An investor guide to negative emission technologies and the importance of land use

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INEVITABLE POLICY RESPONSE

Executive Summary

Negative Emission Technologies (NETs) are the next investment frontier and offer trillion dollar upside opportunities for investors.[1] Within NETs, forest-related Nature-Based Solutions (NBS) could generate US$800 billion in annual revenues by 2050, worth US$1.2 trillion today in NPV terms,[2] surpassing the current market capitalisation of the oil & gas majors.[3] Hence, an entire new industry may emerge that values carbon stored in vegetation and soil, unlocking new business models and investment opportunities for avoided deforestation, reforestation and afforestation (hereinafter re/afforestation), and land restoration. Thanks to its low cost, natural forest restoration looks likely to emerge as the earliest feasible investment opportunity. The sector's annual revenues could reach US$190 billion by 2050. Avoided deforestation may generate the remaining annual revenues with US$610 billion by 2050, but it is further from commercialisation as it involves more complex compensation mechanisms (The Inevitable Forest Finance Response: Investor Opportunities, commissioned by the PRI (Principles for Responsible Investment)). Technical solutions, such as Direct Air Carbon Capture, Use and Storage (DACCS) and bioenergy with CCS (BECCS), could generate an additional annual revenue of US$625 billion by 2050.[4] This report provides transparency around NETs assumptions of climate scenarios and corporate net-zero commitments, presents risks and uncertainties associated with NETs, and assesses what upside opportunities NETs – particularly NBS and, within this, forestry – can offer to investors.

Proportion of global GDP covered by net zero targets is growing. Mounting investor pressure and changing consumer preferences are contributing to an increase in net-zero commitments, particularly among heavy emitters in oil & gas, utilities, steel, cement, automobile, food, and aviation. Already, over half of global GDP, 2.6 billion people and a quarter of carbon emissions are covered by a national net-zero target (ECIU, 2020). Since late 2019, the number of companies committed to net zero increased by two-fold from 500 recorded in 2019 to 1,541 in 2020, while the increase for cities was eight-fold from 100 recorded in 2019 to 823 more in 2020 (UNFCCC, 2020). Since January 2020, 379 more companies committed to science-based climate action and joined the Science Based Targets initiative list, increasing the number of companies on the list to 1009 as of October 2020 (Science Based Targets, 2020). At Climate Week NYC 2020, 17 new companies announced science based net zero commitments, including LafargeHolcim the world's largest cement company and C.P.Group, one of Asia's leading conglomerates.

Paris-aligned climate scenarios project that NETs are needed to achieve net-zero.[5] The Inevitable Policy Response (IPR) Forecast Policy Scenario (FPS), commissioned by the Principles for Responsible Investment (the UN-supported investor group representing $86 trillion in AuM), forecasts a forceful, abrupt and disorderly policy response to climate change and quantifies the financial impact this will have on economies and securities markets. It shows that biogenic greenhouse gas (GHG) emissions[6] remain by 2050, as well as emissions from agriculture and fertiliser use, and that NETs are required for truly net-zero global emissions. These emissions are often missed in climate scenarios that focus on energy only and have a blind spot as regards the critical importance of land use. Climate scenarios that limit global warming to 1.5°C require even deeper negative emissions to reach their temperature targets. In 2018, the Interfovernmental Panel on Climate Change (IPCC) set out four representative pathways that align to a global temperature rise of 1.5°C,

[1] Also known as carbon dioxide removal (CDR). NETs are technical solutions and Nature Based Solutions (NBS) that sequester carbon from the atmosphere.
[2] Estimates are in 2019 US$ terms. See Box 1 for further detail.
[3] As of June 2020. Oil & gas majors include BP, Chevron, China National Offshore Oil, ConoccoPhilips, Enterprise Product Partners, EOG Resources, ExxonMobil, Kinder Morgan, Occidental Petroleum, Petrobas, PetroChina Company, Santos, Schlumberger, Sinopec, Suncor Energy, and Total.
[4] The annual revenue is estimated for annual CO_2 sequestration of 5 $GtCO_2$/year at a cost of US$125 per tCO_2 and considers only revenue from sequestered CO_2 emissions.
[5] The Paris Agreement sets out to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" and "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" i.e. net-zero emissions.
[6] Biogenic GHG emissions are related to the natural carbon cycle and result from harvest, combustion, digestion, fermentation, decomposition, or processing of biologically based materials (EPA, 2020).

and even the most ambitious emissions reductions scenario, P1, relies on NETs to sequester 2.5 $GtCO_2$/year by 2050. As policy responses to reduce emissions are delayed, NETs will inevitably grow in importance in keeping global temperature rise to well below 2°C. In P4, total negative emissions are 16 $GtCO_2$ in 2050, corresponding to around half of CO_2 emissions from combustion of fossil fuels today. The reliance of the climate scenarios on NETs increases further in the second half of the century.

Companies realise the need for NETs to decarbonise their value chains and hence meet their net zero targets. While some companies plan to utilise technical solutions, such as Microsoft considering BECCS and DACCS (Smith, 2020) and British Airways' parent IAG exploring DACCS (Otley, 2020), most companies are likely to invest in NBS to offset their CO_2 emissions. Of 42 companies announcing net-zero targets in 2019-20, 26 are planning to use NETs, and 24 of these 26 companies refer to NBS (Vivid Economics using (American University, 2020)). However, the majority of net-zero targets announced by corporates are currently vague, and more detail is needed to understand the contribution of NBS, BECCS and DACCS to emissions reductions commtiments.

In almost all Paris-aligned scenarios, BECCS is the leading NET because of its double gains through energy generation and CO_2 sequestration; yet producing high levels of bioenergy is likely to push the world to its planetary boundaries in terms of water and land availability. In the case of the IPCC scenarios, cumulative BECCS up to 2100 ranges from 151 $GtCO_2$ in IPCC P2 – which has an incredibly ambitious decarbonisation pathway halving emissions from 37 $GtCO_2$ to 19 $GtCO_2$ between 2020 and 2030 - to 1,191 $GtCO_2$ in IPCC P4. However, too much is expected from land as various parties plan in isolation to utilise land for diverse purposes, such as energy security through bioenergy, food security, and urbanisation. As a finite source, land will not be able to deliver all these expectations. An over-reliance on BECCS could threaten biodiversity as it may require harvesting of existing forests and conversion of protected areas to monoculture plantations (Fern, 2018), exacerbating the current biodiversity crisis – around 1 million plant and animal species, 12% of the estimated global specifies, are currently under threat of extinction (IPBES, 2019). Moreover, clearing land for bioenergy could reduce the natural CO_2 sequestration potential of land, cancelling out some of the carbon sequestered through BECCS. The technology could also run counter to a just transition as it is likely to compete with food production for land, pushing up food prices. BECCS may also disadvantage small holders who rely on land for income and food supplies through changes in land tenure. To limit its negative side effects, BECCS should be contained to a sustainable scale, at around 0.5 – 5 $GtCO_2$/year (Fuss *et al.*, 2018).[7]

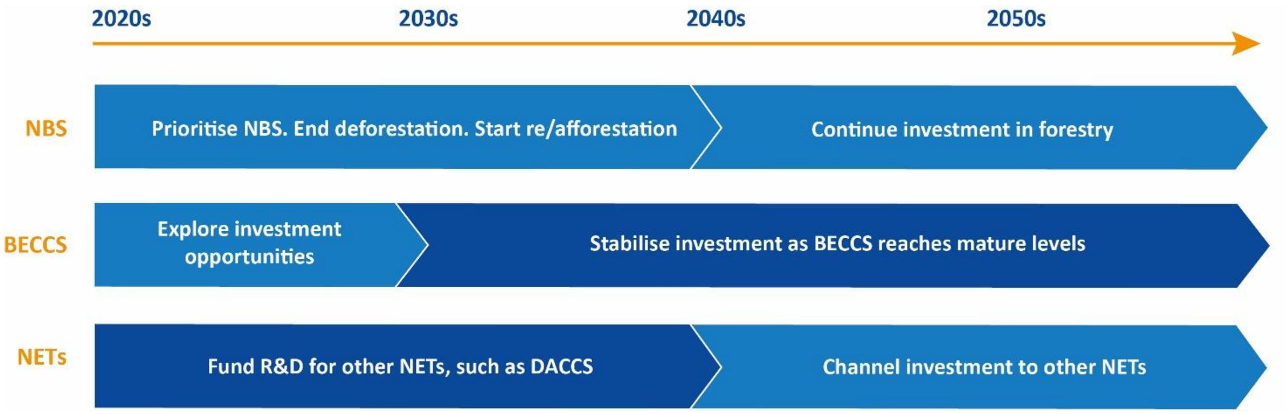
Developing an understanding of NETs will give investors an early mover advantage in the most profitable investment opportunities and help them to judge risks and potential returns accurately. Given the limited sustainable CO_2 removal potential of BECCS, countries, cities and corporates will need to turn to a portfolio of NETs to reach their net-zero targets. Deploying a portfolio of multiple NETs, each at a sustainable scale, would provide a hedge against uncertainties and negative impacts associated with the large-scale application of each NET. Most importantly, to reduce exposure of their portfolios to carbon-exposed sectors, investors need to put pressure on companies to commit to climate action and stop themselves investing in companies with deforestation in their supply chains (Ceres, 2020).

In the near term, investors can reap the greatest financial gains from NBS, especially through measures arresting deforestation and promoting re/afforestation. In the longer term, post-2040, as BECCS approaches its sustainable limit, technical solutions, such as DACCS, are opportunities to watch, as illustrated in Figure 1**.** Besides adhering to the principle of doing no more harm – i.e. ending deforestation and habitat destruction – re/afforestation are the least-costly and most readily deployable at-scale options among NETs. Given the advantages of NBS, deforestation needs to be stopped now, and re/ afforestation should start immediately to decrease overshooting emissions targets and to limit exposure to risky NETs that could have uncertain performance, costs and potential negative side effects in the coming decades. In the longer term, post-2040, technology-focused NETs, such as DACCS, could be economically viable alternatives to BECCS as their costs

[7] At this level of CO_2 removal potential, the literature estimates that the cost of BECCS would range from US$100 per tonne CO_2 to US$200 per tonne CO_2.

are falling – if investors and corporates channel funds towards further research, development, and deployment in 2020s and 2030s (Fuss *et al.*, 2018; Realmonte *et al.*, 2019).

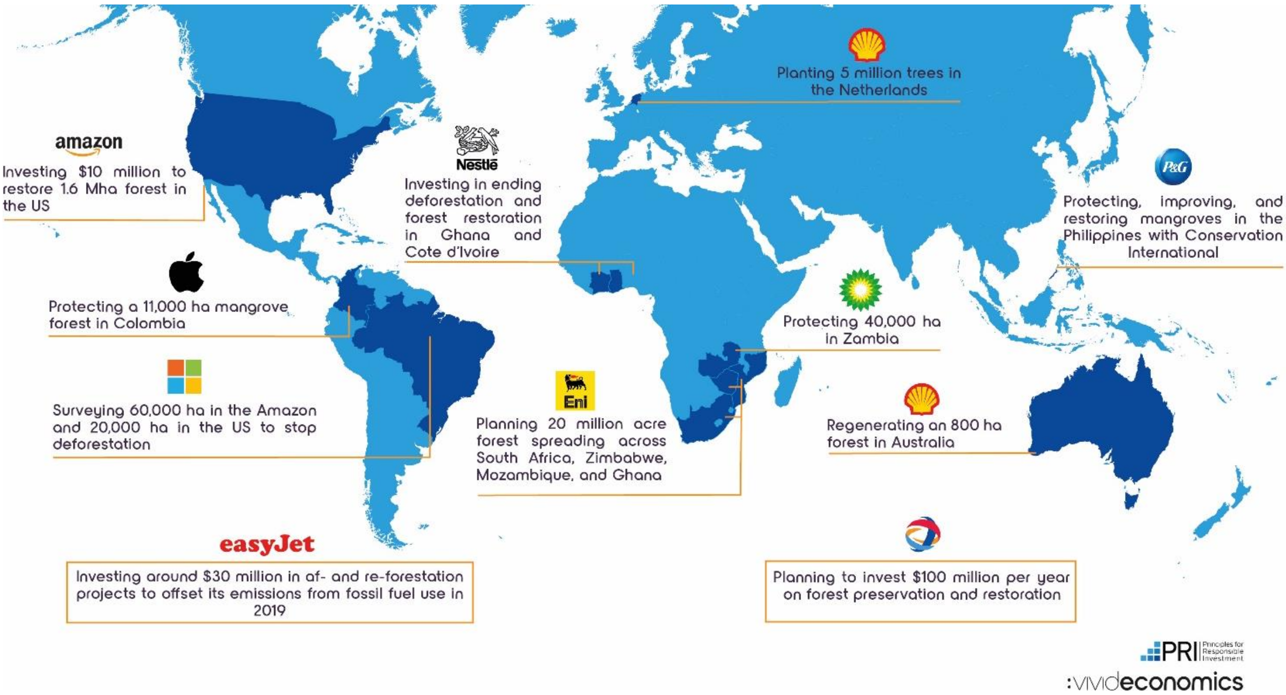
Figure 1 In the nearterm, NBS and particularly forestry provide investment opportunities while focusing on RD&D for other NETs and deploy a feasible amount of BECCS in the long run



Source: Vivid Economics

Big oil and Big tech have already started to channel their resources into forest related NBS to achieve new net-zero targets — and in turn this is driving demand for NBS carbon credits. Shell forecasts that roughly a quarter of emission reductions to reach net-zero will come from natural sinks and has started to invest in forest-related projects, such as the planting of 5 million trees in the Netherlands and regenerating an 800 ha forest in Australia (Shell, 2019, 2020b). BP is currently running an offset programme, protecting 40,000 ha of forest in Zambia. Total is committed to investing US$100 million per year in forest protection (IOM3, 2019; BP, 2020). Technology companies are also pursuing similar projects. Apple is protecting a 11,000 ha mangrove forest in Colombia, and Microsoft has committed to support selected forest projects by paying US$15/t$CO_2$, higher than the global average of US$10/t$CO_2$ (Catanoso, 2020). Amazon has launched the Right Now Climate Fund, investing US$100 million in NBS. The first project of US$10 million was announced in April 2020 to restore and conserve 1.6 Mha forest in the US, removing 18 MtCO_2 from the atmosphere (Amazon, 2020b). Consequently, corporate net-zero commitments are driving the demand for NBS carbon credits. From 2017 to 2018, the voluntary offset market doubled in volume from approximately 50 million to 100 million offsets and in value from US$150 million to US$300 million (Gross, Hook and Powley, 2019a). In 2019, Verra, a carbon credit standard, issued around 100 million voluntary carbon credits, over twice the amount issued previously in a single year (Verra, 2020a). By 2050, the value of the global voluntary offset market could reach US$200 billion, increasing by around a quarter every year (Watson, 2020).

