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 1.1

Executive Summary

Energy
Transitions
Commission

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

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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

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Introduction

Global warming poses severe risks to communities and ecosystems this century. 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] Many countries and companies are therefore now committed to achieving net-zero by mid-century.

The Energy Transitions Commission (ETC) has demonstrated that it is possible to achieve more rapid reductions in 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.[2] Massive clean electrification must be at the core of decarbonisation pathways, combined with deployment of a range of complementary technologies, including clean hydrogen, carbon capture and storage or use (CCS/U) and sustainable bioenergy.

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 scenarios which we describe in this report suggest cumulative emissions between 2020 and 2050 of between 720 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 continuing beyond mid century.

This report therefore describes how a portfolio of CDR solutions, combined with ambitious decarbonisation, could prevent 'overshoot' of the 1.5°C carbon budget. It argues that to meet these objectives it is essential to implement carbon dioxide removals on a scale which could:

- Remove 70-225 Gt CO_2 between today and 2050.
- Deliver ongoing carbon removals of 3-5 Gt per in subsequent years to offset residual ongoing greenhouse gas emissions.

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[1] IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report. Summary for Policy Makers.*

[2] IEA (2021), *Net-Zero by 2050.*

This level of removals could be delivered by a portfolio of CDR solutions including Natural Climate Solutions (such as reforestation projects), engineered solutions (e.g., involving direct air capture of CO_2) and hybrid solutions (e.g., BECCS or biochar). A credible scenario suggests that these could together deliver 165 Gt CO_2 of removals between now and 2050, and an ongoing flow well above the 3-5 Gt CO_2 per annum likely to be required.

But removals on this scale will not occur without forceful policy actions and very significant investment. At present NCS solutions are typically much lower cost, but subject to significant measurement and permanence risks which must be carefully managed: engineered solutions by contrast can in principle be low risk, but are currently far more expensive. Effective actions must therefore combine large-scale but carefully managed investment in NCS solutions in the 2020s, some deployment of BECCS and other hybrid solutions, and the development of engineered solutions to reduce costs for future deployment.

Achieving this could require financial flows of $200bn per year by 2030 versus less than $10bn estimated to be devoted to removals today. A significant proportion of this could be financed by companies buying removal credits in compliance and voluntary markets, and companies should be encouraged to shift the focus of carbon credit purchase from so-called “reduction offsets” to projects that deliver actual carbon removals. But corporate purchases alone will be far from sufficient to deliver the scale of removals required - governments must also play a major role.

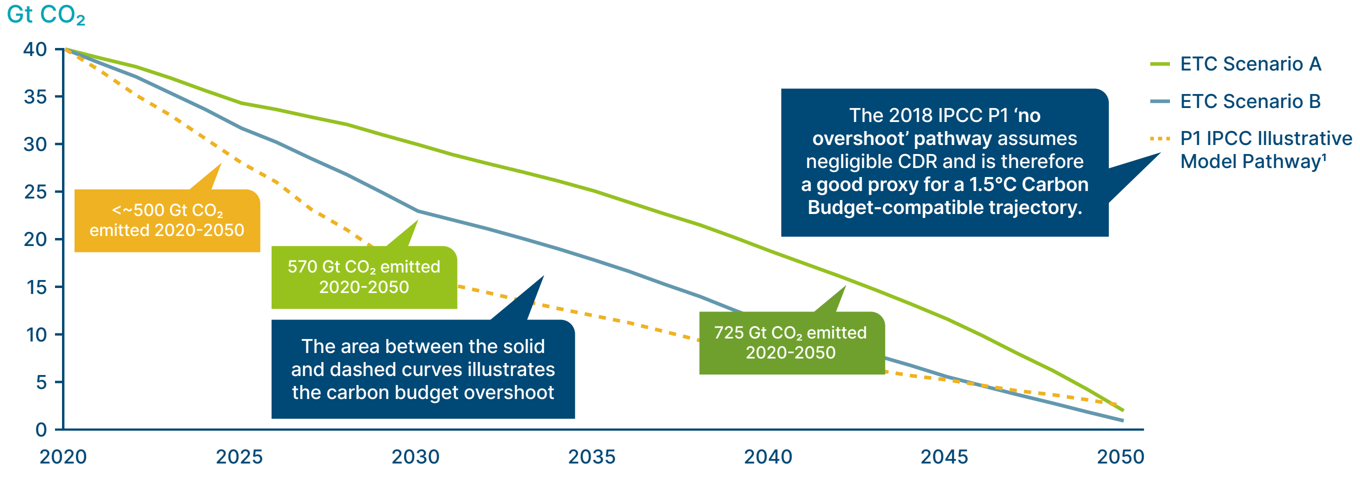
This executive summary sets out the key arguments which support these conclusions, covering in turn:

1. Climate targets and implications for carbon budgets.
2. Emission reduction scenarios and the size of the ‘overshoot’ 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?
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. A forthcoming ETC report will explore in detail the role of carbon capture storage and utilisation (CCS/U) 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



<~500 Gt CO_2 emitted 2020-2050

570 Gt CO_2 emitted 2020-2050

The area between the solid and dashed curves illustrates the carbon budget overshoot

725 Gt CO_2 emitted 2020-2050

The 2018 IPCC P1 ‘no overshoot’ pathway assumes negligible CDR and is therefore a good proxy for a 1.5°C Carbon Budget-compatible trajectory.

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)*

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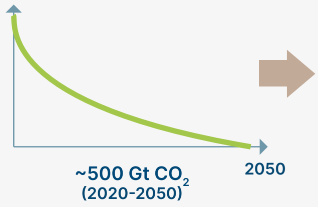
MIND THE GAP: CARBON DIOXIDE REMOVAL (CDR)

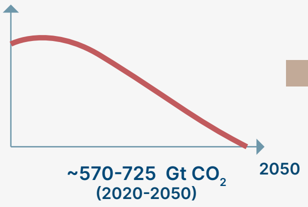
CDR is needed in addition to deep and rapid decarbonisation

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

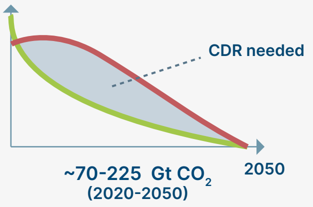
The 1.5°C aligned carbon budget emissions trajectory looks a bit like this:



But even ambitious decarbonisation scenarios look a bit like this:

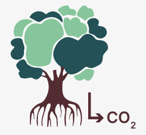


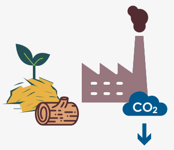
The carbon budget 'overshoot gap' – the amount of CDR needed to stay within the 1.5°C carbon budget – looks like this:

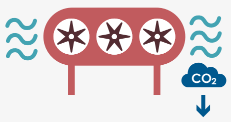


What will it take to scale CDR to keep 1.5˚C alive?

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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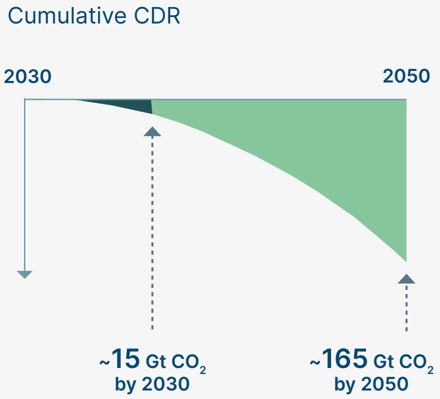
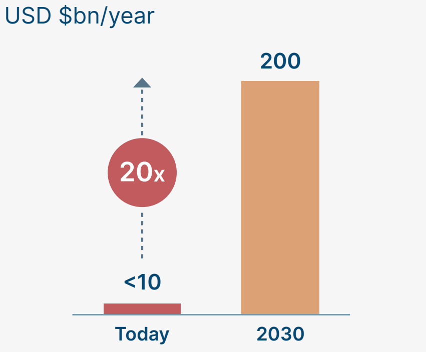
CLOSING THE CDR FUNDING GAP

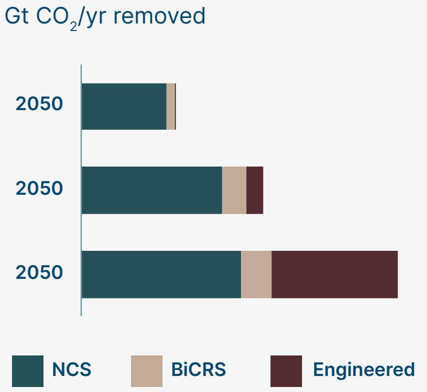
A MASSIVE SCALE UP OF CDR STARTING TODAY



