission Possible Partnership unveils how three of the most carbon intensive industries can reach net zero by 2050 and cut emissions in the next decade".

188 ETC (2021), *Keeping 1.5°C Alive: Closing the gap in the 2020s*.

189 i.e., only within the next decade.

this is clearly in addition to within company (or country) actions and provides a focus on the forms of credit purchase which are most likely to be additional. Policy and funding mechanisms that look to support additional action beyond internal emissions reductions should therefore prioritise actions that are most likely to be additional, and shift away from reductions towards removals over time.

Corporate decarbonisation strategies should prioritise credits from removals and some high-integrity, time-limited, reductions

First, consider the priority hierarchy of addressing atmospheric carbon...

Priority 1: Reduce own country / company / sector emissions as rapidly as possible.

Priority 2: Offset remaining emissions via:

- **a** **Removal credits** to close the overshoot gap[1]
- **b** **Reduction credits** for a transitional period: mainly **avoided deforestation and possible 'exit credits' (e.g. for early coal phaseout)** but with very tight focus on additionality[2]

Further action: Beyond neutralization, additional finance to accelerate high-ambition climate action and clean-tech innovation.

...To develop a high ambition strategy for nature and removals?

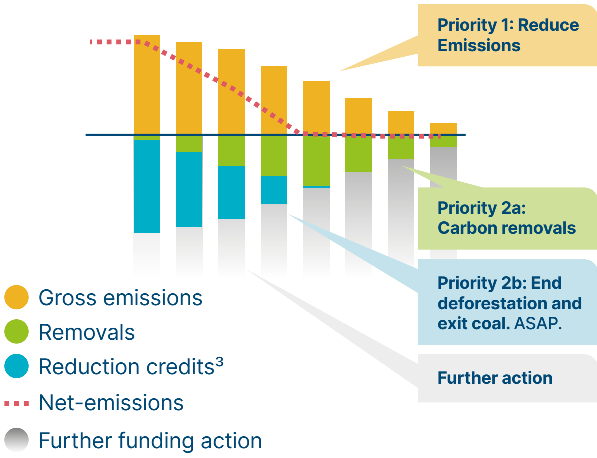


Exhibit 42

NOTES: [1] Overshoot of the carbon budget as defined by the IPCC (2021) and SYSTEMIQ Analysis for the ETC (2021). [2] Assuming time needed to scale up removals market in the 2020s, especially for BECCS and DACCS. Offsetting strategies should transition towards removals over time. [3] Likely to be restricted to time-limited credits for avoided deforestation and possible 'exit credits'. For the purposes of this illustration reduction credits don't contribute to net emissions.

5.4.2 The role of private sector funding

These principles and objectives could suggest the following approach:

In compliance markets, such as the EU ETS or equivalents, total emission credits available should be designed to fall along a path compatible with limiting global warming to 1.5°C, but a limited quantity of removal credits should be allowed to achieve net-zero in 2050 (Exhibit 43). Corporates should then meet their obligations in these compliance markets.

Expanding compliance markets – in both sectoral and geographical coverage – can be an important driver in scaling up removals.

Inclusion of CDR into emissions trading mechanisms can help scale removals

Illustrative introduction of CDR into compliance market over time, CO_2 per year

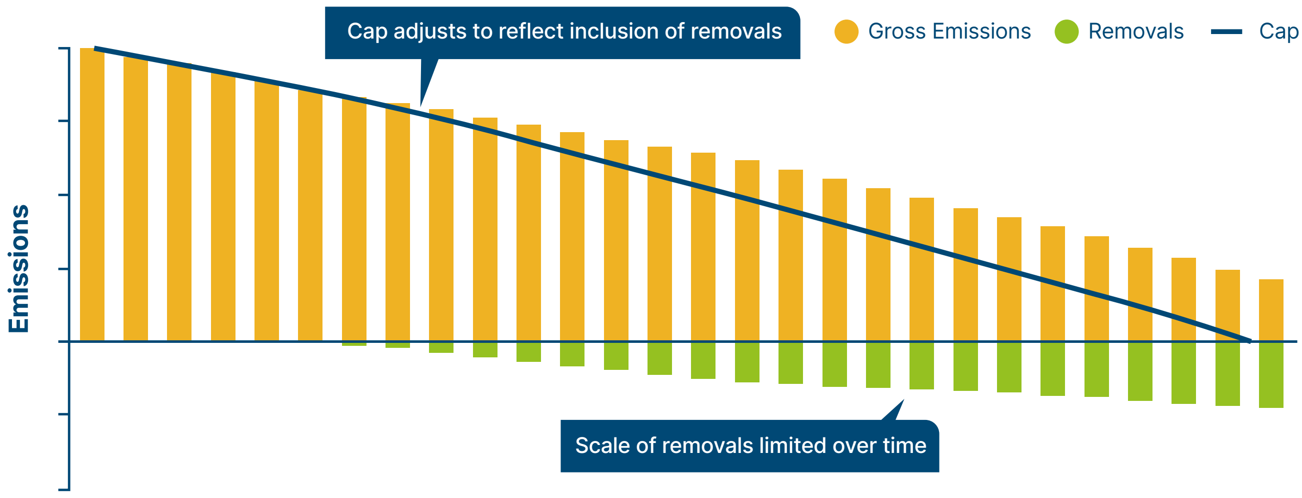


Exhibit 43

SOURCE: SYSTEMIQ analysis for the ETC, based on UK CCC (2019) *The Future of Carbon Pricing (Annex).*

In voluntary markets, where companies go beyond compliance markets and choose to make commitments beyond their legal obligations, there can be no absolute legal rules. And both likely and appropriate practices in these markets will vary by type of company.

- For companies in harder-to-abate sectors such as steel or cement, which need to make major investments to reduce emissions, the overwhelming focus should be on reducing their own emissions as rapidly as possible, rather than diverting funds to purchase credits.
- For many companies the next priority beyond their own Scope 1 and 2 emissions should be to make commitments that enable decarbonisation of supply chains (Scope 3 emissions), for instance via the purchase of green products or services.[190]
- But many companies, particularly in easier-to-abate sectors of the economy, may choose to make commitments to be "climate neutral "or "net-zero" not only in 2050 but at a much earlier date, or to use carbon credits to cover Scope 3 or legacy emissions.[191]

Exhibit 45 shows a range of possible approaches, in which we describe a continuum of these strategies.