Figure 2 Companies have already started to channel their resources to forest-related NBS projects



Source: Vivid Economics

The emerging NBS market provides a unique opportunity to investors to shape its design for their needs while driving its impact. Investors could support the NBS market's institutional development by engaging with policymakers and developing innovative business models and financing mechanisms to channel finance to the market. New financing mechanisms are already emerging. Examples include distressed asset and stewardship models, carbon farming agreements, green bonds, forest insurance provision, carbon off-taker guarantees, and sustainable farming agreements. Investors could also engage with policymakers to promote a global standard for NBS projects which could help to create a global market and unlock the global finance that is crucial for a rapid scale-up.

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1 Investors need to understand risks and opportunities associated with NETs

Paris-aligned climate scenarios and corporate net zero announcements have shown that Negative Emissions Technologies (NETs) are needed to achieve net zero emissions and chip away at the overshoot. To limit global warming to 1.5 or 2°C by the end of the century, reducing CO_2 emissions and capturing CO_2 from large emission sources are not sufficient. Capturing CO_2 using technologies that remove and sequester CO_2 from the atmosphere – NETs – will also be necessary. The Inevitable Policy Response (IPR) Forecast Policy Scenario (FPS), which models a forceful, abrupt, and disorderly policy response to climate change by 2025, shows that biogenic greenhouse gas (GHG) emissions remain, as well as emissions from agriculture and fertiliser use, thereby requiring NETs for truly net zero global emissions. Even then, climate scenarios that limit global warming to 1.5°C require more negative emissions to reach their temperature targets, and as actions to reduce global CO_2 emissions are further delayed, NETs will grow in importance for managing the global temperature rise. The most important NETs are bioenergy with Carbon Capture and Storage (BECCS), direct air capture of CO_2 with CCS (DACCS), afforestation and reforestation (hereinafter re/afforestation), soil carbon sequestration, biochar, and enhanced weathering (see Appendix for a detailed presentation of the selected NETs). While some NETs are already widely employed, such as re/afforestation, others are at early stages of development, such as DACCS, and depend on the supply of other inputs, such as biomass for BECCS and minerals for enhanced weathering.

Relying on NETs for the removal of CO_2 from the atmosphere is risky as there are many uncertainties around their costs, CO_2 removal potential, and side effects. There is ample literature on NETs providing various estimates on costs and CO_2 removal potential, but these consist of extremely wide ranges based on diverging assumptions. Moreover, the potential side effects of NETs are not yet fully understood, increasing the risks associated with these technologies. Reliance on NETs that may prove unfeasible and unsustainable for future negative emissions could delay mitigation action resulting in high levels of CO_2 emissions that could lead to a temperature rise beyond 2°C. More research and demonstration projects are needed to address concerns around the technical capabilities and potential side effects of NETs.

Investors need to properly assess and understand uncertainties and risks associated with the NETs that are utilised by climate scenarios and corporate net zero targets. While most climate scenarios rely on BECCS to meet their temperature targets, corporate net zero commitments also aim to deploy BECCS and Nature-Based Solutions (NBS) to offset their CO_2 emissions. The reliance of climate scenarios on BECCS is an issue as producing the levels of bioenergy projected is likely to push the world to its planetary boundaries in terms of water and land availability, threatening biodiversity, and running counter to a just transition. Companies' increasing demand for NBS credits hints at shifts in the global offset market that may create investment opportunities. Developing an understanding around NETs could allow investors to identify appropriate investment opportunities and judge risks and potential returns accurately.

Against this backdrop, this report provides transparency around NETs assumptions of corporate net zero targets and climate scenarios; discusses risks and uncertainties associated with NETs; and assesses what upside opportunities NETs can offer to investors. The report first provides an overview of corporate net zero targets and how companies aim to achieve these, with a focus on NETs. It then lays out the architecture of the IPCC, NGFS and IEA scenarios, and the role of NETs within those. It also offers an in-depth overview of the six NETs, their costs and carbon removal potential, as well as possible positive and negative side effects. The report concludes with recommendations for investors.

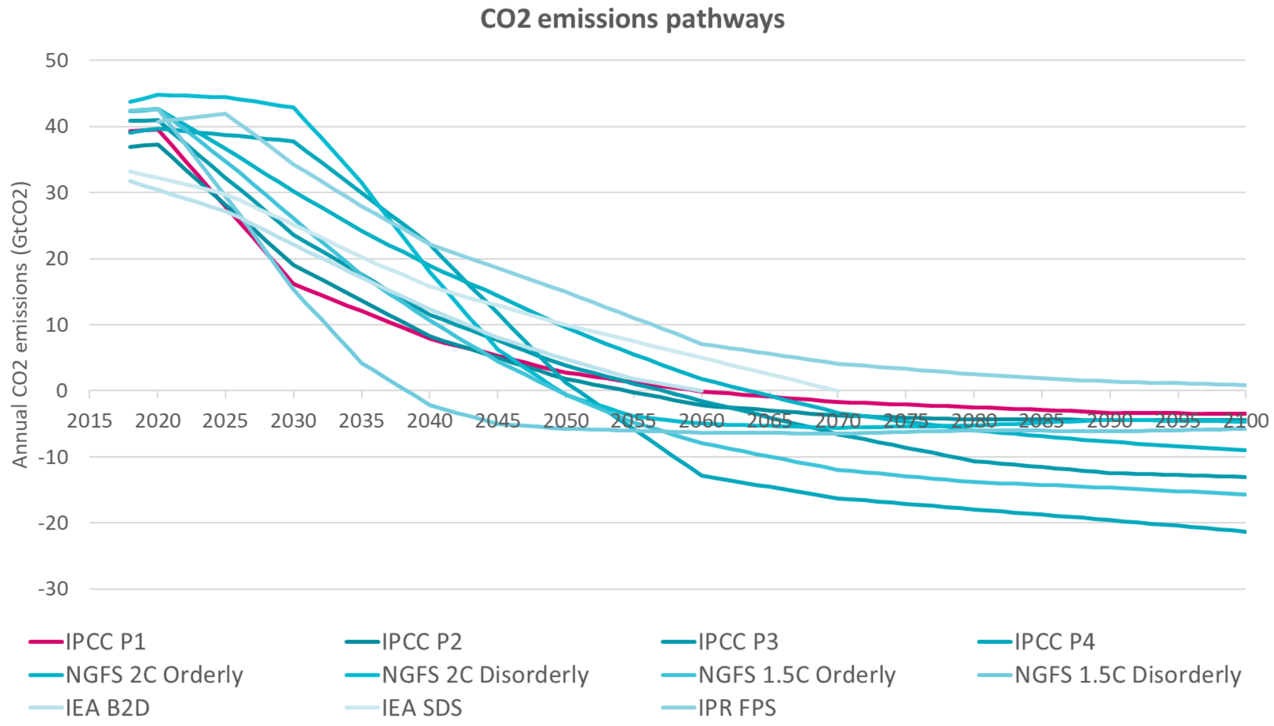
2 IPR FPS and almost all Paris-aligned climate scenarios rely on NETs

For investors it is important to develop an understanding of the climate scenarios and the differences between them as these may have ramifications for investor decisions and financial outcomes. Climate scenarios are projections of future climate constructed to assess the relationships between human activities, emissions, concentrations, and temperature change. Investors have started using climate scenarios for resilience and risk-testing to assess the impact of potential tail climate events on their portfolios. As policy and technology assumptions and architecture of climate scenarios become more realistic, more investors are employing such scenarios for mainstream investment planning and engagement with companies.

To understand differences between climate scenarios, it is essential to consider their architectures across key attributes, such as the shape of the emissions pathway, the year the scenario reaches net zero emissions, the emissions overshoot that needs addressing, and the reliance on NETs to meet carbon budgets. This has recently been explored by a PRI-commissioned paper, Pathways to Net Zero: Scenario Architecture for strategic resilience testing and planning. It sets out key parameters for climate scenarios which include the importance of NET assumptions. Table 4 in Appendix 2 summarises a subset of the key parameters for the climate scenarios considered in this paper.

Climate scenarios' underlying emissions pathways and assumptions can differ dramatically, although they may share similar temperature targets. This report considers Paris-aligned climate scenarios that limit global warming to a 1.5–2°C temperature rise by 2100. These are IPR FPS, IPCC P1–P4, NGFS Order and Disorderly, and Below 2 Degrees (B2D) and Sustainable Development Scenario (SDS) from the IEA. Figure 3 presents the CO_2 emissions pathways of the selected climate scenarios. Although IPCC P1–P4 and NGFS 1.5°C Orderly and Disorderly scenarios have the same 1.5°C temperature target with 66% probability, their CO_2 emissions pathways differ considerably (IPCC, 2018; NGFS, 2020). The selected climate scenarios reach net zero emissions by 2039 at the earliest and 2060 at the latest, a difference of two decades. Overshoot emissions in the net zero year range from 55 $GtCO_2$ to 483 $GtCO_2$, a difference that corresponds to the remaining CO_2 budget over 2018–2100 to stabilise global warming at 1.5°C with 66% probability.

Figure 3 The climate scenarios differ in their emissions pathways although they have similar temperature targets

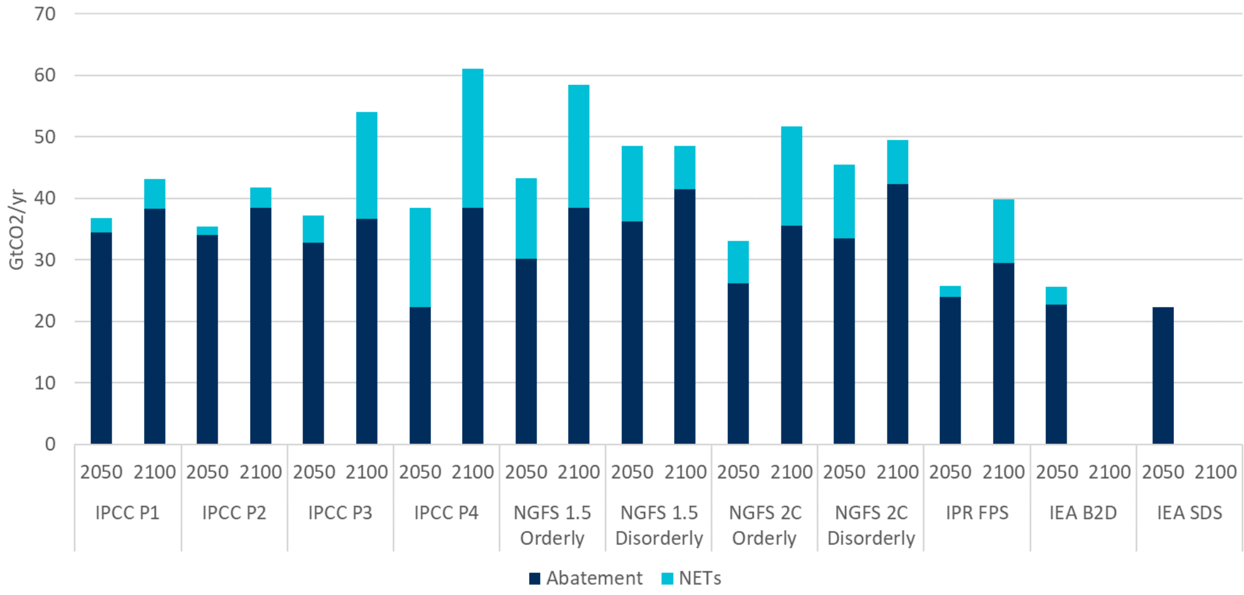


Note: The IPCC P1 scenario is presented in pink as it has the lowest overshoot in the year it reaches net zero among the IPCC P1–P4 scenarios. It is a scenario in which social, business and technological innovations result in lower energy demand while living standards rise, and its reliance on NETs is low compared with the other climate scenarios.
The NGFS 2°C scenarios are also known as the *Representative* scenarios, and the NGFS 1.5°C scenarios as the *Alternative* scenarios.

Source: Vivid Economics, using IPCC data (IAMC & IIASA, 2019), NGFS data (IIASA, 2020), IPR data (IPR, 2019b), and IEA data ('Energy Technology Perspectives 2017', no date; IEA, 2019)

Almost all climate scenarios rely on NETs to reach net zero emissions and limit global warming to 1.5–2°C, but NETs alone will not be enough to reach a well-below 2°C pathway, and decarbonisation of power, industry and transport are needed as a first measure, with NETs covering biogenic and hard-to-abate emissions. Figure 4 shows the shares of NETs and abatement in total emissions reduction for the selected scenarios. IPR FPS, which models a forceful, abrupt, and disorderly policy response to climate change by 2025 and is aligned to a 2°C pathway, shows that NETs are needed to offset biogenic GHG emissions and emissions from agriculture and fertiliser use to reach global net zero emissions. In IPR FPS, global CO_2 emissions decrease relative to 2020 by 26 $GtCO_2$/year in 2050, while the NETs share in total emissions reductions is around 7%. Climate scenarios that stabilise global warming at 1.5°C may require more negative emissions to reach their temperature targets. Regarding the IPCC P1–P4 scenarios, even the most ambitious P1 relies on NETs to sequester 2.5 $GtCO_2$/year in 2050, accounting for 7% of the total emissions reduction. As policy responses to reduce emissions are delayed, NETs will inevitably grow in importance for keeping global temperature rise to well below 2°C. In P4, total NETs emissions are 16 $GtCO_2$ with a far higher share of 42% in the total emissions reduction.