REQUIRING A 20X INCREASE IN FUNDING BY 2030



DELIVERING AN EVOLVING PORTFOLIO OF CDR SOLUTIONS



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

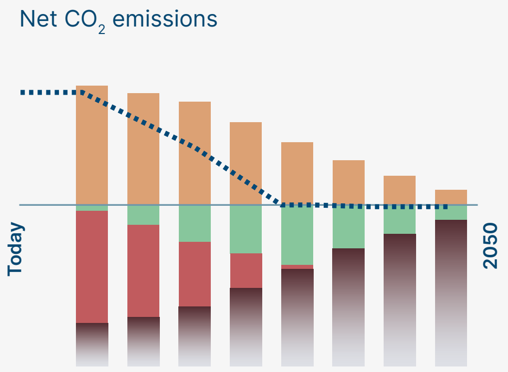
+

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



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

'RESTORE'

1.6 Gt CO_2 per year

300 Mha marginal degraded land (tropics) planted

7 Mha of mangroves restored

13 Mha of peatland recovered

MANAGE

1.6 Gt CO_2 per year

500 Mha (~12-15 %) of forest under improved management

400 Mha (12 %) of cultivated land under improved management

HYBRID / BIOMASS WITH CARBON REMOVAL STORAGE

BIOCHAR

0.1 Gt CO_2 per year

2-5 EJ of sustainable crop residue biomass

40 Mha of biochar applied to farmland

BECCS

0.2 Gt CO_2 per year

~4 EJ of sustainable biomass from residues and dedicated energy crops

~170 BECCS 1 $MtCO_2$ /yr scale facilities

ENGINEERED SOLUTIONS

DACCS

0.1 Gt CO_2 per year

235 TWh Of clean power, <10% of 2050 supply

~80 DACCS facilities

NINE ACTIONS TO SCALE CDR IN THE 2020s

In addition to rapid and critical decarbonisation 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*

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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’.[3] 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.

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[3] Griscom et al. (2017), *Natural Climate Solutions.*

I. 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.

In 2015 the world committed in Paris to keeping global warming above pre-industrial levels to “well below 2°C” and to aim for 1.5°C. In 2018, the IPCC described the growing and severe harm which would result if warming rose above 1.5°C.

Due to the complex nature of earth systems, climate science often deals in probabilities. At the current rate of greenhouse gas (GHG) emissions no decarbonisation pathway gives us a very high chance of limiting warming to 1.5°C. Yet reaching net-zero by mid-century is technically and economically feasible. The ETC therefore believes that we should set emissions reductions objectives to deliver at least a 50:50 chance of keeping global warming below 1.5°C, and a more than 90% chance of staying below 2°C. To achieve this, the IPCC recommends that cumulative CO_2 emissions between 2020 and mid-century must be limited to a “carbon budget” of 500 Gt CO_2.[4]

Carbon budgets can be estimated because concentrations of greenhouse gases in the atmosphere produce “radiative forcing effects” which increase atmospheric temperature. Other key GHGs, including N_2O, CH_4 and the fluorinated gasses, must therefore also be reduced. How much depends on whether they are long- or short-lived gasses and their relative ‘warming effect’.[5] For example:

- For the long-lived gases – in particular CO_2 – what matters is how cumulative emissions increase the future stock, since that stock will continue to have a global warming effect long after new emissions are reduced to zero.
- In the case of methane, which has a far shorter half-life - the global warming effect would stabilize if emissions ceased to rise and would reduce rapidly if the flow of emissions fell. As a result cutting methane emissions is a powerful short-term lever for reducing global warming.

The IPCC carbon budget target therefore also assumes a reduction of around 50-55% in annual methane (CH_4) emissions and 30% in annual nitrous oxide (N_2O) emissions by mid-century.

Objectives and policies must also reflect the fact that the impact of atmospheric GHG concentrations on global temperatures could 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). In addition, it is possible that, beyond some thresholds or “tipping points” positive feedback loops could become so strong as to trigger highly non-linear and irreversible climate change.

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 could imply a smaller acceptable budget.
- 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“negative emissions” beyond 2050, are unacceptably risky.

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[4] IPCC (2021), *Climate Change 2021: The Physical Science Basis. Summary for Policy Makers.*

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

II. 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 – a reduction of around 25% compared to today.
- 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 CO_2, but more importantly, a faster reduction in the 2020s , reaching 20 Gt CO_2 by 2030 – a reduction of around 45% compared to today.

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

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

Previous work of the Energy Transitions Commission,[6] suggests that CO_2 emissions from the Energy, Building, Industry, & Transport (EBIT) sectors could be reduced from today's 34 GtCO_2 per annum to around 2 Gt by mid-century through a combination of energy productivity improvements, clean electrification, and the wide-scale deployment of other zero-carbon technologies (hydrogen, sustainable bio-energy, CCS/U). Halting deforestation and changing agricultural practices could reduce CO_2 emissions from Agriculture, Forestry, and Other Land-use (AFOLU) from today's net 6-7 GtCO_2 to about <1 GtCO_2, and N_2O emissions could be cut by 40%. Total CH_4 emissions across all sectors could be reduced by around 40%.

Achieving these reductions will require forceful policies. But even if achieved they will still be insufficient to give a 50% chance of limiting warming to 1.5°C. Comparing ETC's Scenario A with the IPCC's carbon budget shows an overshoot of 225 Gt CO_2 over the next 30 years.[7] EBIT emissions do not fall fast enough in the 2020s to keep cumulative emissions within budget – IPCC pathways to meet a 1.5°C climate objective require around a ~50% reduction by 2030, our illustrative Scenario A would result in only a ~25% reduction.

[6] ETC (2018), *Mission Possible* ; ETC (2020), *Making Mission Possible.*

[7] In addition to on-going residual emissions of 2-3 GtCO_2 from 2050 onwards.

Faster emission reductions might be possible. The recent ETC report on "*Keeping 1.5°C alive*"[8] sets out six categories of actions which could bring emissions closer to the 1.5°C pathway.[9] These actions deliver significant emissions cuts by 2030; methane by ~40% and carbon dioxide by ~45%. Actions include accelerated closure of coal power generation, significantly reduced deforestation, and accelerated progress on road transport electrification, alongside decarbonisation of heavy industry and energy efficiency improvements. Yet even in this case, if these actions could be agreed and implemented, cumulative CO_2 emissions between now and 2050 would likely exceed the 1.5°C budget by around 70 $GtCO_2$.

While the precise scale of removals required will depend on future success with emissions reduction, it is clear that carbon dioxide removals at significant scale are essential – at least in a range of 70-225 $GtCO_2$ and still more if action to reduce gross emissions falls short of our Scenario A.

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

- To compensate before mid-century for the likely gap between the acceptable carbon budget and actual CO_2 emissions. Our scenarios suggest a need for at least 70-225 Gt CO_2 of removals between now and 2050.

- To compensate after mid-century for continuing residual emissions of both CO_2 and N_2O, which might run at about 3-5 Gt CO_2 /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.