Beyond carbon markets, private sector participants can also support the scale up of removals outside of carbon markets, by investing in R&D for emerging technologies and solutions, and payments for additional mitigation outside of their value chain that isn't in the form of 'carbon credits'.

To ensure any such voluntary commitments have integrity, trusted standard setters (e.g., the Integrity Council for the Voluntary Carbon Market (IC-VCM)), the Science-Based Targets initiative (SBTi), the Voluntary Carbon Market Integrity initiative (VCMI) and others) have a valuable role to play in advising on appropriate use of credits and appropriate use of terms such as "climate neutral" or "net-zero".

Given the principles set out above, we recommend that these standard setters should:

- Make it clear that by 2050 the world will need all residual gross emissions to be matched by *removals.*
- Encourage a significant focus on *removals* at much earlier dates.

190 For example, the recent commitment by Unilever, IKEA, Amazon and others to zero carbon shipping in their supply chain by 2040. Aspen Institute (2021, *Companies Aim to Use only zero-carbon ocean shipping by 2040.*

191 Various concepts around emissions neutrality exist, including carbon neutral, climate neutral, net-zero, carbon negative, and climate positive. This report uses 'climate neutral' to refer to all gross greenhouse gas emissions being offset.

- Limit the use of *reduction* offsets to situations where additionality can be clearly proven.[192]

As for the appropriate use of language, it would be useful if more standardised terminology could be agreed. At present there is huge divergence in how different words are used, to which gases they apply, what scope they cover, and the treatment of removals versus reductions. Exhibit 44 sets out non exhaustive examples of this diversity. The ETC is not proposing a comprehensive and definitive solution, but we do propose an approach to restricting the reducing the use of the term 'net-zero' via the following principles and limitations:

- All companies using a particular language, should provide precise definitions of how words are used, covering at least the dimensions shown in Exhibit 44.

- A claim that a company "is net zero" should only be made if a company's entire gross residual emissions, for all greenhouse gases, are already fully matched by high quality removals not reductions, and should be accompanied by;
  - A clear explanation of whether this covers only Scope 1 and Scope 2 emissions, or also Scope 3. If the former this should be made clear via the use of words such as "is net zero in relationship to its own directly controllable emissions".
  - A commitment and a strategy to rapidly reduce Scope 1 and 2 emissions for all greenhouse gases in line with the SBTi 80 to 98% guideline by 2050 or an equally ambitious decarbonisation pathway.
  - Clear information on what the remaining gross emissions are.

- A claim that a company "has a net-zero strategy" or "is net-zero aligned" should only be made if the company has a clear strategy to reduce at least its Scope 1 and Scope 2 emissions, of all GHGs, by 2050 to a level which is consistent with SBTi guidelines (i.e., 80-98%) and with the residual fully matched by removals, and not reductions.[193] A high ambition strategy would shift focus on "offsets" from high integrity reductions towards removals over time.

Companies use different terminologies for their sustainability claims, but it does not necessarily mean they are doing different things

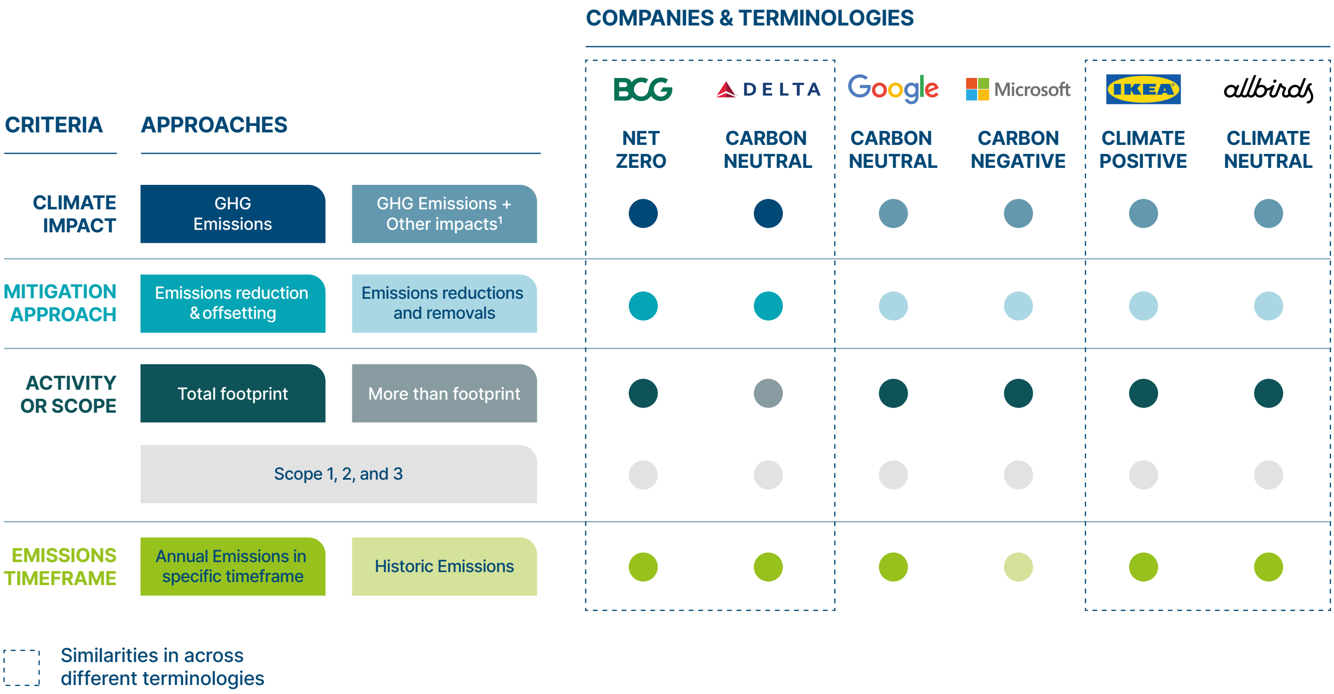


Exhibit 44

NOTES: ¹ Other impacts include but not limited to biodiversity, human rights, as well as justice and equality.
² Illustrative, based on publicly disclosed examples. There are no official definitions of these terms.
³ Adapted from WEF Analysis; Delta Air Lines; sustainability.google; Allbirds (2020) *Sustainability Report Net Zero* ; BCG; Microsoft (2020) *Environmental Sustainability Report*.

192 In the case of avoided deforestation, proving additionality may be extremely difficult except where governments are also involved to ensure the jurisdictional approach described above. And in the case of exit from existing coal, credits should be time-limited (e.g., to before 2030) since beyond some date existing coal plants would in any case close as the cost of removals falls below the marginal cost of running the existing coal plants.

