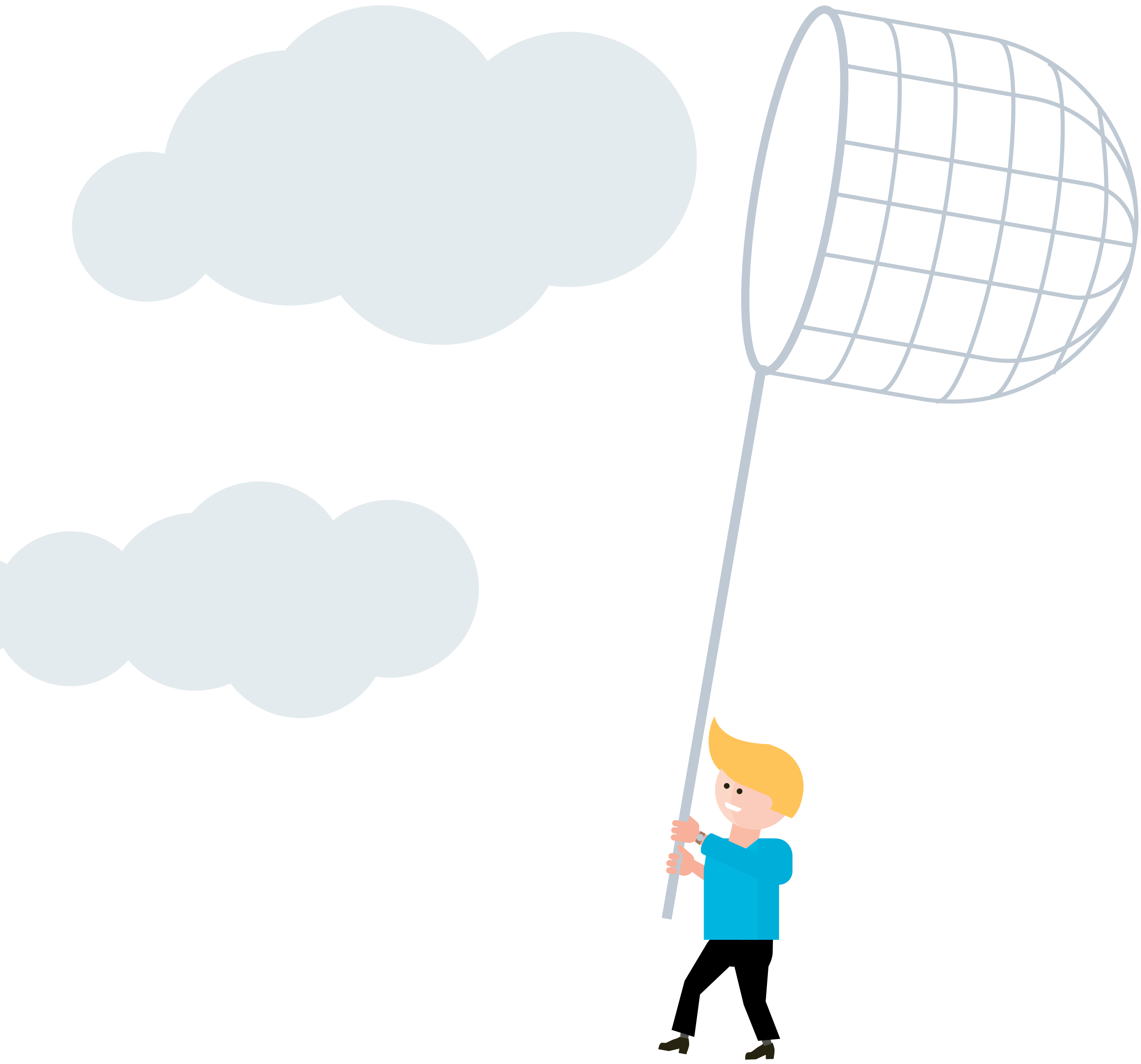
Extracting CO_2 from the air: carbon capture and storage



Why use negative emission technologies? Because the objectives cannot be achieved without them

With the 2015 Paris Climate Agreement, the international community undertook the commitment to keep global warming well below 2° C, and if possible below 1.5° C. The best way of achieving this target would be to reduce the quantity of emitted greenhouse gases as quickly as possible. This could be accomplished by, for example, using renewable energy instead of fossil-based fuels, and substituting high-emission technologies with climate-friendlier options.

