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In a Nutshell!

What are negative emissions and why do we need them?

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In a Nutshell!

If global warming is to be kept below 2°C, and ideally to 1.5°C, some of the carbon dioxide (CO_2) we emit will need to be removed from the atmosphere. This is the conclusion that has been drawn from the climate models of the Intergovernmental Panel on Climate Change. The removal of CO_2 from the atmosphere is also referred to as "negative emissions".

Afforestation is one tried and tested means of removing CO_2 from the atmosphere. However, forest fires and pests can cause the carbon sequestered in this way to escape back into the air – and as climate change accelerates, the risk of this happening is growing. Another drawback of afforestation is that it requires large areas of land.

Other CO_2 removal methods are (still) very costly, and some require further research. The first commercial plants for removing CO_2 directly from the air are already operational. Although they don't require a lot of land, they do use a lot of energy. The captured CO_2 is stored underground.

We do not yet know exactly how much CO_2 can be permanently removed from the atmosphere using these different methods, or how much it might cost. Climate models make it clear that although **some negative emissions will be necessary, they should complement** rather than replace ambitious measures to prevent CO_2 emissions. CO_2 removal could be used to capture a limited amount of unavoidable greenhouse gas emissions, primarily from agriculture and certain industries. However, this does nothing to change the fact that we must stop using coal, gas and oil as soon as possible.

What are negative emissions?

There are two approaches to limiting the amount of greenhouse gases in the atmosphere:

- The first approach focuses on **preventing greenhouse gas emissions**. The quantity of greenhouse gases entering the atmosphere is reduced by replacing high-emission technologies or using energy more efficiently. Examples include the replacement of fossil fuels by renewable energy, and energy efficiency technologies such as building insulation, that reduce the amount of energy we consume. Until now, most climate measures have focused on preventing greenhouse gas emissions[1] rather than on removing CO_2 from the atmosphere.
- **CO_2 removal** involves extracting carbon dioxide from the air. This approach is also referred to as "negative emissions"[2], since it reduces the amount of CO_2 in the atmosphere[3]. Despite the name, the climate impact of negative emissions is in fact extremely positive. The best-known example of negative emissions is afforestation, where trees capture carbon and store it as wood.

When talking about "negative emissions", it is important to draw a careful distinction between gross and net values. "**Gross positive emissions**" means the amount of greenhouse gases that enter the atmosphere, while "**gross negative emissions**" means the amount of greenhouse gases removed from the atmosphere. The term "**net emissions**" refers to the difference between the two. Positive net emissions occur if the amount of greenhouse gases entering the atmosphere exceeds the amount that is removed, causing a further build-up of these gases in the atmosphere. Negative emissions occur if the amount of greenhouse gases removed from the atmosphere exceeds the amount emitted, causing their atmospheric concentration to decline.

1 As well as CO2, there are various other greenhouse gases such as methane and nitrous oxide. While solutions exist for preventing at least some emissions of all greenhouse gases, CO2 is currently the only greenhouse gas for which removal techniques are being developed.

2 The Intergovernmental Panel on Climate Change (IPCC) defines negative emissions as the removal of greenhouse gases from the atmosphere by deliberate human activities, i.e. in addition to the removal that would occur via natural carbon cycle processes.

