Energy Transitions Commission

Reaching climate objectives: the role of carbon dioxide removals

May 2021

ETC Consultation Paper

Supported by

WE MEAN BUSINESS COALITION

What is this Energy Transitions Commission Consultation Paper?

About the ETC

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 consultation paper is based upon analyses carried out by ETC knowledge partner SYSTEMIQ, with the financial support from We Mean Business. It was discussed and refined with ETC members but has not been endorsed by them at this stage. It builds upon prior ETC reports, especially Making Mission Possible (2020), Making Clean Electrification Possible (2021) and Making the Hydrogen Economy Possible (2021), and draws upon analyses carried out by ETC knowledge partners BloombergNEF, alongside analyses developed by Climate Policy Initiative, Material Economics, McKinsey & Company, Rocky Mountain Institute, The Energy and Resources Institute, and Vivid Economics for and in partnership with the ETC in the past. We also reference analyses from the International Energy Agency and IRENA. We warmly thank We Mean Business, our knowledge partners and contributors for their inputs and look forward to carrying the conversation further during consultation.

What is the objective of this paper?

This ETC Consultation Paper aims to provide a conceptual framework for assessing the role of carbon dioxide removals in meeting emissions reduction and climate objectives. The goal is to gather perspectives and insights from stakeholders in industry and the climate science community to consult on the appropriate and feasible role of carbon dioxide removal in 'net zero' pathways to limit warming to 1.5°C. Ultimately, it aims to inform the way net-zero targets are set by countries and corporates. One of the underlying assumptions is that emission reduction targets are essential to get to net-zero in 2050, and that carbon dioxide removals should complement, not replace, emission reduction measures.

The paper assesses the need for carbon removals, the technologies which can provide them, and alternative options for financing them. Illustrative scenarios are used to provide indicative orders of magnitude; estimates will be refined through more detailed sectoral work (undertaken in partnership with the Mission Possible Partnership) over the coming months.

What are the key consultation questions?

- What is the overall scale of need for carbon dioxide removal prior to mid-century and beyond, in order to stay within a 1.5 degree global warming carbon budget within the context of relatively ambitious assumptions on within-sector emissions reduction pathways?
- What types of carbon dioxide removal methods are available, and what are the relevant timescales, technical and practical volumes, permanence of capturing and storage and costs? More specifically, in the coming three decades, what is the role of nature-based climate solutions vs BECCS, DACCS and other hybrid or technological solutions? Are there other options not described in this paper which should be considered?
- Who should purchase these carbon removals and how much? How should public and private responsibility be allocated, such that removals will complement and not replace within-sector decarbonisation efforts, while unlocking investments to deliver removals with speed and at scale?

How can input be provided?

The ETC welcomes responses to this Consultation Paper. Comments can be provided via a dedicated online form which can be found on the ETC Website until June 30th, 2021. The ETC will also consult via virtual fora during the second and third quarters of 2021, please indicate interest in joining such conversations via the consultation form. Responses received will inform an updated report to be published later in 2021.

Further information can be found at the ETC website, **https://www.energy-transitions.org/.**

Introduction

This ETC Consultation Paper aims to provide a conceptual framework for assessing the role of carbon dioxide removals in meeting emissions reduction and climate objectives. It aims to inform the way net-zero targets are set by countries and corporates. One of the underlying assumptions is that emission reduction targets are essential to get to net-zero in 2050, and that carbon dioxide removals should complement emission reduction measures.

The paper assesses the need for carbon removals as well as alternative options for financing them. Illustrative scenarios are used to provide a sense of orders of magnitude; estimates will be refined through more detailed sectoral work over the coming months.

Scenarios produced by the International Panel on Climate Change (IPCC) show that if we are to have a 50% chance of limiting global warming to 1.5°C and a 90% chance of limiting it to 2°C,[1] cumulative CO_2 emissions between now and mid-century must be limited to a "carbon budget" of 500 gigatons (Gt) CO_2. This budget assumes a reduction of around 50% in annual CH_4 emissions and 30% in annual nitrous oxide (N_2O) emissions by mid-century.

Based on previous work from the Energy Transitions Commission,[2] reasonably optimistic assumptions suggest that CO_2 emissions from the Energy, Building, Industry, & Transport (EBIT) sectors could be reduced from today's 33 Gt per annum to around 1-2 Gt by mid-century thanks to a combination of energy productivity improvements, clean electrification, and the deployment of other zero-carbon technologies (hydrogen, sustainable bio-energy, CCS/U). Halting deforestation and changing agricultural practices could reduce CO_2 emisions from Agriculture, Forestry and Other Land-use (AFOLU) from today's net 6 Gt CO_2 to about <1 Gt CO_2, and N_2O emissions could be cut by 30%. Total CH_4 emissions across all sectors could be reduced by 40%.

However, even these dramatic reductions, which will require forceful policies to achieve, would be insufficient to give a 50% chance of limiting warming to 1.5°C. Comparing our base case scenario with the IPCC carbon budget shows an overshoot gap of 186 Gt CO_2, or about about 6-7 Gt per annum over the next 30 years. This reflects the fact that EBIT emissions do not fall fast enough in the 2020s to keep cumulative emissions within budget: while IPCC pathways to meet the climate objective require around a 50% reduction by 2030, our illustrative reasonably optimistic scenario would result in at most a 26% reduction.

It is therefore essential to deliver CO_2 emissions reductions as soon as possible, and to accelerate the reduction in N_2O and CH_4 emissions in the EBIT, waste, and AFOLU sectors. This may require societal shifts at scale, for example in how we travel and what we eat. But, it is certain that "carbon dioxide removals" (CDR) will be required in addition to limit global warming within acceptable limits.

Such carbon removals could be achieved via multiple routes including Natural Climate Solutions (NCS[3]), Bio-Energy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS). They could be used (i) to deliver a faster reduction in the rate of accumulation of atmospheric GHGs than can be achieved via emission reductions in the EBIT and AFOLU sectors alone, (ii) to offset small but still important residual emissions in both EBIT and AFOLU sectors by 2050 and beyond, and (iii) if necessary, to achieve absolute negative emissions around mid-century and beyond if those are required to neutralise an overshoot of the GHG budget over the next 30 years.

1 Estimate. Derived by approximating the probability distribution for a carbon budget which would limit warming to below 2°C using a normal distribution.
2 ETC (2018), *Mission Possible*; ETC (2020), *Making Mission Possible*
3 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*).

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.

A crucial issue is therefore how to finance and implement these carbon removals. One option would be for companies in the EBIT, waste, and AFOLU sectors to purchase carbon removal offsets on top of achieving ambitious reduction pathways for their own emissions "within the company". Some companies will and should choose to do this voluntarily, and company purchases of offsets could be encouraged by setting "offset targets" in complement to existing "science-based targets", or via carbon taxation incentives/regulation. An alternative and possibly more efficient option might be for governments to take the primary responsibility for purchasing carbon removals, potentially using carbon tax revenues to finance the required expenditures, while still leaving an important role for voluntary company action.

This report therefore sets out for consultation a range of possible approaches to the financing of required carbon dioxide removals, together with key principles required to ensure permanent and efficient carbon removal. It covers in turn:

1. Climate objectives and remaining GHG budgets
2. Current emissions and illustrative scenarios for EBIT, waste and AFOLU emissions reductions
3. Emissions reduction scenarios compared with the GHG budget – the size of the overshoot gap
4. Options, potential scale, and costs of CO_2 removals
5. How to finance carbon removals – options for consultation

Contents

Table of Exhibits

Objective, methodology and definition of terms

The objective of this consultation paper is to assess the role of "carbon removals" in achieving climate objectives. We estimate how large the need for such removals might be, what form they could take, and present options for who should pay to achieve them. This requires the following elements:

Defining a climate objective and a **"carbon budget"**. The IPCC has estimated the stream of future GHG emissions and the resulting concentrations of different GHGs in the atmosphere that would be consistent with different probabilities of limiting global temperature rise to either 1.5°C, or 2°C, or higher. In this paper, we focus on a GHG budget which gives a 50% probability of staying below 1.5°C and a 90% probability of staying below 2°C.

Future temperatures will be determined by emissions of both CH_4 (a short-lived gas) and CO_2 and N_2O (long-lived gases). To generate a "carbon budget", the IPCC first estimates feasible reductions in annual CH_4 and other non-CO_2 GHG emissions and then defines the maximum amount of CO_2 which could be emitted while staying within the climate objective. We use the IPCC's estimate of this carbon budget to compare with our own scenarios for feasible emissions reductions.

Estimating feasible emissions reduction pathways for the EBIT, AFOLU, and waste sectors:

- The pathway for the EBIT sectors draws on the ETC's Making Mission Possible report,[4] and our recent reports on clean electrification and hydrogen.[5] Past ETC work has shown that the EBIT sectors could get close to net-zero emissions by mid-century: here we describe a possible reduction pathway decade by decade. These estimates will be refined during this year, both through more granular sectoral decarbonisation roadmaps (especially in the harder-to-abate sectors of the economy) and through a deep-dive analysis of how fast emissions reductions could be accelerated in the 2020s (especially in the easier-to-abate sectors).
- The pathway for the AFOLU sectors builds on the analysis of the Food and Land Use Coalition,[6] along with recent academic analysis of emission levels and mitigation potential. Estimates of current and future AFOLU emissions are inherently less certain than EBIT emissions.
- Our estimates for possible waste sector emissions reductions (which are dominated by CH_4) are derived from estimates by the World Bank, International Water Association, and the UK Climate Change Commission's waste decarbonisation pathway.[7]

Estimating the overshoot gap between the carbon budget and the illustrative emissions reduction pathways which must be closed by some category of "carbon removal" in order to either (See Exhibit 1):

- Offset the ongoing residual emissions which will still be produced by the EBIT, AFOLU, and waste sectors beyond mid-century.
- Offset the fact that emissions from the EBIT, AFOLU or Waste sectors cannot be reduced fast enough in the 2020s and 2030s to stay within the cumulative carbon budget; or
- Potentially, to generate "absolute negative emissions" in the second half of the century if these are needed to compensate for an overshoot of the carbon budget between now and mid-century.

Identifying the options to achieve "carbon removals", including NCS, BECCS, and DACCS. Here two methodological details should be noted:

- When CCS is applied to fossil fuel-based energy production or an industrial process, this is already included in the "net emissions" of the EBIT sectors and so is not counted as a "carbon removal".

4 ETC (2018), *Mission Possible*; ETC (2020), Making Mission Possible.
5 ETC (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy*; ETC (2021), Making the Hydrogen Economy Possible: Accelerating clean hydrogen in an electrified economy.
6 FOLU (2019), *Growing Better: Ten Critical Transitions to Transform Food and Land Use.*
7 UK CCC (2020), *Balanced Net Zero Pathway Assumptions; International Water Association*, "How can more water treatment cut CO_2 emissions," accessed February 2021; World Bank (2018), *What a Waste 2.0*

- Natural climate solutions such as a reforestation and other restoration of nature will be among the actions by which the AFOLU sector achieves abatement; so, only additional NCS above this level counts towards closing the overshoot gap.

Identifying options for who should pay to achieve "carbon removals".

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

- "Net emissions" for the EBIT sector means emissions after the application of CCS in energy production and industry, but before the purchase of offsets to achieve carbon removals.
- "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.
- "Nature-based Solutions" (NBS) are activities that harness the power of nature to deliver services for adaptation, resilience, biodiversity, and human well-being, including reducing the accumulation of greenhouse gases (GHGs) in the atmosphere. "Natural Climate Solutions" (NCS) can be considered as a subset of NBS with a specific focus on addressing climate change. NCS has been defined as 'conservation, restoration, and/or improved land management actions to increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, agricultural lands, and oceans'.[8] These can be coupled with climate smart technologies that increase long term storage of carbon dioxide.
- "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 removal offset" or "carbon removal purchase" refers to the process by which either a government or company purchases/finances carbon removal. A "carbon removal offset" indicates a company purchasing carbon removals for the purpose of offsetting their existing emissions, instead of direct emissions reduction interventions.

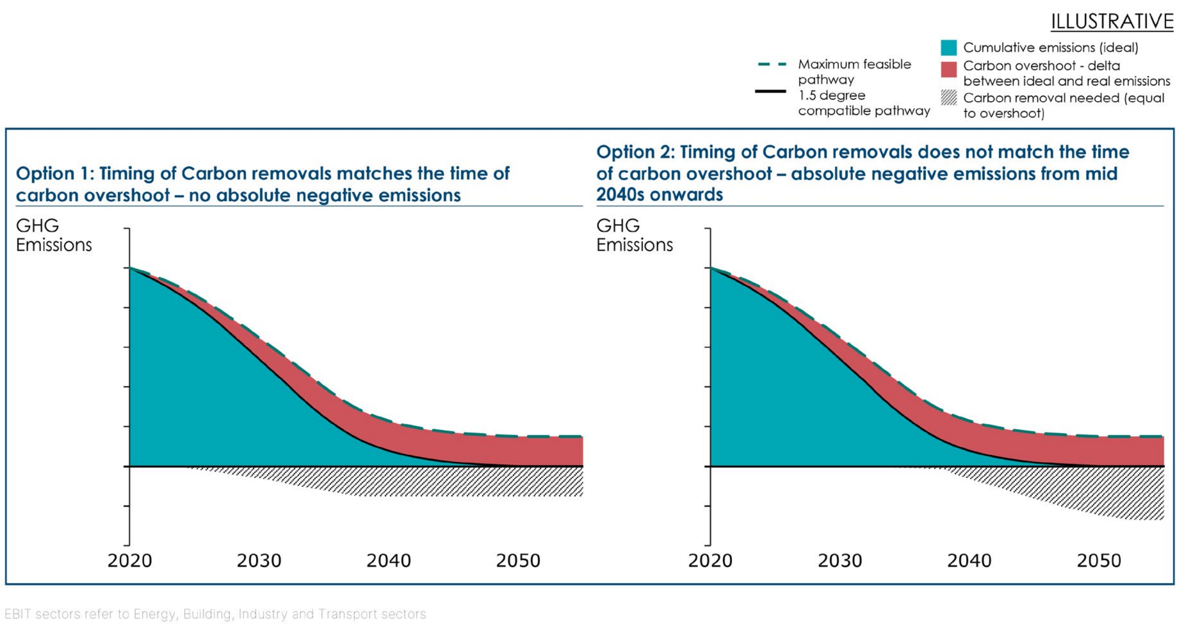


Exhibit 1: Schematic illustration of role of carbon removals with and without overshoot.

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

Chapter 1: Climate objectives and climate budgets

To avoid severe harm to human welfare, global warming should ideally be limited to 1.5°C and the probablity of exceeding 2°C should be small. In this paper, we therefore propose to focus on a climate objective of ensuring a 50% chance of staying below 1.5°C and a 90% chance of staying below 2°C. IPCC estimates suggest that this could be achieved if annual CH_4 emissions were reduced by ~50% and N_2O emissions by ~30% towards mid-century and if net cumulative CO_2 emissions during 21st-century stayed within a "carbon budget" of 500 Gt CO_2.

GHG impacts on global warming: stocks and flows

Human-induced emissions of greenhouse gases are causing significant global warming. Currently, the concentration of CO_2 in the atmosphere is approximately 417 ppm,[9] indicating a 50% rise in the concentration of atmospheric carbon dioxide relative to the pre-industrial age,[10] while CH_4 concentrations have increased from 770 ppb to 1890 ppb.[11] To-date this has resulted in an average global warming of ~1.0°C above preindustrial levels.[12]

Time is running out yet ambition to decarbonise must remain high. As described by the IPCC, missing the 1.5°C target and instead aiming for 2°C of warming will have significant adverse consequences for unique and threatened natural ecosystems such as the Arctic region, extreme weather events such as coastal flooding and other climate-risks such as low crop yields and heat-related deaths.[13]

The main gases responsible for global warming are CO_2, N_2O, CH_4 and fluorinated gases, the latter we exclude in the remainder of our analyses.[14] In each case the "forcing effect" which induces global warming is a function of the atmospheric concentration of the given greenhouse gas at any time. Differences in the average lifetime of the gases have implications for whether emission objectives should focus on the stocks or flows:

- CO_2 and N_2O are both long-lived gases, which once accumulated in the atmosphere take many decades or indeed centuries to dissipate. As a result, annual flows must be reduced to zero to prevent further increases in atmospheric concentrations and thus temperature. The appropriate objective for these long-lived gases is therefore to ensure that cumulative emissions from now on do not exceed defined maximum quantities. It is possible to express N_2O emissions on a carbon equivalent basis (with one ton of N_2O having an equivalent forcing effect of ~265 tonnes of CO_2) and it would therefore be possible to define a "carbon equivalent budget" which covers both CO_2 and N_2O emissions. However, the IPCC first develops estimates of the likely evolution of N_2O emissions, and then calculates a "carbon budget" for cumulative acceptable emissions of CO_2 alone, an approach which we follow in the rest of this document.

