GREENPEACE

Net Expectations

Assessing the role of carbon dioxide removal in companies' climate plans.

Briefing by Greenpeace UK

January 2021

Executive summary

To stabilise global temperatures at any level – whether 1.5˚C, 2˚C, 3˚C or 5˚C – carbon dioxide (CO_2) emissions must reach net zero at some point, because of CO_2's long-term, cumulative effect. According to the Intergovernmental Panel on Climate Change (IPCC), limiting warming to 1.5˚C requires net-zero CO_2 to be reached by about 2050.

A small proportion of emissions is likely to be unavoidable and must be offset by carbon dioxide removal (CDR), such as by tree-planting (afforestation/reforestation) or by technological approaches like bioenergy with carbon capture and storage (BECCS) or direct air carbon capture with storage (DACCS).

Since the IPCC's 2018 special report on 1.5˚C, numerous companies have committed to reducing their emissions to net zero. Over 300 companies have signed the Business Ambition for 1.5˚C pledge, and initiatives involving over 1,000 companies are part of the UN Race to Zero campaign. As companies publish the details of their climate plans, this briefing aims to help investors and others interpret what would be an appropriate role of CDR in a world that achieves the Paris goals.

Companies' net-zero plans to date vary widely in how much they rely on CDR, in terms of scale, purpose and mechanism:

- **Some companies aim to avoid or minimise the use of CDR and have specific plans to directly prevent most emissions. Others plan to use CDR to offset a majority of current emissions.**

- **Some companies even in hard-to-abate sectors – such as cement, steel and marine freight – plan to cut emissions directly, by innovating where necessary. Conversely, others plan to use CDR to offset even easy-to-abate emissions, such as in power generation.**

- **While a few companies plan to deliver CDR in specific projects, many plan to simply purchase credits on carbon markets, which have been beset with integrity problems and dubious accounting, even where certified.**

Limits and uncertainties

The IPCC warns that reliance on CDR is a major risk to humanity's ability to achieve the Paris goals. The uncertainties are not whether mechanisms to remove CO_2 "work": they all work in a laboratory at least. Rather, it is whether they can be delivered at scale, with sufficient funding and regulation, to store CO_2 over the long term without unacceptable social and environmental impacts.

To illustrate the need for regulation, the carbon dioxide captured by forests is highly dependent on their specific circumstances, including their species diversity, the prior land use, and future risks to the forest (such as fires or pests). In some cases, forests and BECCS can increase rather than reducing atmospheric CO_2. Similarly, geological CO_2 storage must be monitored and regulated centuries into the future.

Both afforestation/reforestation and BECCS require large land areas to deliver significant removal. If deployed on agricultural land, they are likely to increase food prices; on wild land, they may reduce biodiversity. For example, using BECCS to remove 12,000 Mt/year of CO_2 (the median in 2100 in IPCC 1.5˚C pathways with low overshoot) would require a land area devoted to bioenergy equivalent to one to two times the size of India, or 25-46 percent of total world crop-growing area. DACCS is highly energy-intensive. Capturing three quarters of present CO_2 emissions would require half of present global electricity generation and heat equivalent to half of final energy consumption.

The IPCC reports that the maximum sustainable CO_2 removal in 2050 by new forests is somewhere between 500 and 3,600 Mt per year. The maximum for BECCS is between 500 and 5,000 Mt. However, since they compete for land, these potentials cannot simply be added to each other. To put these in perspective, Eni and International Airlines Group each anticipate using forests to offset 30 Mt/year of CO_2 by 2050: just these two companies could thus exhaust up to 12% of the available total.

About 500 Mha of previously-forested and currently unused land could be available for reforestation i.e. without necessarily impacting food or biodiversity. This could remove 3,700 Mt/year of CO_2.[1 2] To put this in perspective, Shell has proposed planting 50 Mha of forest to offset its own emissions:[3] doing so could thus effectively claim one tenth of the sustainably available total for just one company.

How much CDR?

In no modelled pathway can the Paris goals be achieved without rapid emissions reductions. It should thus be stressed that CDR is not an alternative to emissions reduction, and in fact can only play a minority role in mitigation. Most scientists and practitioners agree that CDR should be used to offset only the emissions that are hardest and most expensive to abate. This varies by industry sector.

Integrated assessment models are useful tools for identifying cost-effective ways to meet energy needs within climate limits.

According to 1.5˚C pathways reported by the IPCC and the (1.75˚C) Beyond 2 Degrees Scenario of the International Energy Agency, aligning with the Paris goals would imply a maximum reasonable use of CDR by companies, relative to their present absolute emissions, roughly as follows:

Power companies: 0%, before 2050;

Car companies: 20% of emissions from vehicles on the road in 2050; sales should be close to 100% zero-emission vehicles by this point;

Heavy industry: steel 25%, cement 35%, chemicals 45%, all in 2050;

Airlines: 30%, in 2060.

The remainder of emissions reductions (the vast majority) must be achieved by energy efficiency, by changing fuels, by end-of-pipe capture or by reducing activity levels. As new technological options become available, residual fossil fuel and industrial process emissions can be reduced further.

Assessing companies' CDR plans

Given the uncertainties and limitations of CDR, it is always better to reduce emissions directly. CDR should be used at most for a minority of net zero targets, and not to offset any activities that can be reasonably avoided by other means within the stated timescale (such as power and light-duty vehicles).

Companies' climate plans should state clearly:

- **How much of the target is to be achieved by CDR rather than direct emissions reduction;**
- **On what basis any remaining emissions are judged unavoidable;**
- **What technological innovations are being pursued in order to reduce the unavoidable amounts;**
- **Whether any CDR relied on or invested in is included in countries' or other companies' climate targets (to ensure it is not double-counted);**
- **Where CDR is taking place, by what mechanisms, and with what governance to ensure its carbon integrity and to prevent negative social and environmental impacts.**

When engaging with companies on their climate plans, investors and other stakeholders might find these issues a helpful starting point.

Contents

ABBREVIATIONS

AFOLU	agriculture forestry and other land use emissions
AR	afforestation or reforestation
B2DS	(IEA) Beyond 2 Degrees Scenario
BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CDR	carbon dioxide removal
CO_2	carbon dioxide
DACCS	direct air capture of carbon with storage
IAM	integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
Mha	mega (million) hectares
Mt	mega (million) tonnes
REDD+	reducing emissions from deforestation and forest degradation
SDS	(IEA) Sustainable Development Scenario
SR15	(IPCC) Special Report on Global Warming of 1.5˚C
SRCCL	(IPCC) Special Report on Climate Change and Land
tCO_2	tonnes of carbon dioxide
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

Purpose of this briefing

Limiting global warming to 1.5˚C above pre-industrial levels will require global CO_2 emissions to reach net zero by around 2050, according to the Intergovernmental Panel on Climate Change (IPCC).[4] [5]About thirty governments have so far committed to reduce CO_2 emissions in their countries to net zero,[6] and companies too are now setting their own net-zero targets.

Over 300 companies have committed to net-zero by signing the Business Ambition for 1.5˚C pledge, an initiative of the UN Global Compact.[7] Initiatives involving over 1,000 companies are part of the UN Race to Zero campaign.[8] The Science-Based Targets Initiative – a collaboration of CDP, the UN Global Compact, World Resources Institute and WWF that has so far certified 529 companies' 1.5˚C or 2˚C climate targets[9] – is developing net zero guidance and criteria.[10]

Many of these net-zero plans include use of carbon dioxide removal (CDR) to offset some emissions, mostly either by tree-planting or by technological approaches such as bioenergy with carbon capture and storage (BECCS) or direct air carbon capture with storage (DACCS), rather than reducing all of their actual emissions. Some companies go further than net-zero, committing to become net negative, in that they will remove more CO_2 from the atmosphere than they emit (e.g. Microsoft[11]).

Yet, while many model pathways used by the IPCC involve extensive use of CDR, the IPCC also warns that "CDR deployed at scale is unproven, and reliance on [CDR] is a major risk in the ability to limit warming to 1.5°C."[12] The uncertainties are not whether various CDR approaches "work": all are capable of removing CO_2 in the right conditions. Rather, the uncertainties are at what scale the approaches can be deployed, in terms of cost, governance, measurability and environmental and social impacts.

As an influential 2015 paper put it, "A failure of [CDR] to deliver expected mitigation in the future, due to any combination of biophysical and economic limits examined here, leaves us with no 'plan B'.... 'Plan A' must be to immediately and aggressively reduce [greenhouse gas] emissions".[13] A precautionary approach would be to put efforts into developing CDR technologies, while also cutting emissions at the level that would be needed assuming limited CDR availability.[14]

It is broadly agreed that CDR should be used only to offset emissions that cannot be avoided, and that reducing emissions directly is always the preferred and less risky option.[15] However, the exact scope of what cannot be avoided is still debated.[16]

This briefing aims to help investors and others interpret and assess the feasibility of the role of CDR in companies' climate plans.[17] It starts by reviewing some companies' approaches, to illustrate the issues at stake. It then reviews the technological status of CDR, the uncertainties, risks and limits to CDR deployment, and how much CDR is possible or needed in energy models.

This briefing aims to help investors and others interpret and assess the feasibility of the role of CDR in companies' climate plans. It starts by reviewing some companies' approaches, to illustrate the issues at stake. It then reviews the technological status of CDR, the uncertainties, risks and limits to CDR deployment, and how much CDR is possible or needed in energy models.

2. CDR in companies' climate plans

Many of the companies that have committed to net-zero emissions have now published plans for how they will achieve it. This section assesses how the plans vary in scale of CDR reliance, purpose to which it is put and mechanism by which it is to be delivered.