In the view of the Intergovernmental Panel on Climate Change, however, the measures that have been resolved to date with the aim of reducing emissions will no longer suffice to overcome the problem of man-made climate warming. And this is where the concept of negative emissions comes in: the aim here is to additionally apply technological solutions ("negative emission technologies") in order to extract a portion of already emitted and still difficult to avoid residual greenhouse gases from the atmosphere and subsequently store them in a suitable manner. According to the calculations of the Intergovernmental Panel on Climate Change, depending on the applied model scenario, between a hundred and a thousand billion tonnes of CO_2 will have to be removed from the atmosphere in the course of this century in order to achieve a net-zero balance. By way of comparison, the annual global level of CO_2 emissions is currently around 37 billion tonnes.

What does the term "net-zero emissions" mean?

Net-zero emissions means that the quantity of greenhouse gases emitted into the atmosphere does not exceed the capacity of natural (forests and soil) or technical sinks to bind these gases. On balance, no additional greenhouse gases would be emitted and the warming of the planet due to human activity would then no longer increase.

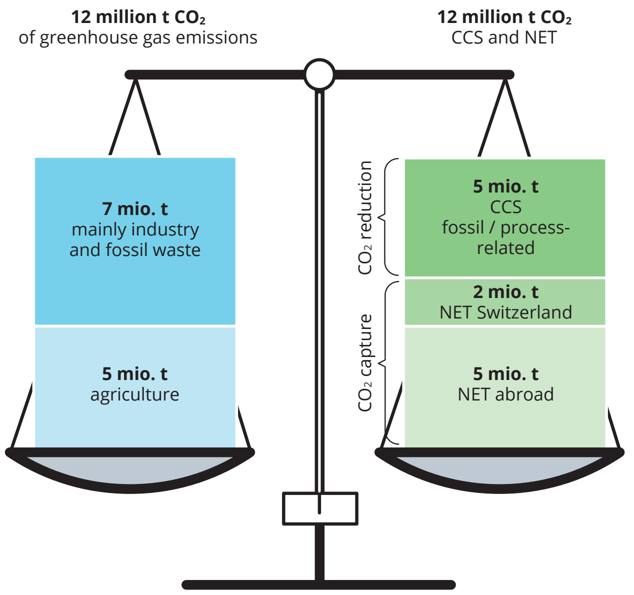
Two methods for achieving the target: CO_2 reduction and CO_2 capture

Climate models show that, for the compensation of difficult to avoid residual emissions, negative emission technologies are an essential complement, but at the same time they are no more than that. They cannot under any circumstances act as a substitute for ambitious CO_2 reduction measures. For this purpose, they do not have sufficient potential, and their application is associated with very high costs and too many uncertainty factors. Achieving the declared climate objectives will require both methods for reducing the level of greenhouse gases in the atmosphere: primarily **the reduction** of the volume of emitted greenhouse gases, and in addition the application of **carbon capture processes**, together with the use of greenhouse gas sinks for the residual emissions.

Switzerland, too, has declared a net-zero target

The Federal Council wants Switzerland to be climate-neutral by 2050. It primarily aims to achieve this ambitious goal with the aid of reduction measures, while only residual emissions, i.e. greenhouse gas emissions that cannot be completely avoided (for example, laughing gas from the agriculture sector or CO_2 emissions from cement production and waste incineration), are to be compensated through the reduction of greenhouse gases. This means that the same quantity of CO_2 that is emitted has to be removed from the atmosphere. Because every tonne of CO_2, regardless of when and where it is emitted, contributes to an equal extent towards climate warming, this can occur anywhere in the world.

By 2050, Switzerland wants to be in the position to remove 7 million tonnes of CO_2 a year from the atmosphere at home and abroad. It also aims to capture at source and permanently store an additional 5 million tonnes of CO_2 emissions a year (principle of carbon capture and storage, CCS) from fossil sources. Thus the Federal Council estimates that the quantity of residual emissions that Switzerland will not be able to avoid despite all the efforts aimed at reducing them will reach 12 million tonnes of CO_2 p.a. by 2050. By way of comparison, in 2020 a total of 43.4 million tonnes of CO_2 were emitted in Switzerland.



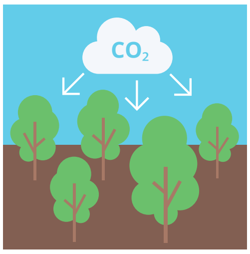
Capturing and storing carbon: how can this be accomplished?

