Chapter 5:

Removing carbon from our atmosphere

Getting to net zero emissions of long-lived gases for Aotearoa will require removals of carbon dioxide from the atmosphere. This could mean planting more trees or using carbon capture and storage. Whichever measure we decide to take, we must explore options for removing carbon from our atmosphere and the steps we need to take to get there.

This chapter outlines those options in detail, discussing opportunities and challenges and quantifying them when possible.

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5.1 Introduction

Achieving net zero emissions of long-lived greenhouse gases and limiting global warming will require the removal of carbon dioxide (CO_2) from the atmosphere. This is because, even with a focus on gross reductions in emissions, there could still be residual emissions stemming from hard to abate sectors such as carbon dioxide from cement manufacturing and nitrous oxide from agriculture.

There are three broad approaches which could be used for the removal of carbon dioxide from the atmosphere:

1. increasing biological uptake (e.g. through plants, soils and oceans)
2. engineering direct capture from the atmosphere
3. increasing inorganic reactions with rocks.

5.1.1 Increasing biological uptake

Increased biological uptake and storage on land is the most well-known and used option for emissions removals. Forests store large amounts of carbon in the trees themselves and in the soil of the forest floor. They can be a source of carbon neutral energy when processed into biofuels for use to generate process heat, electricity or motive power. In Aotearoa, the establishment of new and management of existing forests is currently the lowest cost emissions removal option.

There are challenges to the use of forests for removing carbon dioxide in Aotearoa, including competition for land, social and community acceptance and, as the Parliamentary Commissioner for the Environment has warned, risks of unintended carbon release as the result of extreme events such as fire, flood or pest infestations, particularly as the physical impacts of climate change intensify.[1]

5.1.2 Engineering direct capture from the atmosphere

Carbon capture and storage (CCS) is the process of direct capture of emissions from the atmosphere (for example, from fuel combustion or large-scale industrial processing activities) followed by permanent storage in a reservoir. The steps involved in CCS include emissions capture, purification and compression, transport and injection and storage. The application of CCS combines a number of processes and technologies – many of which are mature and used in oil and gas production activities. Others are in various stages of technological readiness. The readiness of CCS is at a markedly different stage compared with forestry.

[1] (Parliamentary Commissioner for the Environment, 2019)

Traditionally, depleted or producing oil and gas reservoirs are used for long-term storage in CCS as they are known not to leak – having held methane and carbon dioxide for millennia. CCS may also be limited by social and community acceptance, uncertainty around potential although unlikely induced seismicity, land and resource requirements and sensitivities around the inappropriate use of land (a taonga) by placing waste material into Papatūānuku.[2] However, this may not be an issue if it involves reinjecting the fields own gas.

Bioenergy with carbon capture and storage (BECCS) combines the two emissions removal options by integrating biological capture with various capture and storage methods. BECCS is an alternative option to both forestry and conventional CCS. Emissions are sequestered from the atmosphere through forest and non-forest vegetation. Once mature enough for the intended use, forests or non-forest vegetation are harvested and the biomass is burned for energy. Carbon dioxide emissions from the biomass combustion are captured, compressed and stored using conventional CCS technology. BECCS carries many of the same risks as both forestry and CCS.

5.1.3 Increasing inorganic reactions with rocks

Carbon removal through increased inorganic reactions with rocks includes enhanced terrestrial weathering and mineral carbonation. These processes accelerate the natural break down of silicate rocks to carbonate minerals. When these rocks break down, a chemical reaction takes place with carbon dioxide in the atmosphere (enhanced terrestrial weathering) or from a separately supplied source, for example, from a captured industrial emissions stream (mineral carbonation). However, these processes are not accounted for in national or international carbon accounting frameworks and are not considered in our emissions budgets or first round of advice.

5.1.4 Future options

There may be future options for ocean process to remove carbon dioxide from the atmosphere, also known as 'blue carbon'.[3] Seaweed can rapidly sequester carbon and store it indefinitely if it sinks to the deep ocean.[4] Mangroves and seagrasses are also effective at removing carbon dioxide and also provide adaptation benefits. However, robust measurement and accounting frameworks are required to include this option in emissions budgets. This has not been considered in this first round of advice.

The extent to which Aotearoa relies on carbon dioxide removals to meet net emission targets is dependent on the scale of emissions reductions in other sectors. A strong reliance on offsetting emissions through carbon dioxide removals could divert action and investment away from reducing gross emissions in other sectors – such as energy, industry and transport.

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[2] (Jaram, 2009).

[3] "Blue carbon" involves both the organic matter captured by marine organisms, and how marine ecosystems could be managed to reduce greenhouse gas emissions (Lovelock & Duarte, 2019). Increased carbon dioxide in the atmosphere results in an increase in marine dissolved inorganic carbon which benefits plant productivity increasing carbon stocks but leads to loss of seagrass biodiversity, decreasing carbon stocks. (Macreadie et al., 2019)

[4] (Lovelock & Duarte, 2019)

5.2 Forests

This section describes the potential for forests in Aotearoa to remove carbon dioxide. The intent is to provide an indication of the scale and feasibility of different options for increasing carbon dioxide removals by forests.[5]

In forests, carbon dioxide removals can be enhanced by:

1. increasing the amount of land in forest – by planting new forests, or letting native forests regenerate on previously cleared land,
2. avoiding deforestation, and
3. increasing the amount of long-term carbon stored by existing forests and their products.

This section describes the different sequestration rates of different types of forest, the amount of land available for new forests and opportunities to increase sequestration through avoiding deforestation. It also addresses increasing the amount of carbon stored in each hectare of forest and increasing the conversion rate to long-life wood products. The section identifies potential challenges involved with forestry as an emissions reduction option, including the uncertainty of relying on carbon dioxide removals, including from the physical impacts of climate change. This section does not discuss issues such as accounting, biofuels, policies and how forest sequestration would be used alongside emissions reductions in budgets and targets. These are discussed in other parts of this report.

5.2.1 Context

Aotearoa was once almost entirely covered in forests, with just the mountain tops and low-lying wetlands free from tree cover.[6] This began to change following the arrival of the first people on the shores of Aotearoa more than 700 years ago, as some forest began to be cut and burned to make way for tracks, settlements and crops.

With the arrival of the first European settlers, large amounts of land began to be cleared for timber, settlements and to create grassland. Land clearing accelerated as agriculture grew, with large areas of native forest burned to make way for pasture.