Scale of CDR reliance

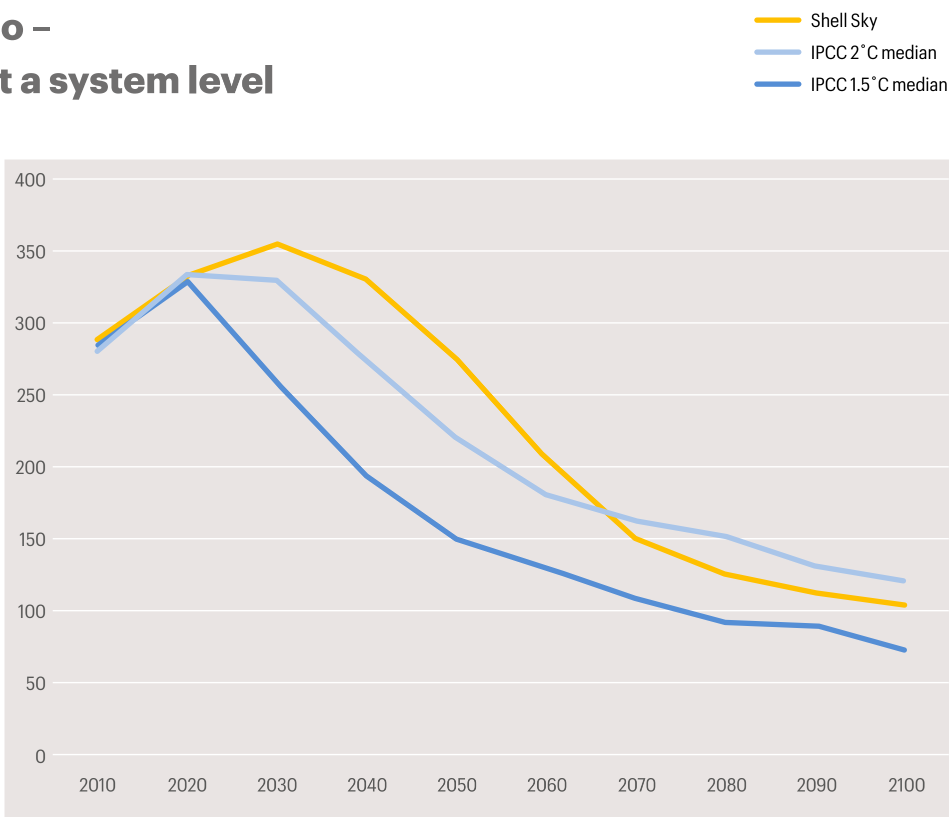
There is significant variation in how much companies' climate plans rely on CDR. Several companies have committed to fully decarbonising the most emissions-intensive parts of their business without CDR, such as by switching to 100%-electric vehicle fleets (e.g. AstraZeneca[18]) or 100% renewable energy (e.g. Unilever[19]) or selling 100% zero-emissions products (e.g. Ford for light-duty vehicles[20]). Cement manufacturer Lafarge has said, "Offsetting is a very last resort, to be used once everything else has been done."[21]

At the other end of the scale, some companies rely on CDR to a very large extent, especially in the airline and oil & gas industries. For American Airlines, CDR will be used to offset emissions equivalent to about 50% of the present total;[22] for International Airlines Group (British Airways), it is over 95%.[23 24] Shell has not yet published details of its net zero plan, but has suggested it could include planting forests the size of Spain to act as carbon sinks.[25] Eni plans to buy more than 30 $MtCO_2$ a year of forest credits.[26 27] Given the uncertainties and physical limits of CDR (page 10), these companies' plans could exhaust a disproportionate share of the globally available potential (page 13), leaving less for other companies, individuals and countries.

Several companies that have published net-zero plans have not specified whether CDR is part of them, such as BP,[28 29] EDF,[30] Enel,[31] Iberdrola,[32] Toyota[33] and Volvo.[34]

Shell's Sky scenario – Large-scale CDR at a system level

For fossil fuel companies, the issue goes beyond their own emissions, to the size of the market for their products. In Shell's "Sky" scenario, projected demand for oil and gas are already significantly higher than most IPCC 2˚C scenarios, as shown in the graph. However, to increase ambition to 1.5˚C, Shell states that adding new forest area the size of Brazil[35] is "required" to offset global emissions, rather than further reducing fossil fuel consumption.[36 37] Based on this analysis, Shell concludes, "there is a low risk of Shell having stranded assets, or reserves that we cannot produce economically, in the medium term".[38]



Projected oil and gas demand in Shell Sky scenario and in IPCC median 1.5˚C and 2˚C scenarios

Purpose of CDR

It is generally agreed that only unavoidable emissions should be offset by CDR, while easier-to-abate emissions should be avoided directly, such as in power generation (page 13).

However, not all companies in hard-to-abate sectors rely on CDR in their climate plans: some are pursuing leading-edge innovation so as to directly cut emissions, sometimes faster than the techno-economic models suggest. Shipping company Maersk has committed to net-zero operations by 2050 without offsets, including having net-zero vessels on the water by 2030.[39] Steel producer ThyssenKrupp aims to be directly carbon neutral in its operations by 2050.[40] Heidelberg Cement, while not setting a company-wide net-zero target, plans to offer a CO_2-neutral concrete by 2050, not relying on offsets.[41]

In contrast, some companies plan to offset even some (albeit a minority) of their easy-to-abate emissions in power generation: 5% of present emissions for Duke,[42] 10% for Southern.[43]

Delivery of CDR

There are three main approaches companies take to CDR:

- **Applying CDR within their own supply chain ("insetting"), such as by funding suppliers to plant trees on their sites or manage soil such that it absorbs more atmospheric carbon: Burberry,[44] Unilever.[4546]**

- **Develop/manage CDR projects: e.g. Southern Company,[47] VW[48],[49] Walmart.[50]**

- **Purchase CDR credits on carbon markets:[51] e.g. American Airlines,[52] Duke Energy,[53] International Airlines Group.[54]**

Issues with carbon markets are discussed on page 9.

In contrast, some companies plan to offset even some (albeit a minority) of their easy-to-abate emissions in power generation: 5% of present emissions for Duke, 10% for Southern.

3. CDR technologies and their status

This section describes the three highest-profile approaches to CDR and their current state of development and deployment. Afforestation/ reforestation features most in company climate plans.[55] [56] BECCS plays the largest role in IPCC scenarios; while DACCS has attracted much media attention.

Afforestation/reforestation (AR)

The simplest and cheapest[57] form of CDR is by growing trees, either in new areas that were not previously forested (afforestation) or restoring former forests (reforestation). AR relies on natural processes rather than new technologies, and so is in one sense "proven". However, accounting for the reduced carbon dioxide is complex.[58] The amount removed from the atmosphere depends on the stability of the new forest (including whether it is itself vulnerable to climate change), on its species content and on the previous land use it replaces: in some cases, a monoculture plantation on a previously rich ecosystem can increase rather than decrease emissions.[59] Furthermore, forestry projects in the Global South have often been highly controversial, over their human rights and ecological impacts.[60]

Bioenergy with carbon capture and storage (BECCS)

While plants store carbon, sequestration capacity can be increased by periodically "harvesting" the carbon and storing it geologically, by burning the plants (trees or crops) to produce bioenergy, combined with carbon capture and storage (CCS). While bioenergy is a proven technology, accounting for how much carbon is captured in a given tree/forest/ecosystem is highly complex and often disputed. Bioenergy grown on the wrong soils, or replacing existing biomass, or using excessive inputs (such as fertiliser and machinery) can emit more CO_2 than it absorbs.[63]

CCS is more nascent: there are only 21 commercial-scale plants in existence worldwide, with capacity to capture 40 Mt/year (about 0.1% of total global CO_2 emissions). All but five of these are used for enhanced oil recovery[64] rather than dedicated storage. Only one captures CO_2 from bioenergy, from the fermentation of maize to produce bioethanol,[65] and none from bioenergy combustion. Views on the viability of CCS are divided. While it is clear CCS has not been deployed in line with earlier hopes, some advocates see rising interest,[66] while others have abandoned the technology, in particular because of its high cost.[67]

With estimated cost of \$100-200/tCO_2 in 2050,[68] BECCS is likely to remain more costly than many other mitigation options.

"Natural climate solutions"

Many company plans put the primary emphasis of CDR on "natural climate solutions" (NCS), reflecting strong public acceptance for ecosystem protection and restoration, compared to distrust over technological approaches such as BECCS and DACCS.[61] As well as forest, NCS can target wetland, peatland or coastal ecosystems.

However, the term is used ambiguously, sometimes meaning any approach relying on the biosphere, or sometimes limited specifically to wild and biodiverse ecosystems. In the former case, many industrial-scale monoculture plantations cause severe social and environmental impacts, and are less effective at carbon mitigation than genuinely nature-based approaches. Natural forests store six times as much carbon as agroforestry and 40 times as much as plantations, according to one study.[62]

On the other hand, the least controversial approaches often involve protection of existing ecosystems. While such protection is necessary, it cannot be considered part of a net-zero plan, since it is required in addition to, rather than in alternative to, emissions reduction (see page 10).

Direct air capture of carbon, with storage (DACCS)

A more purely technological approach – not using natural processes – is to capture CO_2 from the atmosphere by reaction with chemical solvents or sorbents, and then store the CO_2 using CCS. This has the advantage of requiring much less land, but the technologies are very early-stage and extremely expensive: currently \$600-1,000/tCO_2; it is hoped this can be reduced to \$100-300/tCO_2.[69] There are 15 direct air capture pilot plants worldwide, operated by three companies,[70] with a combined capture capacity of about 0.01 MtCO_2/year, although only one of them is combined with storage.[71] As a result, their future availability remains very speculative,[72] although "silver-bullet" hopes have led to high-profile media coverage.

Carbon capture and utilisation (CCU)

An alternative to storing captured CO_2 is to use it as an industrial feedstock for manufacturing synthetic fuels or chemicals.[73] This has received increasing attention in recent years, as proponents have sought some way to make a saleable product out of captured carbon, to recoup the capture costs,[74] though others dispute whether CCU can be a useful stepping stone to CCS.[75] Thus Carbon Engineering's DAC plant in British Columbia, Canada, is not storing the removed CO_2 but using it as an input in manufacturing fuels.