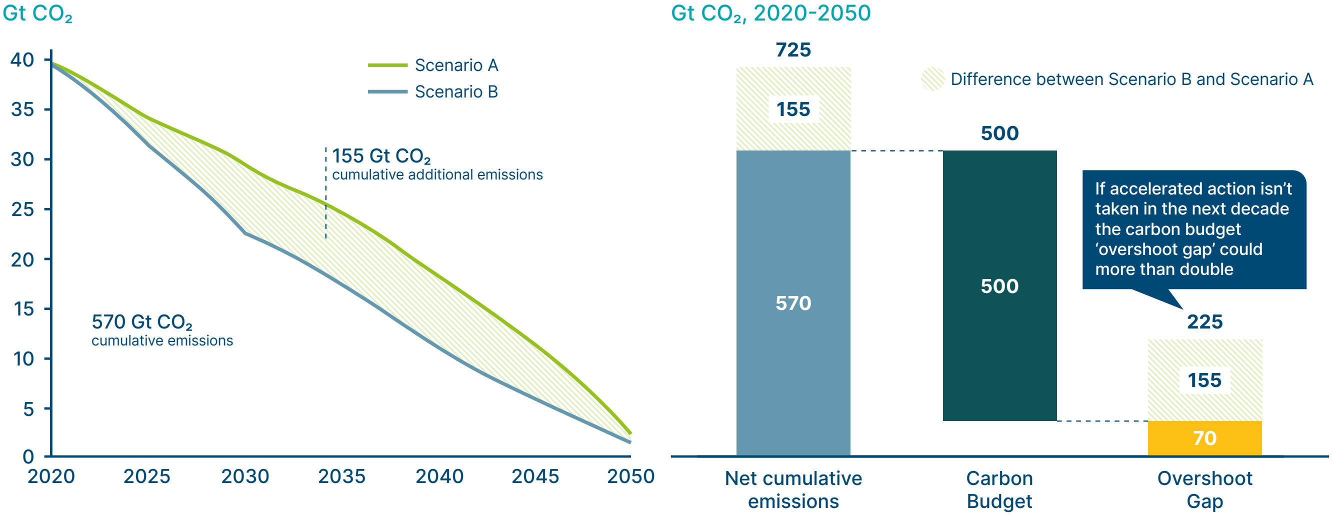
But any such strategy which relies on removing CO_2 after the 'budget' has already been overshot carries a danger of triggering potentially irreversible ipping points and self-reinforcing feedback loops. The world must therefore commit to a combination of gross emission reductions and removals which stays within a 500 Gt CO_2 carbon budget.

Exhibit 2

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



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*

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

[9] The 'low or no overshoot' illustrative pathways described in the IPCC (2021) *Climate Change 2021: The Physical Science Basis.*

III. Potential scale of carbon dioxide removals

- 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 3.5 Gt CO_2/yr by 2030 and 12 Gt CO_2/yr in 2050.

To mitigate the carbon budget overshoot gap identified in ETC's decarbonisation scenarios it will be necessary to deploy carbon dioxide removal solutions at scale before mid-century. Potential CDR technologies need to combineda process for removing CO_2 from the atmosphere and placing it in permanent storage. There are three main categories of technologies which are already technically feasible :

- **Natural Climate Solutions (NCS)**,[10] which use natural photosynthesis processes to capture CO_2 from the air, and which 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.
- **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 store it in a mineral rather than biochemical form. These include BECCS and Biochar.

For each of these options we consider how much could feasibly be deployed between now and 2050, by assessing, via literature reviews and expert consultation**:**

- The theoretical technical potential and how much of this might be 'cost-effective' to implement.[11]
- Real world deployment constraints on the pace of scale up and on how much of the cost effective potential can be achieved by when.
- The profile of annual carbon sequestration over time and the implications for cumulative removal achieved.

In addition there are a range of more nascent solutions – e.g., enhanced weathering, ocean alkalinisation and ocean fertilisation, which are currently at earlier stages of development and will require research funding to address undertainties about the impacts of application at scale.

Natural Climate Solutions (NCS)

Natural Climate Solutions 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. Natural climate solutions store carbon in live biomass (for example, trees) and in soils.

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 recently pre-existing natural ecosystem, but might involve afforestation of land which has not been forested for centuries.

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[10] 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*).

[11] 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.

- **‘Manage’ solutions** improve how land is managed to increase carbon sequestration, without changing the current primary use of the land e.g., through increased soil carbon sequestration on crop or pasture land, or improved management of existing forests.

The largest opportunity for NCS is in the tropical and sub-tropical belt, where substantial positive community and biodiversity co-benefits can be expected.

Four considerations are important in assessing the potential scale of NCS removals:

- **NCS solutions in particular have a significant implications for land use**.
  - Our cost-effective estimate for ‘Restore’ solutions assumes that that reforestation projects could be implemented on about 300 Mha of land in the next decade, with 7 Mha of coastal land and 16 Mha of peatland also restored within that timeframe (Exhibit 3). This is approximately 8% of standing forest area. To achieve maximum sequestration outcomes by mid-century, this area should be ‘planted’ or allowed to naturally re-grow over the next decade.
  - In principle improved practices could be applied to the vast majority of cultivated land. Published estimates 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.
  - To account for the implementation challenges inherent over such a large area, in our CDR estimates we assume that for “Manage” NCS solutions only 50% of the theoretically cost-effective potential is 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 (Exhibit 3).[12]
- **Restoration of degraded land into forest or wetlands is a simple concept but challenging to execute** due to the high risk of reversal, limits to available land, and political uncertainty. As a result the feasible cost effective potential may be considerably less than estimates of maximum technical potential. Efforts should be focused on geographic areas such as the tropics, which have high sequestration density and relatively low risk of wildfire, and where innovative technology, governance and financing can be used to reduce reversal risks.[13]
- **Improved management of existing land uses such as forestry or farming can lead to enhanced soil and biomass and better soil quality.** Here the cost-effective potential tends to be a higher proportion of the maximum technical potential since these approaches build on existing uses of the land rather than requiring land-use change.
- **Achieving the full potential of NCS requires early action**. Our supply-side estimate of CDR potential presented in Exhibit 4 below suggests that carbon removal via restoration of forests, peatlands and wetlands could grow to reach ~2 Gt CO_2/year by 2030 (increasing slightly to <3 Gt CO_2/year by 2050), while improved management solutions could in principle deliver a larger ~3.5 Gt CO_2/year by 2030.[14] It is important to note however that to achieve the ~2 Gt CO_2/year of restoration removals by 2030 would require much earlier action and massive scale up in stable financial support, given the inherently gradual growth rate of any nature-based sequestration.

It is critical to note that NCS sequestration must be *in addition to* reducing annual net AFOLU emissions by around 6 $GtCO_2$ by 2050 - primarily achieved via ending deforestation.[15]

Engineered solutions

Engineered solutions rely on technology, particularly carbon capture & storage (CCS), to artificially capture and store atmospheric CO_2. Direct Air Capture (DAC) is the most prominent engineered solution today:

- **Direct Air Capture (DAC)** is a chemical process that can capture CO_2 from ambient air, with the CO_2 then stored in products or geological formations **(DACCS)**. In principle the technical potential of DACCS sequestration is significant,

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[12] FOLU (2019), *Growing Better*, IIASA Data from GLOBIOM 2019.

[13] 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.

[14] Roe et al., (2021), *Land-based measures to mitigate climate change: potential and feasibility by country:* Note based on analysis from average annualised estiimates of sequestration potential 2020-2050.

[15] 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’ from occuring is therefore the main CO_2 emissions reduction lever for that sector.

but DACCS will always entail significant energy costs and DAC technologies are currently only demonstrated at very small scales (4000 tCO_2/year[16]). Nevertheless one or more variants of DAC are likely to become commercially viable by 2030, with large-scale application thereafter.[17] Future sequestration potential from DACCS is highly dependent on the pace of cost reduction and the resulting industry growth rate. Assuming a 25% annual industry growth rate from 2025, DACCS capacity could reach ~4.5 Gt CO_2/year by 2050.[18] This volume of DACCS would require 13,500 TWh/year of clean energy – equivalent to around 10% of the global electricity required in the ETC's 2050 scenarios.

Hybrid / Biomass with Carbon Removal (BiCRS)solutions[19]

Biomass with Carbon Removal and Storage (BiCRS) is an umbrella term for hybrid solutions which combine photosynthesis with various forms of storage technology. 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. BECCS can undoubtedly play a role in carbon dioxide removal: the crucial questions are the scale of sustainable supply of biomass and the optimal use of land.