There is now around 10 million hectares of forest in Aotearoa, spread across public and private land. The 7.8 million hectares of **natural forest** in Aotearoa are made up of about 6.5 million hectares of

[5] Emissions removals by forests refers to the net effect of carbon released from deforestation and carbon sequestered from forest growth.

[6] Prior to the arrival of humans, about 80% of Aotearoa was covered in forests. (Ministry for the Environment, 2019)

mature native forest and much of the rest is land that was once cleared, but where native forest is regenerating.[7] Mature natural tall forest store around 920 tCO_2 per hectare.[8][9]

The 2.1 million hectares of **plantation forest** is 90% *Pinus radiata* which is harvested at 25 to 30 years of age. Around 1.4 million hectares of these forests were first established prior 1990 (pre-1990 forests) and the remaining 0.7 million hectares were established after 1989 (post-1989 forests).

Carbon accumulates in forests as the trees grow. Post-harvest, the carbon is then stored in wood products and is released back into the atmosphere depending on the product mix. The life of the carbon post-harvest is determined by the wood product and the time it takes to decay. Radiata pine forests harvested at 28 years, then replanted, could store an average around 517 tCO_2 (not including harvested wood products (HWP)) to 752 tCO_2 (including HWP) per hectare.[10] For the storage of carbon dioxide to be retained at this average level, the cycle of planting and harvesting would need to continue indefinitely.

Non forest vegetation

Small areas of trees and vegetation on other land, such a riparian planting along waterways or shelterbelts on farms, also remove carbon dioxide and store carbon, but to a much lesser degree. This is partly due to the small areas planted and partly because they are generally smaller tree species which cannot store large amounts of carbon. In these areas trees and vegetation provide other important ecosystem services however, such as enhancing water quality and biodiversity, recreation and biodiversity conservation.

Although they do provide benefits, these small areas of vegetation often do not contribute to the overall 'net' emissions of Aotearoa in the same way as forests. This is for several reasons, such as the ability to reliably count small areas of planting, as well as track their harvesting and/or deforestation.

There are different ways of accounting for carbon losses and gains within forests, depending on the purpose. These include international accounting for our targets, and domestic accounting in the Emissions Trading Scheme. *Chapter 3: How to measure progress?* gives more information on accounting approaches.

5.2.2 Options for increasing forest carbon dioxide removals from the atmosphere

A range of options exist to increase the carbon dioxide that forests can remove from the atmosphere. These include:

- new native and exotic plantation forests,
- new permanent native and exotic forests,
- avoiding deforestation,

[7] Under UNFCCC reporting guidelines, self-sown exotic trees such as wilding conifers and grey willows established before 1 January 1990 are classified as natural forests in the Land Use and Carbon Analysis System (LUCAS).
[8] (Paul et al., Unpublished).
[9] A mature native forest will, on average, neither gain nor lose carbon. (Holdaway et al., 2014)
[10] (Wakelin, Paul, et al., 2020)

- increasing carbon stocks in natural and planted forests, and
- increasing the proportion of long-lived wood products.

The various options have different rates of carbon removal and storage, and also vary in their costs, co-benefits, and interactions with other removal options. They also have quite different impacts on local communities and differ in their social and cultural acceptability. Policies have provided incentives for planting exotic forests and to a lesser extent, for native afforestation.[11] While there is currently a higher focus on natives planting and restoration, there is also limited knowledge on the cash flow, carbon benefits and co-benefits of non-pine forests, along with limited processing infrastructure and markets. Table 5.1 outlines the key opportunities and challenges associated with carbon dioxide removals by forests, forest products, and soils, although more detailed considerations of the impacts and policy implications are contained in later chapters.

Table 5.1: Options for increasing carbon removals through forests, forest products and soil

Option	**Opportunities and challenges**
Exotic plantation forests	Plantation forests are established forests with an intention to harvest at some stage. In Aotearoa most exotic commercial forests are radiata pine – almost all of which is in a clear-fell regime. This type of forests has well established markets for their products, provide employment and ensures Aotearoa has a sustainable supply of wood products, now and in the future. Exotic forests also provide increased biodiversity compared to pasture.[12] These forests can sequester carbon quickly. One hectare of radiata pine could sequester carbon at an average rate of about 34 tCO_2 each year, over 30 years – although the rate of growth is much slower in the first five years.[13] Once the trees are harvested, the carbon stored in the finished product decays over time and is ultimately released back into the atmosphere. The rate of release depends on what the harvested wood is used for (see *Carbon storage in forest products* below). If trees are replanted, the growth cycle begins again. If this cycle is repeated indefinitely, an area of land in plantation forest may be thought of as a long-term carbon sink. The long-term average carbon stock of about 600 tCO_2 per hectare is reached after around 20 years for a forest that is on a 28-year rotation. [14]

[11] (Ministry for the Environment, 2020a)
[12] (Borkin & Parsons, 2010; E. G. Brockerhoff et al., 2001; Stephen M. Pawson et al., 2008; Steve M. Pawson et al., 2010)
[13] Data from (Ministry for Primary Industries, Unpublished)
[14] For the storage of carbon dioxide to be retained at this average level, the cycle of planting and harvesting would need to continue indefinitely.

Option	Opportunities and challenges
	Planting and ongoing management costs range from $1,200 to $7,000 per hectare (usually on the lower end)[15]. Including silviculture and harvesting costs, a landowner may earn, for example, a return equivalent to approximately $400 per hectare per year in the East Coast[16] (excluding carbon revenue). However, the overall revenue depends heavily on factors such as log price, site access and distance to port or processor. Aotearoa also has well-established markets and processing infrastructure for pine trees. Other exotic species are also planted in commercial forests, either as a monoculture or as a mixed species forest, such as douglas fir, redwoods, macrocarpa or eucalypts. Some of these species such as eucalypts grow faster than pine but sequester carbon at a lower rate.[17] Yet, there are potential benefits to diversifying commercially planted tree species, including increasing the sector's resilience to fire, pests and pathogens,[18] as well as to volatile international markets. Owners of some existing commercial forest and some iwi/Māori-collectives, have expressed an interest in converting exotic forests to native species following harvest, while others are actively managing their exotic forests.[19] There are also other management practices for exotic forest: • *Selective harvesting / Continuous cover forest* in which trees are harvested individually or in small groups, providing a more even cash flow. This approach requires individual tree inventories and skilled staff. It has been applied in Canterbury and is widely practiced in some European countries and in tropical forests. • *Short rotation coppicing.* Regrowth of trees from stumps means that replanting is not required, which reduces a major cost. The carbon removal value depends on the density of planting and frequency of harvest. Pilots using willow in Aotearoa show potential for producing biomass for energy generation or chemical production. • *Short rotation forestry* involves planting a site then felling trees of typically 10 to 20 cm diameter after between eight and 20 years. This approach is not widely practiced in Aotearoa. The trees are usually used for biomass for energy generation or chemical production.