In most cases, the captured CO_2 ends up back in the atmosphere: when a fuel is combusted, or when chemicals break down.[76] Therefore, unlike CCS, CCU delays rather than prevents atmospheric emissions, and combined with bioenergy or direct air capture, it recycles rather than removes CO_2 from the atmosphere. As such, it may be best considered as a separate technology rather than jointly as "CCUS".[77]

The experiences of forest sinks and carbon markets

While BECCS and DACCS are new and unproven approaches, CDR is not a novel concept: forest-based carbon sequestration has long been part of the climate toolbox. The IPCC's First Assessment Report in 1990 proposed among its response strategies "expansion of forest areas as possible reservoirs of carbon,"[78] and forest expansion is included in the UNFCCC's REDD+ programme (as the "plus", alongside Reducing Emissions from Deforestation and forest Degradation), introduced in 2005 to enable international funding for forest measures in the Global South. This history can provide useful lessons for future use of CDR.[79]

Unfortunately, the experience has been more often negative than positive, as attested by an extensive literature. In particular, failures to establish effective governance of REDD+ have left some researchers asking whether the programme has contributed at all to mitigating climate change.[80] Meanwhile, numerous forest-carbon projects have displaced local – often Indigenous – people from their homes and land, prohibited the subsistence forest uses on which they depend, and in some cases led to violence and militarisation.[81]

Carbon markets – both regulated and voluntary – have been part of climate mitigation since the Kyoto Protocol of 1997, and are now seen as a key tool for companies to deliver CDR. However, the experience here too has been sobering. Even where certified by professional consultancies or regulated by public bodies, it has generally been impossible to establish that projects generating carbon credits have been additional to what would have happened in any case.[82] For example, a study for the European Commission in 2016 found that 85% of Certified Emissions Reduction projects under the Clean Development Mechanism are unlikely to have delivered any climate benefit.[83]

A potential lesson then is that CDR projects must be designed holistically, taking into account not only carbon accounting but also wider social and environmental impacts, and within a framework of strong and effective regulation.[84] These risks provide further reasons that reliance on CDR should be minimised.

4. Uncertainties and limitations

While most IPCC scenarios include some amount of CDR (mostly BECCS, plus some AR), there has been significant debate in the scientific community about the risks of relying on unproven technologies and about their sustainability. Several studies have therefore explored the climate effectiveness (permanence and additionality) of CDR approaches, the social and environmental impacts (especially arising from AR's and BECCS' land requirements) and the challenges of establishing a large-scale governance system to ensure effectiveness and minimise negative impacts. In these three areas lie the greatest uncertainties and limitations to CDR.

As a general guide, any CDR can be judged part of a net-zero plan only if it is not also counted in any other company's or country's net zero plan, because achieving the Paris goals requires all to meet net zero. Going a step further, CDR outside a company's own supply chain should arguably occur in countries that have their own credible net-zero plans, and be additional to (not part of) those plans. This is a very high standard, but to do otherwise would be trading on others' inaction and so cannot be considered consistent with the Paris goals.

Climate effectiveness

Due to the long lifetime of CO_2 and its cumulative impact on the atmosphere, any that is removed must be stored safely for many centuries.

However, biosphere-based carbon storage carries risks in this regard.[85] For example, carbon stored in forests can be returned to the atmosphere if the forests die due to pests, fires or human activity, or if forests are degraded due to climate change.[86] Not only must forests therefore be carefully monitored and regulated, there is a strong case for planting more than is required for a given temperature target, to allow for some to be lost.

Geological storage is therefore considered more permanent, as most scientists believe that CCS done properly is "safe",[87] and that there are sufficient suitable storage sites and appropriate techniques to make it unlikely that the CO_2 will later leak out. However, experience to date with CCS gives cause for concern: CO_2 pipelines have often leaked,[88] and storage sites found to be less secure than previously believed.[89] [90] Regulation will be required to ensure that local geology is fully studied and that best practices are applied.

Even where removal and storage are effective and secure, an inherent conceptual problem with offsetting lies in the notion of additionality: for there to be a climate benefit, an offset must deliver something that would not have happened anyway. But in the history of carbon markets and forest offsets, the baselines against which to judge this have been all but impossible to meaningfully establish.[91]

As a general guide, any CDR can be judged part of a net-zero plan only if it is not also counted in any other company's or country's net zero plan, because achieving the Paris goals requires all to meet net zero. Going a step further, CDR outside a company's own supply chain should arguably occur in countries that have their own credible net-zero plans, and be additional to (not part of) those plans. This is a very high standard, but to do otherwise would be trading on others' inaction and so cannot be considered consistent with the Paris goals.

Unsustainable land and energy requirements

The IPCC notes that "Most CDR technologies … raise substantial concerns about adverse side effects on environmental and social sustainability."[92] The most significant of these arises from the large land requirement for AR and BECCS: if deployed on agricultural land, they are likely to increase food prices; on wild land, they may reduce biodiversity.[93][94] In some scenarios, large-scale afforestation could cause increases in food prices of 80% by 2050, and CDR in general could cause a rise in undernourishment of 80-300 million people.[95]

Using BECCS to remove 12,000 Mt/year of CO_2 (the median in 2100 in IPCC 1.5˚C pathways with low overshoot[96]) would require an estimated 380-700 Mha of land devoted to bioenergy growing: this is equivalent to one to two times the size of India, or 25-46 percent of total world crop-growing area.[97]

About 500 Mha of previously-forested and currently unused land could be available for reforestation i.e. without necessarily impacting food or biodiversity. This could remove 3,700 Mt/year of CO_2.[98][99] To put this in perspective, Shell has proposed planting 50 Mha of forest to offset its own emissions:[100] doing so could thus effectively claim one tenth of the sustainably available total for just one company.

The largest potential for AR and BECCS is in the Tropics, due to land availability, productivity, albedo effects and costs;[101] however, it is in such regions that the greatest threats to food security and biodiversity are likely to be experienced, and also where land-related human rights violations are especially prevalent (page 9).

In contrast to AR and BECCS, DACCS requires little land, but extremely large energy inputs, both to drive air through the machines (since air has very low CO_2 concentration compared to power plant chimneys and industrial waste gas streams) and to generate high temperatures to separate captured CO_2 from the sorbent. Capturing three quarters of present CO_2 emissions would potentially require half of present global electricity generation and heat equivalent to half of final energy consumption.[102]

Governance

Given the above risks both to climate effectiveness and to wider sustainability, effective governance is vital to any use of CDR. Any company relying on CDR will need not only to demonstrate that such issues are effectively addressed, but also address how their use of CDR fits in a wider global picture. Engaging with the international dimension of governance is thus crucial.

There are several aspects to the governance required.[103] First, there is a need to oversee CO_2 removal, to verify net removals are accurately accounted for, including reflecting prior land use and operational emissions.[104] Second, regulation is required to manage sustainability impacts of CDR, such as to prevent use of land that is needed for food production or that has high biodiversity value, and to protect the rights of forest peoples.[105] Third, CO_2 transport and processing for CCS must be monitored and regulated; geological and biological storage sites must be monitored generations into the future.[106]

Across all of this, international institutions must be created to deliver incentives, funding and penalties.[107] One of the largest uncertainties in the scalability of CDR is thus the extensive institutions that would be required, at a global level, and these would have to remain effective over the very long term.[108] This is a crucial dimension of feasibility, but is not addressed in the models that suggest large-scale usage of CDR.[109]

The IPCC notes that "Most CDR technologies … raise substantial concerns about adverse side effects on environmental and social sustainability." The most significant of these arises from the large land requirement for AR and BECCS: if deployed on agricultural land, they are likely to increase food prices; on wild land, they may reduce biodiversity. In some scenarios, large-scale afforestation could cause increases in food prices of 80% by 2050, and CDR in general could cause a rise in undernourishment of 80-300 million people.

5. How much CDR?

The amount of global warming depends on the cumulative global emissions of CO_2: each additional ton of emissions adds to the temperature. Thus, to stabilise temperatures at any level – whether 1.5˚C, 2˚C, 3˚C or 5˚C – emissions must reach net zero at some point.[110] [111] Since some emissions are near-impossible to avoid, some amount of CDR will be necessary to offset them.

In no modelled pathway can the Paris goals be achieved without rapid emissions reductions. It should thus be stressed that CDR is not an alternative to emissions reduction, and in fact can only play a minority role in mitigation.

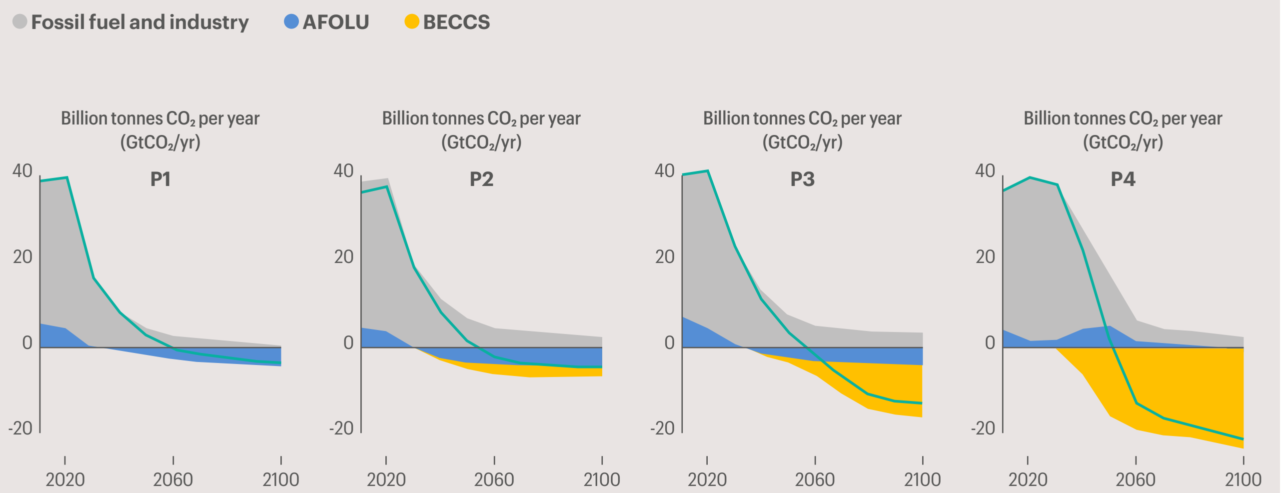
In no modelled pathway can the Paris goals be achieved without rapid emissions reductions.[112] It should thus be stressed that CDR is not an alternative to emissions reduction, and in fact can only play a minority role in mitigation. Rather, there is a balance to be struck between the amount of reliance on CDR (given its uncertainties and physical limits – page 10) and the pace of emissions reduction.

However, weighing the achievability and cost of present emissions reduction against the unknown achievability, cost and risks of future CDR is inherently somewhat subjective. The aim of this and the previous sections is to help readers make that judgment.

IPCC illustrative pathways

A key tool for analysing these trade-offs is integrated assessment models (IAMs – see box), the analytical workhorse underpinning IPCC mitigation reports. IAMs generally identify the least-cost ways[113] of meeting energy service demands while staying within a given climate limit. CDR is thus used in the models where it is expected to be cheaper than direct abatement of emissions.