- **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 in underground storage. It can also provide soil quality co-benefits.[20]

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

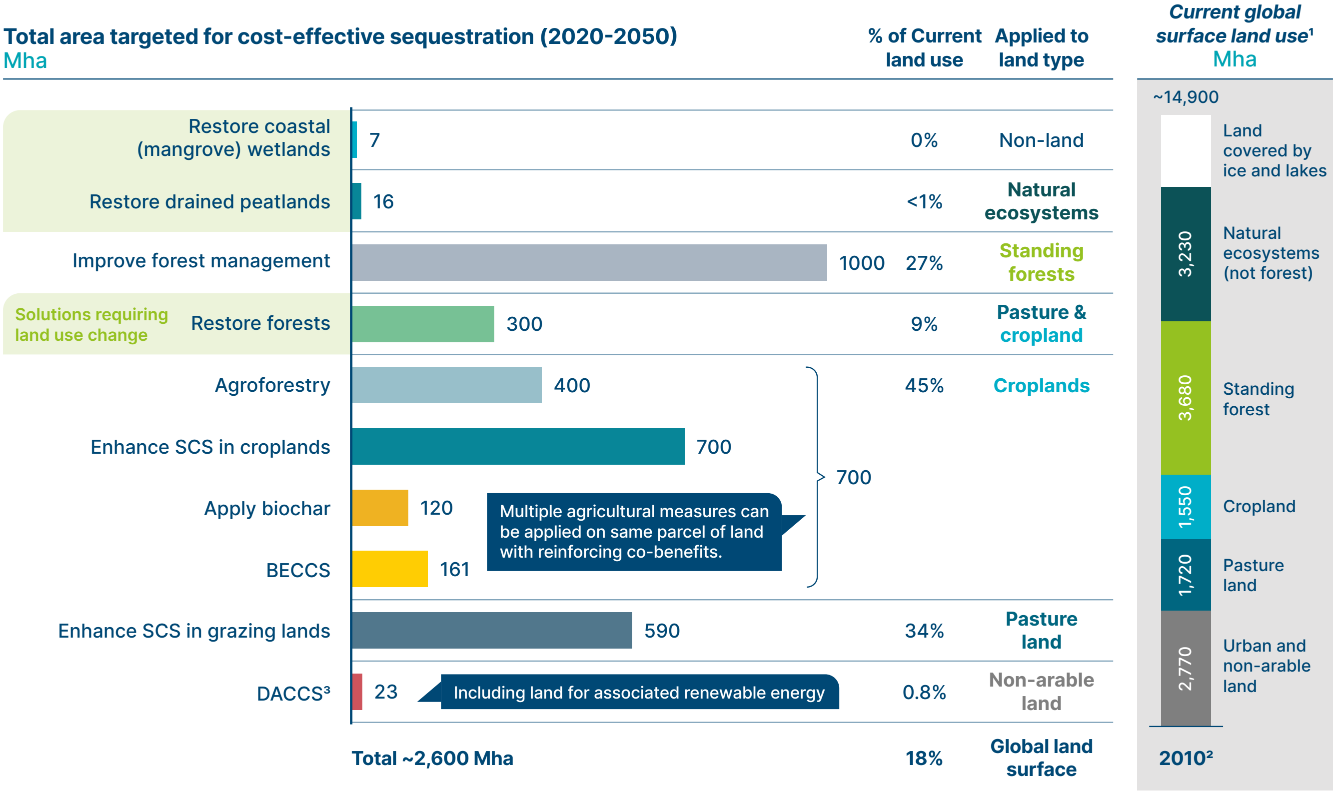

Exhibit 3

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.

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[16] Climeworks' recently opened 'Orca' facility in Iceland is estimated to capture around 4000 tonnes of CO_2 per year.

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

[18] Hannah et al. (2021) *Emergency deployment of direct air capture as a response to the climate crisis*.

[19] WRI (2020), *Carbonshot: Federal Policy Options for Carbon Removal in the United States*.

[20] The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*; Biochar is shown to improve soil water and nutrient retention and reduce erosion.

Our illustrative supply-side CDR estimate assumes ~1 Gt CO_2/year is sequestered by BECCS in 2050, delivered through an even split of dedicated energy crops and forestry residues. Biochar, in this assessment, is assumed to draw on crop residues as a feedstock, and could sequester ~0.3 $GtCO_2$/year by 2050. These estimates consider the constraints on sustainale biomass supply assessed in the ETC report *Making a Sustainable Bioeconomy Possible* (2021). In theory, the biomass feedstocks utilized by BECCS could be used for other BiCRS solutions which do not priotise energy production.

Total potential sequestration and resource implications of CDR solutions

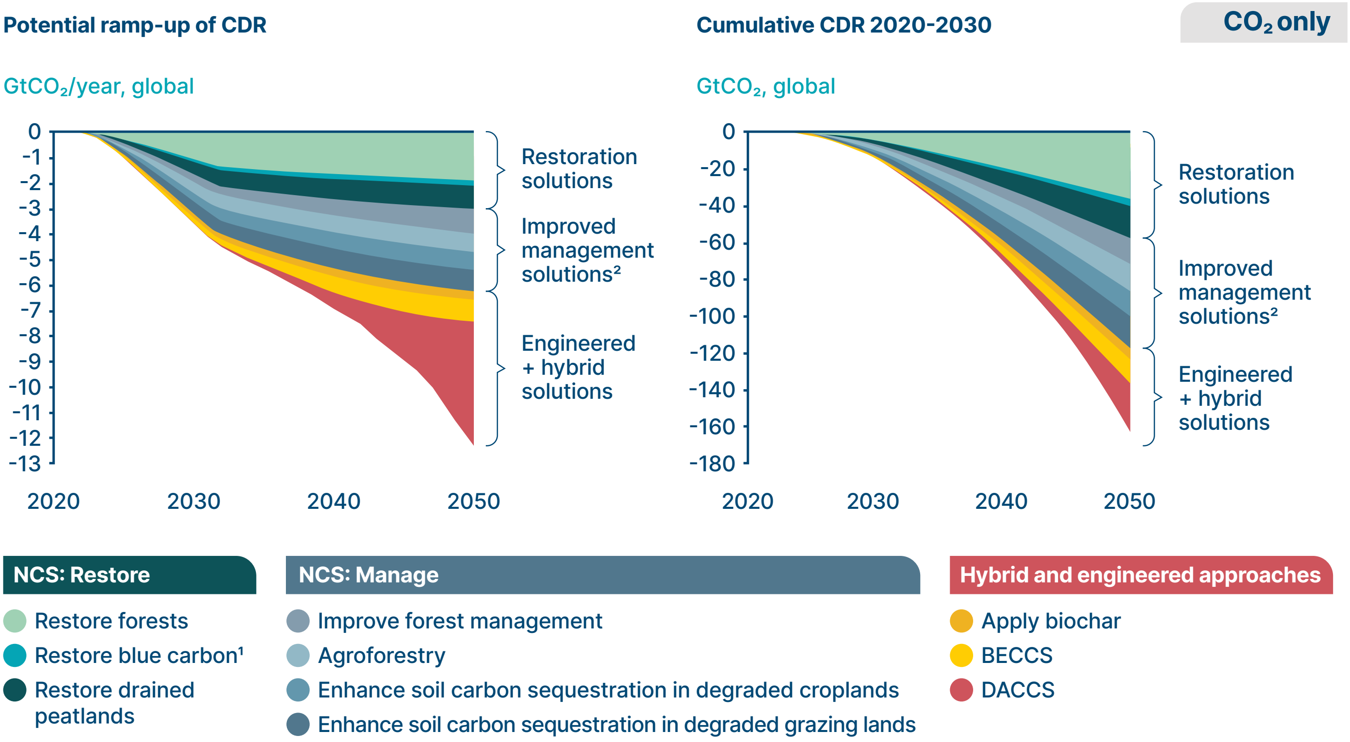
Exhibit 4 presents an estimate of the potential annual flow of CDR achievable over time and the cumulative sequestration between now and 2050:

- Total cumulative removals reach 165 Gt CO_2 by 2050 – in the middle of the required range of 70-225 Gt CO_2 indicated in Exhibits 1 and 2. This reinforces the need to reduce gross emissions foster than Scenario A assumes. Over the period to 2050, NCS solutions dominate the cumulative effect with 58 Gt CO_2 from NCS-Restoration solutions and 60 Gt CO_2 from NCS improved management solutions.

- Total annual flows could reach ~12 Gt CO_2 by 2050 which is significantly more than sufficient to meet the on going removal need of around 3 to 5 Gt CO_2/year. This reflects the assumption that engineering solutions would become feasible at a larger scale by 2050. Much of this DACCS potential may not however be required given likely falls in the cost of achieving gross emission reductions. Potential annual sequestration from NCS would plateau in the long-term, from decades to centuries, as reforestation projects reach maturity (and if no further land freed up for restoration).

Exhibit 4

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



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).

IV. Risks in different types of CDR solutions and how to manage them

- Natural climate solutions are currently much lower cost than engineered solutions, but often face higher risks (i.e., around permanence and measuring volumes of sequestration).
- Risks facing all forms of removal options 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.
- 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 projects face inherent risks with respect to:

- Accurate estimates of sequestration volumes.
- Sequestration of carbon taking place gradually over a number of years.
- The permanence of sequestration, which can be reversed through forest fires, insecure finance and the return of economic drivers of deforestation.