3 In this context, "negative" refers to a number below zero, i.e. one preceded by a minus sign.

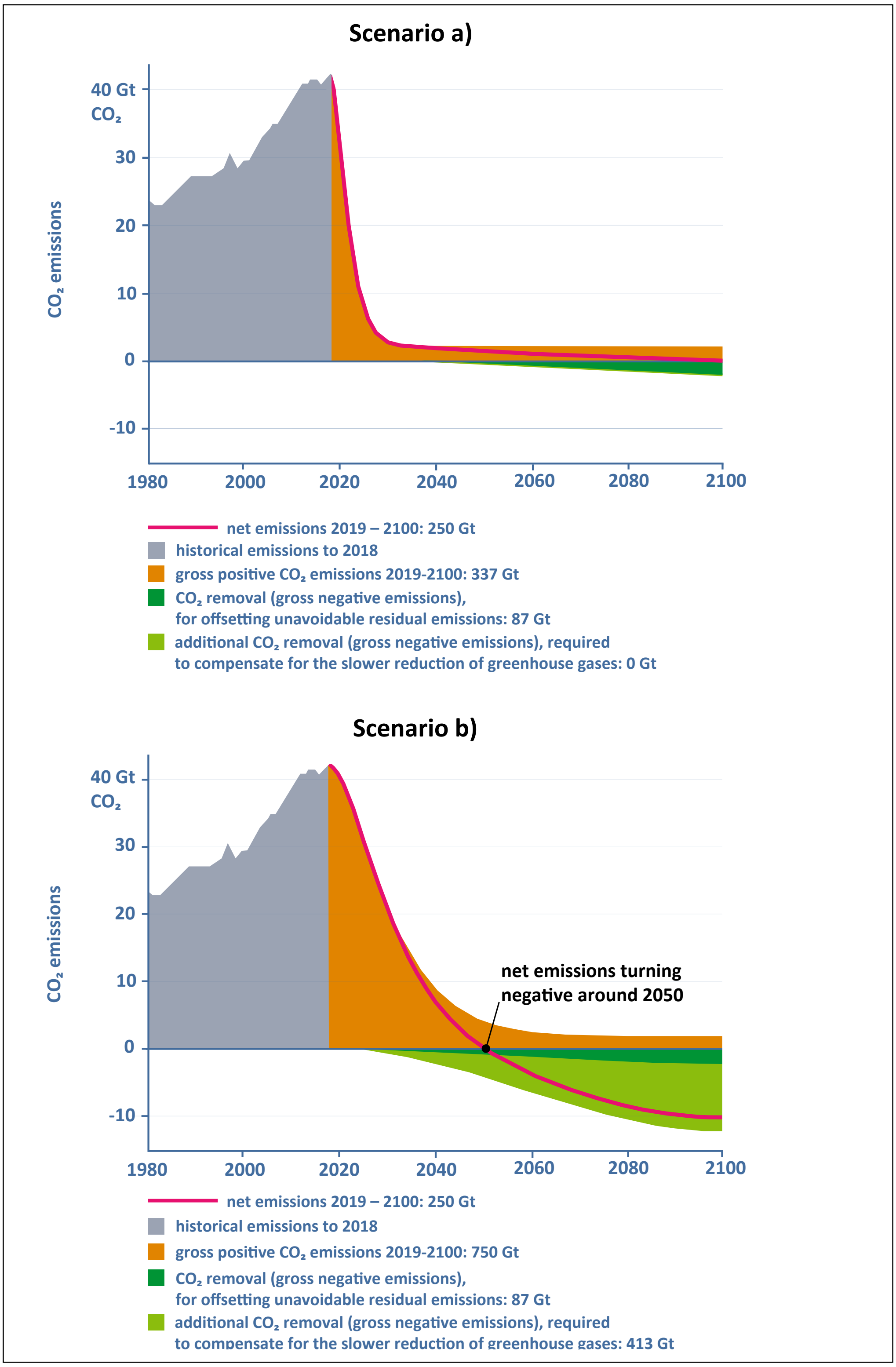


Figure 1: Two global scenarios for reaching the 1.5°C goal. In Scenario a) the demand for CO_2 removal is reduced to a minimum by immediate and drastic reductions of CO_2 emissions. In this scenario, only the unavoidable residual emissions need to be compensated. In scenario b) the CO_2 emissions are being reduced at a slower pace. In order to reach the 1.5°C nevertheless, massive CO_2 removal is required in the second half of the century. The graphs only cover CO_2, other greenhouse gases are not included. Sources: This graphic was published in adapted form in Fuss et al. 2020 [1] (Copyright Elsevier).

As well as the direct emissions from burning fossil fuels, humans are responsible for various other types of greenhouse gas emissions. Particularly methane and nitrous oxide from agriculture and waste management play an important role. Deforestation and the drainage of peatlands for agriculture cause emissions. Climate change itself can also lead to additional greenhouse gas emissions, for example when desertification kills off vegetation, or when melting permafrost releases methane into the atmosphere. To achieve greenhouse gas neutrality[4], these greenhouse gas emissions must also be offset by CO_2 removal.

According to the IPCC, we will need to achieve global greenhouse gas neutrality by 2070-2100 if we are to meet the 1.5°C target [2].[5] By this date the total amount of CO_2 removed from the atmosphere would need to be equal to total global greenhouse gas emissions. But in order to do this, we will have to start removing CO_2 from the atmosphere much sooner. In other words, we need to achieve gross negative emissions long before 2050. Moreover, in the second half of this century, the amount of CO_2 removed from the atmosphere will need to be greater than the amount emitted, i.e. we will need to achieve net negative emissions. The extent to which CO_2 removal is required also depends on how quickly emissions of the greenhouse gases methane and nitrous oxide are reduced.