IPCC Illustrative Pathways



Source: The IPCC's Special Report on 1.5˚C

The IPCC's Special Report on 1.5˚C (SR15) used 90 pathways generated from IAMs, focusing on the 53 of these involving low or no "overshoot",[114] which are less environmentally risky.[115] Since these pathways reflect a range of different assumptions and approaches to limiting warming to 1.5˚C, the report presented four illustrative pathways to represent the differences between them:[116]

- **P1: major societal and behavioural changes enable significant reduction in energy demand, while increasing living standards. No CCS is used: the only CDR approach is AR.**
- **P2: moderate shifts towards sustainable behaviours and international cooperation; a limited role for BECCS alongside AR.**
- **P3: societal and economic trends follow historical patterns; resulting growth in energy demand is offset mostly by technological substitution, including a large role for BECCS and some AR, with fairly low overshoot.**
- **P4: more emissions-intensive economies and lifestyles drive large growth in fossil fuel use; after overshoot to 1.8˚C, considerable BECCS is required to bring temperatures back down to 1.5˚C by 2100: with such high overshoot, P4 is sometimes considered not to be a 1.5˚C pathway.[117]**

A key finding from IAMs – as shown in the four illustrative pathways – is that the CDR requirement is greatest where energy demand grows the most: keeping CDR low requires a move to more sustainable economic patterns and behaviours. In other words, relying mainly on technological substitutions (rather than change in behaviours and economic structures) is likely to require larger use of CDR.[118] Put the other way around, uncertainties about future availability of large-scale CDR suggest a need not only to change technologies but also to reduce activity levels relative to business-as-usual in some emissions-intensive sectors such as aviation and fossil fuels.

Maximum sustainable potential

Several studies have raised concerns about a tendency of IAMs to favour (delayed[125 126]) technological solutions over other (near-term) mitigation approaches, resulting in unduly high levels of CDR reliance.[127] They are complemented therefore by more detailed, bottom-up studies of CDR approaches.

Global CO_2 emissions in 2018 were about 40,000 Mt/year.[128] Based on a review of hundreds of bottom-up studies,[129] the IPCC's SR15 report estimates the sustainable potential[130] of each CDR approach in 2050, as lying within the following uncertainty ranges (for each approach in isolation; they cannot be added to each other, as the approaches compete e.g. for land):[131]

Integrated assessment models

One of the key tools for exploring energy and climate futures is integrated assessment models (IAMs). These provide detailed, bottom-up representations of the energy and land use systems,[119] combined with a simple climate model, and explore their behaviour many decades into the future under a given set of assumptions.[120]

IAMs are based on mathematical representations of techno-economic processes. Their strengths are that they reveal interactions across a whole system, and permit exploration of major change. Their weaknesses are that they are not suited to representing political, social or behavioural change; such drivers are generally pre-determined as (exogenous) input assumptions.[121] Furthermore, IAMs are highly sensitive to assumptions on technological costs and energy demands.

Demand for energy services (such as heat, power or travel) is commonly treated exogenously,[122] so that the models cannot look for solutions that change the structure of societal energy usage, only the technologies that deliver it. To explore these types of changes, they must be built into the design of the study (before running the model). Several modelling studies – one of which created the P1 pathway – have done this, proposing ways to significantly reduce or restructure these energy demands,[123 124] which leads to lower need for CDR.

IAMs are thus powerful tools for exploring the future, but caution is required in interpreting their results.

- **AR: 500 – 3,600 Mt/year**[132 133]
- **BECCS: 500 – 5,000 Mt/year**
- **DACCS: 500 – 5,000 Mt/year.**

Note that there remain large uncertainties in the potentials;[134 135] the upper end is considered "extremely difficult" to achieve.[136] In particular, the studies compiled to make these estimates focus largely on physical and economic factors: they do not address the availability of appropriate governance structures (see page 11).[137]

To put these in perspective, Eni and International Airlines Group each anticipate using forests to offset 30 Mt/year of CO_2 by 2050 (page 6): just these two companies could thus exhaust up to 12% of the available total.

Note that many IPCC pathways exceed the top end of this range; these pathways are likely to be unfeasible or unsustainable. The reason for the inconsistency is that these pathways are generated using IAMs that model the whole energy system, and do not look at CDR in sufficient resolution to assess feasibility.[138] A 2018 report by the European Academies Science Advisory Council concludes, "These technologies offer only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios." It recommends that such scenarios not be used as a basis for policy making.[139]

CDR use by sector

How much can a company reasonably rely on CDR to meet its net-zero target? The answer varies by sector, as it would make little sense to use limited CDR potential to offset emissions that are relatively easy to abate directly. In other words, CDR should be used where it is most needed, to offset the emissions that are expected to be most expensive (or technically difficult) to mitigate by other means, such as in heavy industry, freight transport and aviation. IAMs can help inform this judgment.

Power generation must be fully decarbonised before 2050 (not offset elsewhere), a robust finding across almost all models, and reported by the IPCC.[140] This is because zero-carbon alternatives are readily available and cost-competitive, such as wind and solar.

IAMs include a high level of resolution, but detailed emissions breakdowns by sub-sector[141] are not often published. For this reason, detailed analysis of emissions reductions – including in the IPCC's SR15 report and analyses by the Science-Based Targets Initiative[142] – tend to use the IEA's Beyond 2 Degrees Scenario (B2DS). Published in 2017, B2DS is not aligned with limiting warming to 1.5C degrees but to 1.75˚C. [143] Accordingly B2DS should be considered at the lower end of the ambition required to meet even the "well below 2 degrees C" goal of the Paris Agreement.

As an approximate guide, based on 1.5˚C pathways reported by the IPCC and in the B2DS, the Paris goals would imply a maximum reasonable use of CDR by companies, relative to their present absolute emissions, as follows:

Power companies: 0%, before 2050;

Car companies: 20% of emissions from vehicles on the road in 2050; sales should be close to 100% zero-emission vehicles by this point;[144]

Heavy industry: steel 25%, cement 35%, chemicals 45%, all in 2050;[145]

Airlines: 30%, in 2060.[146]

The remainder of emissions reductions must be achieved by energy efficiency, by changing fuels, by end-of-pipe capture or by reducing activity levels. These targets reflect absolute emissions rather than intensities. Similar information is not available for other sectors; however, heavy industry and aviation are considered the hardest-to-abate sectors, so other sectors will generally need to make smaller use of CDR. [147]

There is a need for more information on detailed mitigation pathways. It is recommended that multi-model findings by industry sub-sector should be published in the Working Group III (Mitigation) report of the IPCC's Sixth Assessment Report, likely to be published in 2022.[148] Modellers could usefully make such information available regularly and systematically, especially now that the IEA has discontinued the B2DS in favour of the less ambitious Sustainable Development Scenario (SDS). [149]

6. Conclusions

Given the uncertainties and limitations of CDR, it is always better to reduce emissions directly. CDR should be used at most for a minority of net zero targets, and not to offset any activities that can be reasonably avoided by other means within the stated timescale (such as power and light-duty vehicles).

For the UK's net-zero target, the Committee on Climate Change recommends aiming to meet the target through domestic action, without use of international carbon credits,[150] on grounds that all countries must deeply reduce emissions (leaving few cheap credits), that the UK has a responsibility to reduce its own emissions rather than outsourcing the problem, and that historically carbon markets have often not delivered additionality.[151] The same arguments should apply to companies.

The Science-Based Targets Initiative does not count emissions-reduction offsets towards achievement of company targets, but suggests they should be a voluntary extra.[152] This suggests a possible way to think about CDR too. Achieving the Paris goals is likely to require removing some CO_2 from the atmosphere; there are ways to do so without causing negative social and environmental impacts, such as by ecosystem restoration. Companies can helpfully support such initiatives.

Problems arise however when CDR is seen as a vital plank of mitigation strategies, as limiting climate change may become subject to its inherent uncertainties. And when CDR is deployed at a large scale, negative impacts begin to become inevitable. Some researchers now propose that targets and accounting for CDR should be separated from those for emissions reduction, in order to help manage these risks and assumptions transparent.[153]

In similar spirit, companies' emissions reductions should be judged more important than their overall net-zero targets. Companies' climate plans should state clearly:

- **How much of the target is to be achieved by CDR rather than direct emissions reduction;**
- **On what basis any remaining emissions are judged unavoidable;**
- **What technological innovations are being pursued in order to reduce the unavoidable amounts;**
- **Whether any CDR relied on or invested in is included in countries' or other companies' climate targets (to ensure it is not double-counted);**
- **Where CDR is taking place, by what mechanisms, and with what governance to ensure its carbon integrity and to prevent negative social and environmental impacts.**

When engaging with companies on their climate plans, investors and other stakeholders might find these five issues a helpful starting point.

Appendix: Other CDR approaches

This briefing has focused on the three highest-profile CDR approaches: AR, BECCS and DACCS. There are other approaches being considered at a smaller scale:

- **Soil carbon sequestration:** Managing agricultural land in such a way as to increase the retention of CO_2 (in organic matter from plants and animals) in soil.[154]
- **Biochar:** Growing trees and burning them in low-oxygen conditions to form charcoal, which is then spread in soil.
- **Enhanced weathering:** Crushing silicate rocks and spreading over wide land areas: dissolved CO_2 in rainwater is then captured by a chemical reaction.
- **Ocean fertilisation:** Adding nutrients – primarily iron – to the ocean so as to encourage phytoplankton growth, which absorb CO_2 by photosynthesis.
- **Ocean alkalinisation:** Adding chemicals to the ocean that react with dissolved CO_2 to form stable compounds, allowing the ocean to absorb more CO_2 from the atmosphere.

The various approaches may be categorised by how they capture and how they store CO_2. Capture is either biological (by photosynthesis) or chemical. Storage may be in biomass (plants), in soils, in the ocean or in geological reservoirs (by CCS).[155] This is shown in the table below.