[15] Based on data for the ENZ model, establishment costs vary with region and quintile for structural regime; 28 years, 833 initial stocking, thinning to waste to 500 stems at age 7. Includes new land planting, not regeneration at thinning and moderate walk hindrance. Weed control costs are included but fencing costs are highly variable and site specific so are not included (Peter Hall, Scion, Pers. Comms).

[16] Figures based on East Coast case study, structural regime, assuming log price of $115 per m^3, costings and volume assumptions from (Pizzirani et al., 2019) and discount rate of 6%.

[17] This is because eucalypts would have a lower diameter at breast height.

[18] Because different species and sites are more or less susceptible to these threats.

[19] For example (Lake Taupō Forest Trust, 2020; Te Runanganui o Ngati Porou, 2018)

Option	Opportunities and challenges
	Wilding control is part of all exotic plantation forest management activities, to prevent the expansion of wilding conifers and other species.[20] Wilding conifers are established tree weeds that can have negative economic and ecological impacts. Wildings are currently spread over 1.8 million hectares in Aotearoa, with the potential to expand to 20% of the country by 2035.[21] Estimations of the carbon sequestered by wilding conifers are ongoing.[22] A large-scale change from livestock farming to plantation forestry triggered by carbon price and other incentives would represent an economic transformation which would inevitably affect some communities in terms of the local workforce and culture. [23] This is explored further in *Chapter 16: Overall implications.*
Native plantation forests	Some plantation forests consist of native species. There is limited information on native plantation carbon dioxide removal rates, which vary with the species planted. The NZ ETS lookup tables have one value covering native forests, which indicate 323 tCO_2 is removed after 50 years.[24] When the planted forest area is larger than 100 ha and registered for ETS, forest managers are required to do field measurements so that the actual tree growth is registered. Under certain circumstances using species such as Kauri, native plantation forests remove carbon dioxide at greater rates.[25] instead of values from the look-up value[26]. Growth and harvest rotations for native species are considerably longer than for pine trees that could resulting in lower environmental pressure. As with exotic plantation forests, the harvest and planting cycle would need to be continued indefinitely or a continuous cover management approach used for the forest to be considered a permanent carbon sink. It is likely that timber harvested from native plantations would go into long-lived products that would store carbon for a long time. Extreme versions of this is timber in whare tipuna (meeting houses), some of which has been there for centuries.

[20] Wilding conifers include douglas fir, pines, birch, cedar, cypress, larch and redwoods. Pinus contorta (lodgpole) is the most invasive.
[21] (Ministry for Primary Industries, 2020c)
[22] Thomas Paul, Scion, Pers. Comms.
[23] (New Zealand Productivity Commission, 2019)
[24] (Ministry for Primary Industries, 2017)
[25] For example, measurements of a stand of 69-year-old Kauri in Taranaki show that it sequesters about 19 tonnes of CO_2 per hectare each year, on average. The stand is estimated to store about 1,300 tCO_{22} per hectare. (Tane's Tree Trust, 2014, p. 5)
[26] (Te Uru Rākau, 2018b)

Option	Opportunities and challenges
	The longer rotations also mean there is a long delay before earning timber income. Profits vary substantially, depending on factors such as location, species, carbon income and other potential income streams (e.g. from honey, eco-tourism, medicines). Native plantation forests are more expensive to establish compared to pines because of the cost of seedlings and management required to ensure survival rates. Costs vary widely depending on factors such as site and desired density. Active planting establishment costs are around $6,600 per hectare.[27] If local seed sources are available and the climate and site fertility are favourable, the forest may naturally grow (or revert).[28] There is an up-front cost of around $1,100 per hectare for fencing[29] and ongoing annual costs of around $500 per hectare for pest and weed control. There would also be infrastructure costs such as roading and periodic thinning and/or pruning. There are not currently well-developed markets and processing capacity for native timbers in Aotearoa. In addition, native forests face additional regulations with respect to sustainable forest management.
Permanent exotic forests	Some exotic forests are established with no intention of harvest.[30] While it is difficult to anticipate owners' future actions, Scion estimates that around 6% of the exotic forest trees might not be harvested. Such forests can remove about 2,800 tCO_2 per hectare over 100 years. However, unmanaged pine forests are likely to 'fall over' and degrade after about 100 years. Over time the carbon stored would be released back into the atmosphere.[31] In theory, if these forests are actively managed, some exotic species could act as a nurse crop and accelerate the establishment of native forests.[32] This process could take between 100 and 300 years, depending on factors such as climate, pest control, forest management, soils and seed sources. The oldest pine forests in Aotearoa are around 100 years old. This approach could achieve quick and early carbon removals together with the long-term ecological benefits of native forest.

[27] (Bergen & Gea, 2007; Pizzirani et al., 2019)
[28] For example, tōtara regeneration in Northland (Tōtara Industry Pilot, 2019)
[29] Based on estimates from conservation covenants (Scrimgeour et al., 2017), similar to the national of average of $8/m; estimates vary with slope and region. (MPI, 2017)
[30] (NZ Carbon Farming, 2019)
[31] (Brockerhoff et al., 2003)
[32] (Brockerhoff et al., 2003)