Figure 4 All climate scenarios rely on NETs to reach a well-below 2°C pathway, but abatement is also needed



Note: The abatement element shows the emissions reduction from abatement from 2020 to 2050 and 2020 to 2100. The NETs element shows total negative emissions from NBS and technical solutions in 2020 and 2050.

Source: Vivid Economics, using IPCC data (IAMC & IIASA, 2019), NGFS data (IIASA, 2020), IPR data (IPR, 2019b), and IEA data ('Energy Technology Perspectives 2017', no date; IEA, 2019)

3 Companies are committing to net zero and realise the need for NETs to decarbonise their value chains

Corporate climate action is gaining momentum. In line with the Paris-aligned climate scenarios, mounting investor pressure and changing consumer preferences are contributing to an increase in net zero commitments, particularly among heavy emitters in the oil & gas, utilities, steel, cement, and aviation sectors. Already, over half of global GDP, 2.6 billion people and a quarter of carbon emissions are covered by a national net-zero target (ECIU, 2020). Since late 2019, the number of companies committed to net zero increased by three-fold from 500 recorded in 2019 to 1,541 in 2020, while the increase for cities was eight-fold from 100 recorded in 2019 to 823 more in 2020 (UNFCCC, 2020). At Climate Week NYC 2020, 17 new companies announced science based net zero commitments, including LafargeHolcim the world's largest cement company and C.P.Group, one of Asia's leading conglomerates.

Despite the Covid-19 pandemic and the global economic slowdown, more companies are committing to climate action, and the trend is expected to persist. Since the beginning of 2020, more multinational companies have announced net zero targets by 2030–50. Since January 2020, 379 companies have committed to science-based climate action and joined the Science Based Targets initiative (SBTi) list. This increases the total number of companies that are taking science-based climate action to 1009 as of October 2020 (Science Based Targets, 2020).

Companies realise that NETs such as NBS and technical solutions – BECCS and DACCS – are needed in addition to continuing to decarbonise their value chains. While some companies plan to utilise technical solutions, such as Microsoft considering BECCS and DACCS (Smith, 2020) and British Airways' parent IAG exploring DACCS (Otley, 2020), most companies are likely to invest in NBS to offset their CO_2 emissions. Table 1 (and Table 2 in the Appendix 1) sets out how selected companies plan to deliver their net zero commitments. Column 6 presents the NETs that companies plan to utilise, while column 7 shows emissions reductions considered by companies alongside NETs. The assessment of 42 corporate net zero commitments announced over 2019–20 shows that 26 referred to NETs in their net zero commitments, and 24 of these companies refer to NBS (Vivid Economics using American University, 2020).

Table 1 Companies' net zero targets and measures to achieve them

Company	Sector	Market capitalisation	Date of announcement	Net zero year	How to achieve it	
					NETs	Other measures
Apple	Technology	US$1,821bn	July 2020	2030	• Partnership with the non-governmental organisation (NGO) Conservation International to restore mangrove trees	• Recover materials of devices returned for recycling • Solar panel projects to power data centres • Carbon-free aluminium-smelting process • Energy efficiency
P&G	Consumer products	US$325bn	June 2020	2030	• Offset or eliminate 30 $MtCO_2$ • Partner with the NGO Conservation International and WWF • Afforestation • Restore peatlands, wetlands • Protecting mangroves	• 100% renewable energy use • CCS
Shell	Oil & gas	US$116bn	April 2020	2050	• Afforestation • Reforestation	• Energy efficiency • Using lower-carbon energy products • CCS
Microsoft	Technology	US$1,540bn	January 2020	2030 (carbon negative)	• DACCS • BECCS • Soil carbon sequestration • Afforestation and reforestation	• Eliminate dependency on diesel • Internal carbon tax • 100% supply of renewable energy • Includes Scope 3 emissions

Company	Sector	Market capitalisation	Date of announcement	Net zero year	How to achieve it	
BA	Airline	US$3bn (IAG)	January 2020	2050	• Offset carbon emissions: protection of rainforests and reforestation • DACCS: Partnering with start-up that has created an innovative absorbent material to remove CO_2 emissions directly from the atmosphere	• Sustainable aviation fuel • Replacing older aircraft
Repsol	Oil & gas	US$22bn	December 2019	2050	• Reforestation • Other nature-based solutions (if goals cannot be reached via other means)	• Scaling up renewable energy portfolio • CCS • Increasing production of biofuels and chemical products with low-carbon footprints • Producing green hydrogen • Linking management pay to emission reductions • Includes Scope 3 emissions
Qantas	Airlines	US$11bn	November 2019	2050	• Carbon-offsetting activities: protecting the Great Barrier Reef, reducing wildfires in Australia and securing 7,000 ha of Tasmanian forest	• Develop sustainable aviation fuels • More fuel-efficient aircraft
Amazon	E-commerce	US$1,586bn	September 2019	2040	• Reforestation	• Electric delivery vehicles • Use of renewable energy • Reduced packaging

Source: Vivid Economics using information from company announcements and press releases (Qantas, 2019; UN PRI, 2019; British Airways, 2019; IKEA, 2019; Nestlé, 2019; Amazon, 2020a; Ambrose, 2020; Shell, 2020a; Total, 2020; Apple, 2020; Bass, 2020; Casey, 2020; Environment & Energy Leader, 2020; Evans, 2020).

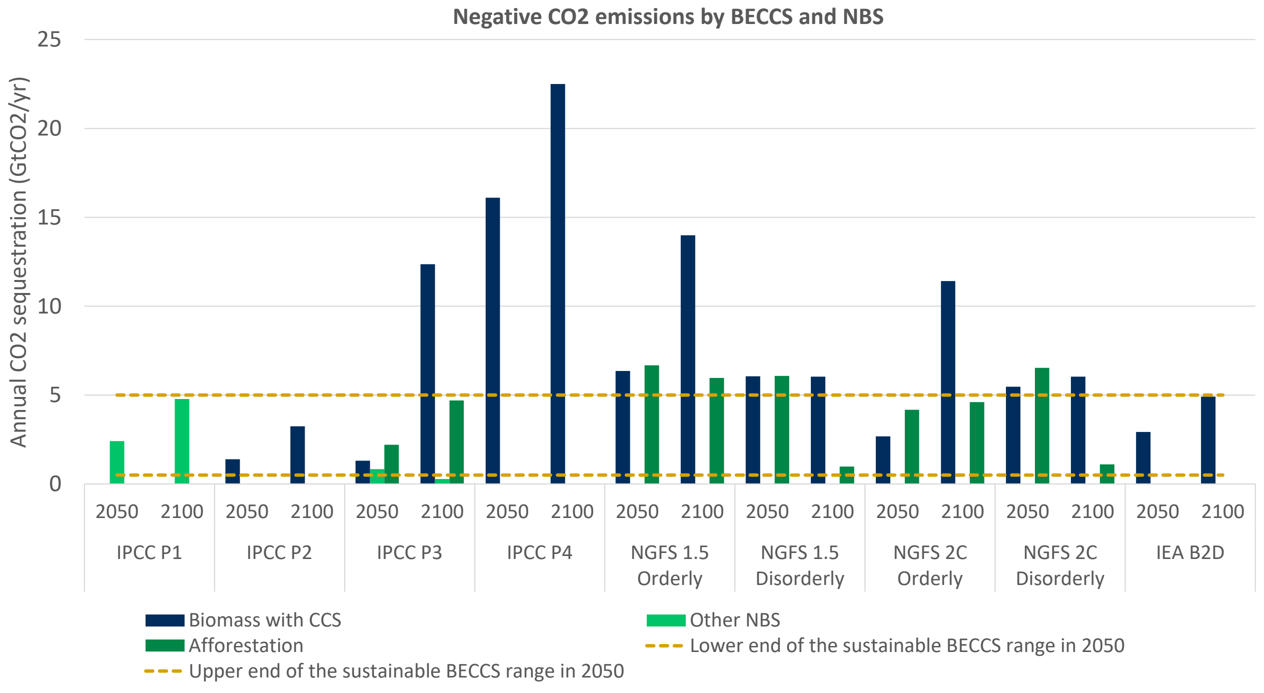
4 Climate scenarios rely largely on BECCS, but it is unlikely to deliver projected negative emissions

In almost all Paris-aligned climate scenarios, BECCS is the leading NET as it offers double gains through energy generation and CO_2 sequestration. The climate scenarios utilise BECCS, afforestation, and other NBS for negative emissions but at different levels. Figure 5 presents annual CO_2 emissions removed from the atmosphere by these three NETs in 2050 and 2100 for the selected climate scenarios. IPR FPS uses realistic assumptions about sustainable deployment of the NETs. BECCS accounts for only 0.8 $GtCO_2$/year by 2050 but rises to 8 $GtCO_2$/year by 2100, increasing its share from 40% to 80% of the total negative emissions. Regarding the IPCC scenarios, at one extreme, P1 and P2 act early in abatement and do not significantly overshoot their carbon budget. That is why, in these scenarios negative emissions do not reach 5 $GtCO_2$/year by 2100. At the other extreme, IPCC P4 acts late to reduce emissions and relies only on BECCS to chip away at the emissions overshoot. Negative emissions by BECCS exceed 16 $GtCO_2$/year by mid-century, corresponding to around half of today's CO_2 emissions from combustion of fossil fuels. IPCC P3 and the NGFS scenarios lie between these two extremes and utilise BECCS and NBS – i.e. afforestation and other NBS. These scenarios deploy BECCS and NBS at comparable levels by 2050, but negative emissions from BECCS surpass negative emissions from afforestation and other NBS by the end of the century.

BECCS' contribution to cumulative negative CO_2 emissions is significant. In IPR FPS, cumulative BECCS is 1.3 $GtCO_2$ in 2050, growing to 54.5 $GtCO_2$ in 2100, which is much lower compared with the IPCC scenarios. Cumulative BECCS until 2100 in the IPCC scenarios ranges from 151 $GtCO_2$ in IPCC P2 – which has an incredibly ambitious decarbonisation pathway, halving emissions from 37 $GtCO_2$ to 19 $GtCO_2$ between 2020 and 2030 – to 1,191 $GtCO_2$ in IPCC P4. In IPCC P4, 724 Mha of land, corresponding to more than half of the world's arable land – about 15% of all agricultural land – today, would need to be covered by bioenergy crops by mid-century.[8]

[8] Arable land is only about 30% of all agricultural land, while the rest is pasture land (FAO, 2020).

Figure 5 The deployment of BECCS and NBS varies across the climate scenarios



Note: Other NBS are NBS excluding afforestation.
The dotted lines show the lower and upper ranges of annual CO_2 removal potential of BECCS from Fuss et al. (2018).
IEA B2D reports only CO_2 emissions from fuel combustion for energy and heat generation, whereas the IPCC and NGFS scenarios report combustion and process CO_2 emissions.
The NGFS 2°C scenarios are also known as the *Representative* scenarios and the NGFS 1.5°C scenarios as the *Alternative* scenarios.
IEA SDS does not include NETs.

Source: Vivid Economics, using IPCC data (IAMC & IIASA, 2019), NGFS data (IIASA, 2020), IPR data (IPR, 2019b), and IEA data ('Energy Technology Perspectives 2017', no date)

The reliance of the climate scenarios on BECCS is an issue as large-scale deployment of BECCS is likely to push the world to its planetary boundaries in terms of water and land availability, threatening biodiversity and fuelling social tensions. BECCS requires large areas of land and could lead to deforestation and conversion of protected areas to plantations. Biomass plantations could replace food production and lower food supply, thereby increasing food prices. While plantations and BECCS power plants would increase water demand, water pollution from fertiliser use could affect supplies. Pressure on water and land could threaten the biodiversity depending on these resources. As regards land tenure, large bioenergy producers may outcompete small farmers, forcing them to sell their land to the former. Food price inflation and pressure on land tenure are likely to impact the most vulnerable groups that rely on agriculture for income and spend a large share of their income on food, raising concerns about a just transition to a low-carbon economy (FAO, 2010). These negative impacts require limiting the use of BECCS to a sustainable level.

When deployed at a sustainable scale, BECCS is likely to fall short of delivering the negative emissions projected by most of the climate scenarios. Fuss et al. (2018) estimate that the CO_2 removal potential of sustainable BECCS could range from 0.5 $GtCO_2$/year to 5 $GtCO_2$/year in 2050, as shown by the dashed lines in Figure 5 above. Reid et al. (2019) argue that the yearly CO_2 removal potential of sustainable BECCS could decline in the second half of the century as competition for land intensifies due to population growth and the transferral of biomass production from land that has become arid to more fertile land, exacerbating the gap between the projections of the climate scenarios and the CO_2 removal potential of sustainable BECCS.