		STORAGE			
		Biomass	Land	Ocean	Geological
CAPTURE	BIOLOGICAL	AR	Biochar, soil sequestion	Ocean fertilisation	Biochar, soil sequestion
	CHEMICAL	–	Enhanced weathering	Ocean alkalinisation	DACCS

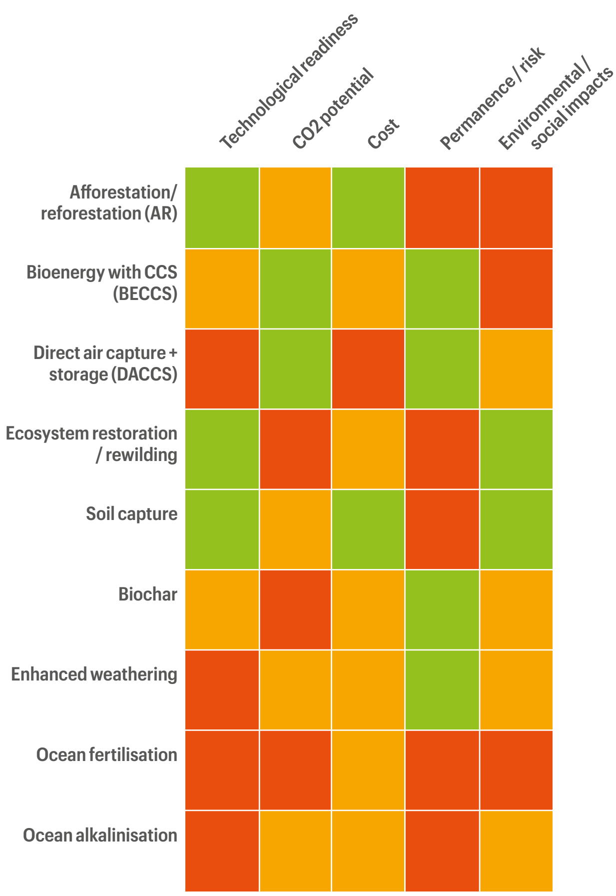
All approaches face barriers and limitations. The permanence of biomass, land and ocean storage may be at risk if the land use changes or higher ambient temperatures reduce storage capacity. The 2050 sustainable potentials for other CDR approaches are assessed as (again, non-additively):[156]

- **SCS: 2,300 – 5,300 Mt/year**
- **Biochar: 300 – 2,000 Mt/year**
- **EW: 2,000 – 4,000 Mt/year**
- **OF: negligible.**

Unlike for BECCS and DACCS, the 2100 potentials for these approaches are unlikely to be much higher than this.

Geological storage is costly and requires significant infrastructure to capture, transport and bury CO_2. For all approaches, there are major uncertainties about measurement, funding and governance.

A summary comparison of the barriers to all of the various approaches, based on a review of the literature,[157] is shown in the table below.



Acknowledgements

This briefing was researched and written by Greg Muttitt, with inputs from Charlie Kronick and Louise Rouse. The author is grateful for comments and feedback by Isabela Butnar and Doug Parr.

Contact Details:
Charlie Kronick
Greenpeace UK
Charlie.kronick@greenpeace.org

Endnotes

1 Note that AR removes less CO2 per hectare than BECCS, because the biomass is the storage sink as well as the removal mechanism.

2 References

IPCC SR15 (op. cit.), p.343

Fuss et al. 2018 (op. cit.), p.16;

R.A. Houghton et al., "A role for tropical forests in stabilizing atmospheric CO2", Nature Climate Change 5, 1022–1023 (2015), https://doi.org/10.1038/nclimate2869

3 A land area the size of Spain = 50.1 Mha. Shell, Energy Transitions (op. cit.), p.4

4 The IPCC is the United Nations body for assessing the science related to climate change. It does not conduct original research, but rather compiles and interprets the body of research that has been carried out by scientific teams worldwide.

This briefing will largely draw from IPCC reports, especially its 2018 Special Report on Global Warming of 1.5˚C (SR15). In addition, the briefing will reference the original research sources where appropriate.

5 (All web pages accessed November 2020)

IPCC, Special Report on the impacts of global warming of 1.5°C above pre-industrial levels (SR15), 2018, p.14, https://www.ipcc.ch/sr15/

6 Megan Darby and Isabelle Gerretsen, "Which countries have a net zero carbon goal?", Climate Home News, 14 June 2019, https://www.climatechangenews.com/2019/06/14/countries-net-zero-climate-goal/

7 United Nations Global Compact, Business Ambition for 1.5 C, https://www.unglobalcompact.org/take-action/events/climate-action-summit-2019/business-ambition/business-leaders-taking-action

8 UNFCC, Race To Zero Campaign, https://unfccc.int/climate-action/race-to-zero-campaign#eq-1

9 Science Based Targets, Companies Taking Action, https://sciencebasedtargets.org/companies-taking-action/

10 CDP, Foundations for Science-Based Net-Zero Target Setting in the Corporate Sector, Version 1.0, September 2020. https://sciencebasedtargets.org/wp-content/uploads/2020/09/foundations-for-net-zero-full-paper.pdf

11 Microsoft, "Microsoft will be carbon negative by 2030", 16 January 2020,

https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/#:~:text=Over%20three%2Dquarters%20of%20this,greenhouse%20gases%20into%20the%20air

12 IPCC, SR15 (op.cit.), p.96

13 Pete Smith et al., "Biophysical and economic limits to negative CO2 emissions," Nature Climate Change, 2015, pp.48-49, https://doi.org/10.1038/NCLIMATE2870

14 Alice Larkin et al., "What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations," Climate Policy, 2017, p.2 https://doi.org/10.1080/14693062.2017.1346498

15 E.g. Smith et al. 2015 (op.cit.), pp. 48-49

European Academies' Science Advisory Council, Negative Emission Technologies: What role in meeting Paris Agreement targets? EASAC policy report 35, February 2018, p.1, https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf

Oxford University Net Zero Network, "Mapping of current practices around net zero targets", May 2020, p.4

16 Gunnar Luderer et al., "Residual fossil CO2 emissions in 1.5–2 °C pathways, Nature Climate Change, Vol.8, July 2018, https://doi.org/10.1038/s41558-018-0198-6

Oxford University Net Zero Network (op.cit.)

17 It does not attempt to review other aspects of net zero plans beyond CDR.

18 E.g. AstraZeneca, "AstraZeneca's 'Ambition Zero Carbon' strategy to eliminate emissions by 2025 and be carbon negative across the entire value chain by 2030", 22 January 2020, https://www.astrazeneca.com/media-centre/press-releases/2020/astrazenecas-ambition-zero-carbon-strategy-to-eliminate-emissions-by-2025-and-be-carbon-negative-across-the-entire-value-chain-by-2030-22012020.html

19 E.g. Unilever, "Unilever to become 'carbon positive' by 2030", 27 November 2015, https://www.unilever.com/news/news-and-features/Feature-article/2015/Unilever-to-become-carbon-positive-by-2030.html

20 Ford, Sustainability Report 2020, p.34, https://corporate.ford.com/microsites/sustainability-report-2020/assets/files/sr20.pdf

21 Sarah George, "Carbon offsetting: How are businesses avoiding greenwashing on the road to net-zero?" edie.net, 10 November 2020. https://www.edie.net/library/Carbon-offsetting--How-are-businesses-avoiding-greenwash-on-the-road-to-net-zero-/7005

22 American Airlines, Environmental, Social and Governance Report 2019–2020, p.17, https://www.aa.com/content/images/customer-service/about-us/corporate-governance/aag-esg-report-2019-2020.pdf

23 There is no single reason for the difference between the two airlines: IAG projects larger activity growth, less efficiency gains and less

use of sustainable fuels

24 Relative to 2020 emissions: mitigation actions such as efficiency and alternative fuels are focused almost entirely on expected demand growth.

British Airways, "Sustainability at British Airways", 25 February 2020, https://mediacentre.britishairways.com/factsheets/details/86/Factsheets-3/208?utm_source=oneworld&utm_medium=landing_page&utm_campaign=sustainability

25 Shell, Energy Transition Report, 2018, p.54, https://www.shell.com/energy-and-innovation/the-energy-future/shell-energy-transition-report.html

This could potentially remove 15 to 100 $MtCO_2$ from the atmosphere, depending on the type and location of forest, assuming 0.1 – 0.6 Mha per tC. (1 tC = 3.7 tCO_2)

Smith et al 2015 (op. cit.), p.4.

26 Eni does not have a net-zero target for its Scope 3 emissions; the forest credits are part of its plan to reduce the emissions from the oil and gas it sells by 80% by 2050.

27 Eni for 2019: Carbon neutrality in the long term, pp.34-35, www.eni.com/assets/documents/eng/just-transition/2019/Eni-for-2019-Carbon-neutrality-in-the-long-term.pdf

28 BP has committed to not using offsets to deliver its 2030 interim climate goals, but sees "offsets helping us to go beyond those aims"; the company does not specify whether offsets will be used to achieve its 2050 net-zero target

29 Giulia Chierchia, "Reimagining energy", BP Week presentation, 14 September 2020, p.11, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/investors/bpweek/bpweek-reimagining-energy-slides-and-script.pdf

30 EDF, "Carbon neutrality by 2050", https://www.edf.fr/en/the-edf-group/taking-action-as-a-responsible-company/our-six-corporate-responsibility-goals/doing-even-more-to-reduce-co2-emissions#carbon-neutrality-by-2050

31 Enel, Sustainability Report 2019, https://www.enel.com/content/dam/enel-com/documenti/investitori/sostenibilita/2019/sustainability-report_2019.pdf

32 Iberdrola, Sustainability Report: Financial year 2019, http://iberdrola.com/wcorp/gc/prod/en_US/corporativos/docs/IB_Sustainability_Report.pdf

33 Toyota Motor Corporation, Sustainability Data Book 2019, https://global.toyota/pages/global_toyota/sustainability/report/sdb/sdb19_en.pdf

34 Volvo Group, Climate Strategy, https://www.volvogroup.com/en-en/sustainability/climate-goals-strategy.html

35 Shell has proposed foresting an area the size of Spain (~50 Mha) to offset its own emissions; Brazil (~850 Mha) is what Shell suggests would be required globally to offset all companies' and countries' emissions

36 Shell argues that "Stretching the goal to 1.5°C isn't simply about speeding up. Rather, something else must happen and society needs to find another lever to pull on a global scale. The key to achieving 1.5°C is developing further capacity to remove carbon dioxide from the atmosphere as the energy system transition proceeds. This is because the rate of reduction of carbon emissions is already maximized in the Sky scenario, so faster removal of carbon dioxide becomes the only option."