If CO2 is extracted from the air and transferred to long-term storage facilities, already produced emissions can be reversed. The various methods and processes applied for the purpose of carbon extraction are therefore referred to as “negative emission technologies”.

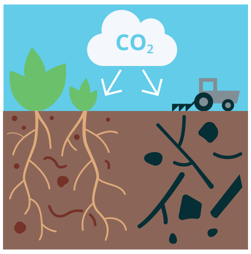
There are several methods for extracting CO2 from the atmosphere. These differ in terms of how they separate the CO2 from the air and how the carbon is subsequently stored in order to keep it out of the atmosphere over the long term.

A study commissioned by TA-SWISS[1] analyses the opportunities and risks associated with five negative emission technologies that are under consideration in Switzerland.

[1] «Chancen und Risiken von Methoden zur Entnahme und Speicherung von CO_2 aus der Atmosphäre: Empfehlungen aufgrund der Analyse des Wissensstandes und einer systematischen Befragung von Fachleuten in der Schweiz», Published by TA-SWISS, vdf Hochschulverlag, Federal Institute of Technology, Zurich, 2023. Further information: www.ta-swiss.ch

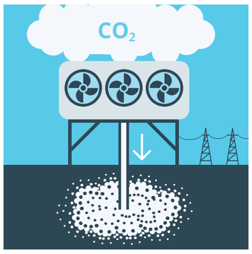


Storage of CO_2 in forests in the form of biomass/utilisation of wood: trees absorb CO_2 from the atmosphere and store the carbon in their wood over the long term, which can be processed into long-lasting products.



Storage of CO_2 in soil in the form of humus or biochar: with the aid of targeted soil management, carbon is integrated into the soil where it is stored, for example with the aid of agri-forestry systems or conservation agriculture concepts.

Capture of CO_2 from chimneys (use of bioenergy with carbon capture and storage – BECCS): plants convert CO_2 into biomass, which produces energy when burned. The resulting CO_2 that is thus released again is then captured and stored beneath the ground.



Extraction of CO_2 from the atmosphere (direct air capture and carbon sequestration – DACCS): here, CO_2 is extracted from the atmosphere with the aid of technical systems instead of by plants. The carbon is then stored beneath the ground.

Accelerated weathering of demolition concrete and rock: in nature, minerals react with CO_2 and in this way bind the carbon. This carbonation process can be accelerated through the application of technological methods.

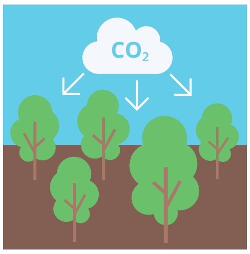
Negative emission technologies: overall opportunities ...

- The application of negative emission technologies could help Switzerland achieve its climate protection objectives without losing sight of the development of economic prosperity.
- The sustainable management of forests and land, and the utilisation of wood and biochar, not only function as CO_2 sinks, but also have the potential to foster biodiversity, improve soil quality and the water supply, and strengthen resilience against drought and heavy precipitation.
- Negative emission technologies can support the circular economy, for example when CO_2 is embedded in concrete waste and bound into new construction materials for recycling.
- Switzerland is currently leading the way in the development and use of various negative emission technologies. The development of these technologies will open up opportunities for Switzerland to further strengthen its position as a centre of research and industry.

... and risks

- Failure to investigate, implement and scale the potential of negative emission technologies could mean that Switzerland will not be able to meet its climate objectives.
- Possible conflicts of interest could arise, for example associated with the use of limited resources such as biomass, water, land and renewable energy.
- The extent to which individual negative emission technologies could harm the environment is not yet clear. The transport and underground storage of CO_2 may also be associated with certain risks.
- Placing too much reliance on negative emission technologies could mean that ambitious climate protection legislation and emission reduction efforts may be neglected.

Forests as carbon sinks: forest management and utilisation of wood



Principle: trees convert atmospheric CO_2 into biomass through photosynthesis, and subsequently store the carbon (C) in wood, roots and the soil. The storage capacity of Switzerland's forests is between 1.6 and 4.5 million tonnes of CO_2 per annum. But forests can only function as $CO_2$2 sinks if they continue to grow and the quantity of wood that is formed exceeds the quantity that rots, is incinerated or is harvested. With all these processes, CO_2 is released into the atmosphere again.