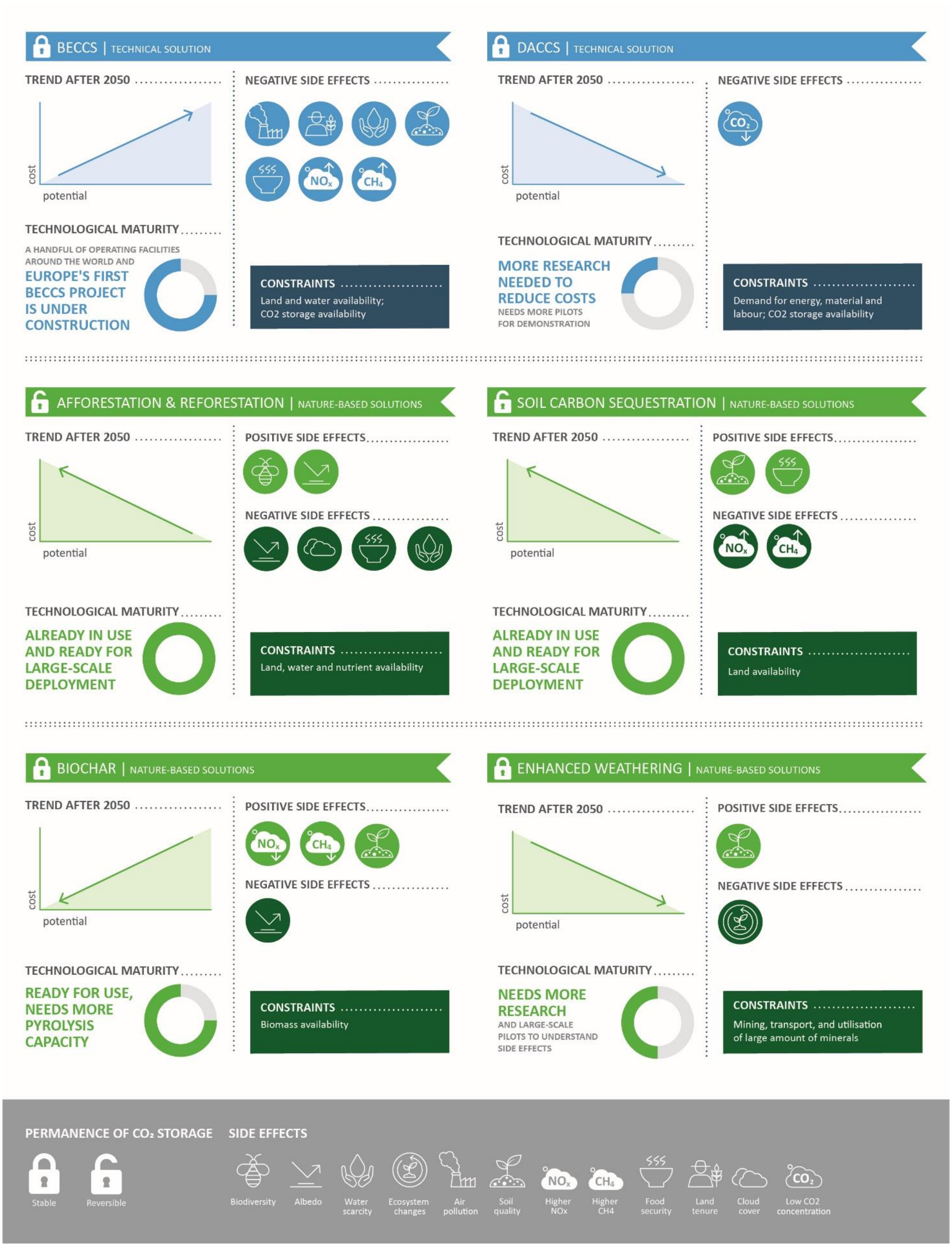
5 A portfolio of NETs with immediate forestry action is required to limit global warming at 1.5–2°C

BECCS needs to be combined with other NETs to deliver negative emissions projected by the climate scenarios because its CO_2 removal potential is limited when deployed at a sustainable level. This section considers six NETs that are widely cited and have potential to deliver significant negative emissions by 2050. These are BECCS, DACCS, re/afforestation, soil carbon sequestration, biochar, and enhanced weathering.

The literature has diverging views on NETs because their scalability is untested and some of them are still in their infancy. Appendix 3 – NETs synthesises findings from literature focusing on the criteria required for feasibility and scalability of these technologies: (i) functional mechanism; (ii) technological maturity; (iii) global CO_2 removal potential; (iv) cost; (v) permanence of CO_2 storage; (vi) constraints; and (vii) potential side effects. Appendix 4 – Feasibility of NETsprovides a comparison of the selected NETs based on the review criteria. Information on the review criteria is compiled from Fuss et al. (Fuss *et al.*, 2018), which reviews and synthesises the recent literature on NETs and is widely recognised and cited, and is adjusted to reflect recent research where available (Griscom *et al.*, 2017; EASAC, 2018, 2019; Fajardy *et al.*, 2019; Reid, Ali and Field, 2019).

Deploying each NET at scale may cause significant negative impacts on the planet, biodiversity, and society. Figure 5 presents positive and negative side effects of the selected NETs discussed in the literature. In term of technical solutions, BECCS may have a number of negative side effects, such as high land and water demand putting pressure on biodiversity and food security, while the negative effects of DACCS are negligible. NBS also have negative side effects, such as water and chemical pollution from fertiliser use, and changes in albedo and cloud cover; however, sustainably managed NBS projects have positive side effects, such as improved soil quality and biodiversity, which are significantly greater in magnitude than the negatives. Most of these positive benefits are externalities, and the development of financial instruments is required in order to monetise these externalities and compensate private parties for action taken which leads to substantial social benefit. Appendix 3 – NETs provides more detail on the positive and negative side effects of the selected NETs.

Figure 6 Each NET has its own characteristics in terms of technological maturity, side effects, constraints, and future cost and carbon removal potential trends

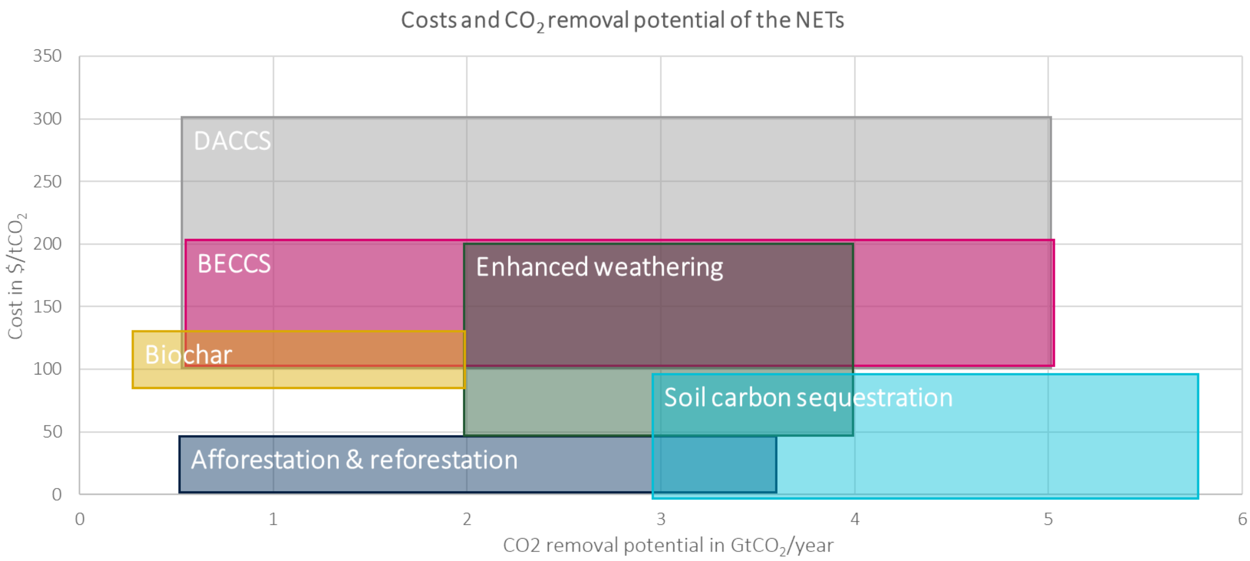


Note: N_2O, nitrous oxide; CH_4, methane.

Source: Vivid Economics, based on Minx et al. (2018)

High uncertainty associated with costs and CO_2 removal potential exacerbates risks and other uncertainties around the NETs. Figure 7 presents the wide ranges for costs and CO_2 removal potential of the selected NETs (Fuss *et al.*, 2018). These are largely due to most of the NETs not yet being tested at scale. More research and demonstration projects are needed to understand the constraints and side effects associated with these technologies. Moreover, as stated in Geden and Schenuit (2020), adoption of the technologies across the globe may depend on criteria other than costs, CO_2 removal potential and side effects, such as geographic conditions (particularly for storage) and local politics, thereby adding to uncertainty.

Figure 7 Afforestation and reforestation, and soil carbon sequestration have the lowest costs among the NETs



Source: Vivid Economics, based on Fuss et al. (2018)

A portfolio of NETs deployed at a sustainable scale could help to meet net zero targets. As shown in Figure 6 and Figure 7, all NETs have considerable uncertainties around their CO_2 removal potential and costs, and deploying them at large scale may cause significant negative impacts on biodiversity and society. Deploying a portfolio of multiple NETs at a sustainable scale would provide a hedge and limit exposure to the uncertainties and negative impacts associated with a large-scale application of each NET.

Investors can reap gains from NBS in the short term, especially by avoiding emissions from deforestation while investing in sequestering emissions from re/afforestation in the short-term. Afforestation and reforestation are the least costly NETs, as shown in Figure 6. The approach is already widely applied, and it can be immediately extended to larger areas of land. Deforestation continues to release significant amounts of CO_2 into the atmosphere. From 2011 to 2015 net forest conversion added 2.9 $GtCO_2$ per year to the atmosphere(Federici *et al.*, 2015). Reversing deforestation now would stop these emissions, and retained forest would serve as a carbon sink and continue to sequester CO_2 from the atmosphere. Re/afforestation need to start now because forests take time to grow and reach their CO_2 removal potential. As forests get saturated and their CO_2 removal potential decreases over time, they could be harvested and replanted to sequester additional CO_2. Harvested material could be used in construction or as fuel for BECCS to store CO_2 permanently. Investing in forest-related NBS would also decrease overshoot emissions and exposure to risky NETs in the long term.

In the long term, technology-focused NETs, such as DACCS, could be economically viable alternatives to BECCS by mid-century as their costs are falling – if investors and corporates channel funds towards further research and deployment (Fuss *et al.*, 2018; Realmonte *et al.*, 2019).[9] However, more research and

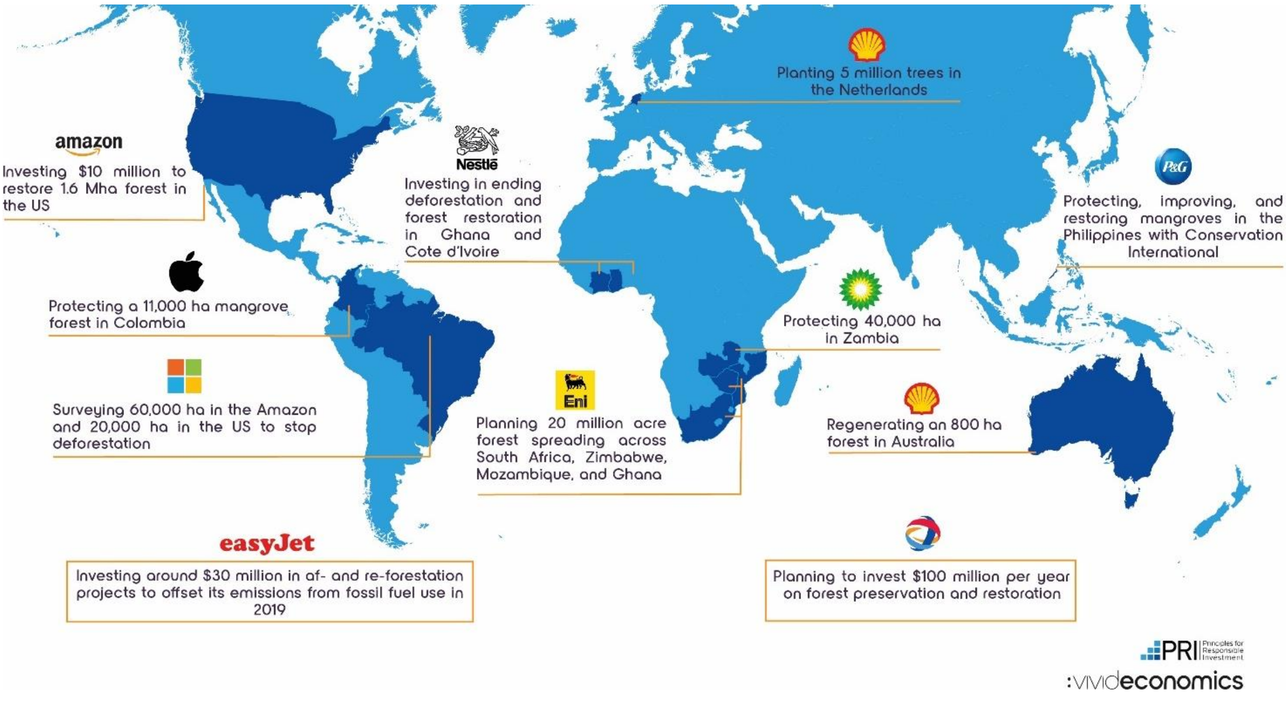
[9] We do not discuss DACCS in detail in this report but will be producing a separate study.

development and pilot projects, alongside financial incentives, are needed to reduce costs of these technologies further and assess their side effects and scalability.

6 Companies and investors have already started to invest in forest-related NBS projects

Companies have already started to channel their resources towards forest-related NBS projects. As shown in Table 1, while some companies plan to utilise technical solutions, such as Microsoft considering BECCS and DACCS (Smith, 2020) and British Airways' parent IAG exploring DACCS (Otley, 2020), more companies, such as O&G, technology and retail majores, are likely to invest in NBS to offset their CO_2 emissions – see Figure 8. Shell forecasts that roughly a quarter of emissions reductions to reach net zero will come from natural sinks and has started to invest in forest-related projects, such as the planting of 5 million trees in the Netherlands and regenerating an 800 ha forest in Australia (Shell, 2019, 2020b). BP is currently running seven offset programmes, one of which is focused on forestry, protecting 40,000 ha in Zambia. Total is committed to investing US$100 million per year in forest protection (IOM3, 2019; BP, 2020). Technology companies are also pursuing similar projects. Apple is protecting an 11,000 ha mangrove forest in Colombia, and Microsoft is partnering with a start-up that uses satellite imaging to identify the appropriate forest projects (Peters, 2019; Catanoso, 2020). Microsoft will finance the identified projects by paying US$15/t$CO_2$ for CO_2 stored – higher than the global average of $10/t$CO_2$ (Catanoso, 2020). Amazon has launched the Right Now Climate Fund, investing US$100 million in NBS. The first project of $10 million was announced in April 2020, to restore and conserve 1.6 Mha forest in the US, removing 18 million MtCO_2 from the atmosphere (Amazon, 2020b). EasyJet claims to have offset all of its emissions from fossil fuel use in 2019, investing more than US$30 million in afforestation and reforestation projects (Ecosystem Marketplace, 2019a).