Option	Opportunities and challenges
Permanent native forests	Establishing permanent native forests can store carbon over a long period of time and can be done either through reversion or active planting. Native trees grow and sequester carbon dioxide relatively slowly and provide greater biodiversity benefits. Most of Aotearoa was once covered in native forest. Some of the land that was cleared to make way for agriculture is now 'marginal' farmland. In places where there is an existing seed source and adequate microclimate and soil conditions, marginal farmland would slowly begin to revert back to native forest if it were fenced to exclude livestock. Species like mānuka and kānuka are usually the first to thrive in these settings. They are followed by other species like rimu after a few decades.[33] Active planting of trees can accelerate this process, particularly where there is a close seed source. There is some emerging evidence of native forests able to regenerate under pine canopy gaps so pines could have a role in native forest restoration.[34] Access to native seedlings, for plantation or for permanent forests, is a constraint to scaling up native forests. A recent survey of native tree nurseries notes their production capacity; there can be a lead time of 2-4 years for accessing native seedlings and it requires planning and cooperation across Government, industry and the public.[35] Permanent native forests continue to sequester carbon for hundreds of years, eventually reaching a steady state of around 920 tCO_2 per hectare. These forests also offer other benefits, such as improving biodiversity, providing a habitat for birds and other native species, as well as cultural, recreational and spiritual benefits.[36] In Te Ao Māori, there are cultural benefits associated with a native forest which include mahi toi (artistic pursuits). For example, Whakairo (carving), tukutuku (meeting house panels), raranga (weaving), rongoa (medicine), kaitiakitanga (preservation of species), toi rakau (making traditional weapons) and associated skills and practices whakatuu raakau (weapon skill). On some leased land that has been returned to Māori (e.g. Ngati Tuwharetoa ki Kawerau) Māori are planting native forests for cultural reasons. There are some Iwi and Hapū managing their native forests,[37] as well as small tourism businesses which use buried Kauri highlighting the value (commercial and traditional) in working with native timbers.[38]

[33] (Wotton & McAlpine, 2014)
[34] (Forbes et al., 2015, 2019, 2020)
[35] (New Zealand Plant Producers Incorporated (NZPPI), 2019)
[36] (Department of Conservation, 2020)
[37] (Ngati Hine Forestry Trust, 2019)
[38] (Ka-Uri Unearthed, 2019)

Option	Opportunities and challenges
	Mature native trees and shrubs are particularly vulnerable to introduced pests, especially browsing mammals like possums, deer and goats. The presence of these animals can affect the composition of the forest, rates of regeneration and carbon sequestration.[39] Predators like rats, stoats and cats can also affect populations of native birds, bats, lizards and insects. They can cause local or total extinction. The survival of many native animals depends on effective pest control.[40] The management costs of permanent native forests vary widely and may include fencing. Expanding native forests on farms would result on a loss of grazing land, and potentially loss of other on-farm functions such as places to put animals to avoid pugging. However, there would be a reduction in the amount of time spent keeping this pasture free of scrub. [41] Manaaki Whenua estimate around 740,000 ha of marginal land not suitable for commercial forests could naturally regenerate (i.e. without planting) if pests are managed.[42] The Ministry of Primary Industries (MPI) estimates around 400,000 ha of the privately owned native forests are suitable for selective harvesting.[43]
Avoiding deforestation	Deforestation is cutting down a forest and converting the land to a non-forest activity such as pastoral agriculture. This leads to a carbon dioxide emission equivalent to that held in the forest (above and below ground) and loss of ecosystem services. This is partially offset by a small gain in soil carbon if the land is converted to pasture. *Chapter 3: How to measure progress* shows that low but non-trivial levels of deforestation contribute between 1.2Mt and 2.4Mt CO_2e- each year on an ongoing basis. The 'glut' of forests planted in the 1990s will be due for harvest in the mid-2020s, which is a natural decision point for replanting or converting to a different land use. Many of these forests are smaller and are also not in the Emissions Trading Scheme (NZ ETS), which means they are not subject to a 'deforestation liability'.

[39] (Anderegg et al., 2020)
[40] (Parliamentary Commissioner for the Environment, 2017)
[41] (Parliamentary Commissioner for the Environment, 2016)
[42] (The Aotearoa Circle, 2020)
[43] (Ministry for Primary Industries, 2020b)

Option	Opportunities and challenges
Increasing carbon stocks in planted forests	Improving forest genetics and forest management techniques could lead to higher wood density and volume. This would lead to an increase in carbon removals and storage per hectare. Current genetics programmes for pine forests focus on breeding traits such as straightness, speed of growth, wood quality and disease resistance. [44] Forest management changes in the last 20 years have increased the stocking rates and volumes. While the effects of these combined improvements have not been formally quantified, experts estimate an increase of volume of the planted forests of 15% by 2030[45] or double productivity by 2050.[46] These estimates are likely optimistic as forest owners may harvest earlier as a result of more rapid growth. Current NZ ETS rules mean that these increases in carbon stocks may be recognised in forests established after 1989, but not those established prior to 1990. *Chapter 3: How to measure progress* details the conditions under which this increase in carbon stock could contribute towards budgets.
Increasing carbon stocks in natural forests	Improved management of around 7.8 million hectares of natural forest in Aotearoa could increase the amount of carbon stored in those forests. Pests such as deer, possums and goats browse on foliage, seedlings and saplings, altering the composition of a forest. Controlling these pests could help to increase carbon stocks, while protecting indigenous biodiversity.[47] If such pests are not adequately controlled, then there may be long-term declines in the carbon already stored in mature forests.[48] Depending on the pest, control can consist of shooting, trapping and poisoning. However, studies have shown that it is difficult to suppress these pests to low enough levels over large enough areas and for long enough to see a response.[49] Carrying out more predator control, fencing out grazing and browsing animals, and preventing fires in regenerating and native forests can result in more native birds, more tree growth and prevent forest decline in the long term.[50]

[44] (Radiata Pine Breeding Company, 2020; Scion, 2020)
[45] Heidi Dungey, Scion, Pers. Comms.
[46] Timberlands expects to double the productivity of Kaingaroa forests in the Central North Island by 2050 (Ellegard, 2020)
[47] (Carswell et al., 2015; Richardson et al., 2014; Wright et al., 2012)
[48] The effects of wild animal control on carbon stocks could be measurable at the centennial timescale. Current studies have been mainly conducted at the decadal timescale. (Carswell et al., 2015)
[49] (Nugent et al., 2010)
[50] (Carswell et al., 2015)