- By comparison, CH_4 is a relatively short-lived gas with a half-life in the atmosphere of about 10-12 years,[15] indicating that the concentration of methane produced by a one-off pulse takes 10 years to halve, as methane is converted (via a complex set of oxidization reactions), into CO_2 and H2O, eventually leaving 2.75 tonnes of CO_2 per tonne of methane emitted. Estimates suggest that increasing concentrations of CH_4 have been responsible for about 0.2°C out of the ~1.0°C of global warming so far.[16] Given the short-lived nature of methane, methane

9 Betts, R. (2021), "Met Office: Atmospheric CO_2 now hitting 50% higher than pre-industrial levels," *Carbon Brief.*

10 Pre-industrial atmospheric concentrations assumed to be 278ppm; Betts, R. (2021), "Met Office: Atmospheric CO_2 now hitting 50% higher than pre-industrial levels," *Carbon Brief.*

11 *Methanelevels.org*, visited 19th April 2021; assuming pre-industrial era began 1850.

12 IPCC (2018), Global warming of 1.5°C. An IPCC Special Report: Chapter 2; based on 2006-2015 reference period; There are, however, uncertainties about historical emissions since the pre-industrial era, as well as geographical variations in the degree of warming, particularly as a result of non-CO_2 climate forces which exhibit greater variation by region compared to CO_2 which, in turn, has lead to important uncertainties in the global temperature response to greenhouse gases.: Myhre, G. et al., (2013), *Anthropogenic and Natural Radiative Forcing.*

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

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

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

16 Economist "*Those who worry about CO_2 should worry about CH_4 too*", 3rd April 2021.

concentrations and forcing effect would stabilise if the flow of new methane emissions ceased to rise. But this does not mean, as some interest groups suggest, that the appropriate objective should be simply to stabilise rather than reduce methane emissions for two reasons. First, (i) because of the ongoing result of increased CO_2 concentrations (ii) and second, because the very fact that methane is short-lived means that reducing methane emissions is the most powerful lever to reduce short-term temperature rises, and thus reduce the risk that feedback loops will take the climate beyond the tipping points discussed below. Objectives for CH_4 emissions are therefore expressed in terms of how fast annual flows should fall over time.[17,18]

- Given the different nature of the long-lived gases (CO_2 and N_2O) and CH_4, estimates of the "carbon equivalent" effect of CH_4 emissions depend on the timescale assumed. Over a 100-year period, a tonne of CH_4 emitted today has a forcing effect (and therefore impact on temperature on average over the period) about 28 times that of a tonne of CO_2 emitted today. Viewed over a 20-year period, though, CH_4's impact is 84 times greater per tonne emitted.[19] Neither measure is in absolute terms the correct one, but the impact of climate feedback loops means that the 20-year calculation is arguably a better measure of the impact of CH_4 in today's specific circumstances, as it might not take another century before feedback loops are triggered.

Feedback loops, tipping points, and implications

Concentrations of greenhouse gases in the atmosphere produce "radiative forcing effects" which increase atmospheric temperature.[20] But the impact of atmospheric GHG concentrations on global temperatures can be magnified by feedback loops which arise either because (i) higher temperatures today generate higher temperatures in future, and do so even if forcing effects cease to increase (e.g., the loss of Arctic sea ice resulting in a diminishing albedo effect);[21] 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" – whether defined in terms of overall temperature, or of local climate and physical effects, positive feedback loops could become so strong as to trigger highly non-linear and irreversible climate change. How near we are to such "tipping points" is debated, and the IPCC carbon budgets indicated below do not explicitly model their potential impact.[22]

The implications of feedback loops and possible tipping points are at least two-fold:

- There should be a strong focus on achieving GHG emissions reductions as early as possible – and in particular reductions in CH_4.
- It seems possible that the IPCC carbon budget referenced as a base case in this report overstates acceptable cumulative emissions and that new information about the power of feedback loops and the potential for tipping points may argue for a tighter budget.

Climate objectives and IPCC carbon budgets

The Paris Agreement committed the world to limiting global warming to well below 2°C above preindustrial levels while seeking to limit it to 1.5°C. But since the relationship between GHG emissions and temperature is probabilistic, climate objectives must be expressed in terms of probabilities.For the purposes of this paper, we propose a climate objective which achieves a 50% chance of limiting warming to 1.5°C and approximately 90% probability of limiting it to 2°C.

The IPCC's estimates the carbon budget compatible with different climate objectives by first assuming a feasible pace of CH_4 and other non-CO_2 GHG emission reductions and

17 Saunois, M. et al. (2020), *The Global Methane Budget 2000-2017.*
18 Assumed that IPCC carbon budgets take the long-lasting products of tropospheric oxidation of CH_4 into account; "Collins, M. et al. (2018), applied a process-based approach to assess the importance of CH_4 reductions for the 1.5°C target. Their modelling approach included indirect effects of CH_4 on tropospheric ozone, stratospheric water vapour and the carbon cycle." IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report.*
19 US EPA, "Understanding Global Warming Potentials", Accessed April 2021.
20 When the earth absorbs more energy from the sun than it emits to space it causes warming, this difference between incoming and outgoing radiation is known as 'radiative forcing'. Greenhouse gasses can exacerbate this warming effect, which is known as the 'radiative forcing effect'.
21 The 'albedo effect' refers to how light surfaces reflect more heat than dark surfaces.
22 IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report.*

then estimating the cumulative emissions of CO_2 which are compatible with different probabilistic climate objectives.[23] If those non-CO_2 emissions reductions are not achieved, then the carbon budget would be reduced. Exhibit 2 shows the results: if CH_4 emissions can be cut by around 50% and N_2O by around 30% by mid-century, then:

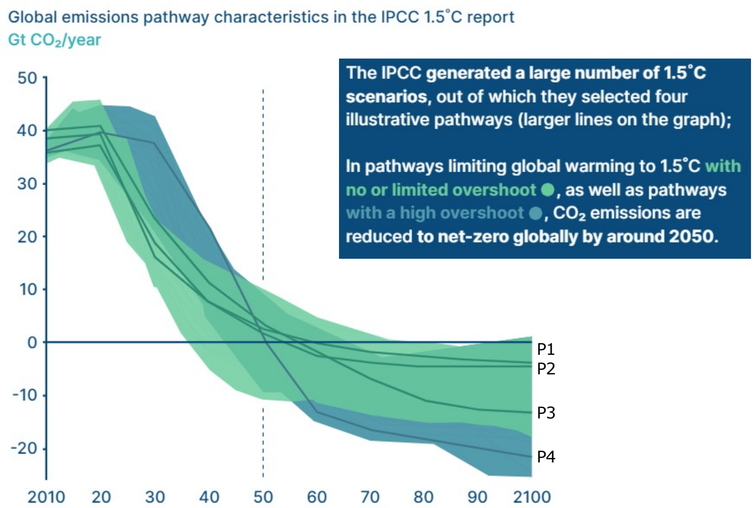
- A 500 Gt "carbon budget" gives a 50% chance of limiting global warming to 1.5°C, while only 330 Gt CO_2 would be compatible with a 66% probability of a 1.5°C limit.

- A 1420 Gt CO_2 budget gives a 50% chance of limiting warming to 2°C, while a 1080 Gt CO_2 would give a 66% chance of this limit. The underlying probability distribution suggests that a 500 Gt budget would be broadly equivalent to a 90% chance of keeping global warming below 2°C.

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

In Section 3 of this report, we assess how potential CO_2 emissions from the EBIT, AFOLU and Waste sectors compare with the 500Gt of carbon budget and the size of the required "carbon removals" to close the gap between forecast emissions and the carbon budget.

Finally, it is important to consider the timing of emission reductions. The "carbon budgets "shown on Exhibit 2 are expressed in Gt of total emissions independent of the shape of reduction between now and mid-century. This implies that a variety of different reduction paths could result in the same temperature effect if the "area under the curve" is the same (see Exhibit 2). But if emission reductions were significantly more delayed than some of the IPCC scenarios assume, feedback loops could result in the cumulative carbon budget being somewhat smaller. This reinforces the importance of early emissions reduction.



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

Chosen carbon budget in this document

	50% chance	66% chance	~90% chance
<1.5 °C	**500** Gt CO_2 from 2020	**340** Gt CO_2 from 2020	N/A
<2 °C	**1420** Gt CO_2 from 2020	**1090** Gt CO_2 from 2020	**500** Gt CO_2 from 2020

CH_4 and N_2O reductions corresponding to chosen carbon budget

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

Source: Betts, R. (2021), "Met Office: Atmospheric CO_2 now hitting 50% higher than pre-industrial levels," *Carbon Brief* (range 489-1189 Gt CO_2e across all models); IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report.*
Note: Carbon Budgets from 2018 have been adjusted to account for ~80 Gt CO_2e emitted 2018-2020

Exhibit 2: To have a 50% chance to remain <1.5 degree warming, IPCC estimates the remaining Carbon Budget to be around ~500 Gt CO_2 from 2020.

23 IPCC (2018), *Global warming of 1.5°C. An IPCC Special Report.*

Chapter 2: Current emissions and emissions reduction scenarios

Today's annual anthropogenic emissions are approx. 37 Gt CO_2, 4.0 Gt CO_2e of N_2O and 402 Mt CH_4. The key question is how fast these emissions can be reduced over time. Our illustrative base case scenario – which would require implementation of forceful policies beyond what has been committed so far – suggests that:

- EBIT CO_2 emissions could be cut from 32 Gt CO_2/Yr today to 27 Gt CO_2/Yr in 2030, 17 Gt CO_2/Yr in 2040 and 1.7 Gt CO_2/Yr in 2050.
- Today's 6 Gt of net CO_2 emissions from the AFOLU sector could be reduced to 1.5 Gt CO_2/Yr by 2030, and <1 Gt CO_2/Yr by 2050, primarily through halting deforestation. In addition, N_2O emissions could be reduced from 2.8 Gt to 1.8 Gt of CO_2e, primarily though improvements in agricultural production.
- Methane emissions could be cut from 400 to 230 Mt per annum, with major potential to reduce CH_4 emissions from fuel production.

The starting point – current emissions

In 2019, global anthropogenic emissions were approximately 37 Gt CO_2, 4.0 Gt CO_2e of NO2 and 402 Mt Methane, as shown in Exhibit 3.[24] In the EBIT sector, CO_2 and N_2O emissions can be estimated fairly precisely, since they primarily result from burning of known quantities of fossil fuels and standard processes of transforming fossil fuel into products. Methane emission estimates are less precise due to uncertainties about the sectoral origin, location and timing of methane leakage despite evolving standards on reporting on methane emissions and improving detection and quantification technologies.[25]

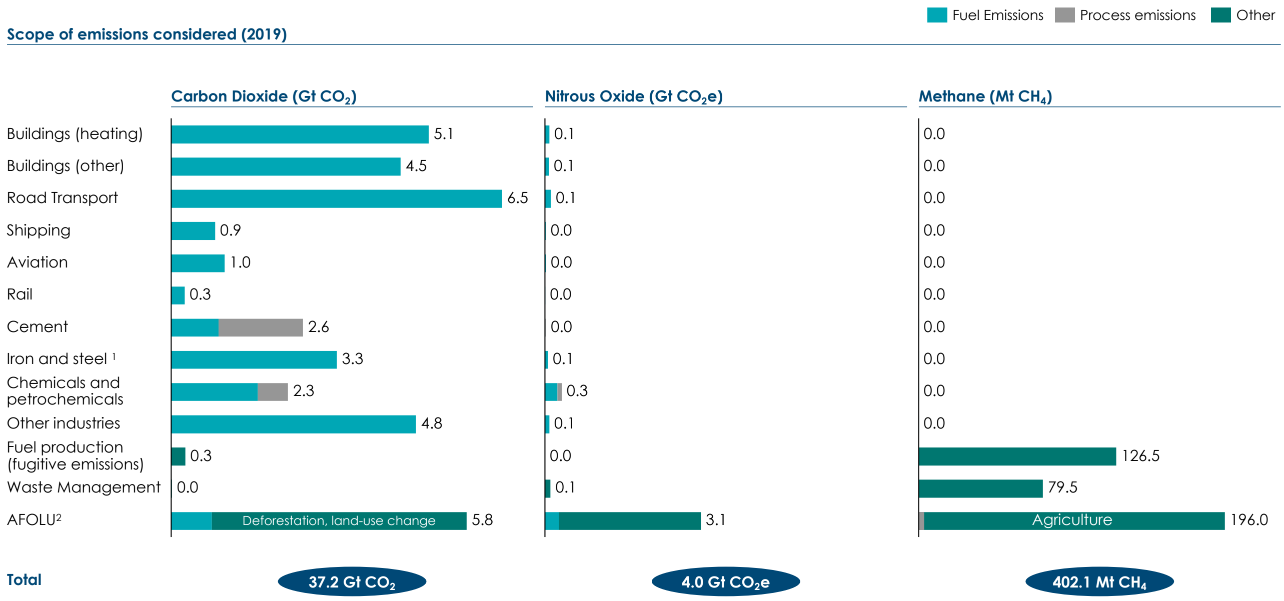
Estimates for AFOLU emissions are inherently far more uncertain than for EBIT. Total estimates for CH_4 emissions from ruminant animals (e.g. cattle), rice paddies and agricultural manure are subject to significant uncertainties. Estimates of CO_2 emissions, which primarily result from land use change rather than fossil fuel use, are inherently uncertain since the emissions resulting when a hectare of forest is cut down or burnt varies very significantly depending on specific local circumstance. Finally it should be noted that estimates of agriculture-related land-use change depend on the robustness of tracking mechanisms and on government self reporting, which may in aggregate produce a bias towards lower estimates than the underlying reality.[26]

It is also important to understand the precise meaning of the estimated ~5 Gt of net emissions of CO_2 today resulting from deforestation and other land-use change in the AFOLU sector. In particular:

- This overall net anthropogenic figure results from a combination of gross emissions which average around 15 Gt, and gross removals (estimated to average around 10 Gt) currently arising from human induced land-use change (see Exhibit 8, left hand side). Although a level of decay and regrowth is a given in the land use sector, emissions from land degradation are increasing faster than removals from forest regrowth, resulting in net emissions increasing over time.[27]
- In addition to human-induced land use change impacts, there are large carbon removals which result from natural terrestrial sinks absorbing CO_2 as a function of pristine natural ecosystems.