Figure 8 Companies have already started to channel their resources to forest-related NBS projects



Source: Vivid Economics

The flurry of corporate climate action has boosted the voluntary offset market, and the upward trend is expected to continue. The voluntary offset market represents 65% of the total number of annual carbon credits issued in 2019 – an almost fourfold increase from 17% in 2015 – and outnumbers the mandatory offset market (World Bank, 2020). From 2017 to 2018, the voluntary offset market doubled in volume from approximately 50 million to 100 million offsets, and in value from US$150 million to $300 million (Gross, Hook and Powley, 2019b). In 2019, Verra, a carbon credit standard, issued around 100 million voluntary carbon credits, over twice the amount issued previously in a single year (Verra, 2020b). This upward trend is expected to continue. A 2020 analysis of 38 large global companies, including major corporations such as Shell, Bosch and EasyJet, reported that these companies had pledged to offset around 90 $MtCO_2e$ per year, 50% higher than the total volume traded in the market in 2016 (EcoSecurities, 2020). By 2050, the value of the global voluntary offset market could reach US$200 billion, increasing by around a quarter every year (Watson, 2020).

There is a shift to NBS within the offset market as most corporate net zero targets rely on NBS projects to offset their emissions. From 2017 to 2018, the value of forestry and land-use-related credits traded in the voluntary offset market tripled to US$172 million, increasing the share of forestry and land-use-related offsets in the total voluntary offset market from 52% to 64% (Ecosystem Marketplace, 2019b). In the wider offset market, forestry-related projects accounted for 42% of the all credits issued over the past five years ('State and Trends of Carbon Pricing 2020', 2020).[10] As forestry projects facilitate the growth of the offset market, this market could provide an enabling platform encouraging the scaling of NBS (Henderson *et al.*, 2020).

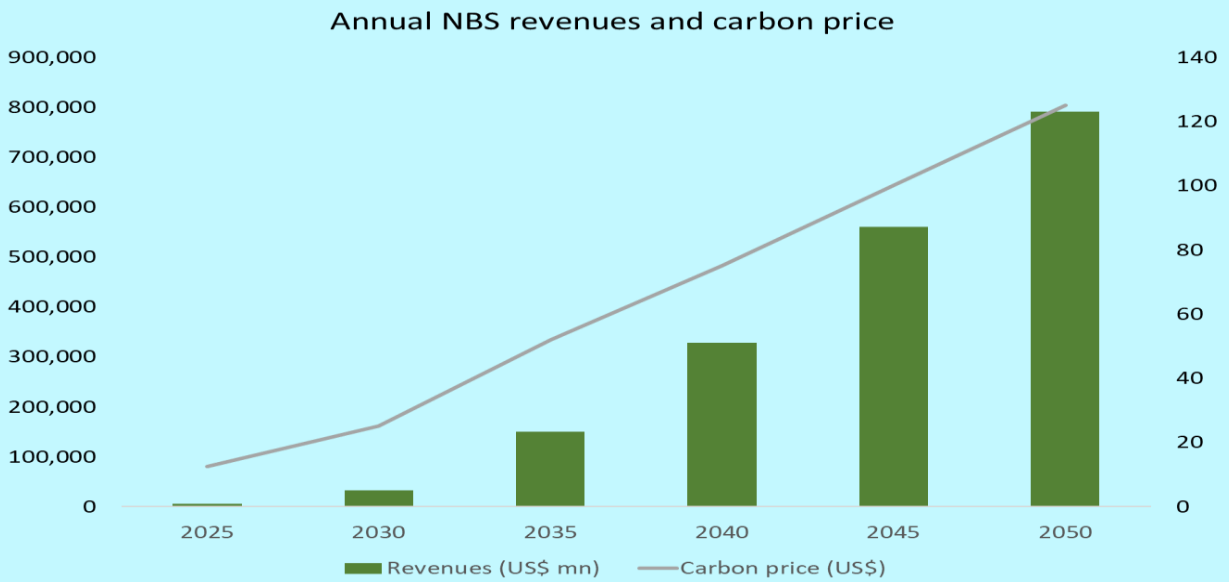
[10] The wider offset market encompasses three types of market: international; independent; and regional, national and subnational mechanisms.

7 Investors can act now to unlock investment opportunities

NETs are the next investment frontier and offer trillion dollar upside opportunities for investors.[11] Within NETs, forest-related NBS could generate US$800 billion in annual revenues by 2050. From today's vantage point, emerging NBS investments are worth US$1.2 trillion in NPV terms (see Box 1), surpassing the current market capitalisation of the oil & gas majors.[12] Hence an entire new industry would emerge that values carbon stored in vegetation and soil, unlocking new business models and investment opportunities for avoided deforestation, reforestation and afforestation (hereinafter re/afforestation), and land restoration. Thanks to its low cost, natural forest restoration looks likely to emerge as the earliest feasible investment opportunity. Technical solutions, such as DACCS and BECCS, could generate an additional annual revenue of US$625 billion by 2050.[13]

Box 1 **The size of the investor opportunity in NBS**

To estimate the feasible size of the investor opportunity in NBS we created a very simple cash flow model to represent the global NBS market. First, we estimated the possible revenue growth of the market over time by using the IPR Forecast Policy Scenario's forward assessment of the number of hectares of reforestation globally, the amount of carbon sequestered, the possible carbon price they would secure, and small ancillary revenues from sustainable forest management. Revenues associated with NBS are driven strongly by the expected carbon price (see graph).



In order to generate estimates of returns (or cashflows), we also need to estimate costs – land, capital, and operational costs. These cashflows then need to be discounted to generate an estimate of the possible NPV of these investments (roughly equivalent to market capitalisation). These will vary significantly by location and need estimating on that basis – global high level averages would be misleading for any single project but can provide an indicative number for investors.

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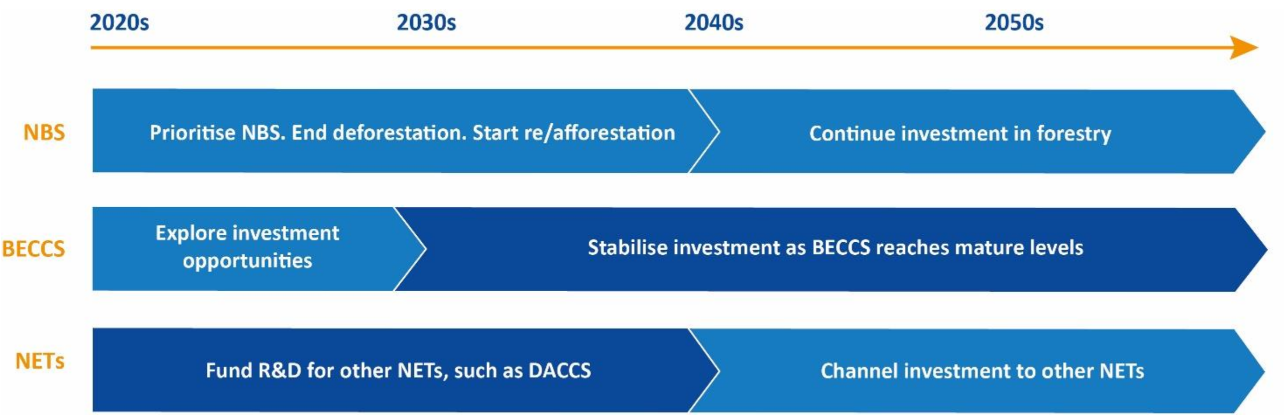
[11] Also known as carbon dioxide removal (CDR). NETs are technical solutions and Nature Based Solutions (NBS) that sequester carbon from the atmosphere.
[12] As of June 2020. Oil & gas majors include BP, Chevron, China National Offshore Oil, ConoccoPhilips, Enterprise Product Partners, EOG Resources, ExxonMobil, Kinder Morgan, Occidental Petroleum, Petrobas, PetroChina Company, Santos, Schlumberger, Sinopec, Suncor Energy, and Total.
[13] The annual revenue is estimated for annual CO_2 sequestration of 5 $GtCO_2$/year at a cost of US$125 per tCO_2 and considers only revenue from sequestered CO_2 emissions.

We used a 9% discount rate, which is consistent with discount rates used in the past for the valuation of forest projects,[14] and estimated an indicative set of costs based on existing sources for reforestation projects.[15] Based on this analysis, we estimate a possible NPV of NBS investments of US$1.2 trillion, with an internal rate of return of 18%. These NPV calculations are very rough, and subject to a number of uncertainties, especially around the price of land, the actual price of carbon secured, and the appropriate discount rate given the possible risk levels associated with these investments in different markets. Nevertheless, they provide an early indication to investors of the possible scale of asset value represented by the NBS opportunity.

Given the advantages of forestry over other NETs, investors can prioritise NBS in the short term and monitor developments regarding technical solutions, such as DACCS, for investment opportunities in longer term. Section 5 demonstrated that re/afforestation are the least costly among the NETs. The approach, already widely applied, could be immediately extended to larger areas of land. DACCS and other NETs could become economically viable alternatives in the longer term, but, as discussed, there are significant uncertainties and risks around their costs and CO_2 removal potential. More research and demonstration projects are needed to lower costs and test the large-scale deployment of these technologies.

Figure 9 In the nearterm, NBS and particularly forestry provide investment opportunities while focusing on RD&D for other NETs and deploy a feasible amount of BECCS in the long run



Source: Vivid Economics

The credibility of re/afforestation projects depends on strong regulation to end deforestation. To mitigate climate change, the total forest-covered area needs to increase significantly over the coming years. If re/afforestation projects fail to turn out a, at least regionally, net-gain in forestry cover, their benefits may be questioned, undermining forestry business models and threatening credibility carbon credits for forestry projects. As mentioned below, there are ways of addressing the credibility issue, such as focusing on jurisdictional programmes and promoting a global standard fror NBS, including standards such as the Architecture for REDD+ Transactions' (ART) The REDD+ Environmental Excellence Standard (TREES), but ending deforestation remains a key factor for credibility.

To unlock investment opportunities, investors need to:

- **Pressure companies to commit to climate action.** Various investor initiatives encourage large companies to reduce emissions and strengthen climate-related financial disclosures. Urging companies to commit to climate action would decrease investor exposure to carbon-intensive

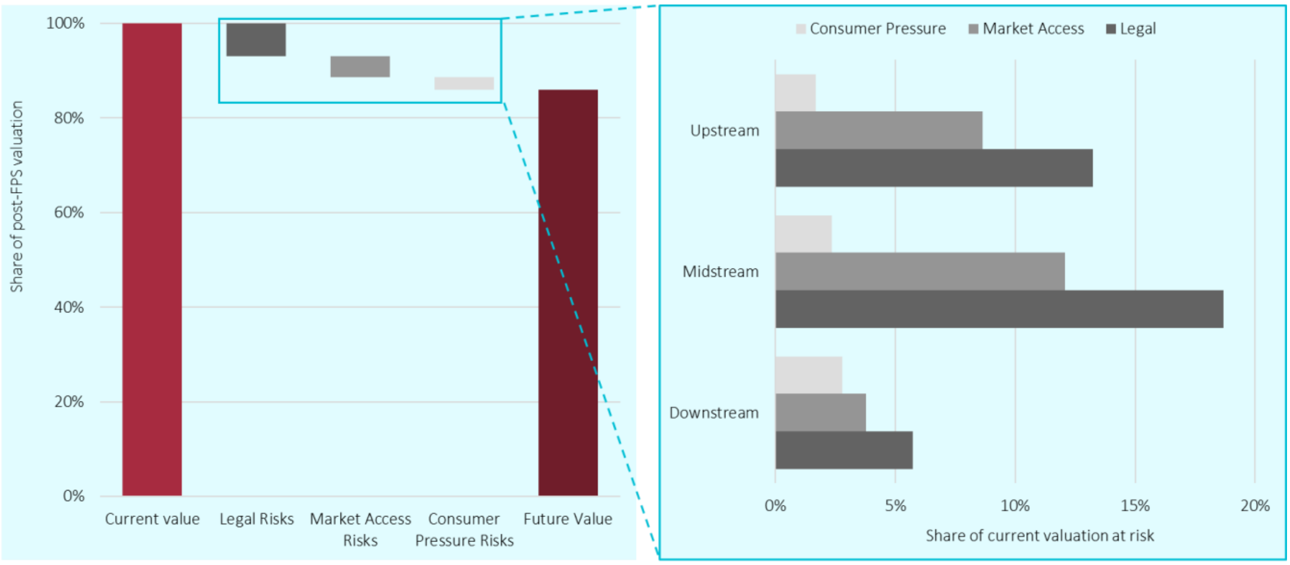
[14] See Bullard, S. H. and Straka (2011); and Ferguson (2018).

[15] For example Summers, D., Bryan, B., Martin, N. and Hobbs (2015); and Zorrilla-Miras, P., Marcos, C., Mulligan, M., Giordano, R., Graveline, N., Máñez-Costa, M., Pengal, P., van der Keur, P., Altamirano, M., Matthews, J. and Lopez-Gunn (2018).

markets. It would also increase the demand for NBS and other NETs projects, facilitating these technologies and supporting their markets, as many companies are likely to rely on NBS and other NETs to offset their emissions. As discussed in Section 3, since January 2020, 379 companies have committed to science-based climate action and joined the SBTi list, increasing the number of companies that are taking science-based climate action to 1009 as of October 2020 (Science Based Targets, 2020), and companies have already started to channel their resources towards forest-related NBS projects, creating a new market for forestry. Last but not least, investors need to pressure companies to commit to using deforestation-free supply chains.

- **Stop investing in companies with deforestation in their supply chain.** Deforestation is a major contributor to global warming. From 2011 to 2015 net forest conversion added 2.9 $GtCO_2$ per year to the atmosphere (Federici *et al.*, 2015). Companies with deforestation in their supply chain expose investors to significant financial risk in terms of potential regulatory action, loss of market access, loss of customers in the short term, and failing to adapt to the transition to a low-carbon economy in the longer term (Ceres, 2020). As shown in Figure 10, risks associated with legal action, market access, and consumer pressure could decrease a company's valuation by around 15%.

