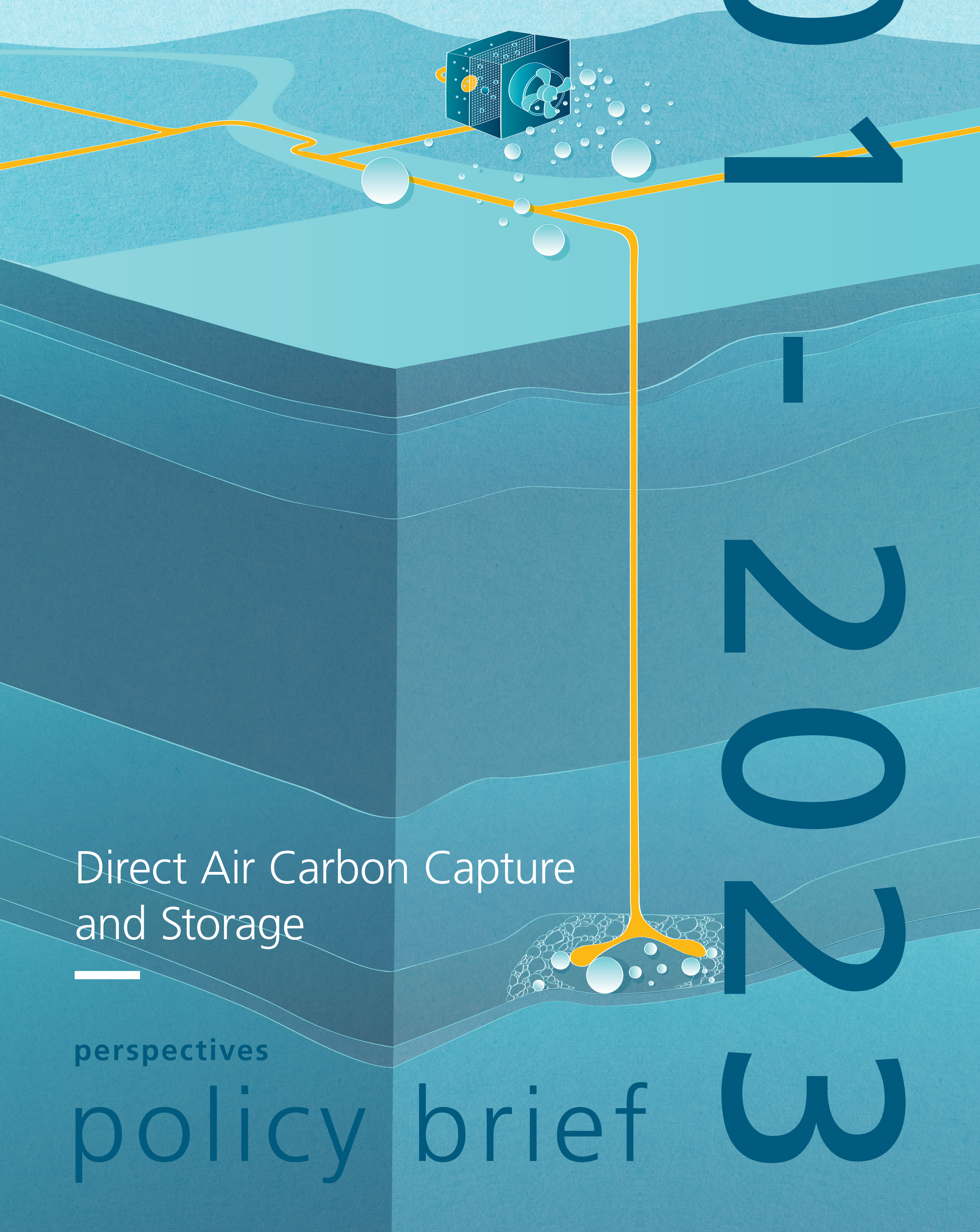
Fraunhofer ISI



01-2023

Direct Air Carbon Capture and Storage

perspectives