Sustainable forest management ensures that a forest is able to perform its many functions (protection, space for economic and recreational activities, etc.) and at the same time contribute towards the reduction of greenhouse gases. Managed forests store more CO_2 than forests left in their natural state.

Afforestation: planting of trees in previously unforested
Reforestation: natural reforestation of unused mountain pastures, resulting in an increase in biomass.
Forest management/utilisation of wood: in a healthy forest, the CO_2 initially remains stored in the trees for several decades. Forest management can be made sustainable through the targeted harvesting of timber, which should be efficiently processed in several stages (cascaded use) into products with a lengthy useful life. In this way, the carbon can be kept out of the atmosphere for as long as possible. At the end of its useful life, the wood is then utilised for heating purposes.

Costs: depending on the source, between 1 and 100 US dollars per tonne of CO_2 (Switzerland).

Negative emission technology potential[2]: if the forest is sustainably managed and the wood is utilised (including substitution effect), approx. 3 million tonnes of CO_2 p.a. (Switzerland).

Level of technological maturity: 9 –10

[2] For all negative emission technologies the potentials cited here are theoretical: the potentials that will effectively be realisable depend on technical, economic and social aspects.

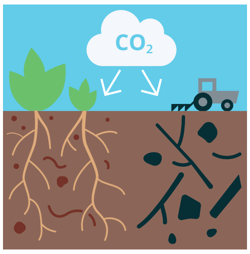
Opportunities

- Promotion of biodiversity, variety and natural rejuvenation of forests.
- Because the source of energy for photosynthesis is natural solar irradiation, this negative emission technology only requires low quantities of technically produced energy for forestry machinery and timber transport.
- Over the long term, the CO_2 balance of Switzerland's forests could be optimised thanks to the promotion of timber growth and taking account of the ecological functions of dead wood. The cascaded use of the wood is a key factor here.
- The use of timber as a construction material means that the embedded carbon remains stored for decades. At the same time, timber could to some extent be used in the construction industry as a substitute for other CO_2-intensive materials such as steel and concrete.

Risks

- The long-term storage of carbon is less assured than the storage of CO_2 beneath the ground.
- Due to climate change, forest fires, periods of drought, forest clearance, pest infestations, etc., the CO_2 could be released into the atmosphere again.
- Shortage of suitable land: there are not enough areas of unforested land in Switzerland to permit large-scale afforestation.
- Natural or planned afforestation could give rise to land use conflicts, for example if potential forest zones in mountain regions are retained in the form of meadows in order to preserve arable land. The use of land for forest management could also influence the storage capacity for other negative emission technologies.

Soil management and biochar



Principle: it is not only trees, but also all other plants that convert atmospheric CO_2 into biomass through photosynthesis and store the carbon in their leaves, stems, roots and fruits. When a plant dies, organisms in the soil break down the plant material and release CO_2. However, some of the plant material is converted into organic matter (humus) and is retained in the soil for a longer period of time.

The balance between humus formation and depletion can be influenced through **soil management**. When humus is formed, the soil absorbs more CO_2 than it releases. The length of time the carbon is retained in the humus ranges from decades to centuries, depending on the type of soil, the method of soil management and the environmental conditions. With the aid of targeted soil management, it is possible to increase the storage duration of organic carbon in the form of humus. This can be accomplished by, for example, minimising the working of agricultural land, improving crop rotation, leaving harvest residue in fields, cultivating deep-rooted plants, converting farm land into pasture land – in other words, by applying conservation agriculture methods.
Through the use of **agri-forestry systems**, i.e. integrating trees and shrubs into crop and animal farming, it is possible to increase the formation of biomass and store organic carbon in the soil.

Biochar, i.e. biomass that is charred at a high temperature and in an oxygen-free environment (pyrolysis) and subsequently worked into the soil, also binds CO_2 as carbon for lengthy periods of time. Biochar is used as a fertiliser additive and in livestock farming as a raw material, and in environmental and energy technology. The carbon content of biochar is only released again very slowly.

Costs of soil management: depending on the source, between 0 and 80 US dollars per tonne of CO_2.
Costs of production and use of biochar: depending on the source, between 10 and 135 US dollars per tonne of CO_2.