Figure 10 Deforestation across a company's supply chain jeopardises its valuation



Note: Case studies from the Chain Reaction Research and Ceres provided information on maximum threshold for consumer pressure, market access and legal risks as a share of current valuation.

Source: IPR (2019a)

- **Move early in the rapidly growing NBS market.** Investors should develop innovative business models, financing mechanisms (as listed below) and expertise to position themselves in an emerging market so they can benefit from a potential large green upside. A way to channel private finance to NBS projects could be through large agricultural and forestry companies, specialist funds that focus on NBS projects, and local agricultural and forestry lenders. Some emissions-heavy companies can also provide exposure to forestry projects as they plan to invest in these to offset their emissions.

- **Support NBS market and institutional development by engaging with policymakers.** Investors can shape the design of the expanding NBS market to suit the needs of private financing. In the short term, this could involve developing new financial models with the government through concessional finance, re-risking activities that transfer risk from investors to government or development banks, and providing technical assistance. Investors could also promote the adoption of carbon pricing as it would provide NBS projects with a sustained return and a price signal for future projects.

- **Promote a global standard for NBS projects.** The current offset market is fragmented due to the variety of available standards. A lack of consensus about accounting of sequestered emissions causes complexity, incurs expenses and creates risks for investors, thus discouraging investment in forest-based carbon sequestration projects (Wise *et al.*, 2019). A global standard for NBS projects, such as the Architecture for REDD+ Transactions (ART) and The REDD+ Environmental Excellence Standard (TREES), and a carbon credit ESG rating could align existing standards and ensure additionality and permanence of CO_2 savings while avoiding double counting and leakage. It could therefore help to achieve a global agreement on accounting standards, addressing a major failure that has hindered progress of REDD+ and re/afforestation (Carton *et al.*, 2020). It could also help to create a global market for NBS projects and allow them to benefit from a large pool of global investors, decreasing financing costs and improving liquidity.

- **Promote sustainability standards for BECCS.** A sustainability standard could ensure that low-carbon agricultural and sustainable land-use practices are deployed in biomass production that limit emissions from supply chains and land-use change. It would also ensure that land and water resources are deployed at a sustainable level, thus protecting biodiversity. This would address stakeholder concerns and possible opposition to BECCS projects and hence accelerate the scale-up of finance dedicated to these.

- **Monitor developments in the DACCS space.** DACCS may emerge as the key NET in the medium term. The technology has no known negative side effects and does not put pressure on land and water resources, ecosystems, or biodiversity. However, due to the low CO_2 concentration in the atmosphere its energy consumption is too high, inflating its costs. More research and demonstration projects may address these challenges, making it a viable option for removing CO_2 emissions from the atmosphere.

New financing mechanisms are emerging that would allow private investors to channel finance towards forest-related NBS projects. As carbon markets extend their geographical coverage and incorporate NBS, more revenue streams will be unlocked from forest-related projects. Consequently, market-based mechanisms will be developed to manage these revenue streams, and the forest finance market will deepen in terms of volume and the number of players. These developments are expected to facilitate much-needed private investment in forest finance. Examples for emerging financing mechanisms are:

- **Distressed asset**, where investors purchase and restore deforested or degraded public and private land to benefit from the carbon stock it produces, with the potential to sell the land on to other investors or to the government for conservation purposes. Restoration can be implemented by a land management company contracted by the investor.

- **Stewardship model**, where an investor leases deforested or degraded land without an ownership change, and the leaseholder receives the benefits flowing from the carbon stock associated with restorative management before returning it to the previous owner. Restoration can be implemented by a land management company contracted by the investor.

- **Carbon farming agreements**, where an investor supports the ‘farming’ of carbon through forest growth by providing the land manager with financing for the initial land purchase and planting costs. In return, the investor receives payments tied to the carbon stock increases. Such a model can be used to finance large land holders or cooperatives of smallholders, reducing the risk to those cooperatives while simultaneously reducing the administrative burden on investors.

- **Sustainable farming agreements**, where an investor supports traditional crop farming practices that reduce emissions or sequester carbon (e.g. in soils) by financing farmers’ land or capital cost. Investors receive payments when the carbon-reduction certificates are created and sold on the market. This too can be used to finance large farmers or cooperatives of small farmers.

- Green bonds, where investors can purchase securitised forest sequestration and carbon-reduction projects. This can allow investors to take stakes in projects already developed by others, and they can be used to aggregate projects that are of insufficient scale for investors, or that are developed by a government or NGO.
- Forest insurance provision, a disaster insurance against carbon losses from extreme weather, disease, or forest fires, which can improve carbon credit ratings and allow for risk sharing. This financing mechanism is currently provided predominantly through public funds, but presents an increasingly viable business for private insurers as the market grows.
- Carbon off-taker guarantees, financial instruments guarantee a future price for carbon credits, reducing carbon price volatility and risk for developers. Like insurance, they allow for risk sharing, and can be underwritten by public or private financial institutions.

Appendix 1 – Corporate net zero announcements

Table 2 Companies' net zero targets and measures to achieve them

Company	Sector	Market capitalisation	Date of announcement	Net zero year	How to achieve it	
					NETs	Other measures
BCG	Business services	US$8.5bn (revenue)	September 2020	2030	• Nature-based and engineered solutions at an annual average of $80 per tonne by 2030	• Renewable energy • Energy efficiency
Total	Oil & gas	US$98bn	May 2020	2050	No evidence	• Reducing carbon intensity of products
BP	Oil & gas	US$73bn	February 2020	2050	• Nature-based solutions: protecting, restoring and creating natural sinks, such as peatland and forests	• Reducing carbon intensity of products • Methane measurements • Reducing methane intensity
Nestlé	Consumer products	US$310bn	September 2019	2050	• Reforestation • Soil carbon sequestration: collaborate with farmers to restore land	• Produce more environmentally friendly products • Use 100% renewable electricity
Ikea	Consumer products	US$19.5bn	September 2019	2030	• Afforestation • Reforestation • Explore ways to remove CO_2 and store it in forests, agriculture and products	• Improve energy efficiency • 100% renewable energy use • More sustainable materials
Thyssen-Krupp	Steel	US$7bn	July 2019	2050	No evidence	• Capturing emissions from steel mills and converting them into chemicals • Replacing coal with hydrogen
Heidelberg Cement	Cement	US$13bn	May 2019	2050	• CCS: develop new technologies for CO_2 sequestration in the cement-making process	• Improve energy efficiency • Increase use of alternative fuels and raw materials

Source: Vivid Economics, using (Nestlé, 2019; Qantas, 2019; UN PRI, 2019; British Airways, 2019; IKEA, 2019; Amazon, 2020a; Ambrose, 2020; Shell, 2020a; Total, 2020; Apple, 2020; Bass, 2020; BCG, 2020; Casey, 2020; Environment & Energy Leader, 2020; Evans, 2020)

Appendix 2 – Climate scenarios

Climate scenarios rely on different assumptions and architecture, and they can be compared for investor purposes when assessing a range of metrics. The PRI-commissioned paper Pathways to Net Zero: Scenario Architecture for strategic resilience testing and planning sets out the key metrics that determine climate scenario characteristics. Table 3 presents a subset of these metrics. Scenario characteristics are crucial for understanding the ambitions and pathways of each climate scenario, as well as the financial impact, and can be used by investors for portfolio construction.

Table 3 Metrics and descriptions used to compare climate pathway scenarios

Metrics	Description
Target temperature (°C)	This describes the temperature above pre-industrial levels with which the scenario is consistent. In most cases this is a constraint reflected in the carbon budget and therefore the pathway.
Probability (%)	This is the probability of achieving a particular temperature outcome. It is a critical datapoint, as the uncertainties within climate science lead to wide ranges of outcomes that can be presented only in probabilistic ways.
Carbon budget over 2018–2100 ($GtCO_2$)	This is the remaining amount of carbon that can be emitted to fulfil a specific temperature and probability combination.
Emission peak year	The year in which CO_2 emissions peak.
Carbon budget is reached (year)	The year when the carbon budget modelled is first exceeded starting from 2018.
Temperature return year	The year when the temperature again falls to, for example, 1.5°. The scenario is unlikely to be at net zero at this point; it will most likely be net negative.
Net zero year	The year in which the scenario has zero net emissions, which means that any residual direct emissions are offset by Carbon Dioxide Removal (CDR) (e.g. CCS, NETS including BECCS).
Overshoot at the net zero year ($GtCO_2$)	The amount of emissions in excess of the carbon budget (potentially driving a temperature overshoot) as at the net zero year.
Emissions reduction in the modelled end year relative to 2018 (%)	This is the percentage reduction in emissions highlighted in the scenario at its end year measured against 2018.

Source: Fulton (2020)

Looking at a number of these metrics highlights the differences in scenario architecture, and particularly the role that NETs play in climate scenarios. Table 4 shows the assessment of each of the selected climate scenarios against the metrics presented in Table 3, and helps investors to compare the different scenario pathways, observe the role of NETs within each, and understand the risks and opportunities to inform business and portfolio planning.

Table 4 Pathway scenario comparison

Organisation	IPCC				IEA		NGFS				IPR
Scenario/Metric	P1	P2	P3	P4	SDS	ETP B2Ds	Orderly	Disorderly	Orderly	Disorderly	FPS
Target temperature (°C)	1.5	1.5	1.5	1.5	1.8	1.75	2	2	1.5	1.5	Below 2
Probability (%)	66	66	66	66	66	50	66	66	66	66	-
Carbon budget over 2018–2100 ($GtCO_2$)	420	420	420	420	880[1]	720[2]	1,000[3]	1,000[3]	400[3]	400[3]	-
Emissions peak (year)	2020	2020	2020	2020	2025	2025	2020	2020	2020	2020	2025
Carbon budget is reached (year)	2033	2033	2030	2028	No overshoot	No overshoot	No overshoot	No overshoot	2028	2030	-
Temperature return (year)	2059	2053	2074	2084	-	-	-	-	2076	2053	-
Net zero year	2060	2055	2058	2051	2070	2060	2064	2050	2050	2039	-
Overshoot at the net zero year ($GtCO_2$)	144	145	271	483	No overshoot	No overshoot	No overshoot	No overshoot	279	55	-
Emissions reduction in the modelled end year relative to 2018 (%)	109	112	132	155	53	100	121	111	137	114	98
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1,218	-	225 (until 2060)	698	461	834	547	-
of which BECCS until 2100 ($GtCO_2$)	0	151	414	1,191		72 (until 2060)	428	343	632	417	257

Organisation	IPCC				IEA		NGFS				IPR
Land area of bioenergy crops in 2050 (Mha)	22	93	283	724	-	-	-	-	-	-	-
Land area of bioenergy crops in 2100 (Mha)	158	154	750	802	-	-	-	-	-	-	-
AFOLU CO_2 emissions in 2100 ($GtCO_2$)	-4,343	-3,614	-4,162	-1,201	-	-	-4,182	-1,078	-5,232	-966	-1,663
Change in AFOLU CO_2 emissions in 2100 relative to 2010 (%)	-181	-178	-158	-129	-	-	-179	-120	-198	-117	-150
AFOLU N_2O emissions in 2100 (kt N_2O/yr)	6,116	4,243	4,007	8,915	-	-	7,099	6,013	7,286	5,942	3,117 (in $MtCO_2$/yr)
Change in AFOLU N_2O emissions in 2100 relative to 2010 (%)	-5	-37	-38	-14	-	-	-12	-25	-10	-26	8
AFOLU CH_4 emissions in 2100 (Mt CH_4/yr)	78	41	69	110	-	-	135	134	135	132	3,993 (in $MtCO_2$/yr)
Change in AFOLU CH_4 emissions in 2100 relative to 2010 (%)	-48	-77	-54	-36	-	-	-26	-26	-26	-27	-27

Note: [1] From Dalman (2020), and until 2070. [2] The 2015–2100 carbon budget (‘Energy Technology Perspectives 2017’, no date). [3] The 2011–2100 carbon budget (NGFS, 2020). AFOLU, agriculture, forestry and other land use.

Source: Vivid Economics, using IPCCS, NGFS, and IEA

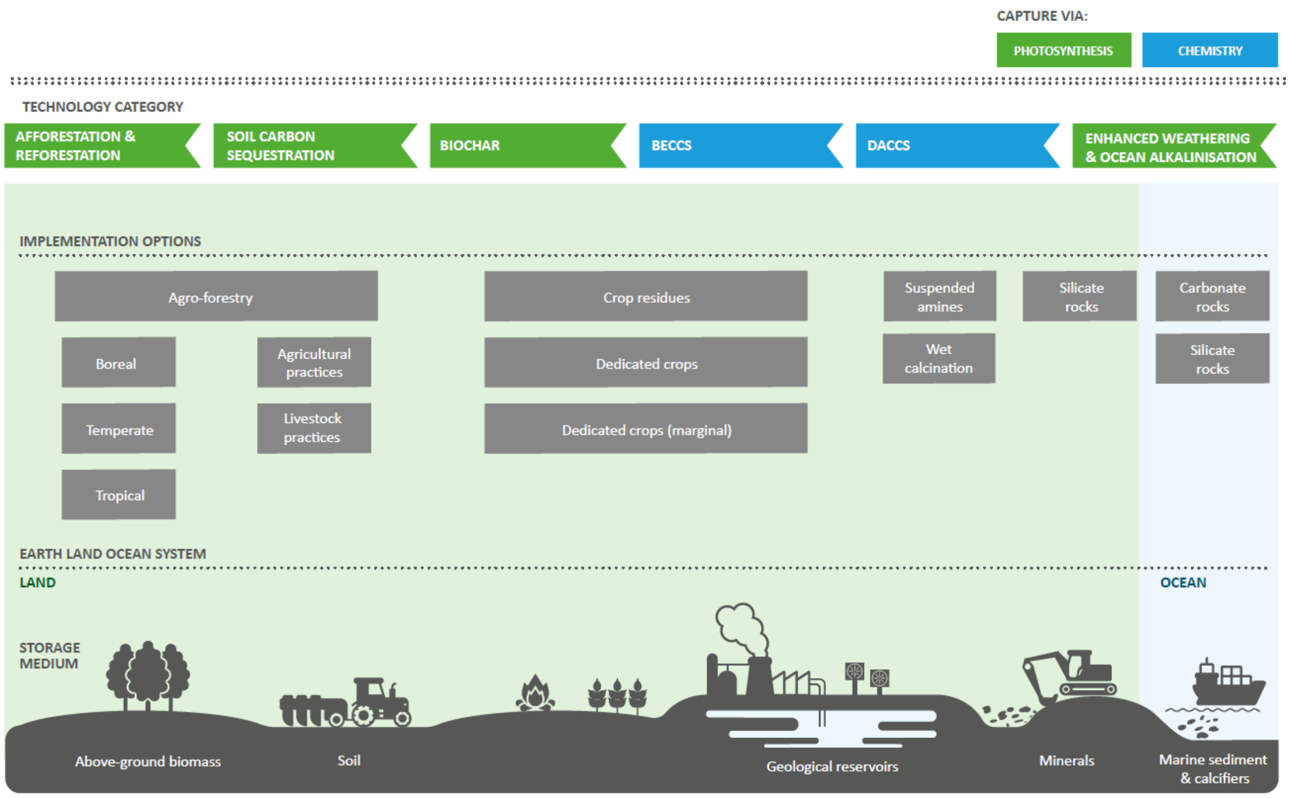
Appendix 3 – NETs

NETs, also known as CDR), are technologies that can remove CO_2 emissions from the atmosphere. NETs are an essential element of the climate scenarios analysed in this report and are used for two reasons:

- to balance CO_2 emissions from hard-to-abate sectors, such as aviation and industry, and reach net zero emissions; and
- to reduce the level of CO_2 emissions in the atmosphere. This may be needed if historical CO_2 emissions in the atmosphere overshoot the carbon budget.