Option	Opportunities and challenges
	Accurately measuring the changes in natural forest carbon stocks that are due to changes in management is not currently possible. Many of the effects are realized over decades or centuries and distinguishing the size of the change from natural changes in the existing forest is extremely difficult. [51] For this reason, changes in natural carbon stocks from management changes are not included in the national GHG accounting and is not included as an option in our modelling. For more information, see *Chapter 3: How to measure progress*.
Increasing carbon storage in forest products	Carbon is not released to the atmosphere at harvest but remains in the products made with the timber. Harvested wood products (HWP) in Aotearoa are an important pool of carbon stocks in our GHG inventory.[52] There are three ways to increase the carbon stored in HWP: 1) increasing the amount of new forests and increasing yields in existing forests (earlier explained), 2) shifting the product mix to more long-lived products 3) making products last longer through, for example through recycling or circular economy approaches (See *Chapter 4d: Waste*). We focus on the second point in this section. Around 60% of the annual harvest is exported overseas as raw materials (logs, wood chips or pulp) and converted into short-lived products such as pulp, paper and packaging materials, which decay relatively quickly.[53] Around 77% of domestic processing results in long-term lived HWP such as houses.[54] Significant investment in domestic processing capacity would be required to achieve increase the volume of timber going to long-lived products. Investing in domestic processing facilities could result in a best-case scenario up to additional removals of 31.3 Mt CO_2 between 2021-2050.[55] Further information on the accounting for HWP is included in *Chapter 3: How to measure progress.*
Increasing soil carbon stock	Aotearoa soils are of relatively high carbon content due to the temperate climate, the comparatively short time during which it has been under cultivation, and the fact that most of it is covered in permanent pasture.[56,57] As such, there may be less potential in Aotearoa to sequester additional soil carbon compared to other parts of the world where soil carbon loss has been greater.

[51] (Peltzer et al., 2010)
[52] (Wakelin, Searles, et al., 2020)
[53] (Manley & Evison, 2017)
[54] (Te Uru Rākau, 2018a)
[55] (Scion, 2018)
[56] (Pastoral Greenhouse Gas Research Consortium, 2015)
[57] (The Nature Conservancy et al., 2020)

Option	Opportunities and challenges
	Current evidence in Aotearoa suggests that soil carbon stocks were lower under irrigated than adjacent dryland pastures.[58] There is some evidence that fertiliser inputs to tussock grasslands increased carbon stock. Occasional pasture renewal is unlikely to greatly affect soil carbon stocks. This contrasted with general losses of carbon due to frequent and repeated cultivation. There is no evidence that fertiliser application rate influenced soil carbon stocks. [59] The science and measurement of soil carbon is still developing and long-term monitoring programmes have been established in Aotearoa.[60] There is little systematic data on practices that could increase soil carbon stocks in Aotearoa such as cover crops, no minimal till, biochar, full inversion tilling and peatland restoration. *Cover crops* provide land cover in between cropping cycles to protect soils from erosion, mitigate nutrient losses and provide biologically fixed nitrogen. Cover crops can store soil carbon and potentially reduce soil N_2O emissions.[61] An international meta-analysis estimated the average emissions reduction potential of cover cropping by increasing soil carbon in cropping systems using field recordings over 54 years at 1.17 ± 0.29 tCO_2e per hectare per year.[62] *No till* or reduced till approaches avoid soil disturbance and associated carbon loss by ploughing. Reducing tillage can lead to increased organic matter accumulation (including carbon) in the undisturbed topsoil. The evidence for this practice is mixed. In some cases, soil carbon increases at shallow depths were offset by decreases at deeper levels. The increase in soil carbon stock can be lost as farmers alternate between tilling and not tilling over several years.[63] As most of agricultural land in Aotearoa is in long term pasture, the overall potential to store carbon would be more limited.[64] Switching to 'no-till' approaches would likely incur capital costs for new machinery such as direct seed drills.[65] Specific costs/capital requirements would likely vary by system type. *Biochar* is a high-carbon, fine grained product created through pyrolysis[66] when biomass is burnt in the absence of oxygen. Biochar can improve soil physical properties, increase and stabilise soil organic carbon stocks, improve soil

[58] (Mudge et al., 2017)
[59] (Schipper et al., 2017)
[60] (NZAGRC, 2019)
[61] Further research is needed to fully attribute this effect, see: (Basche et al., 2014)
[62] Estimates for mean soil depth=22 cm (Poeplau & Don, 2015)
[63] (Griscom et al., 2017; Powlson et al., 2014)
[64] (Baker, 2016)
[65] (Saskatchewan Soil Conservation Association, 2020)
[66] Pyrolysis is the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves a change of chemical composition.

Option	Opportunities and challenges
	biological properties and reduce greenhouse gas emissions.[67] Biochar can be retained in the soil at least for several hundred years. Further research would be needed to better understand the potential of biochar as a long-term option for carbon capture and storage.[68] The potential of emissions reductions from biochar application depends on the production of biochar which in turn is dependent on the amount of biomass available to produce it. Our analysis indicates that biochar production could avoid approximately 0.73Mt CO_2e of waste emissions[69] or 0.32 Mt CO2e from avoided landfill emissions.[70,71] The estimated cost of biochar production is expected to be in the range of $300-$800 per tonne.[72] *Full inversion tillage (FIT)* is a technique that transfers carbon-rich topsoil into the subsoil[73] (potentially slowing its decomposition) and exposes the inverted, carbon unsaturated, subsoil to higher inputs from the new pasture. FIT remains relatively unproven in Aotearoa and elsewhere. A recent trial in the Manawatu found FIT to successfully transfer soil organic content below 10cm. It showed the potential to reduce peak nitrous oxide emissions and maintain pasture production.[74] A model estimated that an additional 3 Mt of carbon could be stored over a 30 year period in high producing grassland soils following a 'one-off' pasture renewal with FIT. [75] This number ought to be treated with caution as such potential is yet to be demonstrated in practice. *Peatland restoration:* Peatland soils hold large pools of carbon, accumulated over many centuries. When peat soils are drained for agriculture, they become a source of greenhouse gas emissions and remain one as long as the land remains drained.[76]

[67] (Hedley et al., 2020)
[68] (Spokas, 2010)
[69] Organic components of landfill and farm fill waste in Aotearoa account for 2.9Mt of solid waste, or 35% of the total, but account for almost all waste emissions This estimates assumes that 20% of this was converted into biochar via pyrolysis without any fugitive emissions (0.2*3.65MtCO2e), Total solid waste emissions are for 2018 from NZ's GHG Inventory.
[70] Griscom et al. (2017) estimate biochar carbon sequestration: 0.18t C/t dm (dry matter). Taking 20% the dry biological waste (wood, garden, and paper (0.2*1.29Mt=0.258) from landfills and assuming an 75% biochar carbon content (biochar tends to be 70-80% carbon).
[71] (1.29/2.9Mt)*3.65MtCO2e*0.2=0.32Mt CO2e
[72] This includes the initial plant capital and a 20 year operating life, see: (Jones & Camps, 2019)
[73] FIT has shown more soil organic carbon than No-till at 21-35cm soil depth.(Angers & Eriksen-Hamel, 2008)
[74] (Pereira et al., 2019)
[75] The estimate assumes 10% farmer adoption (i.e. 367,000 ha, or 6% of New Zealand HPG) and 10% annual pasture renewal. See (Lawrence-Smith et al., 2015)
[76] (Meduna, 2017)