24 Baseline developed from range of sources, including: European Commission, Emissions Database for Global Atmospheric Research (EDGAR), release EDGAR v5.0 (1970 - 2015) of November 2019; IPCC (2019), *Special Report on Climate Change and Land*; IEA (2020), *Energy Transitions Pathway*; IEA (2020), Cement Analysis.
25 Examples including: Methane Intelligence (miq.org) and the IEA (2020), *Methane Tracker.*
26 Harris et al., (2021), *Global maps of twenty-first century forest carbon fluxes.*
27 Forest regrowth is also often of a lesser quality forest than that which is degraded, resulting in degradation of biodiversity and soils. Freidlingstein et al., (2020), *Global Carbon Budget 2020.*

Assumptions about gross removals from the forestry and land-use change sector, as well as these terrestrial sinks are already taken into account in IPCC estimates of the available carbon budget. Therefore, these carbon removals and cannot therefore be seen as an option to close any GHG emissions overshoot gap. In the carbon budget these numbers are assumed to be constant over time, in reality warming as well as ongoing land-use change might decrease the size of these gross removals and natural sinks.[28]



(1) Due to the production process, process emissions and fuel emissions are typically not separated for iron and steel; (2) AFOLU: Agriculture, Forestry, and Other Land Use change; Note: Estimates of global greenhouse gas emissions in 2019 range widely as a result of varying assumptions, including different assumptions on GWP of methane. The IEA estimates global GHG emissions in 2019 of 51 Gt CO_2e.
Source: SYSTEMIQ analysis for the ETC based on: IEA (2017), Energy Technology Perspectives; EDGAR database; SSP database by IIASA; IEA (2020), Methane Tracker

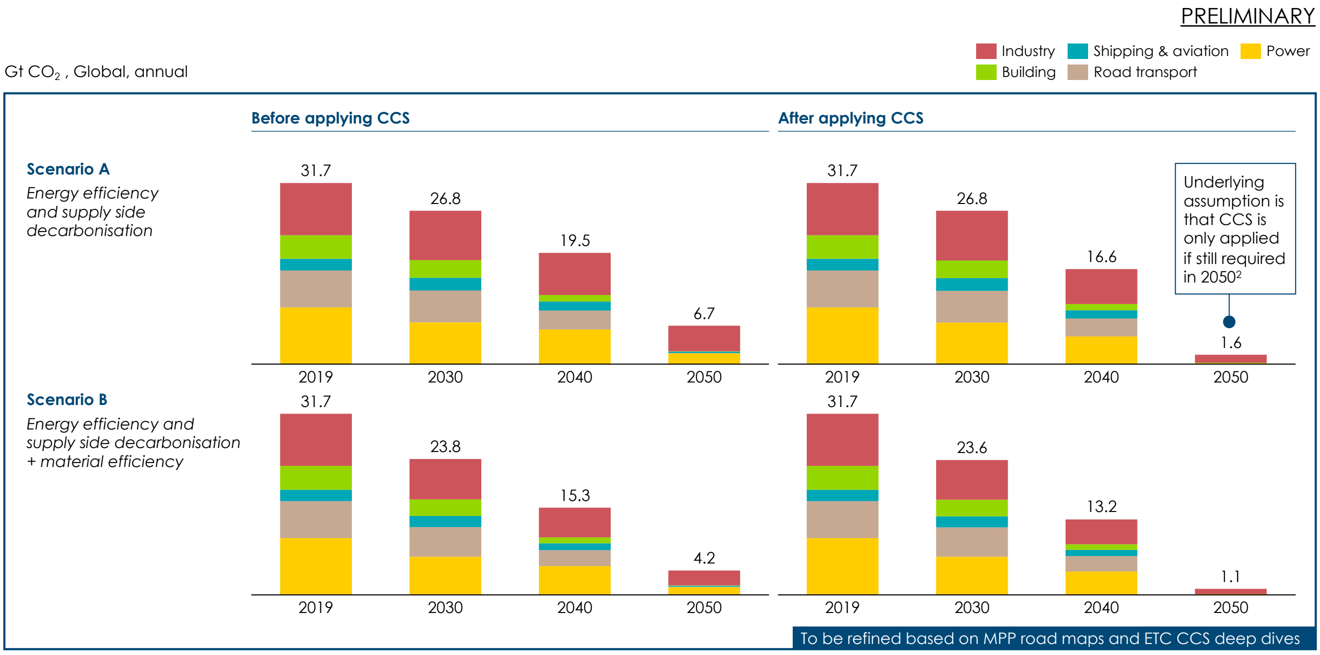
Exhibit 3: Including CO_2, CH_4 and N_2O emissions from EBIT sectors, waste and AFOLU, leads to a total of 37.2 Gt of CO_2, 4.0 Gt CO_2e from N_2O and 402 Mt of CH_4.

EBIT emissions reduction scenarios

The EBIT sectors are currently responsible for around 32 Gt of CO_2 emissions and about 130 Mt of CH_4 emissions (see Exhibit 3).[29] These derive from three main sources (i) energy-related emissions resulting from the burning of fossil fuels, whether used directly or to produce electricity, (ii) process emissions arising from the chemical reactions involved in cement, steel, petrochemical, and other production processes, and (iii) emissions resulting from the extraction, processing and distribution of fossil fuels, which account for almost all EBIT sector CH_4 emissions.[30]

The ETC has previously shown that EBIT sector CO_2 emissions – including those from what have previously been seen as "harder-to-abate" sectors – could be reduced close to zero by mid-century – with net emissions after CCS as low as 1.6 Gt, and still lower if all opportunities for energy productivity improvement could be seized.[31] We have now developed illustrative scenarios for the trajectory of emissions between now and 2050. Exhibit 4 shows the resulting profile over time. Scenario A shows what might occur if only supply-side decarbonisation and energy efficiency improvement measures were deployed; Scenario B shows the potential if all opportunities for energy productivity, including circular economy measures, were also seized.

28 Duffy et al., (2021), *How close are we to the temperature tipping point of the terrestrial biosphere?*
29 European Commission, Emissions Database for Global Atmospheric Research (EDGAR), release EDGAR v5.0 (1970 – 2015) of November 2019; IEA (2020), *Energy Transitions Pathway*; IEA (2020), Cement Analysis.
30 All fossil-fuel related methane emissions covered by the IEAs methane tracker are included in fugitive emissions.
31 ETC (2018), *Mission Possible*; ETC (2020), Making Mission Possible



Note: (1) In 2019, 'biofuels' includes both biomass and waste, generating emissions but the decarbonization pathways assume no further use of waste as an energy source. Emissions from biofuels from 2021 onwards are assumed to only be generated in the feedstock-to-fuel conversion process for biofuels used in transport; (2) We assume CCS to only be applied if still required in 2050 based on the long lifetimes of CCS, the lead times of 5+ years and the limited CCS capacity to date.
Source: SYSTEMIQ analysis for the ETC based on: IEA (2017), Energy Technology Perspectives; IEA (2020), Energy Technology Perspectives; Previous analyses of the Energy Transitions Commission, drawing on data from BloombergNEF.

Exhibit 4: EBIT sectors: Resulting in a ~30 Gt CO_2 decline in emissions under our CCS assumptions by 2050.

These scenarios could be considered "reasonably optimistic"; they assume ambitious policies and private sector action to drive decarbonisation across all EBIT sectors based on robust bottom-up analyses developed in close consultation with industry stakeholders.[32] They are illustrative and will be refined over the coming months. Still more rapid reduction could be possible if society is willing to accept some higher costs (for instance from scrapping existing capital assets before end of life or forcing the widespread use of new technologies before costs have been reduced). The feasible pace of decarbonisation differs between sectors, with the shape of the reduction curve over time reflecting the following assumptions:

- Energy: In the power sector, the falling costs of renewables makes rapid decarbonisation economic, with all developed economies achieving almost complete decarbonisation by 2035 while developing countries meet all growing demand for electricity from zero-carbon sources.[33] Some factors, however, may delay this progress, particularly in developing countries such as China and India, including existing long-term fixed price supply contracts and regional employment challenges. Power-related emissions contract towards zero in the 2040s. Our detailed assumptions about the power sector are set out in the ETC's recent report on clean electrification.[34]

- Building: In the infrastructure sector already electrified activities will further grow, including heating and cooling.

- Industry: Industrial decarbonisation, including the steel, chemicals, and cement sectors, is also possible by 2050, but with gradual progress only in the 2020s as key technologies (such as the use of green hydrogen in steel production) progress through pilot plants and initial commercial deployment stages. Moreover, some industrial decarbonisation – in particular the example of cement – will likely depend on the application of CCS, which in 2050 could account for 5.2 Gt of emissions reductions (reducing residual EBIT emissions from 6.7 Gt to 1.6 Gt), but which is unlikely to be deployed on a large scale before 2030.[35] As for shipping and aviation,

32 ETC (2018), Mission Possible; ETC (2020), *Making Mission Possible.*
33 Variable renewable energy generation costs are already falling below the marginal cost of running coal or gas plants in many locations, leading to declining fossil capacity utilization over time.
34 ETC (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy*
35 Given the limited capacity of CCS to-date, the long lead times of 5+ years from planning to becoming operational and the use of CCS in only a limited number of applications thus far, it is unlikely that CCS operations within these sectors will begin before 2030. In addition, given the long lifetime of capture and storage infrastructure we assume that CCS is only built if it is still required in 2050 and is therefore not treated as a transition technology.

initial assumptions are set out in the ETC's Mission Possible and Making Mission Possible reports,[36] but will be refined during this year.

- Transport:
  - Road transport can and should be electrified, with rapid growth in the share of new auto sales accounted for by battery EVs, and some developed countries planning to ban ICE sales from 2030. However, it still takes time for this new flow effect to work through to the stock of vehicles on the road.[37]
  - Shipping is eventually almost completely decarbonised (most likely through use of fuels such as ammonia derived from 'green' hydrogen) and so too is aviation (using either biofuels or synthetic fuels). In both sectors, progress is initially slow in the 2020s due to low technology readiness and high fuel switch costs but accelerates thereafter. Key initial assumptions here are set out in the ETC's Mission Possible and Making Mission Possible reports,[38] but will be refined during this year.

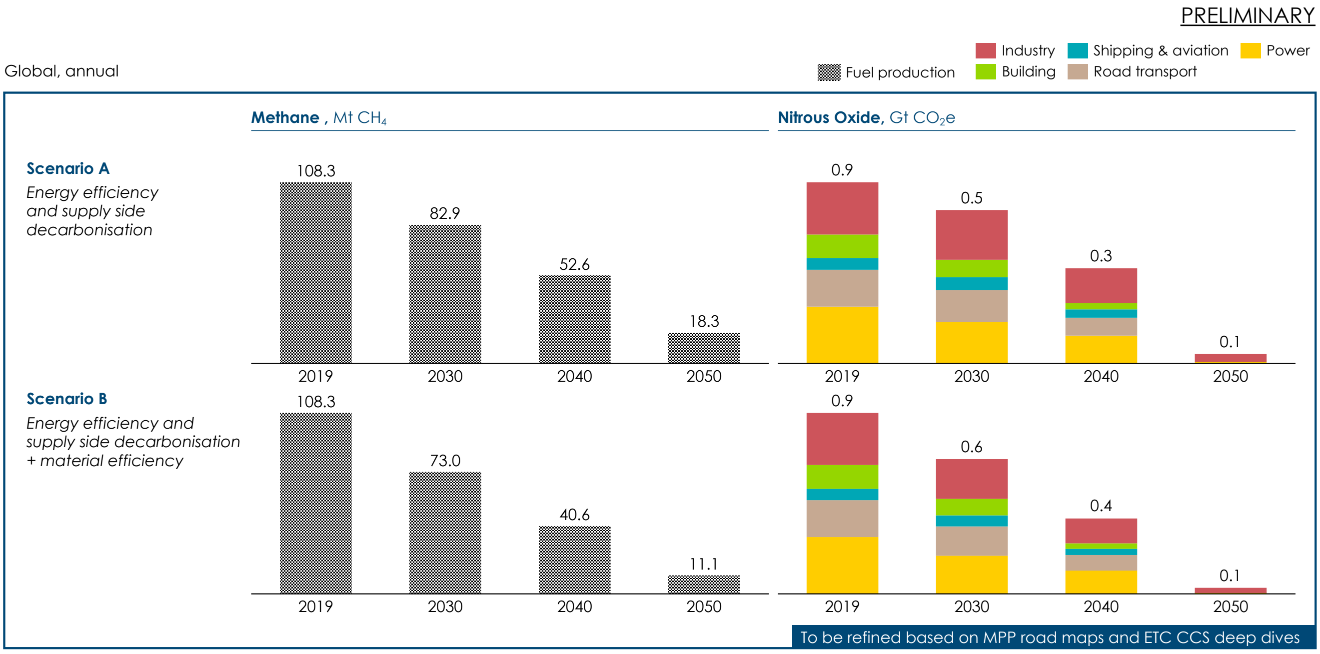
The difference between Scenario A and Scenario B reflects the potential impact of theoretically feasible improvements in three forms of energy productivity:

- Greater technical energy efficiency across multiple applications such as buildings, for example through better insulation, and in transport.
- Improved material efficiency which can reduce the need for primary production of energy-intensive materials, such as steel and cement, through product redesign, more efficient material use, and greater materials recycling and reuse;[39]
- Improved service efficiency, where, in theory, it is possible to deliver higher living standards while using less energy-intensive goods and services, for example through shared use models in transport, changes in transport mode and better urban design. Energy savings here depend on some element of behaviour change, making the true opportunity inherently uncertain, but in principle large.

Energy productivity measures primarily influence electricity consumption which will be almost completely decarbonised by 2050, therefore achieving these measures would make little difference to residual emissions in 2050. Greater energy productivity could significantly reduce total energy demand by 2050 (and thus total costs) but cut residual emissions by only another 0.5 Gt. However, in principle, rapid improvements in energy productivity could be a lever to achieve considerably more rapid emission reductions in the 2020s. Thus, Scenario B shows a fall of 25% between 2020 and 2030 as against Scenario A's 17%. This could significantly impact cumulative CO_2 emissions over the next 30 years: from 686 Gt CO_2 emissions in scenario A to 614 Gt CO_2 emissions in scenario B.

Finally, in the EBIT sectors, it is important to focus also on the major potential to reduce CH_4 emissions from fossil fuel production and use. These will fall naturally as fossil fuels account for a declining share of total energy supply. But they can and must also be reduced rapidly to eliminate CH_4 leakage across the fossil fuels value chain. We estimate that EBIT CH_4 emissions could be cut from 108 Mt to 83 Mt in 2030, 53 Mt in 2040 and 18 Mt in 2050, implying a 100% reduction in flaring emissions and a 40% reduction in leakage/venting. This approximately corresponds to a leakage rate of 0.2% in line with OGCI targets.[40] However, we believe there is further potential to reduce leakage rates beyond this to 0.05% by 2050 through a more ambitious effort to limit leakage and halt venting.[41] N_2O emissions generated by the EBIT sectors could also be reduced, primarily by the displacement of fossil fuels as well as by a greater adoption of abatement technologies in the chemicals sectors, namely nitric acid and adipic acid production. The ETC estimates that incremental capital investments needed to achieve a zero emissions economy by around mid-Century, while significant in absolute dollar terms (US$1.6 trillion per annum on average over the next 30 years), are only about 1% to 2% of global GDP per annum.[42]

36 ETC (2018), *Mission Possible*; ETC (2020), *Making Mission Possible.*
37 Despite improving economics leading to growing shares of EVs in new sales, it will take many years for the fleet to be largely electrified given typical vehicle turnovers of 12 years in developed economies, but much longer in some developing countries; ETC (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy.*
38 ETC (2018), *Mission Possible*; ETC (2020), *Making Mission Possible.*
39 Analysis by Material Economics suggests that in theory, by 2050, such measures could reduce global demand for cement by 34%, steel by 64% and chemicals by 56% relative to BAU.
40 OGCI (2021), *OGCI position on policies to reduce methane emissions.*
41 ETC (2021), *Making the Hydrogen Economy Possible.*
42 ETC (2020), *Making Mission Possible.*



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

Exhibit 5: EBIT sectors: Resulting in a ~90 Mt decline in CH_4 and a 0.8 Gt CO_2e decline in N_2O under our CCS assumptions by 2050.

Waste emissions reduction scenarios

Multiple forms of waste management and disposal – some applying advanced management techniques, but others involving open dumping – produce large CH_4 emissions. Estimates are inherently uncertain but suggest around 80 Mt per annum (see Exhibit 7).[43] These could grow to over 110 Mt by 2050 with population growth and only limited improvements in waste management practices. However, forceful action to bring all countries up to the waste management standards of high-income nations could both reduce CH_4 emissions to 15 Mt per annum and help deliver several UN Sustainable Development Goals in the process.[44] Development support for low-income nations to invest in solid waste and wastewater infrastructure will be critical to seizing this potential.