NETs can be classified under the two general categories : technical solutions; and nature-based solutions (NBS). The focus is on the technologies that are widely studied and that have high potential to deliver feasible and sustainable solutions at scale. These are BECCS, DACCS, afforestation and reforestation, soil carbon sequestration, biochar, and enhanced weathering. Figure 11 presents the selected NETs and their functional mechanisms.

Figure 11 NETs can be classified under technical solutions and nature-based solutions



Source: Vivid Economics, based on Fuss et al. (2018) and Minx et al. (2018)

Technical solutions linked with storage of CO_2

Technical solutions rely on the permanent underground storage of CO_2 removed from the atmosphere. The two widely cited technical solutions are: (i) BECCS; and (ii) DACCS.

(i) BECCS

BECCS combines bioenergy with CCS. Bioenergy is a form of renewable energy that is derived from organic materials known as biomass, which can be used to produce transportation fuels, heat, electricity, and products. Forests or energy crops, such as fast-growing perennial grasses and short-rotation coppicing, can be considered as biomass. The major BECCS technologies are mature, but deployment has been slow. In 2019 there were only five operating facilities actively using BECCS, capturing 1.5 million $MtCO_2$ per year (Consoli, 2019). Europe's first two BECCS pilots are under construction in the UK (Drax Group, 2020).

BECCS plays a major role in most climate scenarios as it offers double gains. Biomass replaces fossil fuels as a source of thermal energy and removes CO_2 from the atmosphere. Depending on the use as biofuel or bioelectricity, CO_2 released during fuel conversion or combustion is captured by CCS and stored underground, resulting in negative emissions.

However, BECCS may not be able to deliver the negative emissions projected by the climate scenarios as concerns about its CO_2 balance and sustainability limit its CO_2 removal potential. The costs and CO_2 removal potential of BECCS are widely studied in the literature, and the consensus is on the lower end of the estimated range. Fuss et al. (2018) report that the CO_2 removal potential of sustainable BECCS would range from 0.5 $GtCO_2$/year to 5 $GtCO_2$/year. Achieving the higher end of the range would require a globally coordinated effort for land governance that accounts for local concerns. This could prove challenging given the low levels of global coordination today. The need for greater global coordination and intensive land management to ensure sustainability is likely to increase costs to US$100–$200/tCO_2.

The CO_2 balance of BECCS depends on the use of bioenergy and emissions from the biomass supply chain and land use change. Bioenergy can be used to generate electricity or produce biofuels. At the current efficiency and CO_2 capture rates, bioelectricity has higher CO_2 reduction potential than biofuels. However, when the limited availability of sustainable biomass is considered, aviation biofuels may need to be prioritised over bioelectricity as aviation has no alternatives to fossil fuel, thus reducing the CO_2 removal potential of BECCS (The Committee on Climate Change, 2011, 2018). The biomass supply chain produces additional CO_2 emissions as it includes steps that consume energy such as production, harvesting, processing, and transportation of biomass. Conversion of land for biomass production may cause direct and indirect emissions. Direct Land-Use Change (LUC) emissions result from the decrease in the total carbon stock of the converted land, whereas indirect LUC emissions are due to changes in land use elsewhere as the previous activity on the converted land is relocated. When all these emissions and the lower CO_2 capture rate of biofuels are considered, the CO_2 balance of BECCS may end up being carbon-positive.

Delivering BECCS projected by the climate models is likely to push the world to its planetary boundaries in terms of water and land availability, threatening biodiversity and socially sensitive issues, such as food supply and land tenure. Requiring large areas of arable land, bioenergy could replace food production and reduce food supply, increasing food prices locally and globally. As regards land tenure, large bioenergy producers would reach economies of scale and are likely to outcompete small farmers, forcing the latter to sell their land to large landowners, such as agriculture companies. Food price inflation and reduced land tenure are likely to impact the most vulnerable groups that rely on agriculture for income and spend a large share of their income on food, raising concerns about a just transition to a low-carbon economy (FAO, 2010). Moreover, biomass production could put pressure on water resources as water used for crops, pollution from fertilisers, and water use in BECCS power plant may threaten supplies.

Agricultural intensification and cultivation of marginal land may relieve the pressure on land. The adoption of modern agriculture practices and expansion of irrigation infrastructure could enhance agricultural productivity, allowing the same amount of food to be produced on a smaller area of arable land. However, agricultural intensification also increases the use of fertilisers, pesticides and other chemicals, resulting in rising biochemical flows and greater biodiversity loss. Marginal land, instead of arable land, could be converted to produce biomass. However, it is hard to predict the area of available marginal land and its biomass productivity as it varies in quality and type. According to Turner et al. (2018), the area of land that is suitable for sustainable BECCS (i.e. devoid of forest, not used for food production, and in close proximity to geological CO_2 storage sites) corresponds to only 10% of the land utilised for BECCS in the climate scenarios that target a temperature rise of less than 2°C.[16]

Bioenergy is likely to have other unintended side effects, such as changes in albedo, evapotranspiration, and cloud cover. Changes in albedo result from activities that alter the properties of land surfaces and hence the reflection of solar radiation. The production of biomass alters land properties and can have a positive or negative effect on albedo depending on the geographic location and the permanency of the land-use change. For example, if dead trees are harvested, this increases snow exposure and can result in a cooling effect (Bernier and Bright, 2017). If biomass is cultivated at higher latitudes, replacing snow cover, there will be a warming effect and this offsets climate mitigation (Fuss *et al.*, 2018). A study of 11 land-use change scenarios for the cultivation of biomass found two scenarios with a warming effect and nine with a cooling effect (Caiazzo *et al.*, 2014).

(ii) DACCS

Direct air capture of CO_2 combined with CCS captures CO_2 from ambient air by chemical processes and then stores it underground. The technologies for DACCS already exist and are in the deployment and commercial development stage. The first commercial DACCS plants are operational in Switzerland, Italy, Iceland, the USA, and Canada. However, they use the captured CO_2 for industrial processes, instead of storing it underground, due to commercial viability.

Forecasts in the literature suggest that, by 2050, costs could fall to as low as US\$100–\$300/tCO_2 removed. As supply chains are established and infrastructure issues resolved, the costs of this technology are expected to decrease gradually from today's US\$600–\$1,000/tCO_2. Additional research and upscaling deployment could reduce costs even further (Fuss et al. ,2018).

The CO_2 removal potential of DACCS would be limited to 0.5–5 GtCO_2/year by 2050. However, if costs decline as expected, energy needs are met by renewables, and no unexpected negative impacts emerge, the technology's CO_2 removal potential could increase to 30 GtCO_2/year by the end of the century (Realmonte *et al.*, 2019).

The CO_2 removal potential of DACCs is constrained by its high energy demand, large facility size, and availability of geological CO_2 storage. Low concentrations of CO_2 in the ambient atmosphere mean that large facilities with high energy demand are needed to capture CO_2. According to Realmonte et al. (2019), removing 30 GtCO_2/year by DACCS would require around 50 EJ/year of electricity and 250 EJ/year of heat, corresponding to more than half of today's global total primary energy supply. Large facilities would have large material and labour needs for construction and need to be located far from residential centres. This is also reflected in the high cost of the approach relative to other methods that deploy CCS, such as BECCS, which capture CO_2 from flue gases with considerable higher CO_2 concentration. Depending on the process utilised, water demand could be also substantial and lead to water stress in areas with limited supplies. As the process decreases CO_2 concentration in the ambient air, it may have negative impacts on local vegetation.

[16] Turner et al. (2018) explore land-use transformations described in the IPCC AR5, evaluating a subset of scenarios from multiple models that report land use, such as GCAM 3.0, IMAGE 2.4, and REMIND 1.5.

Nature-based solutions

NBS rely on natural processes to increase CO_2 stored in the biosphere. The four widely studied natural solutions are: (i) re/afforestation; (ii) land management to increase and fix carbon in soils; (iii) biochar; and (iv) enhanced weathering.

(iii) Reforestation and afforestation

Re/afforestation capture CO_2 through photosynthesis and store it within plant biomass. Afforestation refers to establishing forest cover on land devoid of any trees, while reforestation involves the expansion of forest in recently deforested areas. The approaches are already widely applied and can be immediately extended to larger areas of land.

Re/afforestation require large land areas, raising concerns about land competition. Land competition could negatively impact vulnerable groups through rising food prices since less land would be available for food production, and through changes in land tenure since they tend to rely on agriculture for their income. Moreover, other NETs, such as BECCS, will also require land for biomass plantations, further increasing competition for land.

Planting trees is a low-cost measure, but land competition constrains the global CO_2 removal potential of re/afforestation. Keeping land competition in mind, Fuss et al. (2018) conclude that around 500 Mha of land that was previously forested but is not currently, if used productively, would be available for re/afforestation. This limits the global CO_2 removal potential from 0.5 to 3.6 $GtCO_2$/year in 2050, but the global CO_2 removal potential is expected to decline to zero by the end of the century as forests reach saturation. Costs are likely to be low around US$5–$50/tCO_2. Griscom et al. (2017) estimate that the maximum CO_2 removal potential of re/afforestation could reach 17.9 $GtCO_2$/year if the land available is constrained by human demand for food and fibre, but not costs. However, reaching this potential would require significant dietary shifts in order to release free grazing land for forestry.

The approach has other potential problems. Re/afforestation may increase water demand in already water-constrained areas, as well as water pollution through fertiliser use. A global meta-analysis reviewing 43 studies from 13 countries found that that re/afforestation projects reduced annual river flows nearby by 25% within five years of implementation. After 25 years, the water levels of rivers fallen by 40%, and in some cases dried up entirely. However, this is highly dependent on annual precipitation, the area of forest cover and type of land (Bentley and Coomes, 2020). The use of nitrogen fertilisers may also increase NOx emissions with high global warming potential. Other negative side effects include changes in evapotranspiration through land-use change, and changes in cloud cover and albedo. In terms of positive impacts, forestry may benefit biodiversity, but it is case-dependent and may vary according to local conditions.

There are also uncertainties around the permanent storage of CO_2. Human and natural disturbances, such as legal and illegal logging, fires, attacks by pests, and drought may release CO_2 stored in forests, requiring additional resources for protection and maintenance of large forest areas. Moreover, associated land-use changes may release CO_2 emissions stored elsewhere.

(iv) Soil carbon sequestration

Soil carbon sequestration increases organic carbon content of soils through land management practices, leading to CO_2 sequestration. Land management involves agricultural practices that increase carbon input and decrease carbon losses of soil. Carbon input can include leaf litter, residues, roots and manure, whereas carbon losses occur through respiration resulting from activities such as tilling and deep ploughing. The technology can be deployed immediately as farmers and land managers are already familiar with various land management practices and can readily adopt new ones.

The technology is low-cost at US$0–$100/tCO_2, and its CO_2 removal potential ranges from 2.9 to 5.7 $GtCO_2$/year. CO_2 removal potential estimates from the literature vary widely due to differing assumptions about the land area that is available for soil carbon sequestration practices. Although the annual CO_2 removal potential of soil carbon sequestration is promising, its cumulative CO_2 removal potential until 2100 is severely constrained by sink saturation. Depending on soil type, soil may be saturated after 0–100 years and ceases to sequestrate CO_2 from the atmosphere.

The positive side effects are likely to outweigh the negative ones. Positive impacts include improvements in soil quality and health and hence better crop yield. The technology could therefore contribute to food security through increased food supply and a reduction in the cost of food production as it would eliminate the need for intensive management of land. The technology does not require any change in land use, and its water and energy requirements and impact on albedo are negligible. Potential negative impacts include increased N_2O and CH_4 emissions and water pollution if fertilisers and nutrients run off, but these are limited to a subset of practices.

The CO_2 storage is reversible (non-permanent) and requires constant maintenance even after a sink becomes saturated, potentially adding to the costs of this technology.

(v) Biochar

Biochar is charcoal produced by pyrolysis of biomass – in other words, heating it in the absence of oxygen – and it can hold CO_2 for many years. Biochar can be used as a soil additive to improve soil fertility and store CO_2 in soil. The practice is currently in limited use for improving soil quality due to a lack of incentives and experience with large-scale plants. More research is needed to understand how the method performs against the review criteria.

Biochar can remove around 0.3–2 $GtCO_2$ per year by 2050 at a cost of US$90–$120/tCO_2 removed. The availability of biomass for biochar production is the main constraint to the CO_2 removal potential of the method. Both cost and CO_2 removal potential estimates are highly uncertain as feedstock availability, production technologies, and application strategies require more research.