193 Note: The UNFCCC Race-To-Zero Campaign has convened an expert peer review group that aims to define "net-zero" for corporates.

Exhibit 45

What should a responsible company do? There could be a continuum of action, based on the cost of decarbonisation as a proportion of revenues

Decarbonisation pathways to net-zero by 2050

Cost of decarbonisation as a proportion of revenue

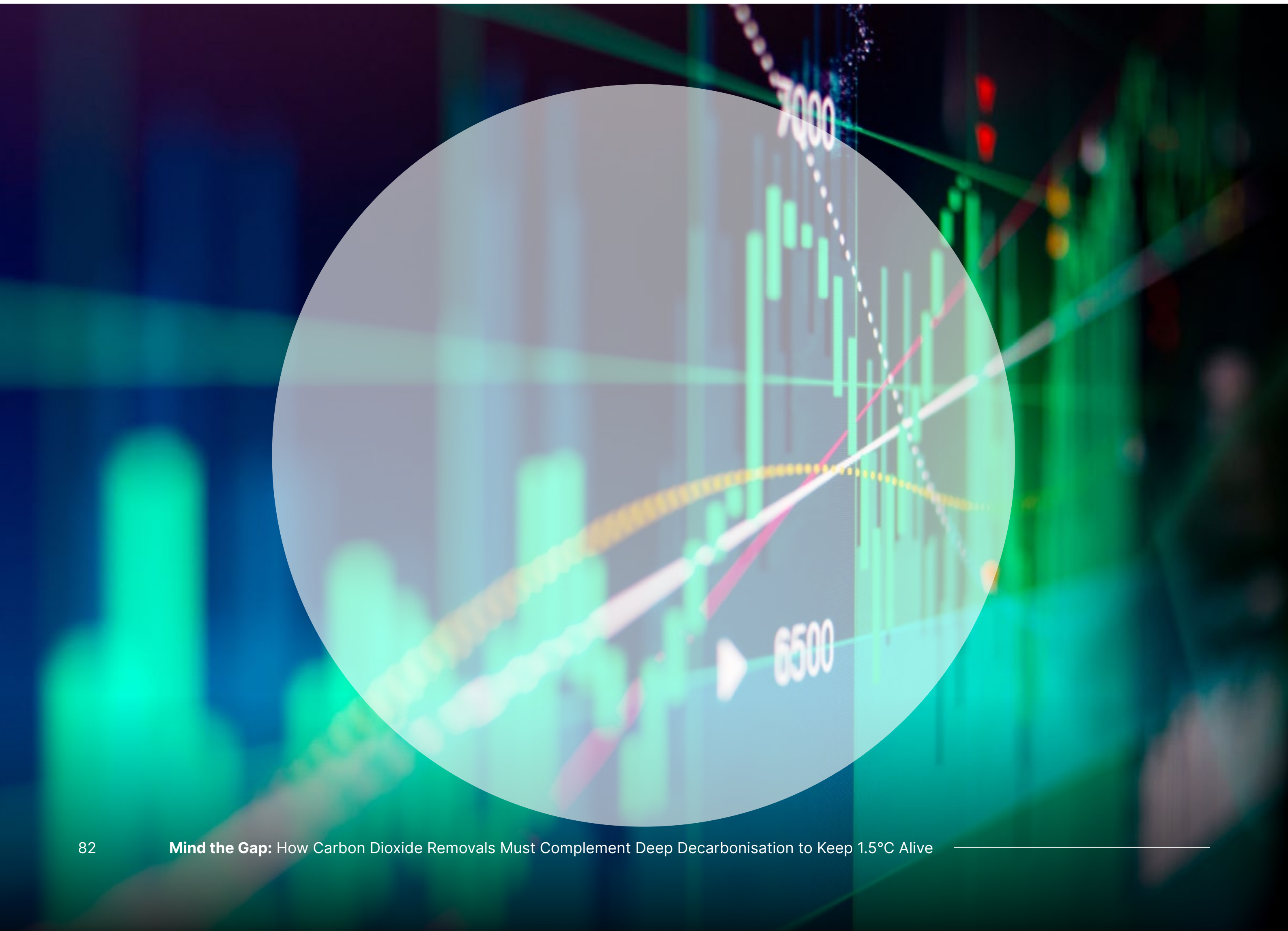
High
E.g. a steel plant

For firms with higher decarbonisation costs money may be better spent on decarbonising own operations, rather than investing in carbon credits to compensate emissions.

Low
E.g. a tech company

For firms with low decarbonisation costs (as a proportion of revenue) **or with high Scope 2 and 3 emissions**, high impact strategies should focus on emissions removals alongside decarbonising own operations.

NOTES: [1] Likely to be restricted to time-limited credits for avoided deforestation and possible 'exit credits'. For the purposes of this illustration reduction credits don't contribute to net emissions.



5.4.3 The vital role of government in funding removals

The approach described above could encourage a significant flow of finance from companies to achieve removals and high-priority forms of reduction, but they will not be sufficient. Total funding flows towards removals from voluntary and compliance markets are likely to be limited in scale, at least in the near term. This implies a gap in overall funding.

Governments will therefore also have to play a major role in funding removals and high-priority emissions reductions, both within their own countries and internationally.

Internationally significant financial support will be needed to flow from richer to poorer countries. Very large financial flows – whether in debt or equity form – will be required to support the development of a wide range of decarbonisation investments across the developing world. Additionally, developed country governments, working in particular via multinational development banks, should play a major role in reducing the cost of capital faced by developing countries.

However, some specific elements of emissions reductions will only occur if there is explicit grant finance, and the ETC's *Keeping 1.5°C Alive* report has argued that ending deforestation and closing existing coal should be two priority uses of the grant elements within international climate finance.[194] In addition to this, further funding is likely to be required to incentivise emissions removals. Indeed Scenario B in this report assumes these emissions reductions are delivered, without which additional removals would be required. Governments in developed countries could and should pay for reductions and removals in developing countries, either within or outside of the mechanisms established through "Article 6" of the Paris Agreement.