There is some dispute about whether climate targets set by policymakers should be based on gross or net emissions. Reducing gross emissions to zero would mean that no greenhouse gases must be emitted at all, which is not possible for example in agriculture. A net zero target means that greenhouse gases can still be emitted, but the emissions must be fully offset by CO_2 removal. The Intergovernmental Panel on Climate Change concludes: "*The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved*" [2].

An important question is to what extent negative emissions ought to be set off against positive emissions. If solely a net emissions target is formulated, it remains unclear how much of it should be achieved through emission reduction and how much through CO_2 removal. This leads to the risk that cheap CO_2 removal methods such as afforestation will be preferably employed over more expensive options to reduce emissions. Hence, the efforts to avoid emissions may slacken. This dilemma can be resolved by setting separate, explicit targets for both approaches. The controversy surrounding this issue can be traced back to differences of opinion about whether negative emissions are truly equivalent to avoided emissions. For example, is burning oil and storing the resulting carbon underground or offsetting it through an afforestation project really just as good as simply leaving the oil in the ground? A closer look at the different CO_2 removal methods can help to answer questions like this. As well as the costs, it is also important to consider the potential risks and environmental impacts associated with CO_2 removal. This makes it possible to compare scenarios that include CO_2 removal against scenarios that exclude it and rely instead on more drastic emission prevention measures.

4 "Greenhouse gas neutrality" includes all greenhouse gases, not just CO2. The term "climate neutrality" is also frequently used.

5 See [2], Table SPM.1 and Figure SPM.5. In these scenarios, CO2 emissions reach net zero by around 2050-2060, much earlier than other greenhouse gases such as nitrous oxide and methane.

How do you remove carbon dioxide from the air?

There are various methods that can be used to remove CO_2 from the air. The main differences lie in how the CO_2 is extracted from the air and in the long-term storage method used to ensure that the carbon is kept out of the atmosphere permanently. Table 1 provides an overview of the different methods. For a detailed discussion of the various techniques, their cost, and their potential for deployment on a global scale, see [3]. For potentials in Germany, see [4] and [5].

CO_2 makes up just 0.04 % of the Earth's atmosphere. This means that to remove one cubic metre or 1.96 kg of CO_2, you need to "filter" at least 2,500 cubic metres of air. Even if your filters were 100 % efficient, you would need roughly 1.27 million cubic metres of air to extract just one tonne of CO_2. Technical appliances for removing CO_2 from the air are expensive and use a lot of energy. Consequently, many CO_2 removal methods harness natural processes in which CO_2 is removed from the atmosphere by plants, which use sunlight to convert the CO_2 into carbon-rich compounds. Depending on how the CO_2 is captured from the air, there are various long-term storage solutions for the sequestered CO_2 – it can be stored as wood in trees, in the soil, in rock (through chemical bonding processes), or by injecting it underground. Some methods focus on amplifying or accelerating predominantly natural biological processes, whereas others rely to a greater or lesser extent on technology.

Storing carbon in vegetation and the soil is often perceived as less risky because it is a "natural" solution [6]. However, in most cases it is actually a less reliable long-term storage solution than injecting the CO_2 underground. Forest fires, droughts or pests can cause the CO_2 to be released back into the atmosphere – and the risk of this happening is exacerbated by climate change ([7] Chapter 7; [8] p. 12; [9] p. 57). Deforestation and mismanagement of carbon-rich soils can also release stored CO_2 back into the atmosphere, which is why it is so important to ensure that natural carbon sinks are permanently protected. In addition to the storage of carbon in vegetation and the soil, the restoration of ecosystems damaged by human exploitation – such as woodland, grassland and peatlands – has a number of other environmental benefits. As well as protection against erosion, these may include positive impacts on biodiversity, the water supply and the local climate [9].