Biochar has both positive and negative side effects. Biochar can increase yield, lower N_2O and CH_4 emissions, and increase the water balance of soil, but these positive impacts vary with soil type, application method and management conditions. One negative impact is that biochar can darken the colour of arable land and decrease its albedo. As a result, more sunlight is absorbed by the soil, increasing the surface temperature. Fine biochar particles blown by wind can decrease radiative forcing further, reducing the benefits of CO_2 being sequestered by biochar.

The permanence of CO_2 sequestration depends on temperature. The residence time varies from a few decades in tropical and subtropical regions with high temperatures, to centuries in cooler regions.

(vi) Enhanced weathering

Enhanced weathering involves extensive use of carbonate and silicate rocks to accelerate geochemical processes on land and in oceans. The process accelerates biogeochemical cycling which sequesters CO_2 from the atmosphere. Spreading the ground rock over land is already practised to counteract soil acidification and could also help to reduce acidity of the oceans due to increased CO_2 concentration.

Depending on the technique used, the CO_2 removal potential could range from 2 to 4 $GtCO_2$/year by 2050 at a cost of US$50–$200/tCO_2 removed. Reported CO_2 removal potential in the literature varies widely and is highly uncertain since it depends on a variety of assumptions and application characteristics. Research on enhanced weathering is at a nascent stage and more evidence is needed on the advantages, disadvantages, and economic and technical feasibility of the method employed at scale.

Enhanced weathering is considered to have low negative impacts, but these need to be studied more. The application of large amounts of rock may have unforeseen impacts on soil properties and water sources, affecting local ecosystems. The method requires the mining, grounding and spreading of large volumes of minerals. The estimates range from 1 to 3 Gt of rock per $GtCO_2$ removed, requiring large infrastructure investments and mobilisation of resources. A positive impact is that it can serve as a nutrient source and enhance soil quality and productivity, especially in tropical areas. This may increase the CO_2 removal potential of BECCS when both measures are used together, but the impact of the method on the carbon content of biomass is poorly studied and needs more attention.

The sequestered CO_2 would be stored permanently in soil or water. In low concentrations, weathering products can be stored as alkalinity – in other worlds dissolved inorganic carbon. In high concentrations, carbonate minerals can form and be stored in soil or washed out to sea, gravitating to the ocean floor.

Appendix 4 – Feasibility of NETs

Table 5 Overview of carbon removal potential, costs, constraints, and side effects of NETs

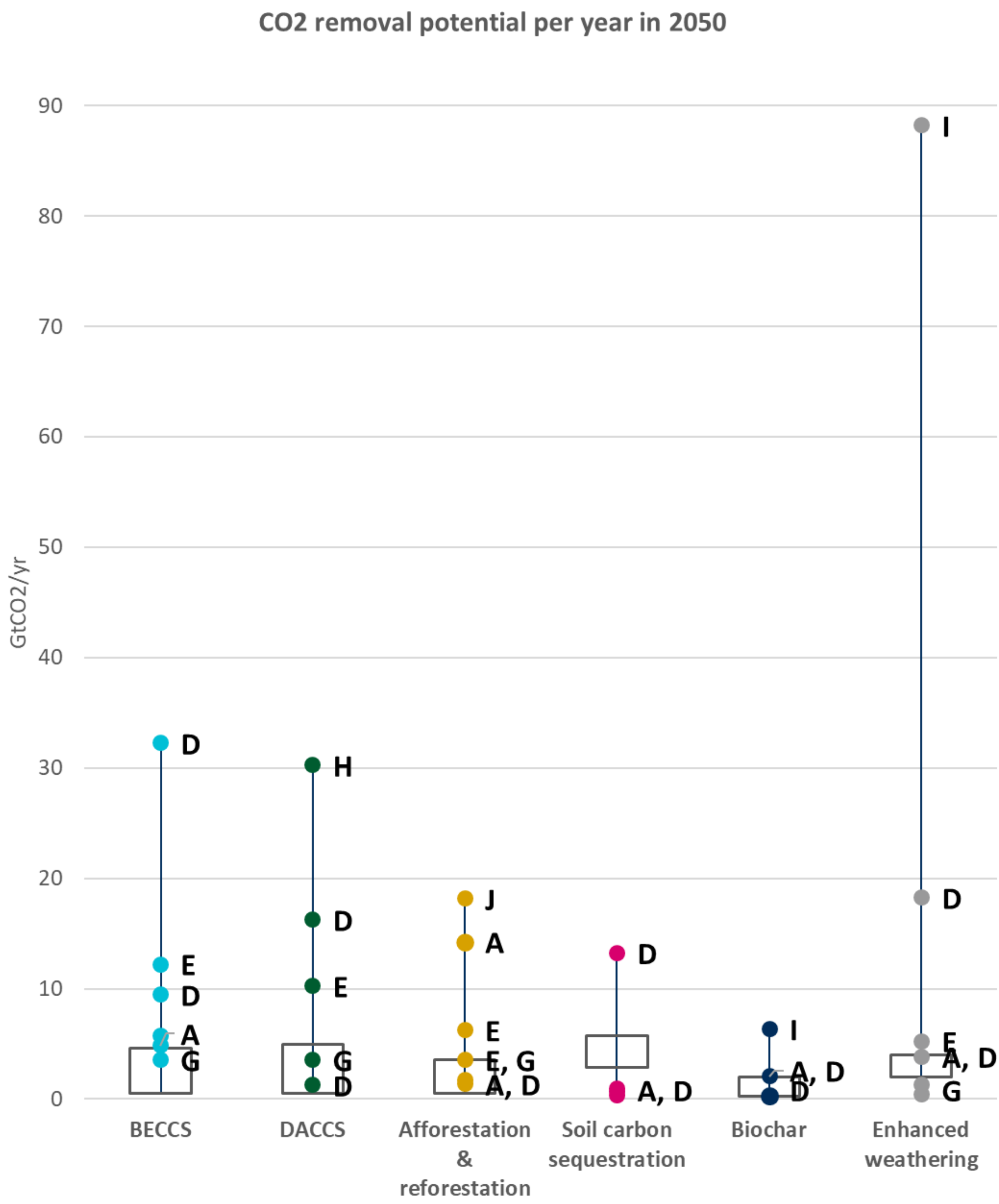
NET	Sustainable CO_2 removal potential per year in 2050 ($GtCO_2$)	Cost in 2050 ($/t$CO_2$)	Constraints	Positive impacts	Negative impacts
Technical solutions					
BECCS	0.5–5 (0.5–32 (2100))	100–200 (15–400)	Land availability; CO_2 storage availability	-	Supply chain and LUC emissions; water scarcity; soil depletion; pollution due to fertiliser use; impacts on food supply and land tenure
DACCS	2050: 0.5–5 2100: up to 30 (0.5–30)	100–300 (30–1,000)	Capital cost; energy demand; material and labour demand for construction; water demand (depends on process)	-	Low CO_2 concentrations in local vegetation

NET	Sustainable CO_2 removal potential per year in 2050 ($GtCO_2$)	Cost in 2050 ($/$tCO_2$)	Constraints	Positive impacts	Negative impacts
Nature-based solutions					
Afforestation and reforestation	0.5–3.6 (0.5–17.9)	5–50 (2–237)	Land competition; water and nutrients requirements	Increases biodiversity (depends on the case)	NOx emissions from nitrogen fertilisers; changes in evapotranspiration, albedo and cloud cover; water scarcity
Soil carbon sequestration	2.9–5.7 (0.4–13)	0–100 (-45–100)	Sink saturation; land availability	Better soil quality and health; food security	Higher N_2O and CH_4 emissions and water pollution (limited to a subset of practices
Biochar	0.3–2 (0.03–6.1)	90–120 (-173–225)	Biomass feedstock availability	Higher yield; lower N_2O and CH_4 emissions; higher soil's water balance	Lower albedo and radiative forcing
Enhanced weathering	2–4 (0.2–88)	50–200 (15–1,000)	Mining, transport, and utilisation of large amounts of minerals; logistical costs	Nutrient source; soil quality	Ecological impacts of mineral extraction and transport

Note: In columns 2 and 3, the main ranges come from Fuss et al. (2018) and are for 2050. The numbers in parentheses show the minimum and maximum values observed in the wider literature and are not year-specific. Figure 12 and Figure 13 below present the ranges and sources in more detail.

Source: Griscom et al. (2017); Martin et al. (2017); Psarras et al. (2017); EASAC (2018, 2019); Fuss et al. (2018); Realmonte et al. (2019); Reid, Ali and Field (2019)

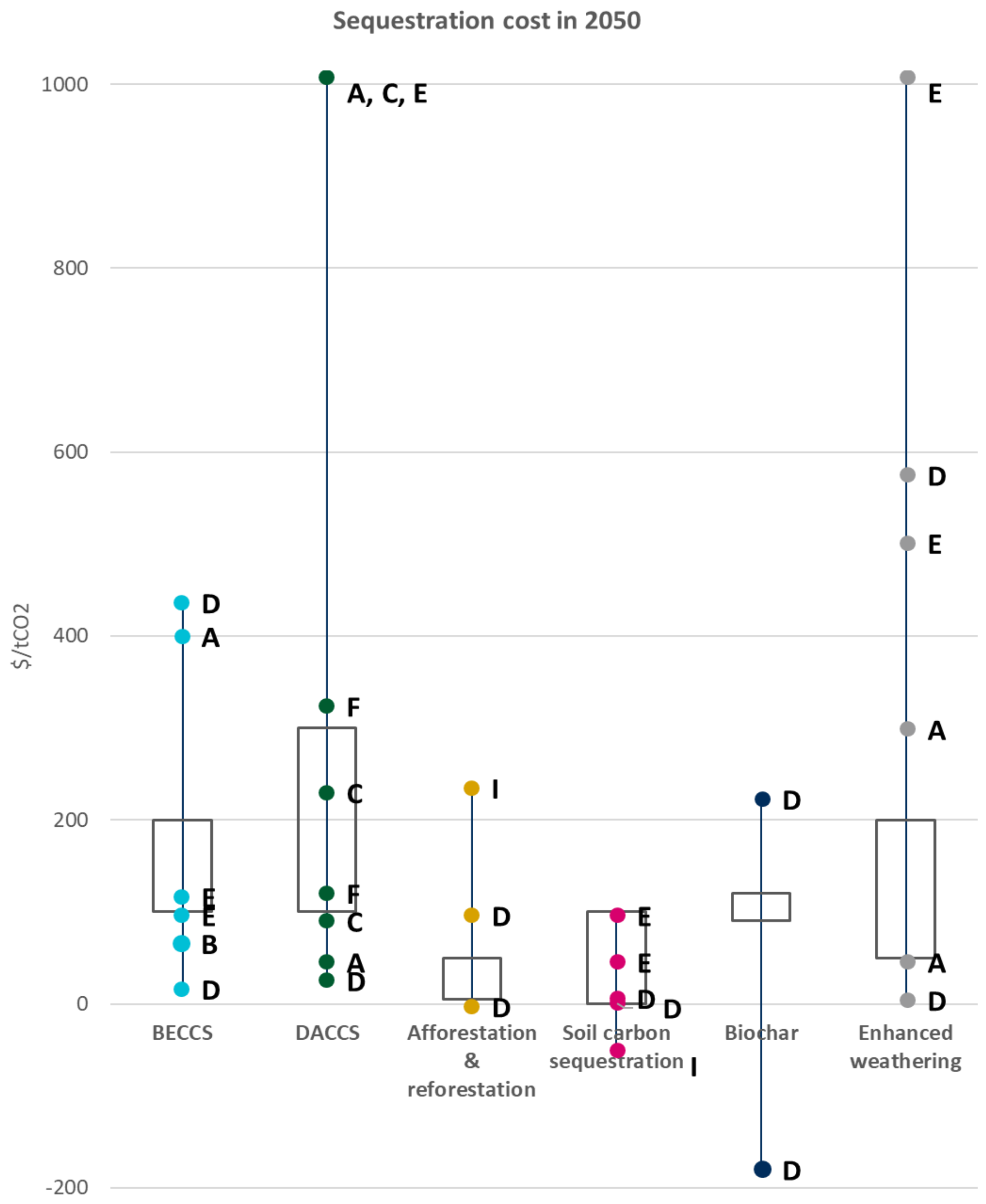
Figure 12 The range of CO_2 removal potential per year for each NET



Note: The graph shows the range of CO_2 removal potential estimates for each NET. The rectangular boxes are the 2050 ranges from Fuss et al. (2018). The lines represent the wider estimates from the literature and are not year-specific.
The letters represent estimates from the wider literature: A = EASAC (2018); B = EASAC (2019); C = Keith et al. (2018); D = Martin et al. (2017); E = Psarras et al. (2017); F = Reid, Ali and Field (2019); G = Smith et al. (2016); H = Realmonte et al., (2019); I = Fuss et al. (2018); J = Griscom et al. (2017).
Not all letters are presented in this graph, but they represent the same sources as in Figure 13. The letters are the same to facilitate comprehensiveness.
If a letter is shown twice, it means that the source reports a range.

Source: Vivid Economics, based on Table 5 above and other sources from the literature.

Figure 13 The range of CO_2 sequestration cost in 2050 for each NET



Note: The graph shows the range of CO_2 removal potential estimates for each NET. The rectangular boxes are the 2050 ranges from Fuss et al. (2018). The lines represent the wider estimates from the literature and are not year-specific.
The letters represent estimates from the wider literature: A = EASAC (2018); B = EASAC (2019); C = Keith et al. (2018); D = Martin et al. (2017); E = Psarras et al. (2017); F = Reid, Ali and Field (2019); G = Smith et al. (2016); H = Realmonte et al. (2019); I = Fuss et al. (2018); J = Griscom et al. (2017).
Not all letters are presented in this graph, but they represent the same sources as in Figure 12. The letters are the same to facilitate comprehensiveness.
If a letter is shown twice, it means that the source reports a range.

Source: Vivid Economics, based on Table 5 above and other sources from the literature.

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Contact us

Vivid Economics Limited
163 Eversholt Street
London NW1 1BU
United Kingdom

T: +44 (0)844 8000 254
enquiries@vivideconomics.com