AFOLU emissions reduction scenarios

The AFOLU sector currently accounts for about 6 Gt of annual CO_2 emissions (of which ~5 Gt derived from the net effect of forestry and land-use change), 3.1 Gt of CO_2 equivalent N_2O emissions and around 190 Mt of CH_4.[45] Compared with the EBIT sectors, it is far more difficult to define both the feasible endpoint in 2050 and the pathway from now till then. This reflects not only the inherent uncertainty about today's emissions already discussed, but also the far more fragmented nature of agricultural production, and inherent complexities arising from the overlap between agriculture, land use changes deriving from agriculture, and the wider role of natural sinks and sources.

Exhibit 8 sets out our illustrative scenario for how emissions might evolve between now and 2050, with net CO_2 emissions reducing to almost zero, N_2O emissions falling 36%, and CH_4 emissions down from 192 Mt to 110 Mt. The key actions required to achieve this would be:

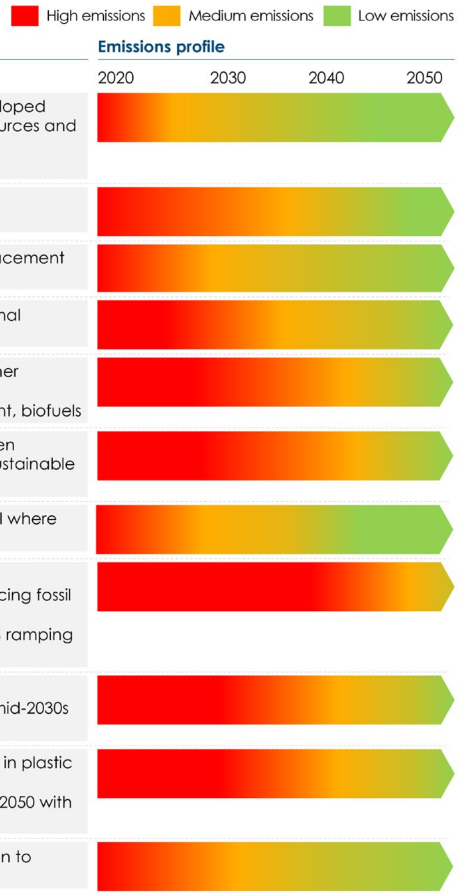
- A major change of direction in land-use, where the most important is to avoid further

43 ETC Analysis, drawing on: UK CCC (2020), *Balanced Net Zero Pathway Assumptions; International Water Association*, "How can more water treatment cut CO_2 emissions," accessed February 2021; World Bank (2018), *What a Waste 2.0.*

44 Presents an illustrative optimistic scenario which assumes that global per capita waste emissions converged with the EU, and that those emissions per capita reduce by a further 50% by 2050 in line with historical EU waste emissions (42% reduction 1995 and 2017, *Eurostat*). For context, the UK Climate Change Commission has a target for 75% reduction of waste emissions by 2050.

45 SYSTEMIQ analysis for the Energy Transitions Commission, drawing on: Roe et al., (2019), Contribution of the land sector to a 1.5 °C world; IPCC (2019), *Special Report on Climate Change and Land*; Global Forest Watch, "New Global Maps Estimate Forest Carbon Fluxes in Unprecedented Detail," January 29th 2021.

Sector	Approach
Power	• Rapid replacement of fossil fuel generation by renewables towards 2035 in developed economies; in developing economies all new-build capacity from renewable sources and phasing out fossil towards 2050 • Large growth of power demand from increased demand across sectors
Buildings	• Full electrification of building non-heating by mid 30's • Increasing adoption of electric heat pumps towards 2050 to replace gas/coal
Light Duty Transport	• Rapid phasing out of internal combustion engines from the early 2020s and replacement by electric vehicles
Heavy Duty Transport	• Electrification of heavy-duty vehicles from the mid- to late-2020s to replace internal combustion engines.
Shipping	• Direct electrification of short-distance shipping and local ferries, powered by either electricity or hydrogen • Long-haul shipping to be powered by ammonia from 2030s and, to a lesser extent, biofuels
Aviation	• Direct electrification of short-haul flights, powered either by electricity or hydrogen • For all long-haul flight, jet fuel replaced by synthetic "power to liquid" fuel and sustainable biofuels from 2030 onwards
Rail	• Almost fully electrified by 2035 with a minor role for hydrogen in long-distance rail where overhead electrification is too expensive
Cement	• Direct electrification of cement kilns from 2035 onwards • Increased use of biofuels and hydrogen to supply high-temperature heat, displacing fossil fuels from mid-2030s • Significant share of energy demand still coming from fossil fuels by 2050 with CCS ramping up from mid-2030s
Iron and steel	• Hydrogen-DRI displaces a significant share of BF primary production from 2030 • Coal-based BF production continues to play a role with CCS ramping up in the mid-2030s • All secondary production is electrified
Chemicals and petro-chemicals	• Direct electrification and increasing use of hydrogen as both fuel and feedstock in plastic and chemicals production • Significant share of energy and feedstock demand still supplied by fossil fuels by 2050 with CCS ramping up from mid-2030s
Other industries	• Direct electrification of majority of energy demand with a minor role for hydrogen to supply high temperature heat in some cases



SYSTEMIQ analysis for the Energy Transitions Commission (2021)

Exhibit 6: Decarbonisation pathway per sector.

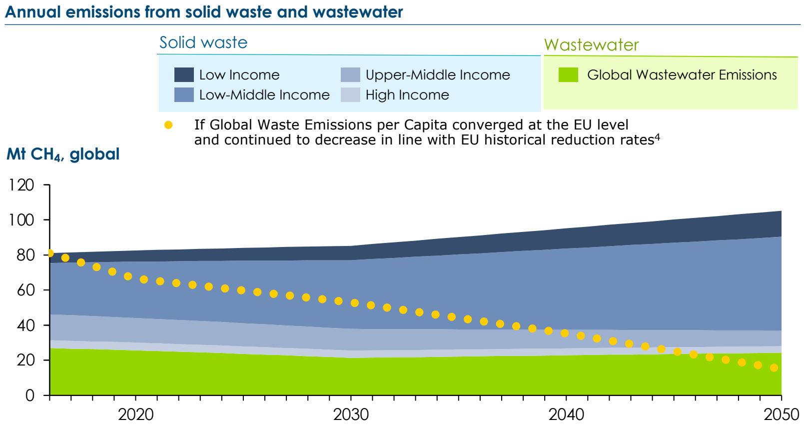
Two primary sources of waste emissions:

~2/3 of waste emissions from poor solid waste management and incineration:

- Emissions from open dumping are estimated to be ~20-fold of landfill emissions.[1]
- 93% of waste in low-income nations is disposed of in open dumps.[2]
- Food and green waste and paper and cardboard contribute the majority of solid waste emissions.[2]

~1/3 of waste emissions from wastewater:

- Only about 20% of all wastewater globally is treated.[3]
- Treating wastewater could cut its GHG emission to about one-third.[3]



***Waste emissions are comprised of ~98% methane.**

Note: Large uncertainty on emissions from waste due to undocumented volumes and impacts of untreated waste

Source: SYSTEMIQ analysis for the ETC based on: (1) Manfredi et al., (2009), *Landfilling of waste: accounting of greenhouse gases and global warming contributions*; (2) World Bank, What a Waste 2.0, 2018 ; (3) International Water Association (2020), "How can more water treatment cut CO_2 emissions?"; (4) European Environment Agency (2019). Note: assumes global per capita waste emissions reduce to 50% of that of the EU today, based on past EU waste emissions mitigation trajectory.

Exhibit 7: If we only apply moderate efforts to mitigate, waste emissions could be responsible for >100 Mt CH_4 per annum in 2050.

deforestation. Our scenario, which builds on the Land Sector Roadmap developed by Roe et al., (2019), assumes that by 2040, annual net emissions from human-induced deforestation and land degradation could be reduced by around 5 Gt CO_2 by 2050. This analysis assumes policies which deliver a 70% reduction in deforestation rates by 2030, achieving a near-total end to land conversion (90% down) by 2040.[46] It is critical to highlight that halting further deforestation is the most urgent and effective action which can be taken to address AFOLU emissions. IPBES estimates that only 20% of tropical forests today are pristine and intact forests, yet these represent 40% of the carbon stored in tropical forests.[47] Policies to achieve this challenging objective include establishment of protected areas, improved land tenure, law enforcement, and supply chain transparency, commodity certification and payments for the protection of forest through voluntary carbon markets or other result-based payment schemes. In addition, reducing peatland and coastal wetland draining and conversion is a key lever. One study finds the drainage of peatlands generates 32% of emissions from land use conversion to cropland yet only provide 1.1% of total crop calories.[48]

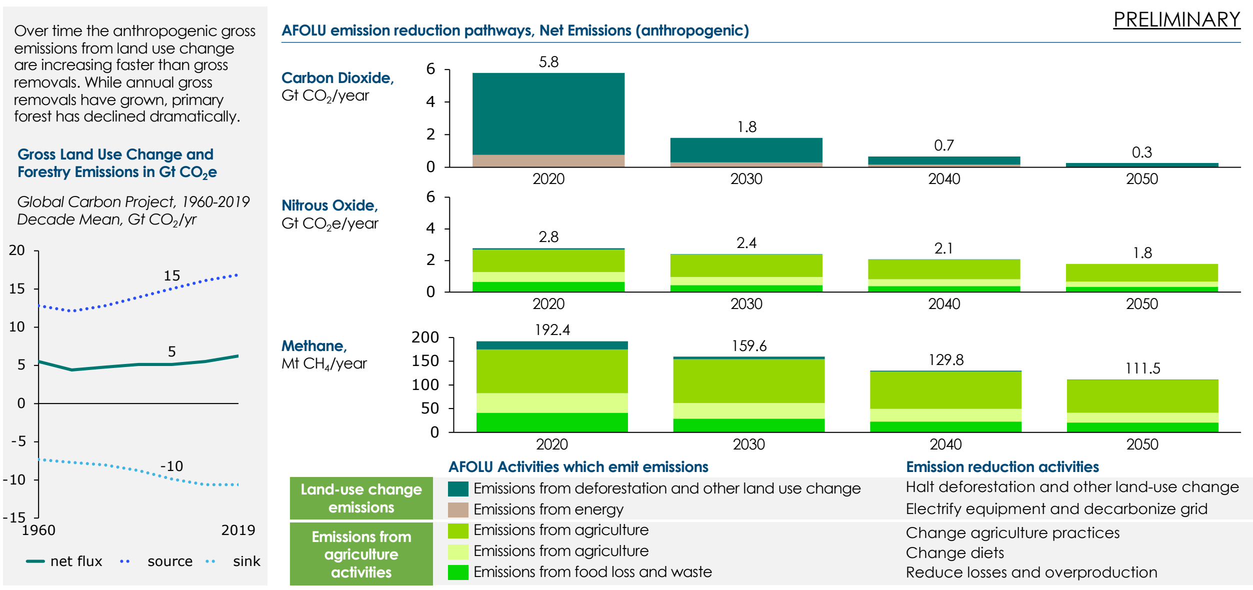
- Significant changes in agricultural production processes and consumer behaviour. Key sources of N_2O emissions include fertiliser use, and animal manure; while CH_4 emissions are primarily produced from enteric fermentation of ruminant animals, rice cultivation and animal manure. Reducing these will require the following:

  – Improvements in agricultural technologies and practices, including better fertiliser management, improved water and residue management of rice fields, and reducing emissions from enteric fermentation by changing livestock feed. These could achieve an estimated 25% reduction in direct agricultural emissions.

  – Demand-side changes which reduce emissions via shifting to plant-based diets and reducing food loss and waste. Our scenario assumes that, by 2050, 50% of the global population adopts a plant-rich diets, significantly reducing demand for GHG-intensive and land-intensive foods such as red meat.[49] On top of that, by 2050, food loss and waste could be reduced by 50%. An estimated one-third of all food produced today is wasted, either prior to reaching the plate due to overproduction, lack of cold storage and inefficient practices in the food value chain (food loss) or 'after the plate' because of consumer behaviour (food waste).[50] These demand shift levers could deliver a 20% reduction in total agricultural CH_4 emissions by 2050 even as the global population continues to grow.

The Food and Land Use Coalition estimated that a global transition for the food system to achieve similar targets would have an investment cost in 2030 less than 0.5% global GDP per annum ($300-$350 billion required each year for the transformation of food and land use systems to 2030).[51]

46 This could bring forestry and land use change emissions into balance, where ongoing emissions from forest decay and management practices would be offset by regrowth from managed land. Roe et al., (2019), *Contribution of the land sector to a 1.5 °C world*; IPCC (2019), *Special Report on Climate Change and Land.*
47 IPBES (2019), *Global Assessment Report on Biodiversity and Ecosystem Services.*
48 Carlson K. M. et al., 2017, *Greenhouse gas emissions intensity of global croplands.*
49 While a greater shift towards plant-rich diets is feasible, it is important to consider that as global population shift signals a growth in middle-classes in developing nations, this also typically drives an increased demand for 'luxury' food items such as dairy and meat. Meat consumption is not eliminated altogether but limited to ~60 grams/day. Source: Hawken, P. (2017), *Project Drawdown: The most comprehensive plan ever proposed to reverse global warming.*
50 FOLU (2019), *Growing Better: Ten Critical Transitions to Transform Food and Land Use.*
51 FOLU (2019), *Growing Better: Ten Critical Transitions to Transform Food and Land Use.*



Source: SYSTEMIQ analysis for the ETC based on: Roe et al,. (2019) and Global Carbon Budget (2020).
Note: Roe et al., (2019) levers for mitigation in 2050 were back-calculated based on policy assumptions stated in paper to show how the emissions for the AFOLU sector could shift over time as the strategies take effect; Roe et al., (2019) indicates an additional max potential of 1.1 Gt CO_2e/yr BECCS, which is excluded in this overview. Emissions from deforestation and degradation adjusted to reflect estimates from Global Carbon Project (average 2001-2018). Farming practices which release emissions include enteric fermentation, rice cultivation, fertilizer use, manure.
Note: The carbon dioxide removal potential of natural climate solutions such as reforestation and natural landscape restoration is not depicted here.

Exhibit 8: Applying a mix of reductions to land-use change and agricultural emissions leads to a decline in annual CO_2 emissions from 5.8 Gt to <1 Gt, while CH_4 emissions reduce from 192 to 112 Mt CH_4.

Chapter 3: The size of the overshoot gap: resulting emissions scenarios and the carbon budget

Comparing our illustrative scenarios for EBIT, Waste and AFOLU sector emissions with the IPCC carbon budget reveals both the need around for ~ 4 Gt per annum of ongoing carbon removals beyond 2050 and at least a 200 Gt gap of excess cumulative CO_2 emissions over the next 30 years.

The combined result of the EBIT, Waste and AFOLU scenarios is shown on Exhibit 9, with total CO_2 emissions cut from 37 Gt to 2 Gt per annum in 2050, N_2O from 3 to 2 Gt of CO_2e and CH_4 emissions reduced by around 40% in 2050. The residual CO_2 and N_2O emissions of around 4 Gt per annum imply a permanent ongoing need for an equivalent level of "carbon removal" each year.

In addition, however, as the right-hand side of Exhibit 10 shows, cumulative CO_2 emissions over the next 30 years are estimated at 686 Gt versus the estimated carbon budget 500 Gt discussed in Section 1. This implies an overshoot gap of around 200 Gt which needs to be closed if the defined climate objective – a 50% chance of limiting to 1.5°C warming and 90% chance of limiting to 2°C – is to be met. Indeed, the gap is likely to be higher still, since our estimated likely CH_4 emission reduction of 40% is less than the median 50% reduction which the IPCC assumes in its scenarios.