policy brief

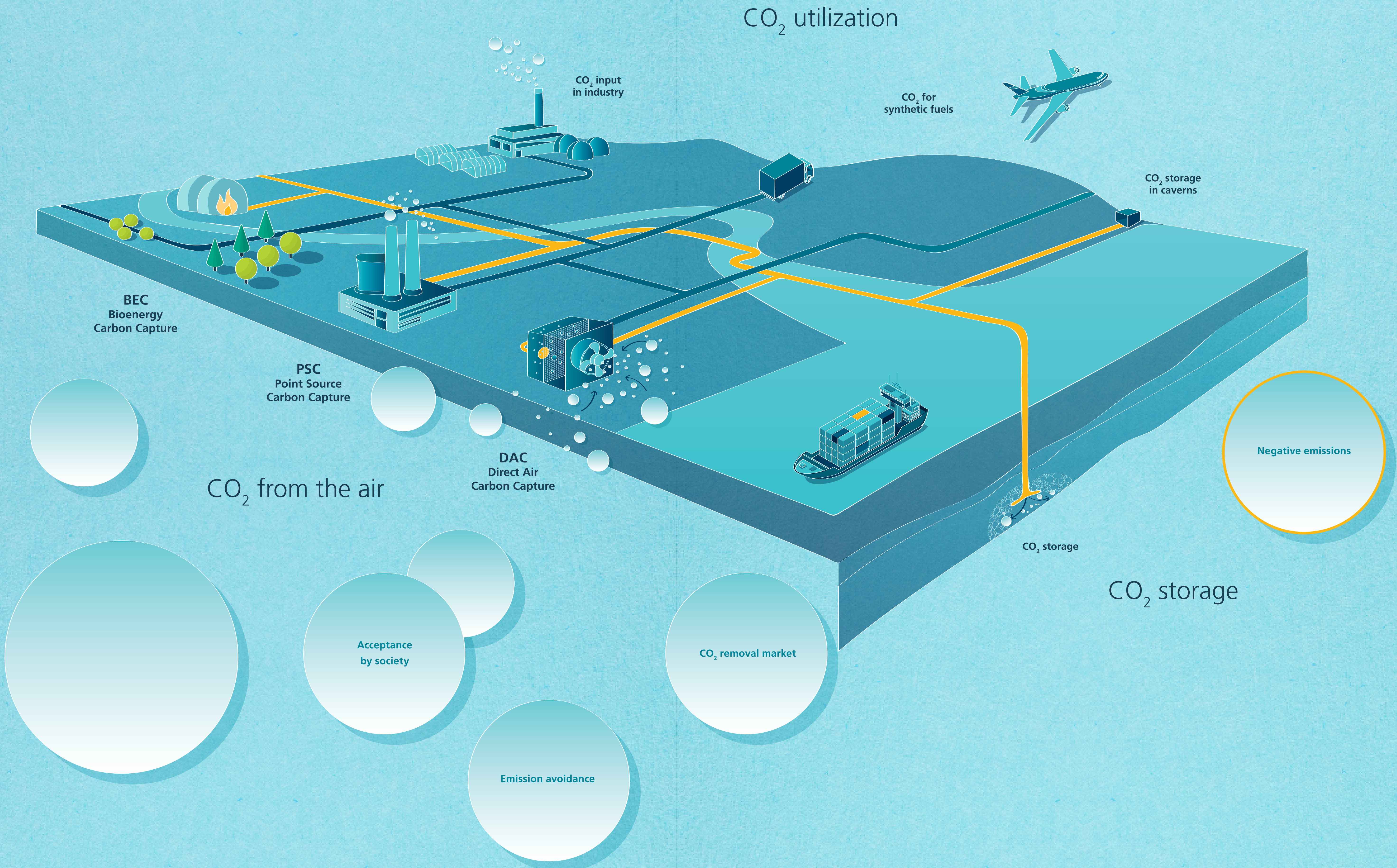
Direct Air Carbon Capture and Storage

A game changer in climate policy?