Engineered solutions such as DACCS currently have much higher costs, and deliver fewer if any co-benefits than NCS. They are also at an earlier stage of development but can offer lower risk since:

- The amount of CO_2 sequestered and stored can be fairly precisely defined, and managed on a year by year basis.
- Permanence in geological storage is inherently easier to ensure, provided robust project design, monitoring and verification systems are in place.[21]

Hybrid / BiCRS solutions have different cost and risk profiles for BECCS and Biochar solutions.

- **BECCS:** Has a similar risk profile to DACCS, but is relatively lower in cost today, and offers clean electricity (and possibly heat) as a co-benefit.
- **Biochar:** Has a lower risk of reversal than Natural Climate Solutions but monitoring of stored carbon in soils is currently undeveloped and challenging.

In the case of BECCS and Biochar (but not DACCS) issues relating to the sustainable supply of biomass must also be carefully considered.

Exhibit 5 summarises several characteristics of different CDR approaches.

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[21] IPCC(2005), *Special Report on Carbon Dioxide Capture and Storage.*

A comparison of key characteristics and risks for selected CDR solutions

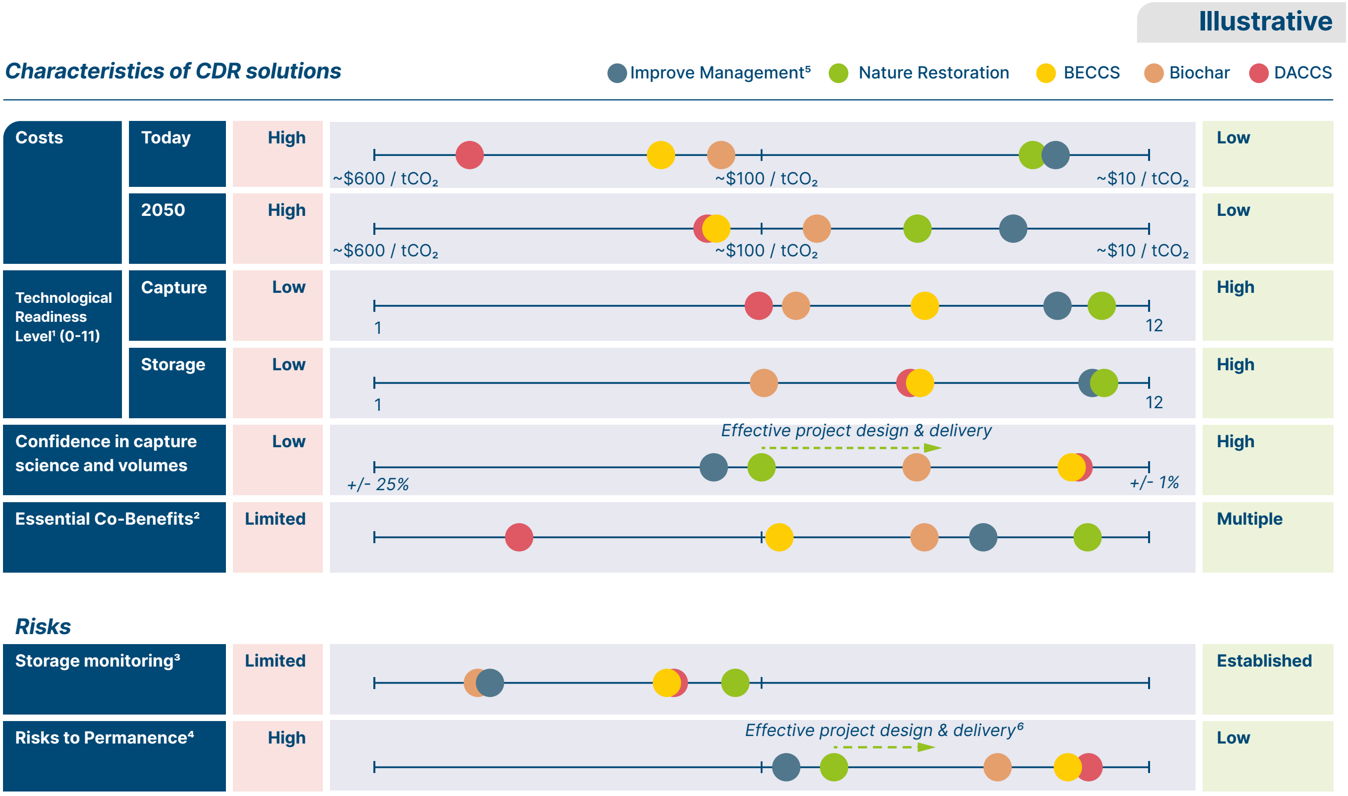

Exhibit 5

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*

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 doing so. For all types of credit, strong systems for monitoring and verifying removals achieved are essential.

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 removals.** Selling NCS carbon credits for carbon reduction or removal to end-purchasers after the carbon sequestration has taken place, can avoid the risk that credits that are sold rely on future sequestration.[22]
- **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.

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:

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[22] 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.*

- **Jurisdictional approaches.** These embed NCS projects within wider national strategies for land use over time. These approaches can reduce the risk that restoring ecosytems in one location is offset by destruction in others and will often be essential to ensure the permanence of avoided deforestation projects.[23]

- **Building resilient business cases with multiple revenue streams.** Layering together multiple revenue streams, such as carbon payments, payments for co-benefits such as ecosystem services, and the sale of high-value native forest products (e.g., Brazil nuts) can increase revenue certainty to landholders and reduce land use change incentives.

- **Monitoring of projects** to ensure that estimates of sequestration are fully delivered (e.g. via satellite monitoring).

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 (e.g. in California's Low Carbon Fuel Standard).

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. 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, 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, may be a good candidate to play this role. In addition, quality assurance on the suitability of offset methodologies is likely to soon be provided by the Paris Agreement's Article 6.4 Supervisory Board, which is to be established following COP26 finalisation of Article 6 rules.

Risk-adjusted costs over time

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. In addition there are likely to be higher monitoring and verification costs than required in engineered solutions. But 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. For NCS, the most economic projects will be implemented and sold first. For engineered solutions such as DACCS, technological development means costs are likely to decline over the next three decades. As a result DACCS projects are likely to become increasingly cost competitive with NCS on a risk adjusted basis.

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[23] Avoided deforestation projects do not deliver CO2 removal , but may be a particularly important sort of CO2 "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.*

V. Funding Removals

- Removals will only occur at the required scale with much greater funding than currently delivered by compliance or voluntary carbon markets – funding will need to increase to over $200bn/year by 2030, from close to zero today.
- For NCS projects in particular significant upfront investment will be required to deliver subsequent annual sequestration; in aggregate this could amount to $750bn during the 2020s.
- 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. However a significant funding gap is likely to remain.
- 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.

Funding requirements

Removals will only occur if someone pays for them. To support the growth in emissions shown on Exhibit 4, which estimates ~3.5 Gt CO_2/year by 2030, 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.[24] In contrast required investment in clean power is around 1.5% of GDP over the same period. This compares with less than $10bn/yr of funding for removals today.[25]