37 Shell, Sky, 2018, p.58, https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky/could-society-reach-the-goals-of-the-paris-agreement/q1.html

38 Shell, Energy Transition Report (op. cit.), p.10

39 Maersk, 2019 Sustainability Report, pp.14-19, https://www.maersk.com/~/media_sc9/maersk/about/files/sustainability/sustainability-reports/apmm-sustainability-report-2019-a4-200227.pdf

40 ThyssenKrupp, Annual Report 2018 / 2019, p.98, https://ucpcdn.thyssenkrupp.com/_legacy/UCPthyssenkruppAG/assets.files/media/investoren/berichterstattung-publikationen/update-21.11.2019/en/thyssenkrupp-gb-2018-2019-en-web_neu.pdf

41 Heidelberg Cement, Sustainability Report 2019, https://www.heidelbergcement.com/system/files_force/assets/document/a4/a3/heidelbergcement-sustainability_report_2019.pdf?download=1

42 Duke Energy, Climate Report 2020, pp.27-28, www.duke-energy.com/_/media/pdfs/our-company/climate-report-2020.pdf

43 Southern Company, Implementation and Action Toward Net Zero, September 2020, p.14, https://www.southerncompany.com/content/dam/southern-company/pdf/public/Net-zero-report.pdf

44 Burberry, "Burberry introduces carbon insetting and Autumn/Winter 2020 runway show certified carbon neutral."17

February 2020,

https://www.burberryplc.com/en/news/news/corporate/2020/burberry-introduces-carbon-insetting-and-autumn-winter-2020-runw.html

45 This is to offset remaining supply chain emissions: Unilever has committed to eliminate CO_2 emissions from its own operations and to halve total greenhouse gas footprint across its value chain by 2030.

46 Unilever, "Unilever sets out new actions to fight climate change, and protect and regenerate nature, to preserve resources for future generations", 15 June 2020, https://www.unilever.com/news/press-releases/2020/unilever-sets-out-new-actions-to-fight-climate-change-and-protect-and-regenerate-nature-to-preserve-resources-for-future-generations.html

47 Southern, Implementation (op. cit.), p.24

48 VW does not specify the role of CDR in its 2050 net-zero target, but states that its general approach is to follow a three-level hierarchy of "reduce, convert and compensate". It is investing in a forestry project in Borneo to offset current emissions.

49 Volkswagen, Sustainability Report 2019, https://www.volkswagenag.com/presence/nachhaltigkeit/documents/sustainability-report/2019/Nonfinancial_Report_2019_e.pdf

Volkswagen, "Borneo, Green Energy & Co.: What Volkswagen is doing for the environment", December 2019, https://www.volkswagenag.com/en/news/stories/2019/12/what-volkswagen-is-doing-for-the-environment.html

50 Walmart, "Walmart Sets Goal to Become a Regenerative Company", 21 September 2020,

https://corporate.walmart.com/newsroom/2020/09/21/walmart-sets-goal-to-become-a-regenerative-company

51 Note that most currently available carbon credits are for emissions reduction rather than CO_2 removal. Such credits should not be seen as contributing to net-zero targets because achieving global net zero and the Paris goals implies that all countries and companies must reduce their emissions to net zero, leaving no further reductions to trade.

52 American Airlines, Environmental, Social and Governance Report 2019–2020, p.14, https://www.aa.com/content/images/customer-service/about-us/corporate-governance/aag-esg-report-2019-2020.pdf

53 Duke Energy, Climate Report (op. cit.), pp.27-28

54 International Airlines Group, Flightpath Net Zero, https://www.iairgroup.com/sustainability/flightpath-net-zero

55 Microsoft is an exception: it explicitly aims to use a portfolio of CDR options, and invests in technology development to lower the costs of approaches such as BECCS and DACCS

56 Microsoft, "Microsoft will be carbon negative by 2030", 16 January 2020,

https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/#:~:text=Over%20three%2Dquarters%20of%20this,greenhouse%20gases%20into%20the%20air

57 IPCC SR15 (op. cit.), pp.343-344

58 Lauren Gifford, "You can't value what you can't measure: A critical look at forest carbon accounting", Climatic Change 161, 2020, https://doi.org/10.1007/s10584-020-02653-1

59 IPCC, Special Report on Climate Change and Land (SRCCL), 2019, p.98, https://www.ipcc.ch/srccl/

60 Wim Carton et al., "Negative emissions and the long history of carbon removal", WIREs Climate Change, 11:e671, 2020, http://doi.org/10.1002/wcc.671

Jutta Kill, REDD: A Collection of Conflicts, Contradictions and Lies, World Rainforest Movement, February 2015, https://wrm.org.uy/books-and-briefings/redd-a-collection-of-conflicts-contradictions-and-lies/

61 House of Commons, Climate Assembly UK: The path to net zero, September 2020, pp.26-27. https://www.climateassembly.uk/report/

Emily Cox et al., "Public perceptions of carbon dioxide removal in the United States and the United Kingdom", Nature Climate Change, Vol.10, August 2020, https://doi.org/10.1038/s41558-020-0823-z

62 Simon Lewis et al., "Regenerate natural forests to store carbon", Nature, Vol, 568, 4 April 2019, pp.25-28, https://doi.org/10.1038/d41586-019-01026-8

63 IPCC SR15 (op. cit.), pp.324-5;

Clair Gough & Naomi Vaughan, "Synthesising Existing Knowledge on the Feasibility of BECCS," AVOID2 report, February 2015, pp.15, 24-5, http://avoidnet-uk.cc.ic.ac.uk/wp-content/uploads/delightful-downloads/2015/07/Synthesisingexisting-knowledge-on-the-feasibility-ofBECCS-AVOID-2_WPD1a_v1.pdf;

Mathilde Fajardy & Niall MacDowell, "Can BECCS Deliver Sustainable and Resource Efficient Negative Emissions?" Energy & Environmental Science 10, 2017, p.1391, https://spiral.imperial.ac.uk/bitstream/10044/1/47928/7/c7ee00465f.pdf

Harper, A.B., Powell, T., Cox, P.M. et al. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. Nat Commun 9, 2938 (2018). https://doi.org/10.1038/s41467-018-05340-z

64 IEA, CCUS in Clean Energy Transitions, September 2020 pp.25-26, https://www.iea.org/reports/ccus-in-clean-energy-transitions

65 In Decatur, Illinois, United States.

66 IEA, CCUS

Global CCS Institute, The Global Status of CCS 2019, https://www.globalccsinstitute.com/resources/global-status-report/download/

67 Gerard Wynn, "The carbon-capture dream is dying," EnergyPost, 3 August 2017, http://energypost.eu/the-carbon-capture-dream-is-dying/

In the words of Francesco Starace, CEO of Enel and chair of trade association Eurelectric, "I think CCS has not been successful. It doesn't work, let's call it what it is – it is simply too expensive, too cumbersome, the technology didn't fly."

Frédéric Simon (2017), "EU power utility boss: 'Coal is finished, the hard question now is gas'," Euractiv, October 4, https://www.euractiv.com/section/electricity/interview/eu-power-utility-boss-coal-isfinished-the-hard-question-now-is-gas/

68 Sabine Fuss et al., "Negative emissions—Part 2: Costs, potentials and side effects", Environmental Research Letters 13, 2018, p.14, https://doi.org/10.1088/1748-9326/aabf9f

69 Fuss et al. 2018, p.20

70 Climeworks (11 projects), Global Thermostat (3 projects) and Carbon Engineering (1 project)

71 IEA, CCUS (op. cit.), p.84

72 IPCC, SR15 (op. cit.), p.346

73 European Commission, "Smart Specialisation Platform: Carbon Capture and Utilization", https://s3platform.jrc.ec.europa.eu/carbon-capture-and-utilization

74 Cameron Hepburn et al., "The technological and economic prospects for CO2 utilization and removal", Nature 575, 2019, https://doi.org/10.1038/s41586-019-1681-6

Cora Fernández-Dacosta et al., "Prospective techno-economic and environmental assessment of carbon capture at a refinery and CO2 utilisation in polyol synthesis", Journal of CO2 Utilization, Vol. 21, 2017, pp.405-422, https://doi.org/10.1016/j.jcou.2017.08.005.

75 Niall MacDowell et al., "The role of CO2 capture and utilization in mitigating climate change", Nature Climate Change 7, 2017, https://doi.org/10.1038/nclimate3231

76 Niklas von der Assen et al., "Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls", Energy and Environmental Science, 2013, https://doi.org/10.1039/C3EE41151F

77 Thomas Bruhn et al., "Separating the debate on CO2 utilisation from carbon capture and storage", Environmental Science & Policy, Vol. 60, June 2016, pp. 38-43, https://doi.org/10.1016/j.envsci.2016.03.001

78 IPCC, Climate Change: The IPCC Response Strategies, Working Group III contribution to First Assessment Report, 1990, p.xxvii, https://www.ipcc.ch/report/ar1/wg3/

79 Carton et al. 2020 (op. cit.)

80 Amy E Duchelle et al., "What is REDD+ achieving on the ground?" Current Opinion in Environmental Sustainability, Vol. 32, 2018, pp.134-140, https://doi.org/10.1016/j.cosust.2018.07.001

Constance L. McDermott, "REDDuced: From sustainability to legality to units of carbon—The search for common interests in international forest governance," Environmental Science & Policy, Vol. 35, 2014, pp.12-19, https://doi.org/10.1016/j.envsci.2012.08.012.

Aarti Gupta et al., "In pursuit of carbon accountability: the politics of REDD+ measuring, reporting and verification systems," Current Opinion in Environmental Sustainability, Vol. 4, Issue 6, 2012, pp.726-731, https://doi.org/10.1016/j.cosust.2012.10.004

Adeniyi Asiyanbi and Jens Friis Lund (eds.), "Stabilizing a policy: reproducing REDD+", Journal of Political Ecology 27, 2020, https://doi.org/10.2458/v27i1.23493

81 J.P Sarmiento Barletti and A.M. Larson, "Rights abuse allegations in the context of REDD+ readiness and implementation: A preliminary review and proposal for moving forward", Center for International Forestry Research (CIFOR), 2017. https://doi.org/10.17528/cifor/006630

Adeniyi P. Asiyanbi, "A political ecology of REDD+: Property rights, militarised protectionism, and carbonised exclusion in Cross River," Geoforum Vol. 77, 2016, pp.146-156, https://doi.org/10.1016/j.geoforum.2016.10.016.