The reductions and removals achieved through this finance should, however, be in addition to the rapid reduction of developed world production emissions to zero. Operationalising the agreement of "Article 6" of the Paris Agreement is critically important, but this implies that the use of any "Article 6" credits to meet national production emission targets should be limited to a subset of removals required to offset residual gross emissions to zero by mid-century.[195]

Financing flows to support avoided deforestation or early coal closure should not therefore be counted as a mechanism to meet developed world NDC commitments, but as a necessary additional contribution to the global fight against climate change. In addition, some countries may choose to describe them as compensating for the excess of consumption over production emissions, contributions in excess of NDC commitments, or for historical emissions.

In their own countries, governments can incentivise the take up of removals through carbon markets – such as compliance markets, or regulation of voluntary carbon markets – or through other policy mechanisms, such as direct support for removals, or agricultural policies or subsidies that encourage uptake of removals. Currently, these mechanisms are not targeted towards removals, but significant opportunities exist to do so, by:

- **Regulating corporate net zero claims, and purchases in voluntary carbon markets**, to ensure funding flows towards high-integrity reductions, and emissions removals.

- **Reforming existing policy and subsidy mechanisms** to incentivise removals. For example agricultural policies and subsidies could be reformed to incentivise soil carbon sequestration, improved forest management and agroforestry.

- **Providing direct support to removals** – either through innovation support, or direct payments for removals.

194 ETC (2021), *Keeping 1.5°C Alive: Closing the Gap in the 2020s*.

195 'Article 6' of the Paris agreement seeks to establish an international emissions trading market, within which emissions reductions within one country, could be counted in another countries' Paris Agreement contributions.

Chapter 6

Actions for the 2020s

Preventing global temperatures from rising more than 1.5°C will require developing a portfolio of CDR solutions, starting from today. Crucially this is in addition to, not instead of, deep emissions reductions to mid-century. CDR solutions will not be enough if the global economy does not also succeed in rapid and ambitious decarbonisation.

The ETC discusses in depth how to deliver action for decarbonisation in its *Keeping 1.5°C Alive* and *Making Mission Possible Series*.[196] Examples of key actions in the 2020s are:

- Decarbonising the power sector and accelerating the phaseout of coal. An immediate ban on the construction of new coal-fired power plants, combined with a phaseout of existing coal plants. Rich developed countries should commit to total phase out by 2030.
- Ending all deforestation and forest degradation by 95% by 2030, particularly in the tropical and sub-tropical belt.
- Scaling up global power supply to greater than 70% low-carbon sources by 2030.
- Rapidly reducing methane emissions, including fossil fuel leakage and agricultural emissions.

Yet even in the ETC's most ambitious decarbonisation scenario 70-225 Gt CO_2 of CDR will be required between now and 2050 to neutralise overshoot of the carbon budget associated with <1.5°C targets.

If this scale of removals is to be achieved it is essential that governments and companies take action in the 2020s to:

- Deliver significant CDR of around 3 to 4 Gt CO_2 per annum by 2030 from a spectrum of solutions.
- Ensure early investment in NCS to deliver further sequestration in subsequent years.
- Support early development of engineered and hybrid solutions to prove feasibility and drive down costs.

This chapter therefore sets out:

- Recommended appropriate quantitative targets for annual CDR by 2030.
- The actions which different combinations of governments and companies must take if these targets are to be achieved.

196 ETC (2021), *Keeping 1.5°C Alive: Closing the gap in the 2020s*. ETC (2020-2022), Making Mission Possible series. ETC (2020), *Making Mission Possible: Delivering a Net-Zero Economy*; ETC (2021), *Making Clean Electrification Possible*; ETC (2021), *Making the Hydrogen Economy Possible*; ETC (2021), *Bioresources within a Net-Zero Emissions Economy*; ETC (Upcoming, 2022), *Carbon Capture Utilisation and Storage*.

6.1 CDR targets for 2030

There is no single global body which can set CDR targets, but to guide coordinated action from industry, corporates and governments it is useful to describe the scale of sequestration which needs to be achieved by 2030.

Recommended CDR targets for 2030 are set out in Box J.

Box J: Recommended targets for 2030 to scale CDR

Recommended targets for 2030:

Combined CDR deployment	• 3.6 Gt CO_2/year of carbon sequestered through CDR. • $200billion/year equivalent market size. • $130billion/year of annual investment in CDR.

	Recommended targets for 2030:	Challenges include:
NCS – Restore	~1.6 Gt CO_2 per annum of CDR. • Planting or recovering ~300 Mha of forest on degraded marginal land, focussing on the tropics. • Re-wetting ~13 Mha of peatlands. • Re-establishing ~7 Mha of coastal wetlands, mangroves and estuaries.	Projects must be deployed at scale in the 2020s to deliver maximum sequestration potential by 2050. Risks of reversal must be reduced. Monitoring and verification must be improved.
NCS - Manage	~1.6 Gt CO_2 per annum of CDR. • Placing ~500 Mha of forest under more sustainable forestry practices. • Performing regenerative agricultural practices on ~400 Mha of cultivated (grazing and crop) land to restore soil health.	Projects must be developed in the 2020s to change current land management practices (e.g., farmers, foresters). Monitoring and verification tools must be improved to quantify the impact of these actions. Methodologies for quantifying sequestration achieved from forest management, soil carbon sequestration and biochar will also need to be agreed.
Hybrid / BiCRS	~0.2 Gt CO_2 of BECCS per annum, drawing on ~1.5 EJ of sustainably sourced biomass. • Building ~35 BECCS facilities of average 5 Mt CO2/yr capacity. ~0.1 Gt CO_2 per annum of biochar sequestration, drawing on ~2-5 EJ of sustainable biomass supply • Apply biochar to ~40 Mha of cropland every year by 2030.	BECCS projects are under development but not yet widely operating at commercial scale. Demonstrating high capture rates will be critical. Certification schemes for sustainable bioenergy feedstocks need to be improved. Biochar projects are currently small and bespoke. Standardised processes need to be developed and costs reduced.
Engineered	~0.1 Gt CO_2 of per annum of commercial scale DACCS.[197] • Bringing online ~80 DACCS facilities, assuming average plant size of 0.75 Mt CO_2 per annum.	DACCS projects are today very high cost. Cost reduction via innovation and deployment required to make DACCS a relia*ble option beyond 2030.*
Novel CDR solutions	Research and pilot projects needed by 2030 to explore potential of additional novel CDR approaches.	Research needed to fully understand environmental and social impacts before investment to bring to commercial scale.

197 Requirign utilising ~125 TWh of wind and ~110 TWh solar power generation Assuming 90% VRE scenario; ETC (2021), *Making Clean Electrification Possible*.