The overshoot gap primarily arises because the shape of the CO_2 emissions trajectory described by our illustrative base case scenario is significantly "back-ended". Thus, as the left-hand side of Exhibit 10 shows, emissions fall far more slowly in the 2020s than in the illustrated IPCC scenarios which are compatible with no / low overshoot of the 1.5°C climate objective. The P1 scenario makes ambitious assumptions for low energy demand by 2050 to avoid reliance on negative emissions technologies such as Bio-Energy with Carbon Capture and Storage (BECCS) whereas the P3 'middle-of-the-road' pathway utilises negative emissions technologies to a limited degree from around mid-Century onwards. ETC estimates for the emissions trajectory will be refined over time, but are unique in being developed from a systematic, bottom-up, industry perspective of a transition which is ambitious yet feasible.

As a result, significantly increased early reductions, beyond our illustrative scenario, would be needed to avoid the need for absolute negative emissions in the 2050s and beyond.

There are three ways in which this overshoot gap could be bridged:

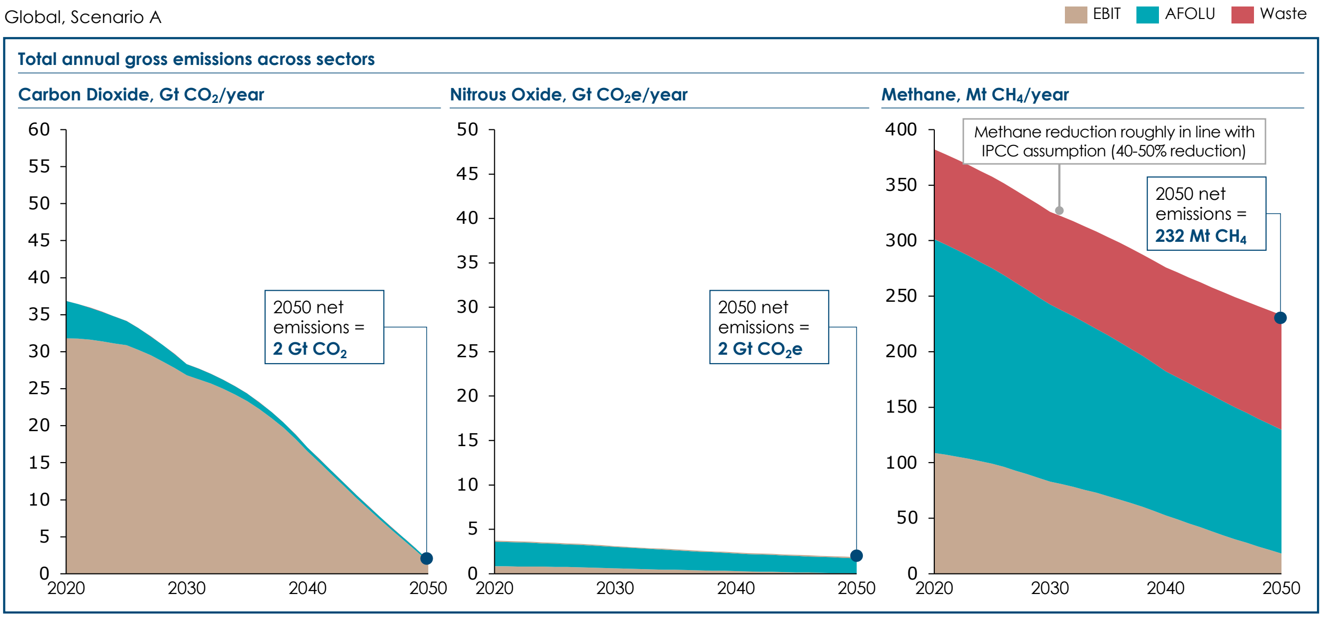
- The first is cut CH_4 emissions faster than shown in Exhibit 9, achieving at very least the 51% assumed in the IPCC scenarios, but ideally considerably more. Our next steps will include more detailed analysis of the potential to cut CH_4 emissions, and in particular for achieving significant early reductions in the 2020s.

- The second is to accelerate the pace of CO_2 and N_2O reductions whether in the EBIT or AFOLU sectors. In EBIT, this would require faster decarbonisation of power, transport, building and industry than we have assumed, together with a strong focus on energy productivity improvement. For instance, if one could move to scenario B rather than A, this would reduce cumulative emissions by 72 Gt CO_2. In the AFOLU sector, it would require faster progress to cease deforestation and peatland conversion into agricultural land.

- The third is to actively remove CO_2 from the atmosphere via "carbon dioxide removals".

PRELIMINARY

Global, Scenario A

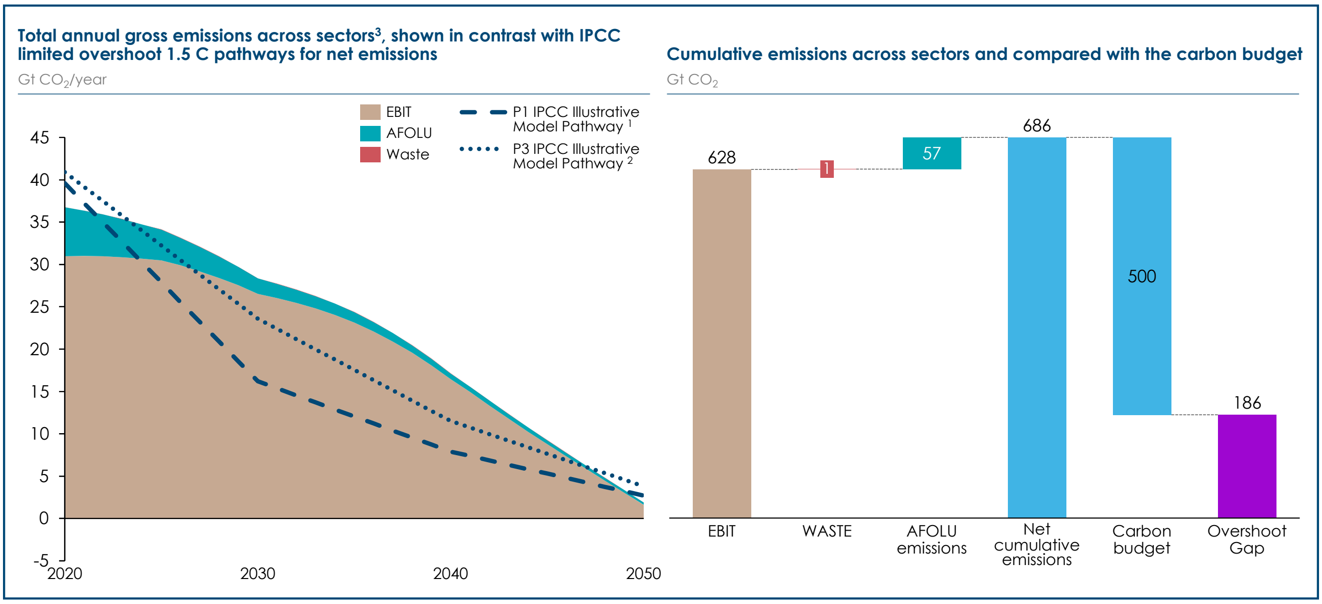


Source: SYSTEMIQ analysis for the ETC based on: IEA (2017), Energy Technology Perspectives; IEA (2020), Energy Technology Perspectives; Previous analyses of the Energy Transitions Commission; IPCC (2018) *Special Report for 1.5C*

Exhibit 9: Total emissions show a decline towards 2050.

Global, Scenario A

PRELIMINARY



Source: SYSTEMIQ analysis for the ETC based on: IEA (2017), Energy Technology Perspectives; IEA (2020), Energy Technology Perspectives; Previous analyses of the Energy Transitions Commission; IPCC (2018) *Special Report for 1.5C*
Note: (1) P1= an ambitious scenario which assumes social and technical innovation drive rapid decarbonization through low energy demand assumptions and investment in afforestation. (2) P3 = A middle of the road scenario which assumes societal and technological development roughly follow historical patterns and drive net emissions reduction by changing the way energy and products are produced. IPCC Integrated Assessment Models modelled 42 scenarios for >1.5C, typically draws on multiple data sources and forward projections, meaning that some variation in starting points is expected (see exhibit 1). (3) Point-source CCS assumed as part of within-sector decarbonization for EBIT sectors.

Exhibit 10: Total CO_2 emissions show a decline towards 2050; cumulative emissions are 186 Gt CO_2 above the carbon budget.

Chapter 4: Carbon Dioxide Removals

A range of carbon removal technologies (CDR) could in principle close the carbon dioxide overshoot gap. Natural climate solutions (NCS) have the greatest proven potential and are likely to be the lowest cost, but BECCS, DACCS and other technologies must also play a role to reach the volumes of carbon removals which will be required to plug the gap. Important issues relating to the permanence of carbon storage need to be analysed further.

Exhibit 11 sets out summary of the technological readiness of different carbon removal technologies, their potential scale of deployment, and possible costs now and in the future.

Natural Climate Solutions (NCS)[52]

The most tried and tested method for capturing carbon dioxide from the atmosphere is the one the planet has been utilising for millions of years: photosynthesis. Natural Climate Solutions apply that biogeochemical process and, in some cases, leverage technology to further support sequestration and long-term or permanent storage. Examples include afforestation and reforestation (including commercial forestry), improved natural forest management and agroforestry, improved agricultural practices to enhance soil carbon sequestration, and marine ecosystem restoration. The largest opportunity for NCS is in the tropical and sub-tropical belt, where substantial co-benefits in terms of positive community and biodiversity impact can be expected. Natural climate solutions store carbon in live biomass (for example, trees), in soils, and, in some cases, in buried biomass. Ocean-

				Resource Considerations and Other Co-Benefits				
	Description	Estimated carbon removal potential in 2050	Estimated costs in 2050		Key Co-benefits[1]	Resource Constraints	Land Required (Mha/Gt CO_2/Yr)	Permanence (years)
Natural climate solutions (NCS)	**TRL at Scale = HIGH** CO2 is sequestered via photosynthesis and stored in biomass and soils via natural processes.	Afforestation/ Reforestation: **1-10** Gt CO_2/Yr Soil Carbon Sequestration: **1-9** Gt CO_2/Yr All other NCS: **0-10** Gt CO_2/Yr	Afforestation / Reforestation: **\$5-50** / tCO_2 Soil Carbon Sequestration: **\$0-100** / tCO_2	Forest and wetland restoration	Ecosystem Restoration	Land Water Fertiliser	~70[2]	10-1000+ (above and below land)
				Commercial Forestry Materials	Displaces Steel & Concrete	Land Water	~130[3]	50-200
Biochar	**TRL at Scale = MEDIUM** Biomass burned in pyrolysis & used to stabilise organic matter	Biochar: **0.5–2** Gt CO_2/Yr	Biochar: **\$30-\$120** / tCO_2	Biochar	Soil Health	Biomass	NA	1000+
BECCS	**TRL at Scale = HIGH** CO2 is sequestered via photosynthesis, the biomass used for bioenergy, & most of the CO2 then captured and geologically stored (CCS)	BECCS from residues: **2-5** Gt CO_2/Yr BECCS from energy crops: **0.5-5** Gt CO_2/Yr	**\$100-\$200** / tCO_2	BECCS from Residues[4]	Energy	Land Water Fertiliser	280 (land also used for other purposes)	100-1000+
				BECCS from Energy Crops[7]	Energy	Land Water Fertiliser	~50[5]	100-1000+
DACCS	**TRL at Scale = MEDIUM** CO2 is captured from ambient air via technology and stored via CCS	**0.5-5** Gt CO_2/Yr	**\$100-\$300** / tCO_2	DACCS from Renewables[6]		Power Water	~5	100-1000+
Mineral Absorption	**TRL at Scale = LOW** Adding mineral materials to accelerate biogeochemical processes on land and in oceans which sequester CO2 through rock weathering and ocean geo chemical processes	Ocean alkalinisation: **~ 1** Gt CO_2/Yr Enhanced Weathering: **2-4** Gt CO_2/Yr	Ocean alkalinisation: **\$14-\$500** / tCO_2 Enhanced Weathering: **\$50-\$200** / tCO_2	Ocean alkalinisation	Habitat Creation	Power Minerals	NA	1000+
				Enhanced Weathering	Soil Health	Power Minerals	NA	1000+

NCS: Natural climate solutions. DACCS: Direct air carbon capture and storage. BECCS: Bio-energy with carbon capture and storage. TRL = Technological Readiness Level
Source: SIQ analysis for the ETC based on: Vivid Economics based on Fuss et al. (2018); Bui et al. (2018) *Carbon capture and storage (CCS): the way forward.*; National Academies (2019), *Negative Emissions Technologies and Reliable Sequestration A Research Agenda*; Smith et al. (2016); WRI Carbon Benefits Index Calculator; Renforth et al. (2017); Roe et al. (2019); Fuss et al. (2018)
Note: (1) List of co-benefits not exhaustive. (2) Not all NCS options have a land use requirement. Figure assumes average of sequestration rates in temperate (3.5 tC/ha/yr) or tropical (4.1 tC/ha/yr) climates for afforested former pasture/crop land. (3) Assumes biomass growth of 5.15 tC/ha/yr and that 36% of total roundwood under bark harvested from commercial forestry is used for materials, of which at least 75% is used to produce medium- to long-life products (i.e., from 'sawn-wood', 'wood-based panels', and 'other industrial roundwood', as defined by the FAO). (4) BECCS from residues does not require dedicated land but uses existing land. Range represents global availability of biomass residues in 2050. Assumes average of available biomass from forest and agricultural residues as reported by Smith et al. (2016) and a 90% carbon capture efficiency in BECCS. (5) Assumes average of available biomass from energy crops as reported by Smith et al. (2016) and a 90% carbon capture efficiency in BECCS. (6) Liquid sorbent DAC. (7) Range represents Food and agricultural systems shift enabling energy crops grown on freed up land to increase above current supply (~0.5-1 Gt CO_2/yr). If 250Mha of additional crop/pastureland made available via food systems transition, ~5 Gt CO_2/yr additional carbon capture and storage theoretically possible via BECCS.

Exhibit 11: An overview of most well-known future carbon dioxide removal options.

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

based removal options are considered under other carbon dioxide removal options below.[53]

Biochar[54] is charcoal produced by pyrolysis of biomass (low-oxygen environment), which is more resistant to decay, which can then be buried to store carbon long-term in soils or, potentially, in geological storage (e.g., placed in abandoned mines).[55] It also provides soil quality co-benefits. It is an established process, but is not widely applied today due to costs versus other energy solutions and low availablity of pyrolosis facilities. NCS coupled with climate smart technology would process biomass which has died from natural causes into biochar to ensure permanence. This integration could be one of several ways to create a high-quality, permanent at-scale removal mechanism. Potential capacity for carbon removal is still widely debated, but could be between 0.5-2 Gt CO_2/yr by 2050.[56] It could potentially be feasible at scale within a decade. Predicted costs for biochar range between \$30 and \$120 per tCO_2.[57]

The total scale of the NCS opportunity is very large and the costs in many cases low, but with large inherent uncertainty deriving from the variety of specific local conditions.

- Estimates of "cost-effective" NCS potential by 2050 range from 2 Gt to 29Gt per annum with a plausible estimate of 6.5 Gt per annum, considering economic and sustainability constraints.[58] The wide range reflects (i) inherent uncertainties about the area and quality of land available, the types of biomass which could be grown, and their precise carbon sequestration, (ii) different assessments of whether land can be devoted to NCS without displacing agriculture which might lead to deforestation elsewhere, (iii) different assumptions about acceptable costs (i.e. what is "cost-effective") and about the availability of finance, and (iv) different assessments of the value of potential "co-benefits" from more sustainable employment, or better local environmental conditions, including reduced water consumption or preserved biodiversity.
- Estimates of the cost of NCS in 2050 range from \$0-\$100 per tonne of CO_2 saved, but these are inherently situation-specific, and need to factor in not only capital and operating expenditure (e.g., the initial cost of reforestation and the ongoing cost of forest management), but also the opportunity cost of using a potentially constrained land resource, for which local stakeholders may need to be compensated.
- There are also important issues relating to the effective management of NCS solutions. As seen in past decades, terrestrial carbon stocks are at risk from human interventions such as deforestation. It is therefore important that NCS solutions are actively managed with secure committed financial means to support both long-term carbon capture, and other co-benefits of forest regeneration such as local livelihoods and biodiversity. Moreover, there is an increasing concern that the capacity of tropical forest carbon sinks to sequester carbon via photosynthesis could be decreasing because of a warming climate.[59] However, with careful land management and improved technology for monitoring, NCS strategies can be reinforcing – the greater the zone of regenerating natural environments, the greater the protection of the standing, intact forests deeper within them and the better the ecological conditions needed to support recovery (e.g., rainfall, localised cooler temperatures). They also provide critical co-benefits such as biodiversity protection, livelihood support, and climate resilience.