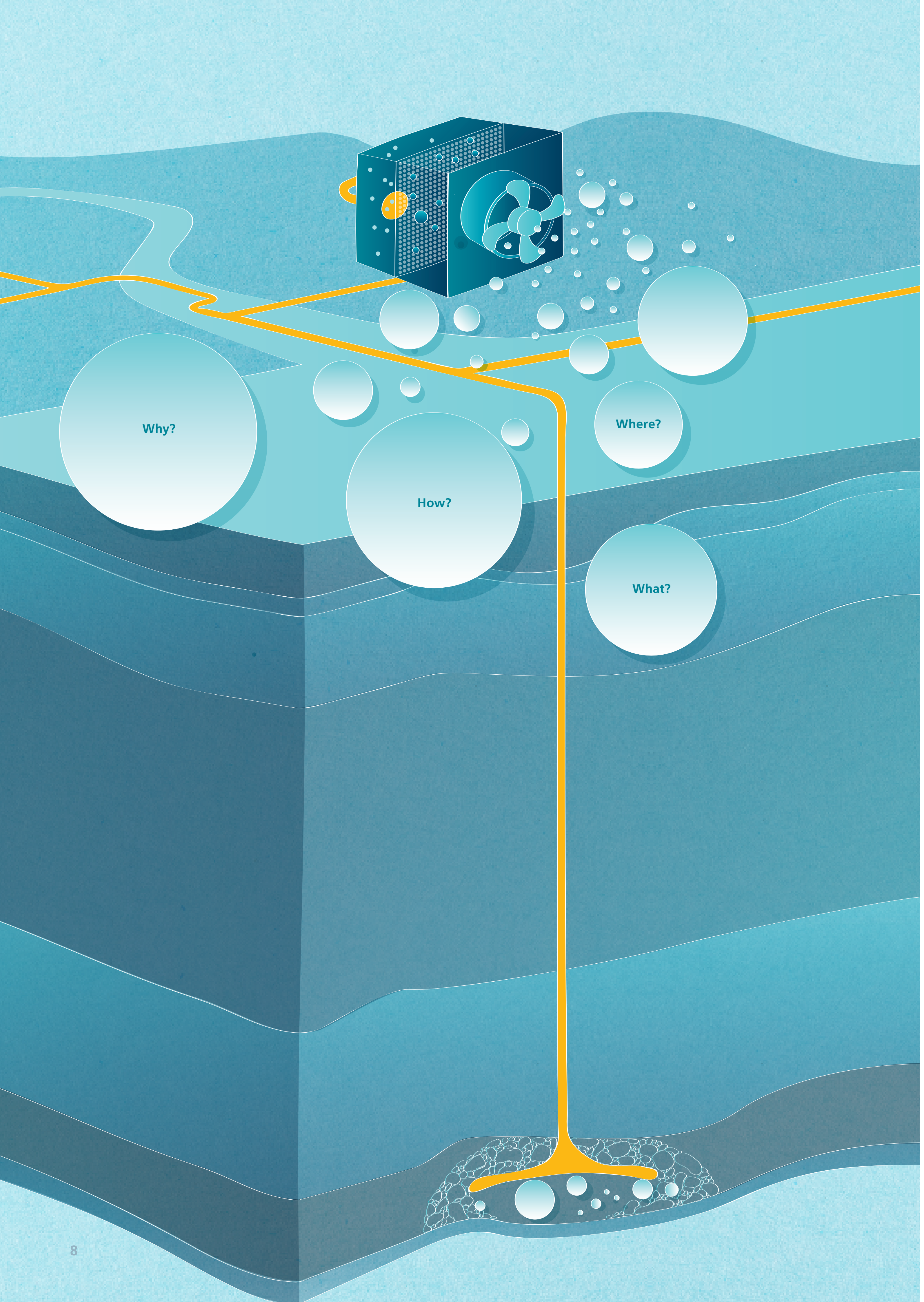
Authors

Barbara Breitschopf, Elisabeth Dütschke, Vicki Duscha, Michael Haendel, Simon Hirzel, Anne Kantel, Sascha Lehmann, Frank Marscheider-Weidemann, Matia Riemer, Josephine Tröger, Martin Wietschel

Contents



CO_2 utilization
CO_2 input in industry
CO_2 for synthetic fuels
CO_2 storage in caverns
BEC
Bioenergy
Carbon Capture
PSC
Point Source
Carbon Capture
DAC
Direct Air
Carbon Capture
CO_2 from the air
CO_2 storage
Negative emissions
CO_2 storage
Acceptance by society
CO_2 removal market
Emission avoidance



Overview and core questions

What is Direct Air Carbon Capture and Storage (DACCS) and could it be a game changer in climate policy? In this policy brief, we answer these and further questions.

01

Why is there a need to address Direct Air Capture and Carbon Storage (DACCS)?

To limit the effects of climate change, the global community is striving to restrict global warming to a maximum of 1.5 °C. To achieve this goal, many countries are developing climate policy strategies. In spite of increasingly ambitious reduction targets for greenhouse gases, existing strategies to mitigate climate change are likely to be insufficient and the window of opportunity to achieve greenhouse gas neutrality is shrinking. Therefore, discussions are increasingly focusing on negative emissions – the removal of CO_2 from the air and its storage – which would reduce the amount of CO_2 accumulated in the atmosphere. Various natural and technical processes are available for this purpose. One of these technical options is Direct Air Capture and Carbon Storage (DACCS).
→ More information on page 13

02

What is DACCS?

Direct Air Carbon Capture and Storage (DACCS) comprises the technical extraction of CO_2 from the air (DAC: Direct Air Capture), its transport from the extraction point to the storage site, and its long-term and safe storage (CS: Carbon Storage), which mostly takes place underground. There are various technology options to extract CO_2 from the air, some of which are not yet market-ready, and which differ, among other things, by their resource use, such as the energy they need. The transport of CO_2 by container or pipe is not a problem from a technical point of view. The options for converting existing gas pipelines for CO_2 transport are being discussed. Geological storage sites are currently considered the most viable option for CO_2 storage, as this technology is mature. However, it remains to be seen how long the CO_2 will remain securely bound underground, as there is no experience of long-term storage, i.e., over millennia. Moreover, the current commercial development of the existing global storage potential is still very small compared to future demand for CO_2 storage.
→ More information on page 13

03

Besides DACCS, how can negative emissions be realized?