6.2 Nine actions to deliver 2030 targets for CDR

Nine near-term actions to achieve CDR in the 2020s

Exhibit 46

In addition to rapid and critical decarbonisation action

Area	Action	Detail	Corporates	Regulators	Governments	Brokers & exchanges	Standard setters[2]	Project developers
Close the funding gap	**1. Scale up voluntary carbon markets by pursuing high-ambition corporate action and encouraging a shift from reduction offsets to removals.**		●				●	
Close the funding gap	**2. Establish compliance carbon markets and expand to include a limited quantity of removals.**		●	●	●			
Close the funding gap	**3. Direct government support for carbon removal via funding of projects or purchase of credits, both nationally and internationally.**				●			
Close the funding gap	**4. Indirect government support for carbon removal via adjustments to existing government spending, e.g. re-directing agricultural subsidies and funding of nature restoration initiatives**				●			
Manage project risk	**5. Address risks around permanence and additionality for CDR solutions**	**NCS:** Ensure continued use of buffer pools, invest in M&V[1] technology, support application of 'Jurisdictional approaches' and prioritise high-impact regions.			●	●	●	●
Manage project risk	**5. Address risks around permanence and additionality for CDR solutions**	**Engineered:** Invest in M&V technology for geological storage and establish norms for long-term maintenance liability. Scale clean power.		●	●	●	●	●
Manage project risk	**5. Address risks around permanence and additionality for CDR solutions**	**BiCRS:** Invest in M&V technology for geological storage and biochar longevity. Establish criteria and verification for sustainable biomass feedstocks.		●	●	●	●	●
Manage project risk	**6. Ensure carbon credits are of the highest possible integrity, via improved standards and regulation.**		●	●	●		●	
Create enabling conditions	**7. Build associated supporting infrastructure (renewable power, CCUS and sustainable biomass supply chains)**		●	●	●			●
Create enabling conditions	**8. Public education; e.g., to levy funding for training for of farmers and land-owners to learn improved soil and forest management and degraded land recovery.**				●			●
Create enabling conditions	**9. Accelerate CDR innovation via research and development grant funding**		●		●			

(Key responsible actors)

NOTES: [1] M&V = Monitoring and Verification;
[2] 'Standard Setters' include voluntary bodies setting standards for corporate action and credits, credit standard setters are often closely associated with brokers and exchanges

Atul Loke for Panos Pictures/Food and Land Use Coalition

Actions to close the funding gap:

In total we estimate that no more than $10 billion per annum is currently supporting removals.[198] The market size must grow to around $200 billion by 2030 – a significant gap.

A massive increase in financing flows from different sources is therefore required. Key actions and key actors are:

1. **Scale up voluntary carbon markets by pursuing high-ambition corporate action and encouraging a shift from reduction offsets to removals.**

   - **Responsible "High Ambition" Corporates** should commit to Science-Based Targets initiative (SBTi) pathways, and additionally commit to voluntary payments focused on truly additional and time-limited opportunities, with increasing focus on funding emissions removals. This voluntary action should be aligned with pathways which reflect their cost of decarbonisation as a proportion of revenue (see Exhibit 45).

   - **Standard setters** should define "High Ambition" pathways for decarbonisation, encouraging funding of removals alongside decarbonisation. They should also establish a clear definition on the language used behind corporate claims by at least 2025, (e.g., 'carbon neutrality,' 'climate neutrality' and 'net-zero'). In particular use of the term 'net zero' should be restricted to companies with ambitious decarbonisation trajectories, with any remaining emissions fully offset by removals (see Chapter 5).

2. **Establish and expand compliance markets, ensuring they include a limited quantity of removals.**

   - **Governments and other market regulators** (e.g., CORSIA) should establish carbon pricing and emissions trading where it doesn't currently exist. Where it does, they should look to expand market coverage and in all cases should consider introducing some limited quantities of removals into these markets, with the combination of emissions minus removals declining towards a cap of 'net-zero' by 2050 at the latest.

3. **Direct government support for carbon removal via funding of projects or purchase of credits, both nationally and internationally.**

   - **Governments of higher income countries** should make financial commitments to purchasing removal credits in the 2020s (to make up for the shortfall in funding from voluntary and corporate markets). For governments to fund approximately 2 Gt CO_2 of removals by 2030 will cost around $100billion. This should include funding and purchase of removals domestically (where contributions can be included in NDC accounting) as well as additional purchase of removal credits internationally (e.g., via climate finance)(where any action should be counted outside of a Government's NDC accounting).

4. **Indirect government support for carbon removal via adjustments to existing government spending, e.g., re-directing agricultural subsidies and funding of nature restoration initiatives.**

   - **Governments** need to increase indirect financial support for CDR through policy action. They should fund domestic nature reservations, marine protected areas, and re-wilding projects. Governments should also make commitments by 2025 to assign environmental outcome measures to agricultural subsidies (e.g., to incentivise soil carbon sequestration).

   - **Governments of lower income countries** should where applicable leverage international development aid to finance NCS solutions and their associated co-benefits for development, including recovery of degraded land.

Actions to manage project risk:

Each CDR solution has risks associated with additionality, permanence and low-integrity credits. The challenge of proving 'additionality' is to predict what would have happened in the absence of a CDR project. 'Permanence' is the risk of carbon being re-released into the atmosphere within a short time-span. 'Low-integrity' means the risk of a credit being sold that does not deliver the promised volume of sequestration, or leads to adverse consequences (environmental or other).

198 SYSTEMIQ analysis for the ETC, and Coalition for Negative Emissions (2021), *The case for Negative Emissions*.

To address risk the key actions and key actors are:

5. Address permanence and additionality risks for each of NCS, engineered and hybrid solutions.

Different actions can be taken to address risk for different CDR categories

a. NCS.

- Investing in Monitoring and Verification (including technology and training).
- Ensuring the continued use of Buffer Pools.
- Supporting the application of Jurisdictional Approaches.
- Prioritising regions such as the tropics.

b. Engineered.

- Establishing long-term liability for maintenance and verification of geological storage sites.
- Scale clean power supplies.

c. Hybrid / BiCRS.

- Establishing long-term liability for maintenance and verification of geological storage sites.
- Establishing criteria and verification for sustainable biomass feedstocks to avoid additionality risks from indirect land use change.
- Investing in Monitoring and Verification of biochar longevity in soils.

I. For NCS solutions:

Natural climate solutions are difficult to measure and verify and face high risks of disruption through both human and environmental drivers.