Up until a few years ago, the injection of CO_2 underground was primarily seen as a means of storing carbon from coal-fired power generation and industrial processes such as steel and cement production. Known as Carbon Capture and Storage (CCS), this approach prevents CO_2 emissions but does not deliver negative emissions. However, negative emissions are achieved if the CO_2 injected underground has been removed from the atmosphere or if it originates from biomass. The technical processes for transporting, injecting and storing CO_2 from these sources are largely the same as for CO_2 from other sources. This makes it possible to build on the lessons learnt from the use of CCS in power plants and industry. In the case of bioenergy facilities, the processes for capturing the CO_2 are also largely the same as for power plants and industrial processes. For capturing CO_2 directly from air, however, specialized separation techniques are required due to the very low CO_2 concentration of the air. Although the individual stages of carbon capture, transport and (underground) storage (CCS) are ready for deployment on an industrial scale,[6] the development and market rollout of CCS technology has advanced far more slowly in recent years than projected in scenarios modelled five to ten years ago [10;11].[7] In Germany, there is still widespread and extremely vehement public opposition to the underground storage of CO_2, and the construction and operation of demonstration plants has had to be halted due to local protests [12]. This opposition can be partly attributed to the technology's association with coal-fired power generation – surveys have found that people are more willing to accept it if the CO_2 comes from industrial processes or biomass plants [13].

Another key issue in the public debate concerns the risks associated with storing CO_2 underground. The potential risks include small, local earthquakes, infiltration of saline water into groundwater, and CO_2 leakage. In the event of leaks, some of the stored CO_2 escapes back into the atmosphere, diminishing the effectiveness of the CO_2 removal process [14;15]. However, many experts believe these risks to be minor, provided that projects are well-managed and carried out at appropriate locations with professional risk management.[8] Despite this, many civil society actors, especially in the environmental sector, reject CCS on the grounds that it is too risky ([16], p. 49).

It is important to distinguish between CCS and carbon capture and utilisation (CCU, see box), which has not attracted the same level of public opposition.

Carbon Capture and Utilisation (CCU) is not a CO_2 removal technology, but could form part of a carbon cycle.

Instead of being injected underground, CO_2 that has been captured from the air or from biomass can be used to produce fuel or chemicals. However, this does not result in negative emissions. The CO_2 will be released back into the atmosphere when the fuel is burnt or at the end of the product's lifecycle. Therefore, even in the case of using CO_2 from air or biomass, CCU's overall impact is CO_2-neutral at best – it does not result in negative emissions. A relevant temporary CO_2 removal effect is achieved if the CO_2 is used to produce very long-lived building materials that store the carbon for several decades. If CO_2 is obtained not from biomass or air capture but from fossil fuels or chemical processes in cement production, the overall process is not CO_2-neutral. The release of the CO_2 into the atmosphere is just delayed by the technical lifespan of the products made from it with CCU. However, CCU reduces total emissions if the reused CO_2 replaces fossil fuels.

Most CO_2 removal methods are still at a very early stage in their development. Exactly how much CO_2 could they remove from the atmosphere and how long would it take? What would it cost? How much energy is required? And what would the environmental impacts be? While scientists are able to make some preliminary estimates, there are still major gaps in their

6 Various carbon capture technologies are technically proven and ready for market, but have not yet been incorporated into the relevant plants. The United States in particular has extensive experience of transporting CO2. Long-term storage solutions have been tested, and ample experience with injecting CO2 has been built up in projects aimed at increasing oil deposit yields [16].

7 For example, a roadmap published by the International Energy Agency in 2009 projects that there will be 100 CCS plants by 2020 [10]. In actual fact, in November 2020 there were just 26 operational plants with a capacity of 0.04 gigatonnes a year [11].

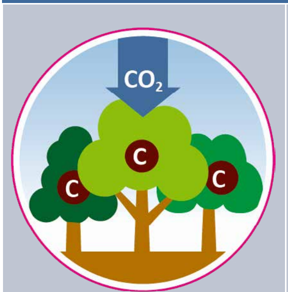
8 For instance, an acatech task force concluded that, from a scientific perspective, CCS is essentially a low-risk, controllable technology [16].

knowledge. However, we can say that many of the solutions for removing large quantities of CO_2 from the atmosphere face serious challenges. The technology-based solutions require high levels of investment in the necessary facilities and often consume large amounts of energy, while carbon sequestration by plants generally requires large areas of land. This could lead to land use conflicts with food production, especially in view of the inevitable changes in agriculture due to climate change and the biodiversity crisis. The emergence and extent of land use conflicts will largely depend on whether the same land can be used simultaneously for CO_2 removal and agriculture, and whether the land is suitable for agriculture in the first place.

The environmental impacts vary on a case-by-case basis, depending on which tree or plant species are planted and on the pre-existing ecosystem. Planting trees or energy crops such as maize or oilseed rape as a monoculture for CO_2 removal could have a harmful impact on biodiversity, while the use of fertilisers could also cause soil and water contamination [9]. However, a natural mix of native tree species can often have a positive effect on biodiversity. Especially if it contributes to the restoration of badly damaged or destroyed ecosystems such as woodland, grassland and peatlands, it is possible for CO_2 removal to benefit biodiversity without necessarily causing land use conflicts with agriculture. However, there are limits on how much CO_2 can be removed from the atmosphere using this approach [9]. Moreover, it will take a long time before any of the options can start making a meaningful contribution to protecting the climate.