Option	Opportunities and challenges
	Avoiding further draining or destruction of the few remaining peatlands and wetlands would avoid emissions in Aotearoa. Restoring drained peat soils and wetlands (including on-farm) could potentially make a modest contribution but further research on this is needed to quantify it.[77] Peat and wetland restoration costs include the costs of native species planting and fencing and vary by region.[78] Maintaining and restoring wetlands also has cultural benefits. For example, many Māori have strong historic and cultural links with wetlands, which are taonga that could be enhanced through their restoration. They can be important habitats for native species and sources of traditional building and weaving materials, medicines, and food.[79]

5.2.3 Limits to removals from forests and risk of reversal

Relying on forests to reach net emissions targets poses challenges, as continuous levels of afforestation would be needed to maintain similar levels of mitigation year on year. Over time the area suitable for new forest establishment would decrease and the newly planted forests would reach their long-term average carbon store, no longer contributing towards targets. There is also an ongoing global risk that the carbon stored in forests could be re-released back into the atmosphere if forests are destroyed or damaged.[80] If the forest is not replaced, this results in a net increase of carbon dioxide in the atmosphere. Future decision makers in Aotearoa could decide to change land-use away from forest, in which case the carbon stored would be re-emitted.

Natural hazards such as wind, fire or pests can also destroy established forests and these are expected to increase as the climate changes.[81] Recent international examples show how vulnerable some forests can be to these kinds of threats and the potential climate impacts of large-scale destruction of forests. The bushfires in Australia in the summer of 2019/20, for example, are estimated to have approximately doubled Australia's emissions for 2019.[82] In Canada, an outbreak of Mountain Pine Beetle in the early 2000s destroyed hundreds of thousands of square kilometres of forest in British Columbia and by 2020 was expected to have led to the release of 270Mt of carbon into the atmosphere.[83] The native forests of Aotearoa are currently under threat from two pathogens, kauri dieback and myrtle rust, which pose significant threats to the survival of many species. Some native trees and shrubs are less susceptible to fire risks, while others are more susceptible.[84]

[77] (Burrows et al., 2018)
[78] For example, in a plan for wetland restoration near the Ōtākaro Avon river, capital costs ranged between $20,000 and $100,000/ha (Regenerate Christchurch, 2018)
[79] (Harmsworth, 2020)
[80] (Anderegg et al., 2020)
[81] (A Reisinger et al., 2014)
[82] (Global Fire Database, 2020)
[83] (Kurtz et al., 2008)
[84] (Wyse et al., 2016)

Forests are likely to become increasingly vulnerable to natural hazards and adverse effects as the impacts of climate change unfold. For example, it has been estimated that as air temperatures rise over time, the number of days with very high and extreme fire danger at forested sites across Aotearoa would increase 70% by 2040.[85] Likewise, the range of many damaging pests and pathogens is likely to increase as climate changes.

Increased air temperature is likely to increase the intensity and irregularity of rainfall, while winter wind speeds are also projected to rise. This would likely lead to more flooding and higher rates of windfall in both native and exotic plantation forests.[86] Some areas are expected to experience more droughts, which could also lead to increased forest losses.

The New Zealand Climate Change Risk Assessment[87] concluded that climate change will have long-term impacts on the integrity and stability of forest ecosystems and species in Aotearoa. The evidence on the risks on tree physiology and broad-scale studies is however limited. Risks for both native and planted forest (the latter as part of land-based production systems) were considered to be 'moderate' by 2050 and to be 'major' by 2100. Important knowledge gaps remain in terms of the speed of impacts, geographic variation and the susceptibility of ecosystem and species.

Accounting rules could potentially allow the release of carbon from major natural events like fire and windstorm to not be counted towards targets and emissions budgets. However, these rules would require forests to be replanted and would prevent further emissions removals by them from being counted. This is discussed further in *Chapter 3: How to measure progress*.

Forest management practices need to consider the risks outline above through a portfolio of alternatives suited to the site conditions and future climate, such as species choice and harvesting techniques (see Table 5.1).

5.2.4 Land available for forestry

The scale of land suitable for plantation forestry

There is a large amount of land across Aotearoa which could be suitable for afforestation. For example, in 2019 Te Uru Rākau's mapping estimated that up to 3.3 million hectares of non-forest land (typically low-producing pasture) could be suitable for afforestation.[88] To put this in context, the Productivity Commission estimated that between 2.0 to 2.8 million hectares of planting could be required to achieve net zero all gases by 2050.[89]

In practice, not all of this land is suitable for planting commercial forests. For example, steep slopes and distance from ports and processing sites cam make harvesting difficult or uneconomic in some places. RMA legislation prevents commercial forestry activities on some steep slopes to avoid environmental impacts such as erosion and flooding.[90] For erosion prone land, establishing

[85] (Watt et al., 2019)
[86] (Parliamentary Commissioner for the Environment, 2019)
[87] (Ministry for the Environment, 2020b)
[88] Te Uru Rākau estimations cited in (Manley, 2019, p. 33)
[89] (New Zealand Productivity Commission, 2018)
[90] (Ministry for Primary Industries, 2020a)

permanent forest or letting land revert to native forest is likely to be a more feasible option. There could be 1.15 to 1.4 million hectares of highly erodible land in Aotearoa suitable for forestry, though these estimates are preliminary.[91]

The relative profitability of different land uses also affects how a piece of land is used. This changes over time depending on market forces and other factors.

Landowners base decisions about what to do with their land on many factors. Even if forestry is the most profitable land use option at a given point in time, some landowners are likely to maintain existing, non-forest, land uses for other reasons. The availability of land for forestry is ultimately a landowner decision.