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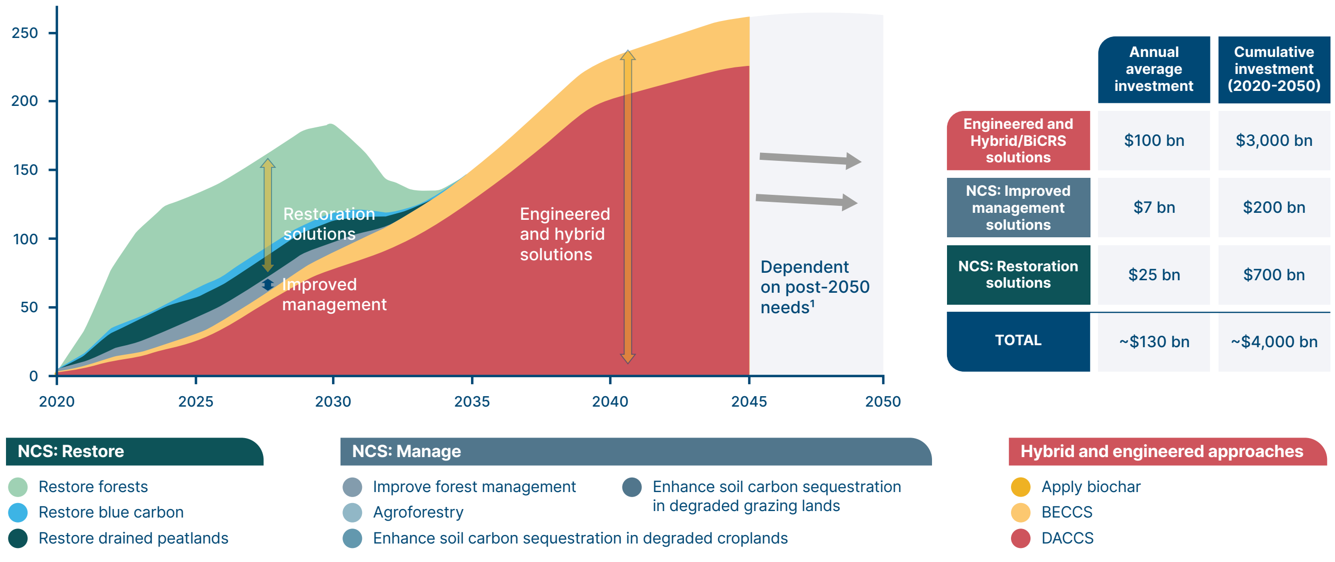
[24] Estimated based on cost estimates for each CDR solution over time.

[25] SYSTEMIQ analysis for the ETC; Coalition for Negative Emissions (2021) *The Case for Negative Emissions.*

Exhibit 6

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

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.*

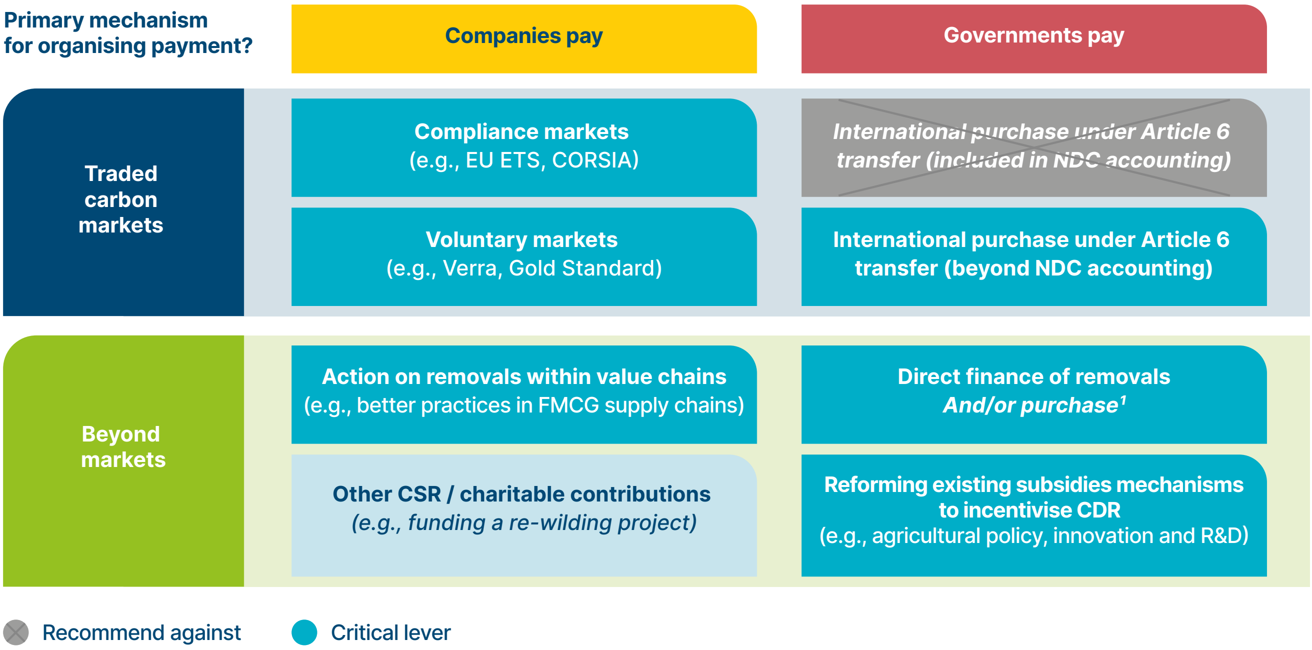
Investment be required upfront to realise this growth in market size. Exhibit 6 illustrates the possible profile of investment needs over time, with a very different profile for:

- **NCS solutions**, where large investments are required during the 2020s in order to make possible future rising volumes of sequestration.
- **Engineered and Hybrid solutions**, with a significant buildup of investments in DAC plant capacity in the 2030s and 40s, but with investment then falling off once the capacity is in place. A similar profile, at a smaller scale, applies to BECCS.

Who could pay and how – carbon markets and direct payments

The financial flows described above will only occur if someone pays for them. Exhibit 7 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 7

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 could pay either via:

- **Compliance markets** (such as EU ETS[26] or CORSIA), in which companies are obliged to purchase carbon credits.
- **Voluntary markets** where companies have no legal obligations, but choose to purchase carbon credits (e.g., to deliver " net-zero" commitments, 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 will play a crucial role in setting the rules and motivations for corporate payments, including establishing compliance market rules and regulations, introducing reporting requirements for the voluntary carbon market, and incentivising direct action in the supply chain (e.g., via agricultural policy).

[26] European Union Emissions Trading Scheme

But governments can also directly finance removals, internationally or domestically:

- **Internationally**, via governments paying for CDR in other countries either; (i) Within the context of Article 6 trading arrangements; Or (ii) as a separate contribution to global net emissions reduction (e.g., utilising international commitments towards "climate finance").

- **Domestically,** via direct funding for domestic CDR.

Current funding flows are insufficient

Total funding flows of all types are currently insufficient to meet the need for removals identified.

- **Compliance markets** are growing in scope geographically, and now cover over 10% of global emissions, however emissions removals within these markets is currently very limited.[27]

- Current financial flows to removals via **voluntary markets** are a small fraction of the required volumes and most are focused on various forms of "reduction offset" credits, as opposed to actual removals. Total removals financed by the voluntary carbon market are estimated to be less than 10 Mt CO_2/yr – 0.3% of the volume required by 2030.[28] Even the most ambitious projections suggest total market size will reach only 1 Gt CO_2/yr by 2030, representing just 30% of the CDR required.

- **Direct government finance of removals** (whether within own country or in others) is 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.[29]

A massive increase in financing flows to support removals is therefore required 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.

Who should pay for removals

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") 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.

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[27] World Bank (2021) *State and Trends of Carbon Pricing 2021.*

[28] Trove Intelligence Research (2021), *Future Demand, Supply and Prices for Voluntary Carbon Credits.*

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

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?

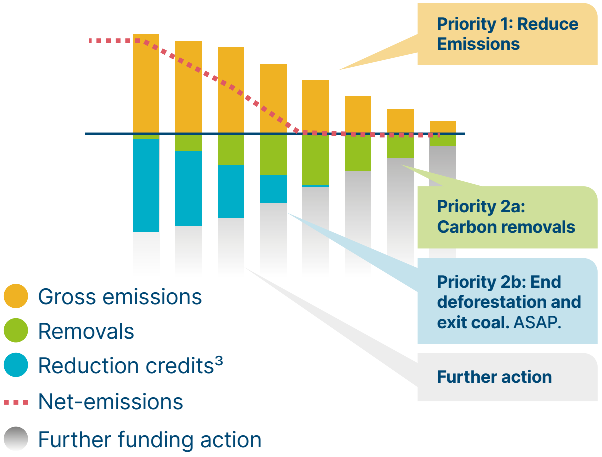

Exhibit 8

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.

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

Provided that corporate purchase of carbon 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:

- Most 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 there is not yet a low/zero cost route to emission reduction and where 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, and that neither is likely to occur without a flow of finance to compensate for additional costs incurred.[30] Neither is likely to occur without a flow of compensation towards low-income countries. Accelerating actions in these two categories (e.g., by bringing forward the closure of an existing coal plant to 2030 or earlier), is therefore likely to be truly additional in many cases.[31]

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.

- Encourages a shift from reduction "offsets" to removals over time.

- Focuses on the purchase of reduction credits which are most likely to be additional.

A prioritisation approach is described in Exhibit 8 below.