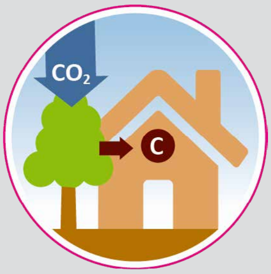
Technological solutions cannot be implemented until commercial plants have been developed and built at scale. And although afforestation projects could begin immediately, the amount of CO_2 removed from the atmosphere depends on the trees' growth rate. All the methods have their pros and cons, and their suitability varies from one part of the world to another. Consequently, it will probably be necessary to employ a mix of CO_2 removal methods.

Options for removing and storing carbon

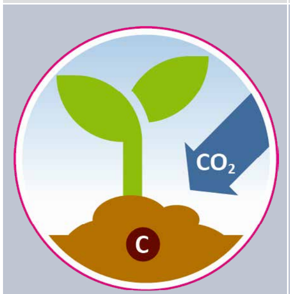


Afforestation: Trees capture carbon from the atmosphere and store it as wood. The advantage of this approach is that tree planting is relatively cheap and doesn't need complex technology. One drawback is that it requires large areas of land: around a quarter of agricultural land in Germany would have to be planted with trees in order to offset all of Germany's unavoidable emissions as estimated by the German Environment Agency.[9] Moreover, there is no guarantee that the carbon will remain permanently stored – forest fires or pests can cause the sequestered carbon to be released back into the atmosphere as CO_2, and the risk of this happening is exacerbated by climate change. Using the wood for bioenergy or for producing short-lived products will also release the CO_2 into the atmosphere. A further drawback that reduces the climate benefits of afforestation is that woodland absorbs more energy than fields and grassland because it reflects less sunlight. Finally, the fact that changes in vegetation also affect the soil carbon budget means that the climate impact of afforestation projects also depends on the type of vegetation that was present before the project began.

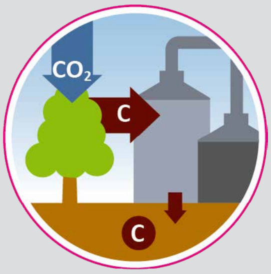
9 The assumptions underlying the land and energy use estimates for the different methods are described in detail in [19]. They are based on the assumption in [25] that approximately 5 % of emissions in Germany are unavoidable and will need to be offset by CO2 removal. These are very rough estimates that are only intended to illustrate the scale of what is required.



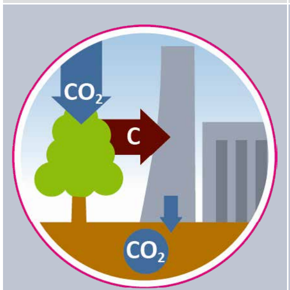
Building with wood: Instead of leaving the trees in the forest, their wood can be harvested and used to make long-lived products such as buildings and furniture. The carbon will remain sequestered until the product is disposed of and burnt – in the case of buildings, this will usually not be for several decades. Timber can replace other, more carbon-intensive building materials such as steel and concrete, thereby achieving a further reduction in CO_2 emissions [17]. Moreover, harvesting the wood frees up space to plant new trees which can then sequester more CO_2. This is important – over time, old, unmanaged woodlands reach an equilibrium where the amount of CO_2 sequestered is only enough to offset the amount of CO_2 released by rotting dead trees.



Soil carbon sequestration: Certain land management practices allow carbon to be stored in the soil. Examples include some types of crop rotation and no-till farming. This approach differs from afforestation in that the land can still be used for agriculture. Moreover, it can potentially improve the soil's ability to store water and nutrients. However, in order to store the carbon permanently, it is vital to employ long-term soil management practices that ensure its retention in the soil. A return to conventional management practices would cause the carbon to break down again and be released as CO_2. After a period of between a few years and several decades, the soil becomes saturated with carbon and cannot sequester any more CO_2. Climate change is once again a risk factor, since rising temperatures cause an increase in soil CO_2 emissions [8].