Despite the uncertainties, it is clear that NCS sequestration represents a major potential for cost-effective sequestration, which can also deliver local social and environmental benefits. For our illustrative base case scenario, we assume NCS sequestration reaching 6.5Gt per annum by 2050. A larger quantity might be available if food systems transition freed up even larger area of land and depending on assumptions about type of biomass.[60] Total sequestration over the next three decades could hence be 164 Gt CO_2 (reasonable

53 This is not an exhaustive list of carbon dioxide removal methods. Other examples not listed here could include, storing deadwood from forests preserved via biochar or torrefaction processes underground.
54 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal.*
55 Thengane et al., (2019), *Biochar Mines: Panacea to climate change and energy crisis?*
56 Fuss et al., (2018), *Negative emissions—Part 2: Costs, potentials and side effects.*
57 National Academies (2019), Negative Emissions Technologies and Reliable Sequestration; Vivid Economics analysis based on Fuss et al. (2018), *Negative emissions—Part 2: Costs, potentials and side effects.*
58 Roe et al., (2019), *Contribution of the land sector to a 1.5 °C world*; IPCC (2019).
59 Duffy et al., (2021), *How close are we to the temperature tipping point of the terrestrial biosphere?*
60 Roe et al., (2019) *Contribution of the land sector to a 1.5 °C world.*

conservative estimate), with a range of 45-400 Gt of CO_2 depending on assumptions.

It is important to note however that this NCS sequestration, primarily through afforestation and reforestation, must be in addition to the 5 Gt CO_2 of reduced AFOLU emissions discussed in Section 2, which will be primarily achieved via avoided deforestation. Simply eliminating deforestation therefore cannot alone be considered sufficient to "close the gap" by neutralising the unabated GHG emissions in the EBIT sector.

It should also be noted that to achieve the 6.5 Gt CO_2 of annual sequestration indicated by 2050, reforestation projects to deliver this would have to start at least a decade or more earlier, and the pace of investment would need to anticipate this.

Bio-Energy with Carbon Capture and Storage (BECCS)

Bio-Energy with Carbon Capture and Storage (BECCS) is a technology in which CO_2 is initially sequestered via photosynthesis (a version of NCS), the biomass subsequently burnt to provide energy, and most of the CO_2 then captured and placed in geological storage. 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. The ETC is currently analysing these issues in detail and will publish a report in the next quarter,[61] but preliminary conclusions are that:

- Devoting all residual waste materials from agriculture and forestry production to BECCS might enable CDR of 2 to 5 Gt CO_2 per annum. But competing demands for these resources – for instance for bio plastics or biofuels to be used in aviation – will significantly reduce this potential.
- Given a small portion of land is already dedicated to energy crop production today, if this biomass were exclusively used for BECCS, it could theoretically yield sequestration of 0.5 to 1 Gt CO_2 per annum. However, by 2050 biomass produced on land dedicated to energy crops could in theory deliver up to 5Gt CO_2 of sequestration per annum if ambitious system change were achieved in food and agricultural sectors, freeing up existing crop and pastureland for other uses, such as biomass production for BECCS. As described in Chapter 2, this would require significant food systems transition shifts in consumer behaviours and in technological innovation (examples include reducing food loss and waste by around 25 to 30%, continued improvements in global crop yields, and global shift towards a plant-rich diet, including reducing meat capita consumption in Europe by two thirds). However, if this land became available, devoting it to rewilding would produce a better result in terms of benefits to nature and devoting it to managed forest will enhance the production of biomaterials.[62]
- The cost of using BECCS to achieve carbon removal in 2050 is estimated to be in the range of \$100-\$200 per tonne of CO_2.[63]
- Using BECCS to achieve significant carbon removals would require significant land resource. To secure 1 Gt of CO_2 capture with dedicated energy crops could require about 50 Mha per year, approximately 3% of global crop land today.[64]

Our illustrative conservative estimate assumes at least 1 Gt of CO_2 annually sequestered by BECCS towards mid-century, with a maximum theoretical potential of 10 Gt per annum if applying dedicated energy crops (5 Gt) plus all available residues (5 Gt). This could result in a reasonably conservative estimate of cumulative sequestration of around 22 Gt CO_2 (range 12-205 Gt CO_2) over the next 30 years. This estimate may, however, be significantly revised in the course of ETC analysis of competing demands for bio-energy.

61 ETC (upcoming, 2021) *Making a Sustainable Bioeconomy Possible.*

62 See extended discussion of the trade-offs in upcoming ETC Bioeconomy Report: In a hypothetical analysis comparing possible uses for freed-up former agricultural land BECCS from energy crops resulted in the most carbon storage and energy generation, but a significant amount of carbon was found to be held in biomass of afforested land and managed forests. The location and condition of the land and the desired outcomes – be they carbon sequestration, energy, materials, or benefits for biodiversity and nature – determine the most appropriate use of land. Managed commercial forests have lesser outcomes for biodiversity than re-wilding projects.

63 National Academies (2019), *Negative Emissions Technologies and Reliable Sequestration*; Vivid Economics analysis based on Fuss et al. (2018), *Negative emissions—Part 2: Costs, potentials and side effects.*

64 ETC (upcoming, 2021), *Making a Sustainable Bio-economy Possible*

Direct Air Capture and Carbon Storage (DACCS)

Direct Air Capture (DAC) is a chemical process which can capture CO_2 from ambient air, with the CO_2 then stored in products or geological formation (DACCS). DAC technologies are at an early stage of development, and only demonstrated at very small scales (50 tCO_2 p.a.).[65] But one or more variants of the capture technology are likely to be commercially viable by 2030, with large-scale application thereafter.[66]

- In principle, there is "no obvious upper limit to the technical potential"[67] of DAC, but it requires very large electricity inputs with the precise quantity depending on achievable efficiency. Current estimates suggest that capturing 1 tonne of CO_2 would require about 2.8 MWH, and 1 GT would therefore require 2,800 TWH.[68] If all the electricity used came from solar photovoltaics, the land requirement would be about 4 Mha (40,000 km^2) per Gt per annum – an area of 200km by 200km.[69] This is an order of magnitude smaller than the land-use requirement per GT using BECCS (10%) and might be significantly reduced as attainable efficiency increases.[70]

- Cost estimates for DAC at current production scale have been around $600 per tonne captured,[71] but it is believed that further R&D plus large-scale deployment could drive costs down to $100-$300 per tonne or lower.[72] The future role for DAC will be crucially dependent on how far and how fast cost reductions can be achieved.

Our illustrative base case scenario assumes only a minimal role for DACCS up to 2040, but around 3 Gt per annum in 2050, with a cumulative sequestration of 15 Gt, and a range of 0-40 Gt by mid-century.

Other, more speculative carbon removals options

Hybrid solutions include those based on mineral absorption or biogeochemical processes.[73] In these cases, technology is leveraged to aid and accelerate known natural biogeochemical processes which sequester carbon dioxide. Mineral absorption solutions explore geochemical inorganic reactions, while other solutions aim to enhance biological uptake through means beyond photosynthesis. These are nascent technologies that haven't been proven at scale and have not yet demonstrated that there are no adverse effects on the environment.

Mineral absorption solutions include:

- Enhanced weathering:[74] Adding crushed carbonate and silicate rocks to accelerate geochemical processes on land which sequesters CO_2 from atmosphere. The process would involve milling silicate rocks and spreading the dust over large areas of managed cropland, speeding up the weathering reaction from proximity to plant roots and increased surface area. This technology could technically be applied today, but its impact is uncertain and further research is needed. When using the annual waste from silicate mining and industrial processes, and estimated sequestration of 0.7-1.2 Gt CO_2/y might be possible. Cost estimates range from $50 to $200 per t$CO_2$; these primarily arise from mineral processing and transport costs.

- Ocean alkalinisation/sea water mineralisation:[75] Increasing concentration of positive-ions such as calcium in the ocean to enhance the natural ability to remove CO_2 and reverse acidification.[76] This could be achieved by adding lime directly to seawater or reacting CO_2 gas and limestone with water and injecting it into the ocean. The chemical

65 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.
66 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.
67 WRI (2020), *Carbonshot: Federal Policy Options for Carbon Removal in the United States*.
68 For instance, a study in 2018 calculated that if by 2100 removal and storage is achieved at 10 times the theoretical minimum energy requirement, removals of 12 GtCO_2 a year would require 80 EJ (22,000 TWh) annually, ie a requirement of 1.8MWH per tonne. The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.
69 Assuming a solar land area requirement of about 1.4 hectares per GWH per annum.
70 ETC (upcoming, 2021), *Making a Sustainable Bio-economy Possible*.
71 American Physical Society (2011), *Direct Air Capture of CO_2 with Chemicals*.
72 National Academies (2019) *Negative Emissions Technologies and Reliable Sequestration*; Vivid Economics analysis based on Fuss et al. (2018), *Negative emissions—Part 2: Costs, potentials and side effects*.
73 Note that this definition does not explore 'geo-engineering' solutions, which do not aim to increase carbon dioxide removal, but instead target changing earth system elements such as the earth's albedo.
74 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.
75 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.
76 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal*.

processes involved are well understood; however, application at scale has never been tested and the ecosystem impacts are not well-known. The full costs have been estimated at $14 to $500 per tonne of CO_2, but these are highly uncertain.

Other solutions applying biogeochemical processes include:

- Ocean fertilisation:[77] Enhancing open-ocean photosynthesis productivity by adding nutrients to increase CO_2 drawdown by phytoplankton, moving carbon into the deep ocean. The science of this carbon transfer is as-yet unproven and fertilisation nutrients (nitrates and phosphorous) are expensive, energy-intensive and (in the case of phosphorous) scarce.

Storage options and permanence

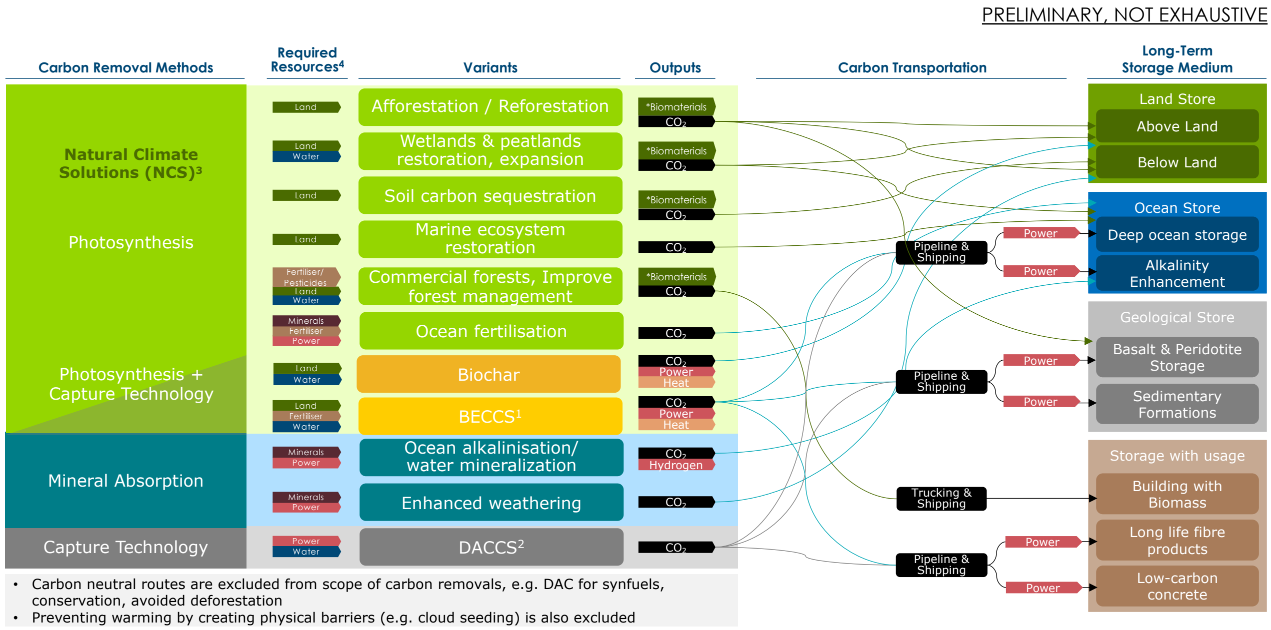
CO_2 removed from the atmosphere could be stored in one of four ways – in land-based nature, in geological storage, in the oceans, or in products and buildings ("storage in use"). Of these, the first two are likely to be the most important. Each entail different resource demands and management challenges,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

- Storage in land/the biosphere involves direct sequestration of carbon into plant biomass and soils and is clearly possible on a large scale. The Food and Land Use Coalition estimates that more than a billion hectares of land could be restored to natural ecosystems while also maintaining global food security.[78,79] However, we need to carefully manage carbon stored in biomass (e.g., reforestation) to protect it from future deforestation driven by the same factors which drove it in the past. Secure finance to ensure continued active management is therefore critical. In addition, there is some concern about increasing instances of wildfire, pests, and disease due to the impacts of climate change, but these risks are highly localised.[80,81] Tropical forests in particular, because of their natural humidity, have little risk for wildfire if well-managed for restoration; temperate forest may be more vulnerable. The duration of storage in land/biosphere could therefore range anywhere from 10 years (in the case of exogenous events such as extreme weather falling trees)[82] to 1000+ years, in the case of ancient peatlands.[83] The addition of biochar and/or other technologies to convert the end-of-life biomass to a permanent storable good could therefore increasingly be required.

- Geological storage makes CCS possible and is also at a relatively high level of technological readiness. It is already used within the oil and gas sector. It secures carbon in sedimentary formations, basalt and peridotite, and has the theoretical potential to store vast quantities of carbon, though with the availability of storage capacity varying greatly by country/region. It is also relatively secure in terms of permanence – depending on the integrity of geological formations chosen, leakage rates are likely to be less than 1% over 100 years.[84] The effective duration of storage could range from 100 years (e.g., failure of storage) to 1000+ years (effective storage with leakage rates of approx. 1% per 1000 years).[85] Using CCS on a large scale will however require extensive carbon transportation infrastructure. The ETC will produce a detailed report on the potential for the three variants of CCS – in industrial processes and as part of BECCS and DACCS – within the next year.

- There could be significant potential for storing carbon in oceans. However, the technologies to achieve this are the most unproven and the possible feedback effects on the ocean are the least clear.

77 The Royal Society & Royal Academy of Engineering (2018), *Greenhouse Gas Removal.*
78 The Food and Land Use Coalition (2019) *Growing Better.* Note this estimate assumes concurrent actions are taken such as dietary shift, agricultural yield improvements and reduction in food loss and waste.
79 The Food and Land Use Coalition (2019) *Growing Better.*
80 Max-Planck-Gesellschaft (2021), "Climate change threatens European forests: Well over half of Europe's forests are potentially at risk from windthrow, forest fire and insect attacks." *ScienceDaily.*
81 Van Lierop et al., (2015), *Global forest area disturbance from fire, insect pests, diseases and severe weather events.*
82 Between 2003 and 2012 approximately 38 mha of forests were disturbed due to extreme weather, mostly in Asia. Source: Van Lierop et al, (2015), *Global forest area disturbance from fire, insect pests, diseases and severe weather events.*
83 Treat et al., (2019) Widespread global peatland establishment and persistence over last 130,000 y.
84 IPCC (2005), *Carbon Capture and Storage.*
85 IPCC (2005), *Carbon Capture and Storage.* Estimates that carbon retained in appropriately selected and managed reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1000 years.
86 This only considers long-term sequestration potential. Use of materials which have a 'short term' storage such as biofuels cannot be considered as carbon removals.