Susan Chomba, et al., "Roots of inequity: How the implementation of REDD+ reinforces past injustices," Land Use Policy, Vol. 50, 2016, pp.202-213, https://doi.org/10.1016/j.landusepol.2015.09.021

Connor Cavanagh and Tor A. Benjaminsen, "Virtual nature, violent accumulation: The 'spectacular failure' of carbon offsetting at a Ugandan National Park," Geoforum, Vol. 56, 2014, pp.55-65. https://doi.org/10.1016/j.geoforum.2014.06.013.

Kristen Lyons & Peter Westoby (Research Associate) (2014) Carbon markets and the new 'Carbon Violence': A Ugandan study, International Journal of African Renaissance Studies, 9:2, 77-94, http://doi.org/10.1080/18186874.2014.987956

82 J.M. Drew and M.E. Drew, "Establishing additionality: fraud vulnerabilities in the clean development mechanism", Accounting Research Journal, Vol. 23 No. 3, 2010, pp. 243-253. https://doi.org/10.1108/10309611011092574

David F Scott et al., "The 'Virtual Economy' of REDD Projects: Does Private Certification of REDD Projects Ensure Their Environmental Integrity?," International Forestry Review 18(2), 261-263, 1 June 2016, https://doi.org/10.1505/146554816818966273

83 Martin Cames et al, How additional is the Clean Development Mechanism? Öko-Institut and Stockholm Environment Institute study for DG CLIMA, ref. CLIMA.B.3/SERI2013/0026r, March 2016, https://ec.europa.eu/clima/sites/clima/files/ets/docs/clean_dev_mechanism_en.pdf

84 Carton et al 2020 (op. cit.)

85 IPCC, SR15 (op. cit.), p.125

86 IPCC, Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report (AR5) of the IPCC, p.845

87 Naomi E Vaughan and Claire Gough, "Expert assessment concludes negative emissions scenarios may not deliver," Environmental Research Letters 11, 2016, http://doi.org/10.1088/1748-9326/11/9/095003

88 Briana Mordick and George Peridas, Strengthening the regulation of enhanced oil recovery to align it with the objectives of geologic carbon dioxide sequestration, NRDC, November 2017, https://www.nrdc.org/sites/default/files/regulation-eor-carbon-dioxide-sequestration-report.pdf

Nicholas Kusnetz, "Exxon Touts Carbon Capture as a Climate Fix, but Uses It to Maximize Profit and Keep Oil Flowing", Inside Climate News, 27 September 2020, https://insideclimatenews.org/news/25092020/exxon-carbon-capture

Sarah Fowler, "'Foaming at the mouth': First responders describe scene after pipeline rupture, gas leak", Clarion-Ledger, 27 February 2020, https://eu.clarionledger.com/story/news/local/2020/02/27/yazoo-county-pipe-rupture-co-2-gas-leak-first-responders-rescues/4871726002/

89 The Sleipner project in Norway, started in 1996, was generally promoted as a successful demonstration of CCS, until fractures were discovered nearby in the caprock in 2013. There have not been indications that the site itself is unsafe, but it is worrying that the fractures were un-noticed in such a high-profile case.

90 Footnote reference:

Richard Monastersky, "Seabed scars raise questions over carbon-storage plan," Nature, 17 December 2013, http://doi.org/10.1038/504339a

91 Gifford 2020 (op. cit.)

Chris Lang, "Larry Lohmann: The problem is not 'bad baselines' but the concept of counterfactual baselines itself", REDD Monitor, 18 October 2016, https://redd-monitor.org/2016/10/18/larry-lohmann-the-problem-is-not-bad-baselines-but-the-concept-of-counterfactual-baselines-itself/

92 IPCC, SR15 (op. cit.), p.121

93 Some IAMs allocate biomass plantation to pastureland, rather than arable or wild land. Achieving such allocation in practice would require intensification of meat/dairy production and/or a global shift towards plant-based diets, and would require extensive governance mechanisms to prevent production on land that creates greater sustainability concerns. In other cases, IAMs use marginal land or abandoned agricultural land, in both cases raising the same governance questions.

Even when using currently unproductive land, CDR may impact on food prices if demand for agricultural land increases in the future, due to both rising population and reduced yields due to climate change or overfarming.

94 Footnote references:

IPCC, SR15 (op. cit.): p.125

Henry Shue, "Climate Dreaming: Negative Emissions, Risk Transfer, and Irreversibility," Journal of Human Rights and Environment 8, 2017, pp.7-8, http://dx.doi.org/10.2139/ssrn.2940987

Gough & Vaughan 2015 (op.cit.), pp.9-11

95 IPCC SRCCL (op. cit.), p.29

96 IPCC SR15 (op. cit.), p.123

97 IPCC SR15 (op. cit.), p.343

Smith et al 2015 (op. cit.), p.5

Felix Creutzig, "Bioenergy and Climate Change Mitigation: An Assessment," GCB Bioenergy, 7(5), 2015, p.18, https://doi.org/10.1111/gcbb.12205

98 Note that AR removes less CO2 per hectare than BECCS, because the biomass is the storage sink as well as the removal mechanism.

99 IPCC SR15 (op. cit.), p.343

Fuss et al. 2018 (op. cit.), p.16;

R.A. Houghton et al., "A role for tropical forests in stabilizing atmospheric CO2", Nature Climate Change 5, 1022–1023 (2015), https://doi.org/10.1038/nclimate2869

100 A land area the size of Spain = 50.1 Mha. Shell, Energy Transitions (op. cit.), p.4

101 Lewis et al. 2019 (op. cit.)

Ulrich Kreidenweis et al., "Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects", Environmental Research Letters 11, 2016. http://doi.org/10.1088/1748-9326/11/8/085001

Fuss et al 2018 (op. cit.), p.34

IPCC SRCCL (op. cit.), p.494

102 G, Realmonte et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature Communications 10, 2019, https://doi.org/10.1038/s41467-019-10842-5

IPCC SR15 (op. cit.), p.346

103 Gough and Vaughan 2015 (op. cit.)

104 While the broad shape of accounting rules exists through the UNFCCC, there are significant gaps, including on monitoring and verification

M.J. Mace et al., Governing Large-Scale Carbon Dioxide Removal: Are we ready? Carnegie Climate Geoengineering Governance Initiative (C2G2), November 2018, https://www.c2g2.net/governing-large-scale-carbon-dioxide-removal-are-we-ready/

105 Creutzig et al 2015 (op. cit.)

Emily Boyd, "Governing the Clean Development Mechanism: Global Rhetoric versus Local Realities in Carbon Sequestration Projects", Environment and Planning A: Economy and Space, Vol. 41, issue 10, 2009, pp.2380-2395. https://doi.org/10.1068/a41341

106 Yuanrong Zhou, "Carbon capture and storage: A lot of eggs in a potentially leaky basket", The International Council on Clean Transportation, 17 January 2020,

https://theicct.org/blog/staff/carbon-capture-storage-and-leakage

Stephen T. Anderson, "Risk, Liability, and Economic Issues with Long-Term CO2 Storage—A Review", Springer Link, 23 July 2016, https://link.springer.com/article/10.1007/s11053-016-9303-6

Allan Ingelson et al., "Long-term liability for carbon capture and storage in depleted North American oil and gas reservoirs - a comparative analysis", Energy Law Journal, Vol. 31, 2010, http://dx.doi.org/10.11575/PRISM/34003

107 Asbjørn Torvanger, "Governance of bioenergy with carbon capture and storage (BECCS): accounting, rewarding, and the Paris agreement", Climate Policy, Vol. 19, NO. 3, 2019, https://doi.org/10.1080/14693062.2018.1509044

108 Laurie Waller et al., "Contested framings of greenhouse gas removal and its feasibility: Social and political dimensions", WIREs Climate Change, 2020, https://doi.org/10.1002/wcc.649

IPCC SR15 (op. cit.), p.343

J.L. Reynolds, "The politics and governance of negative emissions technologies". Global Sustainability 1, 2018, https://doi.org/10.1017/sus.2018.13

109 Isabela Butnar et al., "A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): a transparency exercise", Environmental Research Letters 15, 2020, https://doi.org/10.1088/1748-9326/ab5c3e

Johanna Forster et al., "Mapping feasibilities of greenhouse gas removal: Key issues, gaps and opening up assessments," Global Environmental Change, Vol. 63, 2020, https://doi.org/10.1016/j.gloenvcha.2020.102073

110 The near-linear relationship of temperature rise with cumulative CO2 emissions was robustly established in several papers in 2009 and formed a central plank of the IPCC's Fifth Assessment Report in 2013/14. It is from this finding that the notion of carbon budgets derives.

111 Footnote references:

IPCC, Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report, pp.1106-1108, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter12_FINAL.

pdf

Myles Allen et al., 2009, "Warming caused by cumulative carbon emissions towards the trillionth tonne", Nature 458, pp.1163–1166, https://doi.org/10.1038/nature08019

Malte Meinshausen et al., 2009, "Greenhouse-gas emission targets for limiting global warming to 2°C", Nature 458, pp.1158–1162, https://doi.org/10.1038/nature08017

Damon Matthews et al., 2009, "The proportionality of global warming to cumulative carbon emissions", Nature 459, pp.829–832, https://doi.org/10.1038/nature08047

112 IPCC SR15 (op. cit.), chapter 2

Christa M. Anderson et al., "Natural climate solutions are not enough", Science, Vol. 363, Issue 6430, pp. 933-934, 1 Mar 2019, http://doi.org/10.1126/science.aaw2741

113 Either directly through a cost-minimising objective function or indirectly by representing competitive economic behaviours and decisions.

114 Overshoot refers to temporarily exceeding a temperature target, before using net-negative emissions (via CDR) to bring temperatures back down

115 IPCC SR15 (op. cit.), p.100, 184, 274-276

116 IPCC SR15 (op. cit.), pp.16-17, 109-113, 123;

Arnulf Grubler et al., "A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies" Nature Energy, 3(6), 515–527, 2018, http://doi.org/10.1038/s41560-018-0172-6.