Biochar: When plants die and decay, they release the CO_2 stored inside them back into the atmosphere. By processing them into biochar, it is possible to prevent them from decomposing so that the carbon compounds can be permanently stored. Biochar is a type of charcoal produced by heating biomass to high temperatures in the absence of oxygen. Other than traditional charcoal biochar can be made from materials other than wood, such as plant waste. Biochar production generates energy, although usually only enough to power the production process itself. Incorporating biochar into the soil can improve its ability to store water and nutrients. However, there may also be negative impacts if the biochar is not carefully matched to the soil. More research is needed in this area and into how long biochar really remains stable in the soil.



Bioenergy with carbon capture and storage (BECCS): Biomass such as energy crops, wood waste and other types of organic waste can be burnt to produce electricity or heat. In BECCS, the sequestered CO_2 that is released when the biomass is burnt is captured in the bioenergy plant and stored underground (carbon capture and storage – CCS). As well as the negative emissions, an added benefit of this approach is that it generates energy, whereas other CO_2 removal methods consume energy, sometimes in large quantities. The entire process chain has only been technically proven at scale in the production of ethanol from maize – further research and development is needed for other processes. Because bioenergy plants are generally small and decentralised, transporting the captured CO_2 is logistically complex and expensive. Moreover, the cultivation of timber or energy crops for use as biomass feedstock is associated with various environmental risks and potentially also the same land use conflicts with food production that occur with afforestation projects [18]. However, these challenges do not arise if organic waste is used.

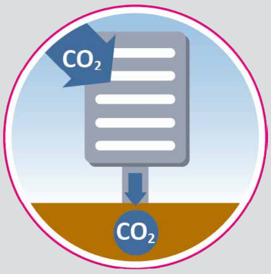
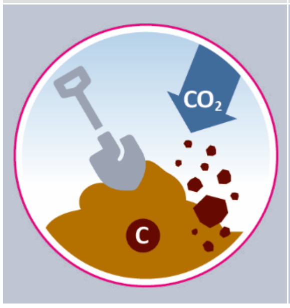
	**Direct Air Carbon Capture and Storage (DACCS):** Instead of plants, this approach uses technology to capture the CO_2, which is removed from the atmosphere with the aid of chemical binding agents. Separating the CO2 from the binding agent requires energy. The CO2 is then stored underground (CCS) and the binding agent is reused. One advantage of this technological approach is that it requires far less land than other methods. It can also be deployed in locations that are unsuitable for growing crops and timber, such as deserts. However, because CO_2 only makes up a small percentage of the Earth's atmosphere, the technology has to filter a huge amount of air. This is expensive and uses a lot of energy. Over 100 terawatt-hours of energy a year could be needed to offset Germany's unavoidable emissions as estimated by the German Environment Agency [19]. That is equivalent to around one sixth of Germany's current annual electricity generation. However, since it is mainly thermal energy that is required, other energy sources such as waste heat from industrial processes or geothermal energy could be used. The technology requires further development before it can be deployed on an industrial scale, but the first demonstration plants are already operational [20].
	**Enhanced weathering:** When natural minerals react with CO_2, carbon is sequestered in the rock. In nature, this rock weathering process occurs over a very long timescale. However, the reaction can be accelerated by finely crushing the minerals and spreading them over large areas of agricultural land, where they can act as fertiliser. This technique is still in the early stages of development. Around 200 million tonnes of rock a year would have to be extracted, crushed and applied to the land in order to offset Germany's unavoidable emissions. This is of a similar order to three quarters of the construction sand and gravel mined in Germany in 2019. It is likely that this approach would be logistically very complex.

Table 1: Options for removing and storing carbon, and how they work

Some of the methods described above can be combined in a cascading use approach that maximises the efficiency of land and wood use and keeps the carbon out of the atmosphere for as long as possible. Initially, the CO_2 sequestered by trees remains stored in a plantation for several decades. If the timber is harvested and used to make buildings or furniture, the carbon stays in these products for several more years or decades. When the products reach the end of their lifetime, the waste wood can be used to generate energy in a BECCS plant or made into biochar. In both cases, the carbon is now stored permanently, either by injecting it underground or as chemically stable biochar.

In addition to the CO_2 removal methods described in Table 1, another option currently under discussion is peatland rewetting. However, this is essentially a method of preventing CO_2 emissions and has little potential for delivering negative emissions (see box). Researchers are also exploring ways of harnessing and increasing the ocean's ability to capture and store CO_2.[10] Various biological and chemical mechanisms are being studied [21], however research in this area is still at an early stage, especially with regard to the impacts on marine ecosystems. In order not to endanger the sensitive and not yet sufficiently understood ecosystems in the ocean, the risks of such interventions must be studied very carefully. In particular, so-called "ocean fertilization", in which plankton growth is stimulated by the addition of nutrients (especially iron) and CO_2 is thereby bound, involves serious risks and is therefore viewed very critically by experts [22].