Negative emission technology potential of soil management: around 2.7 million tonnes of CO_2 p.a. (while the soil remains saturated with carbon, i.e. several decades).
Negative emission technology potential of agri-forestry systems: if 13.3 percent of Switzerland's agricultural land were to be converted into agri-forestry systems it would be possible to compensate up to 13 percent of the greenhouse gas emissions attributable to the agriculture sector.
Negative emission technology potential of biochar in soil: up to 2.2 million tonnes of CO_2 p.a.

Level of technological maturity: soil management and agri-forestry 10, biochar 9

Opportunities

- Increased humus formation, improved ecosystem performance, enhanced soil quality.
- Agri-forestry systems could restrict soil erosion, facilitate water infiltration, improve the physical properties of the soil and act as a buffer against extreme events.
- Biochar binds carbon over the long term and could be used in a variety of sectors.

Risks

- The organically bound carbon in the soil could be released again due to natural occurrences or human activities and climate fluctuations.
- The use of agri-forestry systems could reduce crop yields and increase production costs. This could give rise to utilisation conflicts with the foodstuffs industry. No long-term studies have yet been carried out concerning the feasibility, productivity and improvement of carbon storage in Swiss soil.
- Through the output of biochar, it is possible that harmful substances (e.g. heavy metals) could pollute the soil and subsequently enter the food chain.
- Because of its need for biomass, biochar is in competition with other negative emission technologies.

Bioenergy production with carbon capture and storage (BECCS)

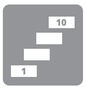
Principle: plants bind CO_2 extracted from the atmosphere and convert it into biomass. During the incineration, smouldering or gasification of biomass, the CO_2 content is released again. In bioenergy systems, it is directly separated from the exhaust gas and stored in deep geological layers or transported in sealed tankers or pipelines to a storage facility abroad. Thus in the case of BECCS, biomass is used on the one hand for the production of energy (i.e. is converted into electricity or heat) and on the other hand as a means of producing negative emissions through the application of suitable technologies.

Because carbon capture and storage is simultaneously combined with the production of renewable energy, high hopes are being placed in this negative emission technology, which plays a major role in all the scenarios drawn up by the Intergovernmental Panel on Climate Change.

Carbon capture pilot plants are already in operation in the USA and the UK. Identifying suitable sites for the construction of safe geological repositories is one of the main prerequisites for the use of this technology. In Switzerland there are currently no storage facilities for captured CO_2, though it could be transported to geological repositories abroad, for example via (new) pipelines. Within Switzerland, this technology would probably be most suitable for use in waste incineration plants, cement factories, sewage treatment plants and the chemicals industry.

Costs: depending on the source, between 30 and 400 US dollars per tonne of CO_2.

Negative emission technology potential: if the entire quantity of available biomass in Switzerland were to be utilised, around 5.1 million tonnes of CO_2 p.a. (from 2050).



Level of technological maturity: 9

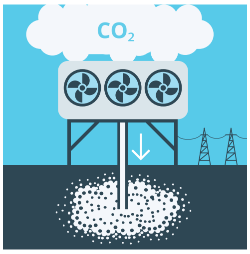
Opportunities

- In theory, CO_2 can be stored in geological repositories for very long periods of time.
- With BECCS, carbon capture could be accomplished more cost-effectively and energy-efficiently than would be the case with direct air capture and carbon sequestration (DACCS), because the concentration of carbon is much higher in exhaust gases than in the atmosphere.
- The BECCS method has economic potential because the cascaded use of the biomass that is no longer suitable for other purposes could become an additional source of revenue for farmers and foresters.

Risks

- If biomass has to be produced specially for BECCS, due to the high requirements for land, water and fertilisers there is potential for utilisation conflicts with the foodstuffs industry, as well as for negative impacts on biodiversity (especially in the case of biomass monocultures).
- The transport of biomass to BECCS storage facilities, the energy and materials required for their operation and the process of storing the CO_2 in geological repositories, are all associated with high energy and material costs and could lead to dependencies on third countries.
- There are still pending issues relating to the duration of CO_2 storage: with respect to storage in geological repositories the risk exists that the CO_2 could gradually escape due to faults or fractures in the rock. This could give rise to social controversies.

Direct air capture and carbon sequestration (DACCS)



Principle: with DACCS, CO_2 is mechanically filtered out of the atmosphere and stored beneath the ground. Here, carbon is captured with the aid of a technical system instead of by plants.