Source: SYSTEMIQ analysis for the ETC (2021).
Note: List of removal and storage options not exhaustive. *If done with limited sustainable forestry within an intact forest landscape. Biomaterials include food, feed, fuel and fiber.
1) BECCS: Bioenergy with Carbon Capture and Storage; 2) DACCS: Direct Air Capture with Carbon Storage; 3) Natural Climate Solutions (NCS) are activities that harness the power of nature to reduce the accumulation of greenhouse gases (GHGs) in the atmosphere and provide benefits for biodiversity and human well-being. These can be coupled with climate smart technology to secure long-term storage of carbon. 4) Artificially added resources, (e.g., natural afforestation doesn't require fertilizer).

Exhibit 12: The options for achieving carbon removal are various and complex.

- Storage-in-use – the storage of carbon in bioproducts which can sequester carbon over a relatively long period of time, such as timber or concrete – has a relatively small capacity compared with the volume of CO_2 which must be sequestered for a 1.5°C pathway.[86] It also has a relatively low permanence, with typical storage durations estimated between 50-200 years. Even if the storage is not permanent, however, it can still play a valuable role since the use of biomaterials typically substitutes for high-carbon alternatives (such as steel or conventional concrete in construction).

Total quantities and costs

Exhibit 13 sets out how a possible combination of different methods of carbon removal might bridge the carbon dioxide overshoot gap. We illustrate a scenario in which NCS plays the dominant role, reaching 6.5 Gt per annum by 2030 and contributing 164 Gt of carbon removal over the 30-year period. BECCS reaches 1.1Gt per annum in 2050 and removes 20 Gt cumulatively, while DACCS develops slowly in early decades but grows rapidly in the 2040s to reach 2.8 Gt per annum by 2050.

Under this scenario the combined annual removals in 2050 of about 10 Gt would more than neutralise our estimated permanent residual emissions of CO_2 (2 Gt CO_2/Yr) and N_2O (2 Gt of CO_2e/Yr), thus generating negative emissions of around 6 Gt per annum.

This illustrative scenario would result in the profile of net emissions over time shown in Exhibit 14. Net emissions after carbon removals (shown by the red dashed line) would roughly track the IPCC P3 scenario (which relies on large negative emissions after 2060 to meet the climate objective) but would still be appreciably higher than in the IPCC P1 scenario, which minimises the need for future negative emissions by achieving more significant reductions in the 2020s. Our illustrated scenario thus still entails a risky reliance on future action. To reduce this risk, it is essential both to accelerate within-sector/ company emissions reductions as much as possible, and to ensure

86 This only considers long-term sequestration potential. Use of materials which have a 'short term' storage such as biofuels cannot be considered as carbon removals.

that carbon removals are achieved as early as possible, particularly in the NCS sector.

The wide range of possible cumulative removals shown in Exhibit 13 – from 57 to 645 Gt CO_2 per annum – also highlights that there is a major risk that this potential is not realised, illustrating the need for strong policies and financing mechanisms to ensure that carbon removals develop fast enough and on a large enough scale to meet the climate objective.

The total cost of achieving these carbon removals will depend on the cost per tonne of CO_2 sequestered, which will vary significantly between different NCS projects, and which for DACCS will decrease over time but at an unpredictable pace. But a simple illustrative calculation shows that, if the average cost across the different types of removal were \$80 per tonne the total cost to close a 200 Gt carbon overshoot gap would be \$16 trillion in total or \$530 billion per annum on average. This is around 0.3% of possible GDP over the next 30 years, compared to our initial estimate that investments to achieve EBIT decarbonization might amount to 1-2 % of global GDP,[87] with about <0.5% to achieve the AFOLU emission reductions pathway.

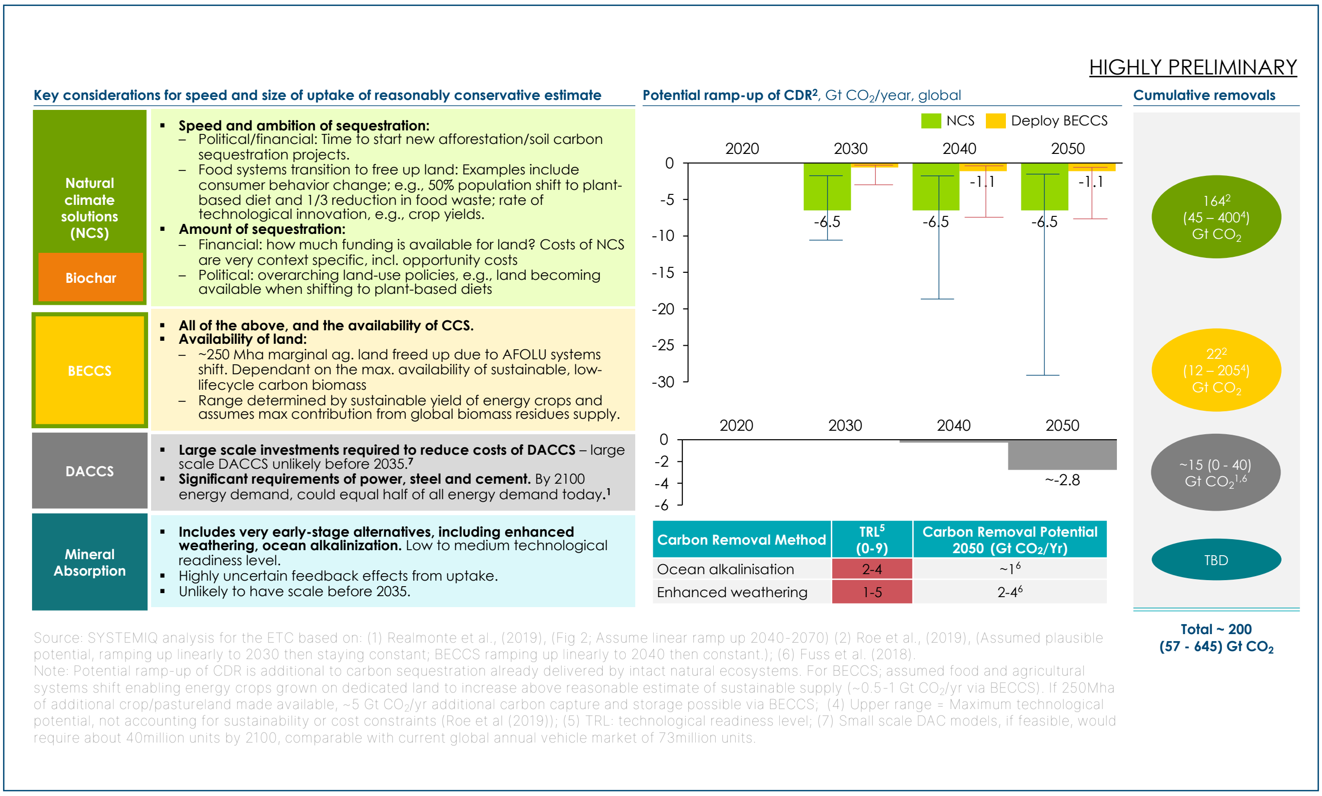
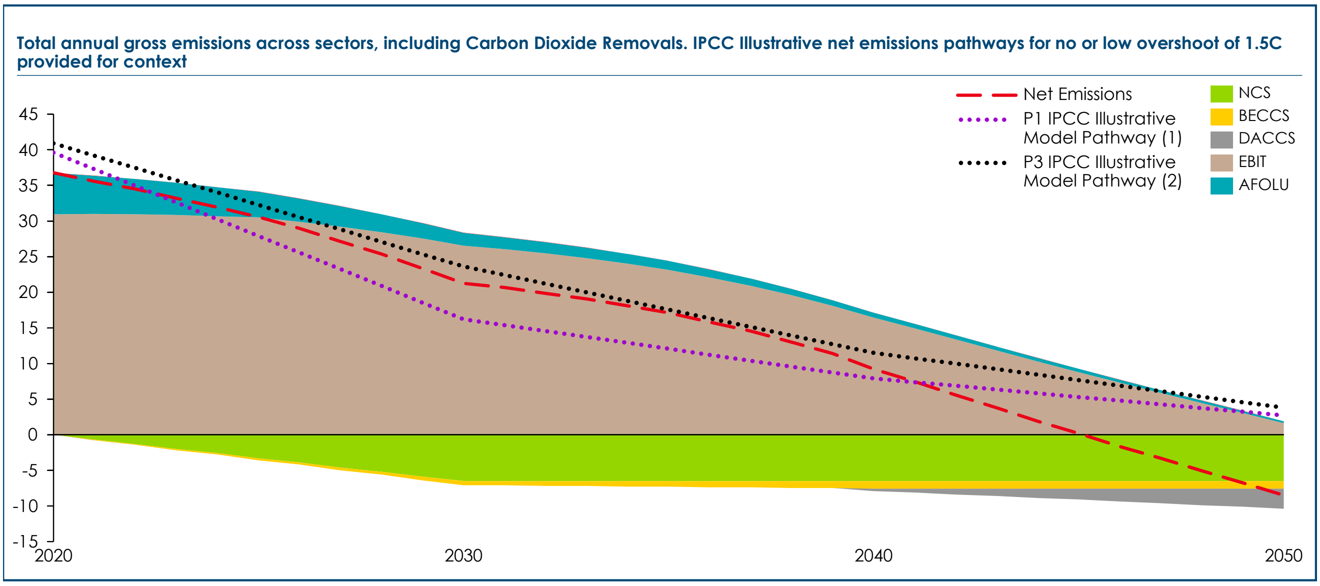


Exhibit 13: A preliminary examination of how CDR methods could cumulatively contribute to the carbon overshoot gap by 2050.

87 In the case of EBIT decarbonisation the upfront investments result in significant reductions in ongoing running cost with the net impact on the level of GDP and living standards being a considerably lower ~0.5%.

Gt CO_2/year, Global, Scenario A

ILLUSTRATIVE



Source: SYSTEMIQ analysis for the ETC based on: IEA (2017), Energy Technology Perspectives; IEA (2020), Energy Technology Perspectives; Previous analyses of the Energy Transitions Commission; IPCC (2018) *Special Report for 1.5C*

Note: (1) P1= an ambitious scenario which assumes social and technical innovation drive rapid decarbonization through low energy demand assumptions and investment in afforestation. (2) P3 = A middle of the road scenario which assumes societal and technological development roughly follow historical patterns and drive net emissions reduction by changing the way energy and products are produced. IPCC Integrated Assessment Models modelled 42 scenarios for >1.5C, typically draws on multiple data sources and forward projections, meaning that some variation in starting points is expected (see exhibit 1).

Exhibit 14: Illustration of total annual CO_2 emissions across sectors, including carbon dioxide removals, and the cumulative emissions compared with the IPCC illustrative pathways.

Chapter 5: How to finance carbon removals – options for consultation

Given the overshoot gap shown in Chapter 3, there are two crucial questions: how to close the gap and who should be responsible for financing the carbon removals. Part of the "how" should entail accelerating within sector/company decarbonisation, but carbon removals will also be required. This section therefore sets out key principles and standards that should govern carbon removal, and options for financing it.

Accelerating within sector/ company decarbonisation

The scenarios for emissions reduction presented in Chapter 2 reflect reasonably optimistic assumptions about the pace of deployment of new zero-carbon technologies across EBIT sectors, and the strength of public policy needed to underpin this transition. The scenarios for emissions reduction would have a minimal impact on economic growth and living standards. They also assume that existing capital stocks turnover gradually rather than being scrapped well before the end of useful life. As a result, while mid-century emissions reach close to zero in both the EBIT and AFOLU sectors, there is a large gap between total emissions in the 2020s and 2030s, and the path required to limit global warming to acceptable levels.

More forceful policies and industry actions could produce faster reductions. There is potential for short term impact via:

- Faster **CH_4** emissions reduction to deliver immediate reductions in radiative forcing effects and hence warming, with low-cost opportunities in fuel production in particular.
- Faster decarbonisation of the EBIT sectors:
  - More forceful private actions and public policies could drive **faster turnover of existing capital stock** (e.g., early bans on the purchase and use of internal combustion engines) and/or more rapid application of CCS to otherwise unchanged industrial processes,
  - A stronger focus on **energy efficiency improvement**, especially in the 2020s and 2030s,
  - **Greater demand-side action** – i.e., reduced consumption of carbon-intensive goods and services – which could drive faster reductions than can be achieved by supply changes alone.
- In the AFOLU sector:
  - A **more rapid end to deforestation**, reversing the apparent increase of 12% in deforestation between 2019 to 2020,[88]
  - A **faster change of farming practices or diets** (moving away from high meat diets), which could accelerate CH_4 emissions reductions.

The ETC will refine its estimates of the feasible pace of within sector/company decarbonisation during the course of this year, including identifying what it would take to achieve reductions faster than in the scenarios shown in Chapter 2.[89] But it is likely that even the most ambitious possible pathway of within sector/company decarbonisation will leave a significant overshoot gap to be closed via carbon removals.

Principles and standards for carbon removals

Carbon removals can only play their appropriate and crucial role if their use is underpinned by principles and supported by standards which make clear their impact over time. The most important principle is that carbon removals must be combined with forceful, within sector/ company decarbonisation, recognising that:

88 Harvey, F. (2021), "Destruction of world's forests increased sharply in 2020", *The Guardian*.

89 This will include developing a refined perspective on decarbonization pathways until 2030, highly granular decarbonization pathways for several hard-to-abate sectors within the Mission Possible Partnership, and a deep dive on the size and speed of uptake of CCS.

- All companies and sectors can and should get close to net-zero emissions within sector (after applying CSS on industrial processes) by mid-century, with carbon removals primarily used to achieve faster emission reductions in the 2020s and 2030s than possible through within-sector action alone.

- Ceasing and reversing deforestation is essential to achieve net zero emissions within the AFOLU sector itself.

Clear **standards** are also required to ensure that carbon removals are effective and permanent, and to distinguish between (i) carbon removal investments which can generate a flow of carbon removals continuing for many decades and with close to permanent storage, (ii) carbon removals which produce a temporary flow but close to permanent storage, and (iii) carbon removals which will result in storage for a number of years but with reversal over the medium time horizon. New developments in remote measurement technologies can help to enhance transparency and accountabilities on actual impact.

Who should purchase carbon removals and how much? Options for private and public responsibilities

Scaling-up carbon removals can entail different forms of investment or other financial flows, with varying levels of complexity.

- In the case of DACCS, for instance, both the carbon removal investment and the carbon storage and therefore impact will be relatively easy to define precisely.

- Some Natural Climate solution projects may be similarly easily defined and measured. But in some cases, NCS projects which achieve carbon removal may entail complex combinations of changing agricultural practice and /or payments to existing landowners to change existing approaches. Co-benefits are therefore more likely to arise, but measurement, certification and management challenges may be more complex.

But whatever the form of removal, we need to decide who should ideally pay for carbon removals, and what quantities of purchase they should make.

- Many companies are already making or considering voluntary purchase of removals, but a purely voluntary approach is unlikely to unleash the scale of finance required. If corporates with net-zero targets were to reduce emissions in line with science-based emission reduction pathways and to remove remaining emissions at their net-zero target date then the demand would be just 50 Mt CO_2 per year – or \$500 million of financing at an illustrative \$10/tCO_2e carbon price, implying a cumulative demand for around 500 Mt (i.e., 0.5Gt) of CO_2 reductions by 2030. This is compared with the around 200 Gt likely to be required over the next 30 years.[90]

- These voluntary purchases could be expanded if companies committed set science-based net-zero targets (in line with emerging guidance from the SBTi) which requires a neutralisation of any residual emissions in addition to within-company decarbonisation.