10 E.g. through the German government research programme MARE:N – Coastal, Marine and Polar Research for Sustainability (https://www.bmbf.de/foerderungen/bekanntmachung-3017.html).

Peatland rewetting has great potential for preventing CO_2 emissions, but is less promising for CO_2 removal

Peatlands store large amounts of carbon in both peat and peat moss. In the past, many peatlands were drained for agricultural use. In drained peatlands, the peat breaks down, releasing large quantities of CO_2 into the atmosphere. Around 5 % of global anthropogenic CO_2 emissions originate from degraded peatlands [9, S. 76]. While these emissions could be stopped by rewetting drained or damaged peatlands, in the short term this is only a means of preventing CO_2 emissions. Negative emissions – i.e. the sequestration of additional CO_2 – can only be achieved if the volume of peat grows. Since this happens extremely slowly, the potential of this approach for delivering negative emissions is relatively limited. Moreover, rewetting could actually accelerate global warming in the short term by causing additional methane and nitrogen oxide emissions. On the other hand, preserving peatlands as a habitat for rare flora and fauna contributes to biodiversity protection and water conservation.

Do we need negative emissions to meet the climate targets?

There are two reasons why we will definitely need negative emissions. Firstly, some emissions are almost impossible to avoid. This is particularly true of emissions from agriculture (nitrous oxide and methane, both of which are potent greenhouse gases) and emissions from certain industrial processes such as cement production. Some of these residual emissions occur at a larger point source, such as a cement plant. This CO_2 can be captured directly there and fed into geological storage (CCS). Since the CO_2 does not have to be removed from the atmosphere in this case, we do not speak of negative emissions. However, emissions from agriculture in particular come from many small, widely distributed sources. To achieve greenhouse gas neutrality, all of these emissions must be offset by removing CO_2 from the atmosphere. Secondly, in many scenarios, the emissions caused by electricity and heat generation and by transport are not reduced quickly enough. So much CO_2 will be emitted in the first half of the century that the 1.5°C target will be missed unless the CO_2 content of the atmosphere is subsequently reduced again [23].[11] The more CO_2 is emitted in the next decades, the more must be removed from the atmosphere later. The faster we complete the global transition to renewable energy, end fossil fuel use and reduce emissions from agriculture, the fewer negative emissions will be required later.

11 In 2018, the world's operational and proposed power plants and industrial facilities were already enough on their own to exceed the total carbon budget that remains if global warming is to be kept under 1.5°C, assuming that they continue to operate as planned until the end of their service life [23]. The budget is the total amount of CO_2 that can still be emitted if global warming is to be kept below a particular target with a specified probability.

Hard to avoid residual emissions in Germany

Based on current knowledge, different studies put the figure for emissions in Germany which are very hard to avoid at between 36 and 74 million tonnes CO_2 equivalent[12] [24] a year, most of which is accounted for by agriculture [4;25;26;27;28]. It is important to bear in mind that these studies' underlying scenarios are already based on ambitious climate action assumptions. For instance, the German Environment Agency has produced a scenario for 2050 based on the following assumptions: a complete transition of the energy and transport sectors to renewable energy, a 50 % reduction in the energy consumption of households, transport, industry, commerce, trade and services compared to 2010, a 25-55 % reduction in meat consumption compared to current levels, a massive increase in electric steel production, and a complete switch to renewable carbon sources by the chemical industry.[13] Even with all these measures, there are still around 60 million tonnes CO_2 equivalent of residual greenhouse gas emissions [25]. Measures to prevent greenhouse gas emissions can cut emissions in this scenario by approximately 95 % compared to 1990 levels. This means that the remaining 5 % will need to be offset by negative emissions. Scenarios that assume less ambitious measures, especially on the demand side, show in some cases significantly higher residual emissions of up to 130 million tonnes of CO_2 equivalents from agriculture and industry for the year 2050 [5].