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

[31] i.e., only within the next decade.

The role of private sector funding

These principles and objectives described in Exhibit 8 could suggest the following approach:

In compliance markets, such as the EU ETS or equivalent, total emission credits available should be designed to fall along a path compatible with limiting global warming to 1.5°C, but include a limited quantity of removal credits allowed to achieve net-zero in 2050.

In voluntary markets, where companies choose to make commitments beyond their legal obligations, there can be no absolute legal rules, but best-practice principles can be defined. High ambition corporates should commit to Science-Based Targets Initiative (SBTi) – or equivalent - pathways to reduce emissions, with any remaining emissions fully neutralised by removals by 2050. Corporate offsets, which currently favour emissions reductions, should shift towards removals over time. However 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.
- 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.[32]

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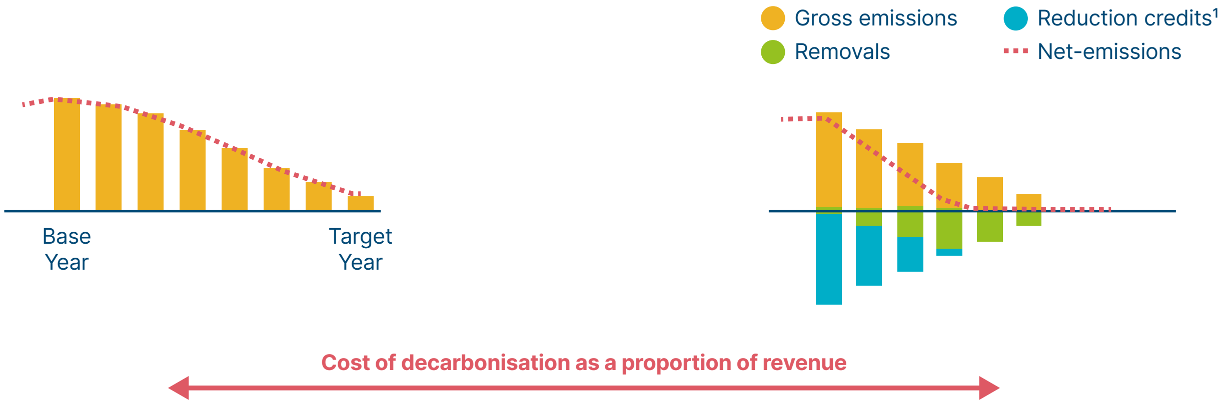
[32] Various concepts around emissions neutrality exist, including carbon neutral, climate neutral, net-zero, carbon negative, and climate positive. This report uses ‘climate neutral’ to refer to all gross greenhouse gas emissions being offset.

Exhibit 9

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

Decarbonisation pathways to net-zero by 2050



High
E.g. a steel plant

Low
E.g. a tech company

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

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.

Exhibit 9 illustrates a continuum of possible approaches.

Beyond carbon markets, private sector participants can also support the scale up of removals outside carbon markets, by investing in R&D for emerging technologies and solutions, or by paying for additional mitigation outside their value chain in ways that do not entail purchase of 'carbon credits'.

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 it will not be sufficient.

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

Internationally significant finance must flow from richer to poorer countries to build zero-carbon economies. Much of this will be in the form of debt or equift finance to support clean electrification and other key decarbonsiation strategies.

However, some specific emissions reductions will only occur if there is explicit grant finance, and the ETC's *Keeping 1.5°C Alive* report argued that ending deforestation and phasing down existing coal power generation should be priority uses of the grant elements within international climate finance.[33] In addition to this, further funding from high-income country governments will be required to finance CDR in lower income countries.

The reductions and removals achieved through this finance should, however, be in addition to the rapid reduction of developed world production emissions to reach net-zero by 2050.

Financing flows to support avoided deforestation or early coal closure, or to pay for CDR, 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. Some countries may choose to describe them as compensating for the excess of consumption over production emissions, or for historical emissions.

In their own countries, governments should develop strategies which make clear the scale of necessary and feasible within-country removals and which ensure that this volume is delivered through:

- **Designing compliance markets** to ensure that net emisisons fall in line with a 1.5°C compatible pathway, reaching net-zero by 2050, and with a limited role for removals alongside rapid reductions in gross emissions.
- **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 regimes** to incentivise soil carbon sequestration, improved forest management and agroforestry.
- **Providing direct support to removals** – either through innovation support, or direct payments for removals.

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

VI. Actions for the 2020s

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

The ETC has described how to deliver action for decarbonisation in its *Keeping 1.5°C Alive* and *Making Mission Possible* series of reports.[34]

But our scenarios for feasible deacrbonisation still suggest that at least 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.

CDR Targets for 2030 and actions to achieve them

There is no global body which can set binding CDR targets, but to guide coordinated action from industry, corporates and governments it is useful to describe the scale of sequestration needed by 2030, with an indication of likely balance between different categories. These are set out in Box A.

Exhibit 10 describes the near-term actions needed if these targets are to be achieved.

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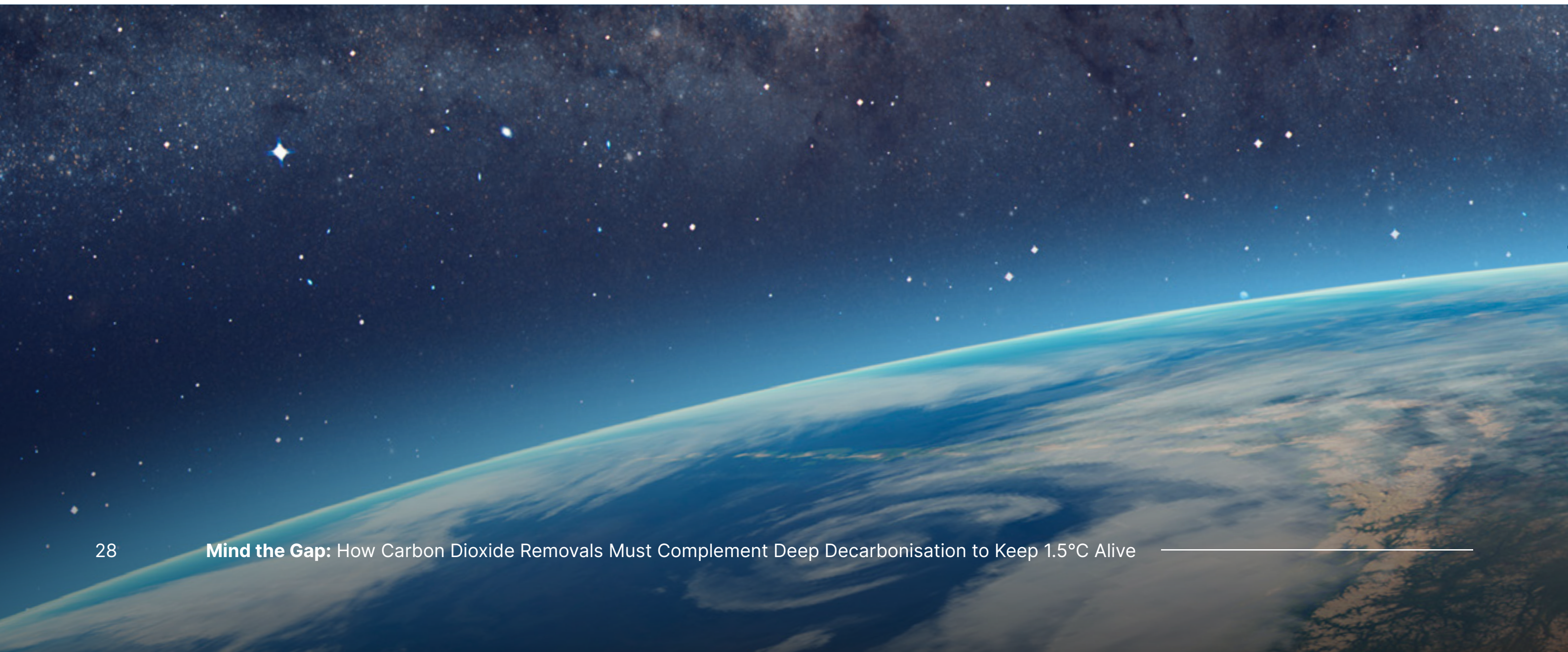
[34] ETC (2021), *Keeping 1.5°C Alive: Closing the gap in the 2020s*. ETC (2020-2022), *Making Mission Possible series*. ETC (2020), *Making Mission Possible: Delivering a Net-Zero Economy*; ETC (2021), Making Clean Electrification Possible; ETC (2021), *Making the Hydrogen Economy Possible*; ETC (2021),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