Trees on farms

Not all of afforestation is likely to occur at large scale. There are many small pockets of land across the country which may be suited to relatively small scale afforestation, or to being fenced off and left to regenerate into native forest. On some farms, trees may be able to be integrated into the farming system, for example, in the form of agroforestry. Trees on farms also provide other benefits such as animal shelter and erosion control. However, not all carbon removals by small scale planting are currently recognised in international and/or domestic accounting.

Farmers already plant trees on their land for many reasons, including riparian plantings along waterways and to create shelterbelts. There is also a proportion of land across farms that is not very productive for livestock farming. A recent study found that, based on net present value analysis, 56% of the low-productivity non-dairy grasslands in the country are likely to financially benefit from afforestation.[92] Beef + Lamb NZ estimated that forestry is likely to be more profitable, on an annuity basis, than (roughly) the bottom 30% of farms.[93]

Estimates of how much of this type of land is available vary but are commonly in the order of 5% of farmland. This is predominantly on sheep and beef farms.[94] Overall, there is insufficient data to quantify the extent of land currently being farmed which is considered marginal and suitable for afforestation, though it could be significant.

Planting on Crown land

There may also be scope for some afforestation on government-owned land. Planting trees on Crown land, including the conservation estate, land held by the Ministry of Defence and land held by the New Zealand Transport Agency could provide a carbon sink. The Department of Conservation

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[91] (Mason & Morgenroth, 2017; Ministry for Primary Industries, 2018; Stats NZ, 2019)
[92] (West et al., 2020)
[93] (Andy Reisinger et al., 2017, p. 50) (Andy Reisinger et al., 2017, p. 50)
[94] Research for the Biological Emissions Reference Group (Andy Reisinger et al., 2017) modelled the effect of planting forests on the most marginal 3-5 % of a farm, but made no assumption of how or whether this could be scaled up nationally (BERG, 2018). In the Cabinet Paper for the Billion Trees Programme, MPI identifies about 4 million hectares of lower producing farmland that could potentially be planted (Ministry for Primary Industries, 2018),

estimated that 59,000 ha of Crown land would be suitable for afforestation, about 29,000 ha of these would be blocks of 50 ha or more in size.[95]

5.3 Carbon capture and storage

There is increasing international interest in the use of carbon capture and storage to meet climate change targets and obligations. For example, most of the pathways the IPCC modelled with no or limited overshoot of the 1.5ºC target relied on large-scale deployment of emissions removal technologies after 2050. The pathways which assume slower reductions in gross emissions from fossil fuel use require removals to scale up to around a third of current global carbon dioxide emissions levels by 2050. There is significant risk that the scale of carbon capture and storage (CCS) technologies required in some of the IPCC's modelled pathways may not be feasible. Globally, there are 21 facilities in operation, three under construction and 35 in various stages of development.[96] Most of these facilities are associated with coal power generation or oil and gas production.

CCS and CCS-based emissions removal options are relatively expensive, emerging technologies with highly variable, site-specific costs tailored to the region's geology. The costs of CCS are influenced by several factors, including concentration of carbon dioxide in the emissions stream, type of capture technology, transport distance to the storage site, presence of existing well and pipeline infrastructure and the energy demand of the process.[97]

In Aotearoa, CCS technology has not progressed beyond the concept and research stage. This is because forestry is currently a lower cost emissions removal option and because zero to low emissions substitutes for fossil fuel combustion for energy are increasingly economic at current policy settings. For fossil fuel use as a feedstock or reductant, zero to low emissions alternatives to achieve gross emissions reduction are being investigated domestically and internationally. As such, interest in CCS has been limited. It is unlikely it would be required to meet our climate change targets and obligations. However, it may play a role in the latter half of the century to maintain net zero emissions in a 1.5˚C compatible pathway and to address residual emissions from hard to abate sectors.

5.3.1 Options for increasing carbon removals through emissions capture

For sectors with hard to abate emissions, such as cement and lime manufacturing, geothermal power generation and ongoing nitrous oxide emissions from agriculture, CCS might be an option in the latter half of the century to maintain net zero emissions in Aotearoa.

Post-combustion carbon capture technology can 'bolt-on' to a conventional industrial plant to capture up to 90% of the emissions stream. Reinjection of fugitive emissions from geothermal power generation and oil and natural gas extraction activities back into the producing field or a nearby

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95 Desktop estimations only that require ground-truthing (Department of Conservation, 2017). The Department of Conservation asked that this estimate should be caveated and noted that the purpose of Public Conservation Land is incompatible with exotic forestry (sub. DR370 to Productivity Commission) (New Zealand Productivity Commission, 2018).

96 (Global CCS Institute, 2020)

97 There are additional costs associated with reservoir mapping, injection, well operation and ongoing monitoring and compliance activities.

storage location is a mature and technically feasible emissions removal option that could be deployed in Aotearoa.

Depleted or producing (oil and) gas fields in the Taranaki region may offer significant storage potential. For example, a 2016 study[98] estimated the total storage potential to be roughly 15,000Mt CO_2. The achievable storage potential would require detailed field assessments but is likely to be significantly less. The primary advantage of these fields over other potential storage sites is that they are well understood geologically and have existing infrastructure which may be adapted for CCS. Given the location near an active plate margin, additional research and analysis would be needed to fully understand and assess the feasibility for permanent storage and risk of reversal from natural disasters such as earthquakes.[99] Additional research would also be required to better understand the potential for induced seismicity and interactions with other subsurface activities.

There are a range of existing regulatory mechanisms and carbon accounting rules which do not currently incentivise the development of CCS. They do not fully account for the environmental, health and safety, access to land, and mineral and property rights associated with the process. There may also be a perception that CCS is merely a means to prolonging the emissions stemming from fossil fuel production activities and fossil fuel combustion for energy, which would be in conflict with ambitions to reduce gross emissions.

CCS and other CCS-based emissions removals options requires consideration around the potential value and roles of land use in climate change. Similar to other infrastructure or plant developments, assessment of ecological and environmental impacts would be required to ensure alignment with broader national government or community objectives. Particularly for bioenergy with CCS, increased competition for land and resources may impact the ability for sectors to decarbonise through the use of biofuels and may remove land from food production. There may also be additional considerations in order to fulfil obligations under Te Tiriti o Waitangi including land and water (taonga) use and allocation, kaitiakitanga and traditional hunting and fishing grounds.