- **Regulators and project developers** should establish best practice monitoring technologies and standards to ensure that once removed, carbon remains in long-term storage in the biosphere. This will require scaling the use of monitoring technologies such as remote sensing to make it easier and safer to undertake. Robust methodologies need to be agreed, reinforced by real world trials and regular monitoring, to validate that 'Manage' and 'Restore' solutions do deliver additional sequestration in practice.

- **Standard Setters** must ensure the continued use of buffer pool methodologies to build safety margins into assumed sequestration from CDR, and ideally, standardise an approach across the market.

- **Project Developers** should prioritise, where possible, the scaling of NCS projects in the tropics, as this region has the highest sequestration potential and lowest risk of environmental disturbance such as wildfire and pests. In doing so they should work with local communities, establishing diverse revenue streams and ensuring clear land rights in order to improve resilience and ensure positive environmental justice outcomes.

- **Governments** should deploy 'jurisdictional approaches' (managing NCS solutions at regional scale to avoid land displacement effects) to ensure forest-based natural climate solutions (including avoided deforestation) are truly additional, even if voluntary company credit purchases help to finance them. Once in place governments can then invite companies that wish to directly contribute through the purchase of removal credits and through blended finance mechanisms.

II. For engineered solutions:

Engineered solutions must address long-term liability for ensuring permanence of geological storage. They also face require sufficient clean power capacity, which drives high costs today.

- **Regulators and project developers** should establish best practice monitoring technologies and standards for geological storage, and clarify long-term liability for monitoring to ensure no leakage is taking place.

- **Governments and project developers** should work together to ensure sufficient scaling of clean power supply, in addition to the decarbonisation of national power grids.

III. For Hybrid/BiCRS Solutions:

Hybrid / BiCRS solutions must overcome risks around responsible sourcing of sustainable biomass for their respective uses, improve measurement of stored biomass carbon (e.g., biochar), and address monitoring and verification of geological storage.

- **Regulators and project developers** should establish common best practice methodologies for monitoring technologies and standards for both geological storage and longevity of stored biomass (e.g., biochar) and clarify long-term liability for monitoring to ensure no leakage is taking place. Robust methodologies need to be agreed, reinforced by real world trials and regular monitoring, to demonstrate that solutions do deliver additional sequestration in practice. To avoid delays to deployment they should also aim to demonstrate via case studies within the next 5 years that real world projects are able to deliver this expected sequestration.

- **Governments** should work with the agricultural and forestry sector to establish criteria for the sustainable supply of biomass from forestry plantation residues, crop residues, and dedicated crops in such a way as to ensure that no indirect land use change has taken place.[199]

199 Discussed further in ETC (2021), *Bioresources within a Net-Zero Emissions Economy.*

6. **Ensure carbon credits are of the highest possible integrity, via improved standards and regulation.**

- **Governments** need to help ensure all high-integrity removals by:
  - Defining or approving standards for emissions removals.
  - Supporting the evolution of an independent third party verification via a new standards body, rating agency, system or equivalent regulations that ensure projects and standards are delivering what they state they deliver (as an additional layer of auditing to the current approach) (see Chapter 4).
- **Carbon credit standard setters** should continue to ensure the carbon market is high-integrity by further tightening additionality criteria for reduction credits and requiring best practice monitoring and verification for both reductions and removals. They should also encourage voluntary carbon markets to begin to shift purchases towards carbon removal.
- **Standard setters** who work with broader corporate targets should work to establish clear definition on the language used behind corporate claims (e.g., 'carbon neutrality', 'climate neutrality' and 'net-zero'). In particular restriction of the use of the term 'net zero' to companies with ambitious decarbonisation trajectories, with any remaining emissions fully offset by removals (see Chapter 5).
- **Brokers** and exchanges should look to transact only high integrity emissions removal credits, and should be transparent about the projects they transact.

Actions to create enabling conditions:

To accelerate the ramp-up of a portfolio of CDR, a range of enabling conditions need to be put into place to allow high-integrity solutions to develop at the rapid pace required.

Key actions and key actors include:

7. **Build associated supporting infrastructure (renewable power, CCSU and sustainable biomass supply chains).**

- **Governments** should account for CDR in infrastructure planning. As demand for delivering CO_2 removals increases, industrial infrastructure planning and approvals processes should take into consideration the capacity of projects to connect to CCS infrastructure and pre-emptively design permitting processes to avoid delays.
- **Government** and industry should consider developing shared CCS transport and storage infrastructure, increasing scale and reducing costs. They should also take into account future CDR when building out clean power capacity.

8. **Public education, including training of farmers and land-owners to learn improved forest and soil management and degraded land recovery.**

- **Project developers** should train communities to recover the economic value of degraded land via improved management practices. To do this they could leverage development finance for Natural climate solutions which also provide other benefits for the public good.
- **Governments** at both local and national level should also consider education and training for farmers and land-owners with the aim of incentivising additional carbon removal.
- **Governments** should develop public communications messaging strategies that communicate that carbon dioxide removal is essential in addition to, not instead of, rapid decarbonisation in gross emissions, and that this must be reflected in future NDCs.

9. **Accelerate CDR innovation via research and development grant funding.**

- **Governments** should create enabling conditions for innovation via research and development financing for nascent CDR technologies including enhanced weathering and oceans-based solutions (see Chapter 3.4).
- **Corporate** actors should consider CDR as a positive outcome for ESG criteria when assessing investment choices.

Glossary

Abatement cost: The cost of reducing CO_2 emissions, usually expressed in US$ per tonne of CO_2.

Afforestation and reforestation: "The planting of new forests on land not currently under forest cover. The forests remove carbon from the atmosphere as they grow."[1]

AFOLU sectors: Agriculture, forestry and other land use change sectors.

Agricultural residues: "There are two types of agricultural crop residues: field residues are materials (including stalks and stubble (stems), leaves and seed pods) left on the ground after the crop has been harvested. Good management of field residues can increase efficiency of irrigation and help control erosion. Process residues are those materials (include husks, seeds, bagasse and roots) left after crop processing. They can be used as animal fodder, as soil improvers, and in manufacturing."[2] A large fraction of crop residues (i.e., 50-70%) should be left on the field to support soil health.