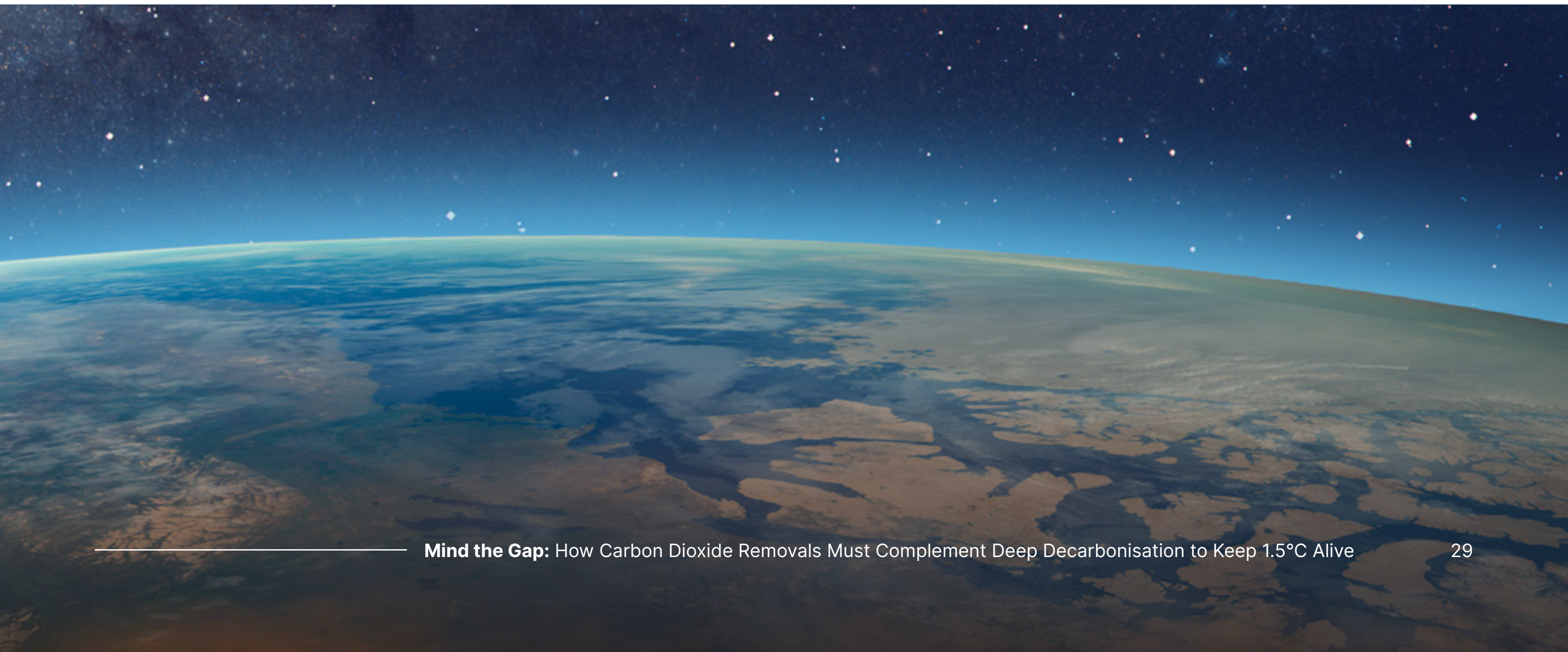
Nine near-term actions to achieve CDR in the 2020s

In addition to rapid and critical decarbonisation action			Key responsible actors					
			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.**		●				●	
	2. Establish compliance carbon markets and expand to include a limited quantity of removals.		●	●	●			
	3. Direct government support for carbon removal via funding of projects or purchase of credits, both nationally and internationally.				●			
	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.			●	●	●	●
		Engineered: Invest in M&V technology for geological storage and establish norms for long-term maintenance liability. Scale clean power.		●	●	●	●	●
		BiCRS: Invest in M&V technology for geological storage and biochar longevity. Establish criteria and verification for sustainable biomass feedstocks.		●	●	●	●	●
	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)**		●	●	●			●
	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.				●			●
	9. Accelerate CDR innovation via research and development grant funding		●		●			

Exhibit 10

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



Box A: 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.[33] • 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 reliable 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.

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

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.

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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

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[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.

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[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.*

Acknowledgements

The team that developed this report comprised:
Lord Adair Turner (Chair), Faustine Delasalle (Director), Ita Kettleborough (Deputy-Director), Mike Hemsley (Head of Analysis), Sanna O'Connor-Morberg (Lead author), Scarlett Benson, Kash Burchett, Tassilo Bismarck, Liesbeth Huisman, Michael Kast, Philip Lake, Tommaso Mazzanti, Hettie Morrison, Elena Pravettoni, Caroline Randle, Trishla Shah, Abindra Soemali, Max Steventon, Andreas Wagner (SYSTEMIQ).

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.

The team would also like to thank the ETC members and experts for their active participation:
Rajit Nanda (ACWA Power); Elke Pfeiffer (Allianz); Javier Bonaplata, Nicola Davidson (ArcelorMittal); Abyd Karmali (Bank of America); Paul Bodnar, Michelle Bolten, Jonathan Posen (Blackrock); William Zimmern, Doris Fuji (BP); Jeanne Ng (CLP); Rob Kelly (Climateworks Australia); Dana Barsky (Credit Suisse); Bin Lyu (Development Research Center of the State Council); Tanisha Beebee (DRAX); Adil Hanif (EBRD); Michael Ding (Envision); Rebecca Collyer, Pete Harrison, Phillip Niessen, Thomas Legge (European Climate Foundation); Eleonore Soubeyran (Grantham Institute, London School of Economics); Matt Gorman (Heathrow Airport); Andrea Griffin, Abhishek Joseph (HSBC); Francisco Laveran (Iberdrola); Chris Dodwell (Impax Asset Management); Yanan Fu (Institute of Climate Change and Sustainable Development, Tsinghua University); Ben Murphy (IP Group), Christopher Kaminker (Lombard Odier); Charles Liang, Jinpeng Ma (LONGi Solar); Jazib Hasan (Modern Energy); Matt Hinde (National Grid); Emil Damgaard Gann, Tord Bjørndal (Ørsted); Shruti Mehra (ReNew Power); Xavier Chalbot, Jonathan Grant (Rio Tinto); Rudy Kahsar (RMI); Charlotte Brookes, Mallika Ishwaran (Royal Dutch Shell); Emmanuel Normant (Saint Gobain); Emmanuelle Simonet, Vincent Minier, Vincent Petit (Schneider Electric); Elham Ali, Tracey Crowe, Brian Dean (SE4All); Camilla Palladino (SNAM); Jesper Kansbod, Martin Pei (SSAB); Matt Beasley (Silicon Ranch); Alistair McGirr (SSE); Abhishek Goyal (Tata Group); Madhulika Sharma (Tata Steel); A K Saxena, Abhishek Kaushik (TERI); Reid Detchon (United Nations Foundation); Mikael Nordlander (Vattenfall); Rowan Douglas, Michelle Rorvick (Willis Towers Watson); Johan Engebratt, Niklas Gustafsson (Volvo Group); Luke Pritchard, Rasmus Valanko (We Mean Business); Jennifer Layke (World Resources Institute); Mark Trueman (Worley).

The team would also like to thank the ETC's broader network of experts for their input:
Amy Ruddock (Carbon Engineering); Oliver Geden (German Institute for International and Security Affairs); Matt Isaacs (Counteract); John Scowcroft (Global CCS Institute); Phil Renforth (Heriot-Wyatt University); Dolf Gielen (IRENA); Emma Watson (SBTi); Steve Smith, Conor Hickey (SSEE, Oxford University); Martin Weymann, Mischa Repmann (Swiss Re); Eli Mitchell-Larson (Oxford University) ; James Cameron (Pollination Group); Gabrielle Walker (Valence Solutions); Stephanie Roe (WWF); Richard Millar (UK Climate Change Committee); Ashleigh Arton, Alex Joss (UK High Level Climate Champions).

The team would also like to thank all those who responded to our May consultation paper and participated in the subsequent consultation process.

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