Oliver Fricko et al., "The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century", Global Environmental Change, 42, pp.251–267, 2017, http://doi.org/10.1016/j.gloenvcha.2016.06.004

Shinichiro Fujimori, "SSP3: AIM Implementation of Shared Socioeconomic Pathways", Global Environmental Change, 42, pp.268–283, 2017, http://doi.org/10.1016/j.gloenvcha.2016.06.009

Elmar Kriegler et al., "Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century", Global Environmental Change, 42, pp.297–315, 2017, http://doi.org/10.1016/j.gloenvcha.2016.05.015

117 E.g. Climate Analytics, Insights from the IPCC Special Report on 1.5°C for Preparation of Longterm Strategies, April 2019, p.11. https://climateanalytics.org/publications/2019/insights-from-the-ipcc-special-report-on-15c-for-the-preparation-of-long-term-strategies/

118 Footnote reference:

IPCC, SR15 (op.cit.), p.122

119 Unfortunately, the term "integrated assessment model" is also sometimes used to refer to highly-aggregated, top-down models of the macroeconomy including climate damage functions – these models are commonly used for cost-benefit analyses to find an optimal level of climate mitigation, as for instance in the Stern Report. Prominent top-down IAMs include DICE, PAGE and FUND. There has been considerable controversy over this class of models, regarding both the way that climate damages are modelled and the appropriate discount rates.

These purely top-down models are not relevant to the subject of this briefing note, which instead uses the term IAM to refer to technologically-detailed models as described in the box. Such models include AIM, GCAM, IMAGE, MESSAGE-GLOBIOM, POLES, REMIND, TIAM and WITCH.

120 Models tend to be structured either around optimisation (finding a means to meet energy demands at the lowest total discounted cost, from the perspective of a single social planner) or simulation (representing the interacting decisions of many actors with differing objectives or behaviours).

121 Francis Li, and Neil Strachan, "Modelling energy transitions for climate targets under landscape and actor inertia", Environmental Innovation and Societal Transitions 24, pp.106–129, 2017, http://doi.org/10.1016/j.eist.2016.08.002.

David McCollum et al., "Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices", Transportation Research Part D: Transport and Environment 55, August 2017, pp.322-342. http://doi.org/10.1016/j.trd.2016.04.003

Evelina Trutnevyte,: "Does cost optimization approximate the real-world energy transition?" Energy 106, 2016, pp.182-193, http://doi.org/10.1016/j.energy.2016.03.038

122 Except to the extent it may be influenced by prices in the model.

123 The P1 pathway achieves this largely by delivering the same energy services through more efficient systems such as public transport (Grubler et al., 2018). Other low-energy-demand pathways consider major lifestyle change (eg less meat-eating, less travel) and/or low population growth (e.g. Van Vuuren et al., 2018).

124 Footnote references:

Grubler et al. 2018 (op. cit.)

Detlef van Vuuren et al., "Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies", Nature Climate Change 8, pp.391–397, 2018, http://doi.org/10.1038/s41558-018-0119-8

125 Since CDR approaches (other than AR) are generally at an earlier stage of development than many other mitigation technologies, they are applied later in the models. An additional reason for delay is that CDR is less timebound (In that traditional mitigation of emissions can only be applied when the emissions occur, whereas CO2 can be removed any time, subject to limitations on overshoot) and the practice of discounting future costs makes later deployment more economically attractive.

126 Footnote references:

IPCC, SR15 (op.cit.), p.123

Johannes Bednar et al., "On the financial viability of negative emissions", Nature Communications vol. 10, 2019, https://doi.org/10.1038/s41467-019-09782-x

127 Alexandre Köberle, "The Value of BECCS in IAMs: a Review", Current Sustainable/Renewable Energy Reports 6, pp.107–115, 2019, https://doi.org/10.1007/s40518-019-00142-3

Sarah Mander et al., "The Role of Bio-energy with Carbon Capture and Storage in Meeting the Climate Mitigation Challenge: A Whole System Perspective", Energy Procedia, Vol. 114, July 2017, pp.6036-6043, https://doi.org/10.1016/j.egypro.2017.03.1739

Kevin Anderson and Glen Peters (2016), "The trouble with negative emissions," Science, 14 October, Vol 354, http://doi.org/0.1126/science.aah4567

Kate Dooley et al., "Co-producing climate policy and negative emissions: trade-offs for sustainable land-use", Global Sustainability 1, e3, 2018, https://doi.org/10.1017/sus.2018.6

128 Pierre Friedlingstein et al., "Global Carbon Budget 2019", Earth System Science Data, 11, 1783–1838, 2019, https://doi.org/10.5194/essd-11-1783-2019

129 Fuss et al., 2018 (op.cit.), pp.14-28. The Fuss et al. survey reviewed and interpreted over 450 studies on the various CDR technologies.

130 These ranges do not reflect minimum and maximum predictions of how much there will be of each type of CDR; rather they reflect uncertainties in the maximum that will be sustainably possible – there could be less.

131 IPCC SR15 (op.cit.), pp.270, 343-345

Fuss et al. 2018 (op. cit.)

132 A much-publicised paper in 2017 suggested a considerably larger potential for "natural climate solutions" of about 11,000 My/year by 2030, including about 3,000 Mt/year from reforestation. However, the feasibility of these numbers has been questioned: for example, they assume that all grazing land in forested ecoregions is completely converted to forest; much of their economic viability calculation rested on an assumption that the reforestation would be creation of temporary commercial plantation that would be logged (hence losing most of the climate benefit) once mature.

133 Footnote reference:

Bronson W. Griscom et al., "Natural climate solutions", Proceedings of the National Academy of Sciences, 114 (44), October 2017, http://doi.org/10.1073/pnas.1710465114

Chris Lang and Simon Counsell, "Offsetting fossil fuel emissions with tree planting and 'natural climate solutions': science, magical thinking, or pure PR?" REDD-Monitor, 4 July 2019, https://redd-monitor.org/2019/07/04/offsetting-fossil-fuel-emissions-with-tree-planting-and-natural-climate-solutions-science-magical-thinking-or-pure-pr/

134 As well as what yields are achievable, a large part of the uncertainty rests on the availability of suitable land (for AR and BECCS). In general, estimates at the higher end of the range put less constraint on use of agricultural or wild land (page 15), and come at higher cost.

135 Fuss et al. 2018 (op.cit.), pp.10-11, 14-15

136 Fuss et al. 2018 (op.cit.), p.29

137 IPCC SR15 (op.cit.), p.343

138 Sean Low and Stefan Schäfer, "Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling," Energy Research & Social Science, Vol. 60, 2020, https://doi.org/10.1016/j.erss.2019.101326

139 EASAC 2018 (op.cit.), p.1

140 IPCC SR15 (op.cit.), pp.112-113

IPCC AR5 (WG3) (op.cit.), p.155

141 Beyond the aggregate demand sectors of industry, transport, buildings and power etc

142 IPCC SR15 (op.cit.), pp.136-144

Science Based Targets initiative, Foundations of Science-based Target Setting, Version 1.0, April 2019, https://sciencebasedtargets.org/resources/files/foundations-of-SBT-setting.pdf

143 IEA, Energy Technology Perspectives (ETP) 2017, p.23

144 In the B2DS, residual greenhouse gas emissions from cars and vans in 2050 are 22% of their 2020 value.

Light-duty vehicles, tank-to-wheel emissions. IEA Mobility Model 2017; data reproduced in SBTi Sector Decarbonisation Approach, Transport Tool v.1.1, https://sciencebasedtargets.org/wp-content/uploads/2018/10/SDA-Transport-tool_v1.1_locked.xlsx

145 The below table shows the residual 2050 CO2 emissions in the B2DS, relative to 2014 emissions, for the largest-emitting industry sectors.

Iron & steel	25%
Cement	35%
Chemicals	45%
Aluminium	00%
Pulp & paper	0%
Other industries	55%

IEA ETP 2017 (op.cit.), Figure 4.7, p.176

Note that these values are approximate, as they are extracted from the graph using the Web Plot Digitizer tool.

146 Total aviation (passenger and freight). IEA ETP 2017 (op.cit.), p.253

147 In IPCC illustrative pathways P1 to P3, the residual emissions are between just 5% and 27% of 2010 emissions in the industry and residential/commercial sectors.

Residual CO2 reductions in 2050 relative to 2010

	Industry	Residential / commercial
P1	9%	5%
P2	26%	20%
P3	27%	10%

IAMC/IIASA, 1.5°C Scenario Explorer and Data hosted by IIASA, https://data.ene.iiasa.ac.at/iamc-1.5°C-explorer

148 ipcc, "IPCC Working Group III releases new schedule, postpones fourth Lead Author Meeting", 12 August 2020,

https://www.ipcc.ch/2020/08/12/ipcc-wg-iii-new-schedule-lam4/

149 The B2DS featured in the 2017 edition of IEA's Energy Technology Perspectives (ETP) report, but was dropped in the subsequent edition in 2020. In the B2DS, CO2 emissions from energy and industry decrease by 64% by 2040 (86% by 2050), compared to 2014 levels (ETP 2017). In the SDS, CO2 emissions from energy decrease by 52% by 2040, compared to 2010 levels (IEA, World Energy Outlook 2020).

The other difference is that B2DS (and other scenarios in editions of the ETP up to 2017) was created using ETP-TIMES, a least-cost optimisation model akin to those appearing in IPCC reports. The SDS is created using WEM, a simulation model based on exogenous policy assumptions: essentially the policies the IEA judges to be the most reasonable; as such, it has a more subjective and political character. For a description of the two models, see ETP 2017, pp.396-405 and IEA, World Energy Model Documentation 2020, pp.10-12.

150 The CCC supports the use of CDR, but argues that the UK should apply it within its own borders rather than offsetting overseas. An equivalent for companies might be to deploy CDR on their own land (or in their supply chain) rather than simply buying credits on the carbon markets.

151 Committee on Climate Change, Net Zero: The UK's contribution to stopping global warming, May 2019, p.262, https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

152 Science Based Targets, FAQS, https://sciencebasedtargets.org/faq/

153 Duncan P. McLaren et al, "Beyond 'Net-Zero': A Case for Separate Targets for Emissions Reduction and Negative Emissions", Frontiers in Climate, Vol. 1, Article 4, August 2019, http://doi.org/10.3389/fclim.2019.00004

154 For example, by reduced/zero tillage, erosion control and cropping choices.

155 An additional storage possibility, not discussed here, is in building materials. For example, timber used in construction stores carbon over the long term; technologies are being explored to store carbon in concrete.

156 IPCC SR15 (op.cit.), pp.270, 343-345

Fuss et al. 2018 (op. cit.)

157 Especially IPCC SR15 (op. cit.), Fuss et al 2018 (op. cit.) and Smith et al 2015 (op. cit.)