Agroforestry: "A multi-use form of land management where trees are grown in association with arable crops or pasture."[2]

Albedo: "The fraction of solar radiation reflected by a surface". [3]

Annual crops: "Crops whose life cycle, from seed to harvest, is complete in less than 12 months." [2]

Anthropogenic emissions: "Emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities".[3]

'Article 6': Article 6 of the Paris Agreement outlines "principles for how countries can "pursue voluntary cooperation" to reach their climate targets".[4]

BECCS: A technology that combines bioenergy with carbon capture and storage to produce energy and net negative greenhouse gas emissions, (i.e., removal of carbon dioxide from the atmosphere). See 'BiCRS'.

BiCRS: Biomass carbon removal and storage. This term includes BECCS and other forms of carbon dioxide removal (e.g., biochar).[5]

Biochar: "The thermal decomposition of biomass in the absence of oxygen forms a charcoal known as biochar. This can be added to soils to improve soil fertility and to act as a stable long-term store of carbon."[1]

Biomass or bio-feedstock: Organic matter, i.e. biological material, available on a renewable basis. Includes feedstock derived from animals or plants, such as wood and agricultural crops, organic waste from municipal and industrial sources (including manure), or algae.

Bioenergy: Renewable energy derived from biological sources, in the form of solid biomass, biogas or biofuels.

Blue carbon: "The carbon captured by living organisms in coastal (e.g., mangroves, salt marshes, seagrasses) and marine ecosystems, and stored in biomass and sediments."[3]

Capital expenditure (CAPEX): Monetary investments into physical assets (e.g., equipment, plants).

Carbon budgets: The maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given probability, taking into account the effect of other greenhouse gas reductions. The remaining carbon budget indicates how much CO_2 could still be emitted while keeping warming below a specific temperature level. Carbon Budgets provide directional insight only and remain highly uncertain. They relate only to anthropogenic emissions or emissions from natural sources arising because of human activity (e.g., land use change), and already allow for the significant carbon sequestration which naturally occurs in forests and oceans.

Carbon capture and storage or use (CCS/U): We use the term "carbon capture" to refer to the process of capturing CO_2 on the back of energy and industrial processes. Unless specified otherwise, we do not include direct air capture (DAC) when using this term. The term "carbon capture and storage" refers to the combination of carbon capture with underground carbon storage; while "carbon capture and use" refers to the use of carbon in carbon-based products in which CO_2 is sequestered over the long term (e.g., in concrete, aggregates, carbon fibre). Carbon-based products that only delay emissions in the short term (e.g., synfuels) are excluded when using this terminology.

Carbon emissions / CO_2 emissions: We use these terms interchangeably to describe anthropogenic emissions of carbon dioxide in the atmosphere.

Carbon dioxide removals (CDR): sometimes shortened to 'carbon removals' refers to actions such as NCS or DACCS that can result in a net removal of CO_2 from the atmosphere. Carbon emissions / CO_2 emissions: We use these terms interchangeably to describe anthropogenic emissions of carbon dioxide in the atmosphere.

Carbon offsets: Reductions in emissions of carbon dioxide (CO_2) or greenhouse gases made by a company, sector or economy to compensate for emissions made elsewhere in the economy.

Carbon price: A government-imposed pricing mechanism, the two main types being either a tax on products and services based on their carbon intensity, or a quota system setting a cap on permissible emissions in the country or region and allowing companies to trade the right to emit carbon (i.e. as allowances). This should be distinguished from some companies' use of what are sometimes called "internal" or "shadow" carbon prices, which are not prices or levies, but individual project screening values.

1 UK Committee on Climate Change (2018), *Biomass in a low-carbon economy.*
2 BP (2014), *Biomass in the Energy Industry – an introduction.*
3 IPCC (2018), *An IPCC Special Report on the impacts of global warming of 1.5°C, Glossary.*
4 CarbonMarketWatch.org (Accessed 2022), "FAQ: Deciphering Article 6 of the Paris Agreement".
5 Sandalow et al. (2021), Biomass carbon removal and storage (BiCRS) roadmap.

Carbon sink: A reservoir for accumulating and storing atmospheric carbon.

Decarbonisation solutions: We use the term "decarbonisation solutions" to describe technologies or business models that reduce anthropogenic carbon emissions by unit of product or service delivered though energy productivity improvement, fuel/feedstock switch, process change or carbon capture. This does not necessarily entail a complete elimination of CO_2 use, since (i) fossil fuels might still be used combined with CCS/U, (ii) the use of biomass or synthetic fuels can result in the release of CO_2, which would have been previously sequestered from the atmosphere though biomass growth or direct air capture, and (iii) CO_2 might still be embedded in the materials (e.g., in plastics).

Direct air carbon capture (DACC): The extraction of carbon dioxide from atmospheric air. This is also commonly abbreviated as 'DAC'.

Direct air carbon capture and storage (DACCS): DACC combined with carbon storage.

EBIT sectors: Energy, building, industry, and transport sectors.

Ecosystem services: Services from nature including nutrient cycling, flood and disease control, and recreational and cultural benefits.[6]

Energy crops: In this report, we use energy crops to refer to 'second generation' crops that are unsuitable for consumption as food, such as miscanthus or short rotation coppice (e.g., willow or poplar).

Enhanced weathering: "Silicate rocks naturally fix carbon out of the air over geological timescales. This process can be speeded up by grinding up rocks (in order to vastly increase the exposed surface area) which can be dispersed over cropland."[7]

Emissions from the energy and industrial system: All emissions arising either from the use of energy or from chemical reactions in industrial processes across the energy, industry, transport and buildings sectors. It excludes emissions from the agriculture sector and from land use changes. (See 'EBIT sectors').

Emissions from land use: All emissions arising from land use change, in particular deforestation, and from the management of forest, cropland and grazing land. The global land use system is currently emitting CO_2 as well as other greenhouse gases, but may in the future absorb more CO_2 than it emits.

Final energy consumption: All energy supplied to the final consumer for all energy uses.

Feedstock: "Raw material, such as biomass, used for energy or material in a process."[8]

Forestry residues: "Small branches, tops, bark, and thinnings left over from commercial forestry operations and residues from wood processing industries (e.g., sawmills). Some residues need to be left for forest soil health. Residues do not include high-quality timber suitable for production of sawn wood."[6]

Greenhouse gases (GHGs): Gases that trap heat in the atmosphere. Global GHG emission contributions by gas – CO_2 (76%), methane (16%), nitrous oxide (6%) and fluorinated gases (2%).

Hydrocarbons: An organic chemical compound composed exclusively of hydrogen and carbon atoms. Hydrocarbons are naturally occurring compounds and form the basis of crude oil, natural gas, coal and other important energy sources.