- Regulation could in principle make such removal purchase mandatory. It would be possible to use carbon pricing/emissions trading schemes to create incentives for increased company purchase – although these would have to be conceived so as to still incentivise (potentially higher cost) within-sector emissions reduction.

- But there are also arguments for locating the prime responsibility for offset purchase with governments, and hybrid options which combine roles for both companies and governments may be feasible.

We discuss pros and cons of these different options below.

Companies purchase offsets to achieve net-zero emissions.

The left-hand side of Exhibit 10 sets out the ETC's illustrative scenario for how rapidly the EBIT, waste and AFOLU sectors could reduce within sector emissions (upper line, "feasible emissions reduction pathway"), and how this compares with the path required to meet our defined climate objective (lower line, "climate objective/responsibility reduction line"). In principle, it could therefore be attractive to require companies to reduce their own emissions in line with the sector-specific

90 The Food and Land Use Coalition (2020), *Nature for Net Zero.*

upper line, while purchasing carbon removal offsets for the difference between the two lines. This would entail significant purchase of carbon removal offsets during the transition with a small ongoing level over the long term, see Exhibit 15.

If the EBIT, waste and AFOLU sectors were one single company, this would be a reasonably straightforward principle to implement. However, in the real world of multiple sectors and companies, implementing this approach is complicated by the fact that different sectors and companies can achieve very different paces of emissions reduction, and have different starting points.

- As Exhibit 16 illustrates, in many countries, the power sector could and should achieve decarbonisation faster than the required climate objective line, while a sector like shipping will find it close to impossible to reduce in line with the climate objective line. Requiring sectors to purchase offsets to cover the overshoot gap between the lines would therefore see all the burden of carbon removal offset purchase fall on the harder-to-abate sectors even if purchasing power may be higher in the easier-to-abate sectors which already face lower within-sector emissions reduction costs.

- Moreover, within sectors, there will be some companies which have already made significant efforts to decarbonise and others not: this makes it arbitrary to assume that a "fair" allocation of carbon removal offset purchase responsibility can be driven by setting the same shape for the "climate responsibility reduction line" for any company, starting from their current emissions.

- Alternative ways of allocating responsibility to cover the overshoot gap could be developed, for instance, with sectors/companies responsible for a fixed percentage of their total carbon emissions. However, if this approach was used to define mandatory requirements, it would be necessary to define for each company the upper "feasible reduction" line – which is in essence what SBTi is doing – since any company which fails to achieve this line should also be responsible for offsetting these excess emissions.

Thus, while either the approach shown on Exhibit 15 or making sectors/companies responsible for a fixed percentage of total carbon removals could be a reasonable basis for setting voluntary carbon removal targets (in addition to ambitious within-company reduction objectives), they are not clearly a sound basis for the mandatory approach which is likely to be required to generate large enough carbon removals to meet climate objectives.

Companies responsible for all remaining emissions – emissions trading scheme or carbon tax-based approaches

Both theoretical and practical implementation arguments instead suggest that the optimal approach could be as shown on Exhibit 17, in which companies/sectors are made accountable for **all** their remaining carbon emissions via payment of a carbon price (whether in the form of a tax or auctioned emission rights within a trading scheme). This has the advantages that:

- While it can and should be combined with overall sector/company targets to reduce within-sector emissions in line with the feasible path,[91] defining precisely that feasible path has no implications for the amount of tax paid, which is based on all remaining emissions.

- It recognises that all emissions have an adverse externality cost and creates incentives to reduce them.

This approach can then generate flows of finance to support CDR in one of two ways (or a combination):

- Where there are wide-coverage emissions trading schemes, it would be possible to set the total level of domestic emissions permits in the scheme in line with the lower "climate objective reduction line" on Exhibit 15, while allowing the purchase of "carbon removal offsets" equal to the difference between this and an ambitious definition of the higher "feasible emissions reduction line". Defining the two lines would be a manageable challenge at the level of an emissions trading scheme, though still inevitably judgemental, as only aggregate national/regional cross-economy lines would need to be defined.

- Alternatively, or in addition, revenues arising from emissions permit auctions or from

91 As especially the NCS removals are often lower-costs than within-sector emission reduction measures, overall sector/company targets should be set such that these cheaper removals are not replacing within-sector decarbonisation efforts.

carbon taxes can be used by governments to finance carbon removals.

- The finance of carbon removals would in this model not be limited to supply from the domestic market.

Government purchase of carbon removal offsets

Making governments rather than companies responsible for the purchase of carbon removals might also have other advantages, particularly where carbon removal is achieved by nature climate solutions in other countries. In particular:

- Governments make Nationally Determined Contributions (NDC) commitments, and they are parties to the principle of common but differentiated responsibility. In addition, developed countries have made commitments to developing countries to assist their transition via "climate finance". This may make governments the natural counterparty to purchase carbon removals from other countries, particularly if these are used to reflect responsibility for (i) historic emissions and (ii) national consumption emissions in excess of national production emissions (due to imports of carbon-intensive goods).

- Governments might in some case be better placed to ensure that the permanence and credibility of more complex NCS projects are underpinned by key public policies.

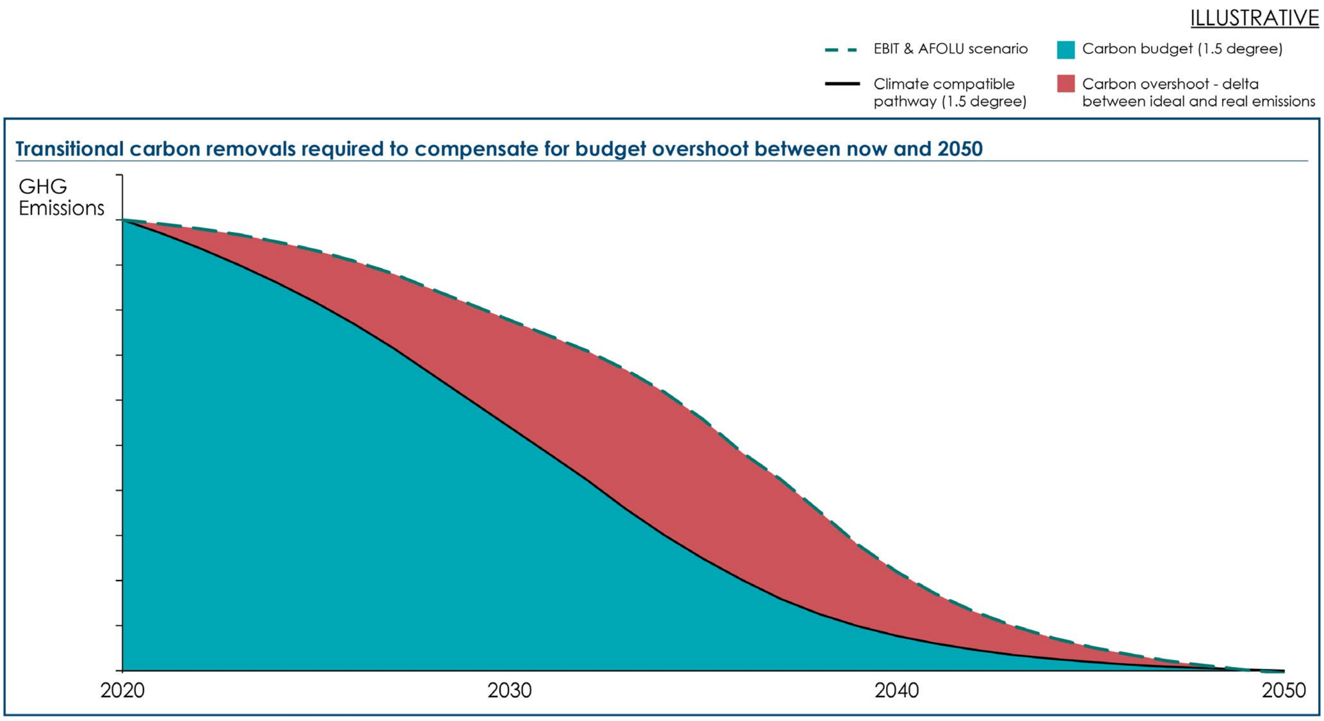
Hybrid solutions – complementary roles for private and public action

Given the scale and immediacy of the challenge, different starting points and varying political feasibility of different approaches in different countries, the optimal approach is likely to differ by country and to combine complementary roles for private and public action. Elements of an optimal approach may combine:

- A major role for governments financing internationally agreed nature-based solutions which ensure a rapid cessation and reversal of adverse land-use change, and rapid growth and investments in NCS;

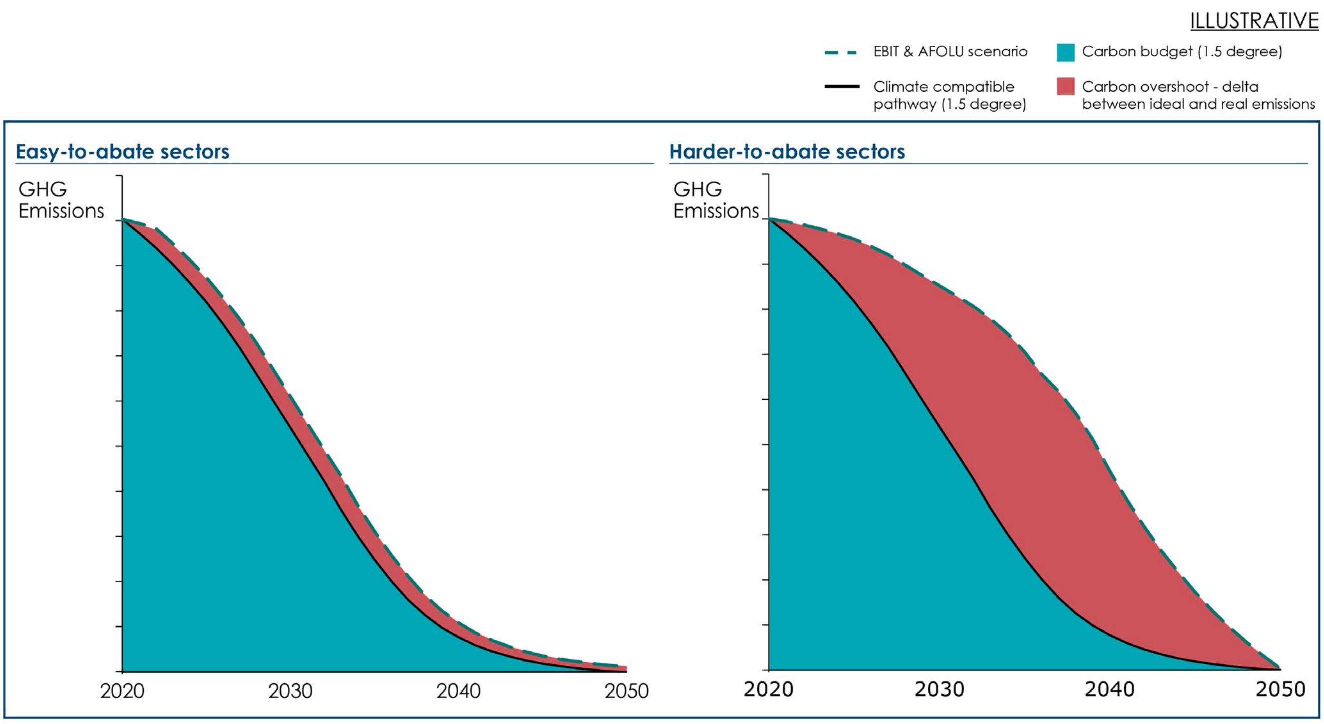
- Emissions trading schemes which ensure emissions reduction paths to zero by 2050, but which allow a limited use of domestic and international carbon removal offset purchase during the transition to bring net emissions into line with clearly defined climate objectives;

- A significant role for voluntary company action but recognising that this will not deliver aggregate carbon removals on the scale required to meet climate objectives. The potential for voluntary purchases could however be maximised if companies accredited by respected international standard setters (e.g., Race to Zero, Science Based Targets initiative) had to set both stretching targets for within-company emissions reductions (existing SBTs) and a lower target for "climate compatible" emissions, with a legitimate role for carbon removal offsets to close the overshoot gap. The latter trajectory could be defined based on the imperfect, but still useful methodologies outlined above (sector-specific trajectories or standard percentage of remaining emissions). Progressive companies could also be encouraged to offset the totality of their remaining emissions.



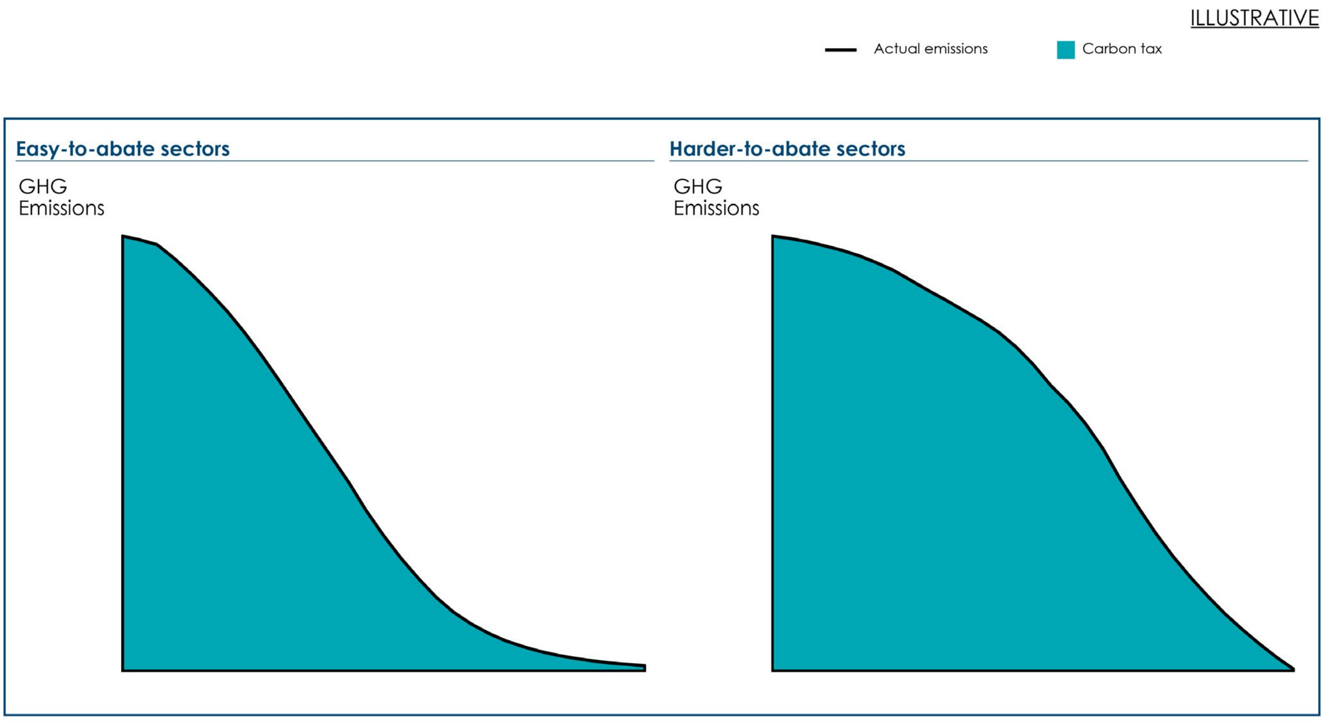
EBIT sectors refer to Energy, Building, Industry and Transport sectors

Exhibit 15: The difference between the climate compatible pathway and the maximal feasible pathway for EBIT & AFOLU scenarios.



EBIT sectors refer to Energy, Building, Industry and Transport sectors

Exhibit 16: The difference between the climate compatible pathway and the sector-specific maximal feasible pathway will differ per sector.



EBIT sectors refer to Energy, Building, Industry and Transport sectors

Exhibit 17: The option to make sectors and companies responsible for all their carbon emissions via a carbon tax.

Energy
Transitions
Commission

Reaching climate objectives: the role of carbon dioxide removals

May 2021

ETC Consultation Paper

Supported by

WE MEAN BUSINESS COALITION