By removing CO_2 from the atmosphere, it is possible to compensate other difficult to avoid residual emissions of greenhouse gases (for example, from the agriculture sector), theoretically including gases that do not contain any carbon at all (for example, laughing gas). The removal of CO_2 from the ambient air is effected with the aid of chemical binding agents (absorption and adsorption processes). The pure CO_2 thus separated by the binding agent is then liquefied, transported and permanently stored deep below the earth's surface. For this purpose, suitable deep geological repositories are available abroad, for example in Iceland and Norway.

The world's first commercial DACCS facility was inaugurated in Iceland in 2021. It was developed by a Swiss company (Climeworks) in collaboration with the Icelandic firm, Carbfix. At full load, it is able to extract around 4,000 tonnes of CO_2 p.a. from the atmosphere. For larger-scale extraction the technology will have to be further developed.

Costs at the current status of development: depending on the process, between 80 and 210 US dollars per tonne of CO_2 (absorption process) and between 560 and 730 US dollars per tonne of CO_2 (adsorption process).
Anticipated costs in the long term: 100 US dollars per tonne of CO_2.

Negative emission technology potential: the total geological storage potential in Switzerland is estimated at a maximum of around 2,500 million tonnes of CO_2.

Level of technological maturity: 7–8

Opportunities

- It should be possible to store CO_2 beneath the ground over very lengthy periods of time. Furthermore, this technology is readily scalable and is not dependent on biomass.
- DACCS is not location-dependent. In order to minimise the costs of transporting the CO_2, as well as the overall associated costs, DACCS facilities could be installed at locations at which renewable energy sources and geological repositories for CO_2 are available.
- Since the process primarily requires heat, either district heat from industrial processes or geothermal energy could be used, depending on the process concerned.

Risks

- DACCS is cost-intensive and is in competition with renewable energy sources. Because the proportion of CO_2 in the atmosphere is low, the facilities have to filter enormous quantities of air. This means that carbon sequestration is both costly and energy-intensive. Furthermore, some of the applied processes require large quantities of chemicals and water.
- With respect to the geological storage of the sequestrated CO_2, depending on the utilised method certain risks could arise relating to the storage duration and the triggering of seismic activity, and thus the potential for causing social controversies.
- Switzerland's long-term climate strategy is oriented on scenarios in which negative emissions from DACCS facilities will be purchased abroad. This could give rise to infrastructure-related and contractual dependencies on third countries, similar to the current situation regarding oil and gas supplies.

Weathering through carbonation

Principle: during weathering, certain minerals such as silicate rocks react with CO_2 and bind the carbon. This chemical process, which is referred to as carbonation, occurs very slowly in nature, but can be technically accelerated. One method consists in finely grinding the rock and distributing it over large areas of agricultural land or forest terrain.

Weathering also takes place in concrete (and is normally undesirable because it causes steel girders in concrete to rust). This process, too, can be technically accelerated. This is good news for the climate: with the aid of new carbonation methods, demolition concrete is able to reabsorb up to 33 percent of the greenhouse gases that were released during its production. Here, concrete rubble is finely ground and combined with pure CO_2 (for example, from BECCS facilities). This produces limestone powder that can subsequently be reused as filler or aggregate for the production of new concrete. This reduces the CO_2 footprint of concrete production.

Swiss companies Neustark, zirkulit and Sika are developing new methods of storing CO_2 in demolition and recycling concrete.

Costs: in the case of demolition concrete, depending on the source and taking account of the investment costs for special equipment, between 140 and 940 US dollars per tonne of CO_2. By 2050 the costs could fall to 75 US dollars per tonne of CO_2. Natural rock: estimated costs are between 70 and 130 US dollars per tonne of CO_2.

Negative emission technology potential: up to 2.5 million tonnes of CO_2 in 2050.

Level of technological maturity: carbonation 5–6, distribution 3

Opportunities

- The accelerated weathering of demolition concrete has the potential to rebind up to 33 percent of the original CO_2 emissions resulting during cement production.
- The chemical binding of carbon in demolition concrete is highly stable and permits long-term CO_2 storage, potentially for centuries.
- Spreading carbonated demolition concrete over agricultural land could also contribute towards the reduction of laughing gas emissions.

Risks

- Spreading finely ground concrete could result in an increase in pollutants in the soil and have a negative impact on plants and organisms. It also involves the use of large areas of land.
- Grinding rock and demolition concrete is associated with a high level of energy consumption.
- The stability of CO_2 fixation as a carbonated material in soil has not yet been sufficiently researched.

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