Internal combustion engine (ICE): A traditional engine, powered by gasoline, diesel, biofuels or natural gas. It is also possible to burn ammonia or hydrogen in an ICE.

Jurisdictional approaches: "integrated landscape planning initiatives aligned with sub-national or national political jurisdictions to facilitate government leadership in advancing green economic development."[9]

Macroalgae: Commonly known as seaweed; includes species such as kelp. Macroalgae are very photosynthetically efficient and can be farmed in the ocean and used as food, other high-value uses, or as a source of energy.

Microalgae: Microscopic phytoplankton cultivated in pools on land. Microalgae are extremely efficient photosynthetic organisms and can be used to produce low lifecycle emissions food and animal feed as well as and other high-value products.

Natural carbon sinks: Natural reservoirs storing more CO_2 than they emit. Forests, plants, soils and oceans are natural carbon sinks.

Natural Climate Solutions (NCS): Actions considered to be a subset of nature-based solutions (NBS) with a specific focus on addressing climate change. NCS has been defined as "conservation, restoration, and/or improved land management actions to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, agricultural lands, and oceans".[10] NCS can be coupled with technology to secure long-term or permanent storage of GHGs, examples include CCS, the use of technologies such as torrefaction to process biomass or monitoring to improve forest management techniques for increased density.

Nature-based Solutions (NBS): Activities that harness the power of nature to deliver services for adaptation, resilience, biodiversity, and human well-being, including reducing the accumulation of greenhouse gases (GHGs) in the atmosphere. Actions to protect, sustainably manage and restore natural or modified ecosystems

6 BP (2014), Biomass in the Energy Industry – an introduction.
7 UK Committee on Climate Change (2018), *Biomass in a low-carbon economy.*
8 BP (2014), Biomass in the Energy Industry – an introduction.
9 Tropical Forest Alliance (Accessed 2022), "A closer look at jurisdictional approaches".
10 Griscom et al. (2017), Natural Climate Solutions.

which constitute natural carbon sinks, while simultaneously providing human, societal and biodiversity benefits.

Negative emissions (or 'net negative' emissions): is used for the case where the combination of all sector CO_2 emissions plus carbon removals results in an absolute negative (and thus a reduction in the stock of atmospheric CO_2).

Net-zero-carbon-emissions / Net-zero-carbon / Net-zero: We use these terms interchangeably to describe the situation in which the energy and industrial system as a whole or a specific economic sector releases no CO_2 emissions – either because it doesn't produce any or because it captures the CO_2 it produces to use or store. In this situation, the use of offsets from other sectors ("real net-zero") should be extremely limited and used only to compensate for residual emissions from imperfect levels of carbon capture, unavoidable end-of-life emissions, or remaining emissions from the agriculture sector.

Ocean alkalinisation: " Increasing ocean concentration of ions like calcium to increase uptake of CO_2 into the ocean, and reverse acidification".[11]

Ocean fertilisation: "Applying nutrients to the ocean to increase photosynthesis and remove atmospheric CO_2."[12]

Organic wastes: "Some key types of organic waste including wood waste, the organic fraction of municipal solid waste, livestock manures, sewage sludge, tallow and used cooking oil. These wastes should be minimised then reused/recycled before being used for energy production."[12]

Operating Expenditures (OPEX): Expenses incurred through normal business operations to ensure the day-to-day functioning of a business (e.g., labour costs, administrative expenses, utilities).

Peat: "Partially carbonized vegetable substance formed by incomplete decomposition of plant material in water. Peat is an important store of carbon, which is released into the atmosphere when peat is burned (for fuel) or when peat soils are brought under cultivation."[13]

Peatlands: "Peatlands contain layers of partially decomposed organic material preserved in waterlogged environments. They contain a large fraction of the world's terrestrial carbon stock and when damaged or destroyed can become large sources of GHG emissions."[13]

Primary energy consumption: Crude energy directly used at the source or supplied to users without transformation – that is, energy that has not been subjected to a conversion or transformation process.

Project-based credits: Carbon credits issued for individual, stand-alone, emissions reduction projects (e.g., avoided deforestation) not part of a larger jurisdiction.

Pyrolysis: the thermochemical decomposition of organic matter into gases, liquids, and a solid residual coproduct (including biochar or charcoal) in the absence of oxygen, which can then be used for its energy content.

Residues: Residues is used in this report to refer to biomass that is generated as a waste or co-product of an industry. Sources include forestry (e.g., bark, branches, and wood chips), agriculture (e.g., cereal straw and husks) and municipal and industrial waste (e.g., waste oils, manure from livestock production, and other organic wastes). See 'Agricultural residues' and 'Forestry residues'.

Rotation period: The time period from planting to harvest.

Sequestration: Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide.

Soil carbon sequestration: "Increasing the amount of carbon stored in soils through improved agricultural practice."[13]

Soil organic matter: "The organic component of soil, which includes the living biomass of microorganisms, and fresh and partially decomposed residues. It also includes well-decomposed, highly stable organic material. Surface litter is generally not included as part of soil organic matter but can become part of it if physically incorporated into the soil. Soil organic matter is of vital importance for nutrient cycling, erosion protection and for its water-holding capacity."[13]

Sustainable biomass / bio-feedstock / bioenergy: In this report, the term 'sustainable biomass' is used to describe biomass that is produced without triggering any destructive land use change (in particular deforestation), is grown and harvested in a way that is mindful of ecological considerations (such as biodiversity and soil health), and has a lifecycle carbon footprint at least 50% lower than the fossil fuels alternative (considering the opportunity cost of the land, as well as the timing of carbon sequestration and carbon release specific to each form of bio-feedstock and use).

Synfuels: Hydrocarbon liquid fuels produced from hydrogen, carbon dioxide and electricity. They can be zero-carbon if the electricity input is zero-carbon and the CO_2 is from direct air capture. Also known as "synthetic fuels", "power-to-fuels" or "electro-fuels".

Technology Readiness Level (TRL): Describes the level of matureness a certain technology has reached from initial idea to large-scale, stable commercial operation. The IEA reference scale is used.

Zero-carbon energy sources: Term used to refer to renewables (including solar, wind, hydro, geothermal energy), sustainable biomass, nuclear and fossil fuels if and when their use can be decarbonised through carbon capture.

11 Royal Society (2018), *Greenhouse Gas Removal Report*.
12 UK Committee on Climate Change (2018), *Biomass in a low-carbon economy*.
13 BP (2014), *Biomass in the Energy Industry – an introduction*.

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