CCS applications can leverage different emissions capture approaches and technologies. These approaches are discussed briefly in the table below. While there is increased international interest in these approaches, there remains considerable uncertainty as to their potential achievable contribution to Aotearoa reaching net zero emissions in practice.[100]

Table 5.2: Options for increasing carbon removals through emissions capture

Option	Opportunities and challenges
Reinjection of geothermal gases and other fugitive emissions	Reinjection has potential to reduce fugitive emissions from geothermal power generation and oil and natural gas extraction. Geothermal fluid contains mostly carbon dioxide with small volumes of methane and hydrogen sulphide. During operation of a geothermal power

[98] (Field, 2016)
[99] (Field, 2016)
[100] (IEA, 2020a)

	plant some of the gases can become separated from the geothermal fluid as a result of changes in temperature and pressure when the fluid is extracted. The gases are released to the atmosphere as a part of the power generation process.[101] It may be possible to reinject some or all of the gases from geothermal power generation and oil and natural gas extraction sites back into the producing field or reservoir or a nearby storage location. The economics and technology for emissions capture and reinjection would depend on the composition of the gases released, the pressure of the gas at the outlet or wells and the volume of gases released. Additional costs may be incurred from the need to site new suitable reinjection wells, increased field monitoring and management and the potential alteration of, or interaction with, the chemistry of producing reservoirs. Reinjection technologies and practices are a deployable emissions reduction option in Aotearoa.
Bioenergy with carbon capture and storage (BECCS)	BECCS is the combination of two capture options: increased biological uptake through forests and plants (biomass) and engineered direct emissions capture. The biomass is harvested and then combusted to generate energy in the form of heat, power or processed into liquid biofuels. The emissions from combustion or processing activities are captured through post-combustion carbon capture technology and then compressed, transported, injected and stored. BECCS is an emissions removal option which could provide net negative emissions. In order to be considered net negative, the emissions associated with production and combustion (or processing) of biomass, emissions capture and transport cannot exceed the amount of emissions removed through biological uptake.[102] The biomass must also originate from sustainably managed forests in order to be considered carbon neutral.[103] Biomass is a key emissions reduction opportunity across industry and transport. Increasing competition for biomass and land through BECCS may increase prices and limit availability. This could constrain the uptake

[101] (New Zealand Geothermal Association, 2019)
[102] (Fajardy & Köberle, 2019)
[103] Woody biomass is considered carbon neutral as the carbon dioxide released during combustion is equivalent to the amount absorbed by the tree during growth. If the wood originates from sustainably managed forests, then this is a renewable energy source.

	of biomass to displace fossil fuels for combustion for energy. Clear government signals and coordination is required to prioritise the resource for its most valuable end-uses across the economy, in terms of displacing emissions. Doing so in a coherent and planned manner may lessen some of the effects of competition.[104] Deployment of BECCS may be further limited by competition for land, potential impacts on water, biodiversity, soil health and social equity (particularly in rural communities).[105] Deploying BECCS as part of a suite of measures could lessen some of these potential impacts.[106] While there is increasing international interest and development of CCS applications, BECCS is a relatively expensive and emerging technology. Deployment of BECCS would be dependent on the coordination of multiple areas of the economy, such as forestry, industry, communities, and government. Given the relatively dispersed nature of large point sources of emissions and bioenergy resources in Aotearoa, cross-sectoral collaboration would be critical to establish the shared infrastructure and investment required to deploy BECCS. An alternative approach to emissions removal through increased biological uptake is through increased use of durable engineered wood products in the built environment. The duration of emissions removal would be limited to the life of the building. *See also Chapter 4b: Reducing emissions – opportunities and challenges across sectors: Transport, Buildings and Urban Form.*
Direct air capture with carbon capture and storage (DACCS)	Direct air capture is the direct engineered capture of carbon from the atmosphere. It involves passively or actively passing large volumes of air over a liquid or solid compound to adsorb (chemically bond) carbon dioxide from the atmosphere. The carbon dioxide is then separated and regenerated with heat, water or both and released in a more concentrated form.[107,108] Once released, the emissions are captured, compressed, transported, injected and stored. DACCS requires a large volume of air flow for a relatively small amount of carbon dioxide capture. Different technologies can be used for direct air capture and adsorption, but the processes all have high energy or heat and water requirements[109] which may be supplied from renewable

[104] (Committee on Climate Change, 2018)
[105] (Fajardy & Köberle, 2019)
[106] (The Royal Society & Royal Academy of Engineering, 2018, p. 8)
[107] (The Royal Society & Royal Academy of Engineering, 2018, p. 59)
[108] (IEA, 2020b)
[109] (IEA, 2020b)

	sources or waste heat depending on project design and location. As with other CCS-based emissions removal options, DACCS has implications on resource use. Globally, DACCS is a developing technology with a limited number of pilot projects. Costs are highly variable but generally expensive.
Carbon capture and utilisation (CCU)	As an alternative to storage, the captured carbon dioxide can be used in other industrial processes or products. There are three main categories of carbon dioxide-based products: fuels, chemicals and building materials. Conventional use of captured carbon dioxide includes production of carbonated beverages and to enhance photosynthesis in hot houses. An emerging application is the production of low carbon concrete. Carbon dioxide can be added and absorbed into concrete during the curing process. This may reduce the amount of cement required to produce equivalent-strength concrete with the benefits of improved durability.[110] However, this may affect the curing time of concrete which can have economic impacts on the end user which could outweigh the emissions reduction benefits and limit uptake. Uptake may also be limited by perceptions of risk in using new products, difference in cost between products and limitations within New Zealand Standards regarding blended cement and concrete products. Another potential application of CCU is in the production of petrochemicals (urea and methanol) where a pure carbon dioxide source can be used in conjunction with green hydrogen. The carbon dioxide source could be supplied from the Kapuni Gas Treatment Plant where it is stripped out from the natural gas during processing. The Kapuni gas field contains a concentration of about 44% carbon dioxide. The extent to which CCU removes emissions is highly dependent on the source of the emissions stream, the category of carbon dioxide-based product it is used in and the lifetime of the product. The deployment of CCU is also dependent on uptake of carbon capture to provide a long term supply of carbon dioxide to produce carbon dioxide-based products. Globally, CCU is an emerging technology with a limited number of pilot projects. Costs are highly variable but generally expensive. *See also Chapter 4a: Reducing emissions – opportunities and challenges across sectors: Heat, industry and power (Industrial Processes and Production).*

[110] (Energy Transitions Commission, 2020)

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