As yet, no-one has modelled a single global climate action scenario in which global warming can be kept to under 1.5°C by 2100 without using some form of CO_2 removal ([7] p. 60). Although optimistic assumptions about technological advances and climate-friendly consumer behaviour significantly reduce the need for CO_2 removal, they do not fully eliminate it [29]. Indeed, it will take a huge global effort even to meet the 2°C target – in purely mathematical terms, without CO_2 removal,[14] global emissions would need to halve every 10 years [30]. However, since the Paris Climate Agreement was signed in December 2015, global CO_2 emissions have actually risen in every year except the first year of the corona pandemic 2020.

Under no circumstances should CO_2 removal be regarded as a substitute for transitioning away from fossil fuels and reducing energy consumption. However, it will be necessary in addition to these measures. Moreover, CO_2 removal can actually help to meet the climate targets more cost-effectively [30;31;32]. The costs of CO_2 removal differ depending on the process [3;33]. Especially for the technologies that have not yet been tried and tested very much, there are still large uncertainties regarding the future cost development.[15] However, for the potential

12 CO2 equivalent is a measure of a chemical compound's global warming potential. It tells us how much one kilogram of a chemical compound contributes to global warming compared to one kilogram of CO2. Because gases in the atmosphere decay at different rates, it is only possible to give their CO2 equivalent for a fixed period of time, usually 100 years after the gas was released. The CO2 equivalent for nitrous oxide (N2O), for example, is 273 for a 100-year period. This means that the greenhouse effect of one kilogram of nitrous oxide is equivalent to the effect of 265 kilograms of CO2. Methane has a CO2 equivalent of 27 (methane of non-fossil origin) to 30 (methane of fossil origin. for a 100-year period [23]. The studies mentioned above largely still use the CO2 equivalents from the Fifth Assessment Report [24], which differ slightly from the current values mentioned here.

13 Biomass will be the primary source of renewable carbon in the short to medium term, while in the longer term, CO2 directly taken from the ambient air could also be an option.

14 In many global scenarios as well as in the scenario database of IPCC Working Group III, CO2 emissions from agriculture, forestry, and other land use (AFOLU) are only reported as net values, e.g. by offsetting CO2 removals from afforestation against CO2 emissions from deforestation and other land uses. Therefore, in many global scenarios, the implied gross CO2 removals from afforestation are significantly higher than the reported net emissions, which usually reach negative values for AFOLU-CO2 over the course of the century because they overcompensate for residual AFOLU-CO2 emissions. Even the few scenarios that appear to have no CO2 removal include afforestation measures in large scale. (see [2], footnote 54).

15 Cost estimates range from about 4 to 40 euros per tonne for afforestation [3] through 115 to 145 euros per tonne for BECCS in industry [34] to 700 euros per tonne for current DAC demonstration plants. Under optimistic assumptions, it appears possible to achieve costs below 200 euros per tonne for DAC in the long term [34].

contribution of CO_2 removal processes to climate protection, the speed with which the processes can be deployed on a large scale is more decisive than the costs.

CO_2 removal's critics fear that the promise of negative emissions in the future could tempt people to relax the measures being taken to protect the climate today. They argue that overreliance on unproven CO_2 removal methods is risky and shifts the burden of tackling climate change onto future generations. However, it would be equally risky to abandon the development of CO_2 removal methods and rely entirely on ambitious emission prevention measures, since this would deprive us of a key tool in our efforts to protect the climate. Consequently, policymakers and the public need to start thinking about the part that negative emissions should play in our strategy for tackling climate change. They will need to decide what role the different CO_2 removal methods should have and which incentives are required to promote the use of these technologies. In the case of afforestation and soil carbon sequestration, another important question is how to prevent the danger of the CO_2 only being stored temporarily before escaping back into the atmosphere at a later point in time due to deforestation or changes in land management. It will also be necessary to discuss the extent to which residual emissions can and should be offset by CO_2 removal in Germany, and the role that international negative emissions markets should have, for example.

Going Deeper

For an in-depth comparison of the different CO_2 removal methods, including details of their cost and potential, see the ESYS Analysis *Biomasse im Spannungsfeld zwischen Energie- und Klimapolitik. Potenziale – Technologien – Zielkonflikte* (German only). *URL: https://www.acatech.de/publikation/biomasse-im-spannungsfeld-zwischen-energie-und-klimapolitik-potenziale-technologien-zielkonflikte/*

The pros and cons of storing carbon underground (CCS) are discussed in detail in the acatech POSITION PAPER *CCU and CCS – Building Blocks for Climate Protection in Industry*. URL: https://www.acatech.de/publikation/ccu-und-ccs-bausteine-fuer-den-klimaschutz-in-der-industrie-analyse-handlungsoptionen-und-empfehlungen/

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