In addition to DACCS, there are other options that can be used to extract CO_2 from the atmosphere and store it permanently. They differ by the type of extraction as well as the type of storage. CO_2 can be extracted by natural binding in organic materials via photosynthesis, or by technical processes. To keep the captured CO_2 permanently out of the atmosphere in the interests of climate protection, there are various forms of sustainable, long-term storage: in organic material (biosphere), in geological reservoirs (lithosphere), in water (hydrosphere) and in durable products such as building materials.
→ More information on page 16

04

What role does DACCS play in climate scenarios?

DACCS plays an important role in many climate protection scenarios as a technical option for achieving negative emissions. However, some climate scenarios do not back DACCS, or do so to a lesser extent, and instead rely on natural removal options such as reforestation or rewetting peatlands. According to the Intergovernmental Panel on Climate Change (IPCC), whether and to what extent DACCS plays a role in climate protection scenarios depends on which assumptions are made regarding the development of the technology and its costs as well as the social acceptance of CO_2 storage. If the costs of DACCS drop as projected by some studies, the relevance of DACCS will increase significantly compared to the other options in climate scenarios.
→ More information on page 16

05

What is the environmental impact of DACCS?

Given the low natural concentration of CO_2 in the air, its extraction is associated with very high energy use. Therefore, for energy efficiency reasons, priority should be given to extracting CO_2 from the available point sources, i.e., from (waste) gases with higher CO_2 concentrations, such as in fossil-fuel power and cement plants. Consequently, DAC plants should be located where low-emission energy sources or forms are available. This is not sufficiently the case, for example, in Germany to date. The advantage of lower land use in comparison to alternative CO_2 removal options that is stated in the literature is only partially valid, because in addition to the use of land for the DAC (Direct Air Capture) plant itself, land is also required for the injection site and for monitoring of the storage site as well as for renewable energy generation, where needed.
→ More information on page 18

06

How much does DACCS cost?

Given that DAC technology is still in its infancy, significant cost reductions can be expected as its application increases. These result from lessons learned and economies of scale when producing the plants, but also from efficiency improvements in the use of energy and materials when operating them. Scientific studies show a high degree of variation with regard to the actual cost reduction potential of DAC. Depending on the assumptions made about expansion, technological developments, availability of low-cost energy sources, and other favorable accompanying factors, very optimistic estimates are around EUR 40, while average values are around EUR 200 per ton of CO_2 from 2050 onward, which is lower than the costs of other emission-reducing measures. Transport and storage costs are so low that they only play a marginal role. Since cost reduction potentials can only be realized if DAC capacities increase significantly, the future availability of DACCS for the negative emissions required depends on the decisions made today concerning capacity expansion and technological advancements.
→ More information on page 20

07

How could a CO2 removal market be designed?

Currently, there is no uniformly regulated market in Europe for the removal of greenhouse gases from the atmosphere (»CO_2 removal market«), but many different, independent emission reduction systems or markets. For example, under the EU Emissions Trading Scheme (EU ETS), CO_2 emissions allowances are traded at a price of around 85 EUR/t CO_2 (December 2022), which is significantly below the average expected future cost of DACCS. Additional emission avoidance systems at the European level are the Effort Sharing Regulation (ESR) and the Land Use, Land-Use Change and Forestry Regulation (LULUCF). So far, there is no possibility for carbon offsetting to take place between these different schemes. Another example are the small private markets for voluntarily offsetting CO_2 emissions related to the use of fossil fuels.

For the necessary market ramp-up of DAC technology and thus also for the use of DACCS to generate negative emissions, clear framework conditions are needed to integrate DAC into existing systems, and economic incentives must be created. At the end of 2022, the European Union published a proposal for a certification scheme that outlines a possible framework for the certification of negative emissions in order to enable the trading of negative emissions in the long term .
→ More information on page 21

08

Are subsidization and regulation needed for DACCS to take off in the market?

So far, no country has comprehensive regulation of DACCS. However, regulations already exist at EU and member state level on individual sub-aspects such as those relating to the transport and storage of CO_2, the so-called CCS Directive. With the exception of the Netherlands, Great Britain and Norway, there are still major gaps in the national implementation of these standards in most member states.

Since market-based incentives for the realization of negative emissions have been lacking or insufficient to date, the development of negative emissions technologies is currently highly dependent on the availability of subsidies. At EU level, there are already funding programs with a broad design, some of which can also be used to fund DACCS projects, such as the EU Innovation Fund. In the three countries mentioned above, the national governments are providing funding for the development of a CO_2 transport and storage infrastructure. An important factor for successful development of DACCS is that funding and regulation go hand in hand. The relevant regulation of production, transport, storage of CO_2 and a CO_2 removal market is a precondition for a target-oriented support system that could form the foundation for the further development of DACCS.
→ More information on page 22

09

What is the state of the social debate on DACCS?

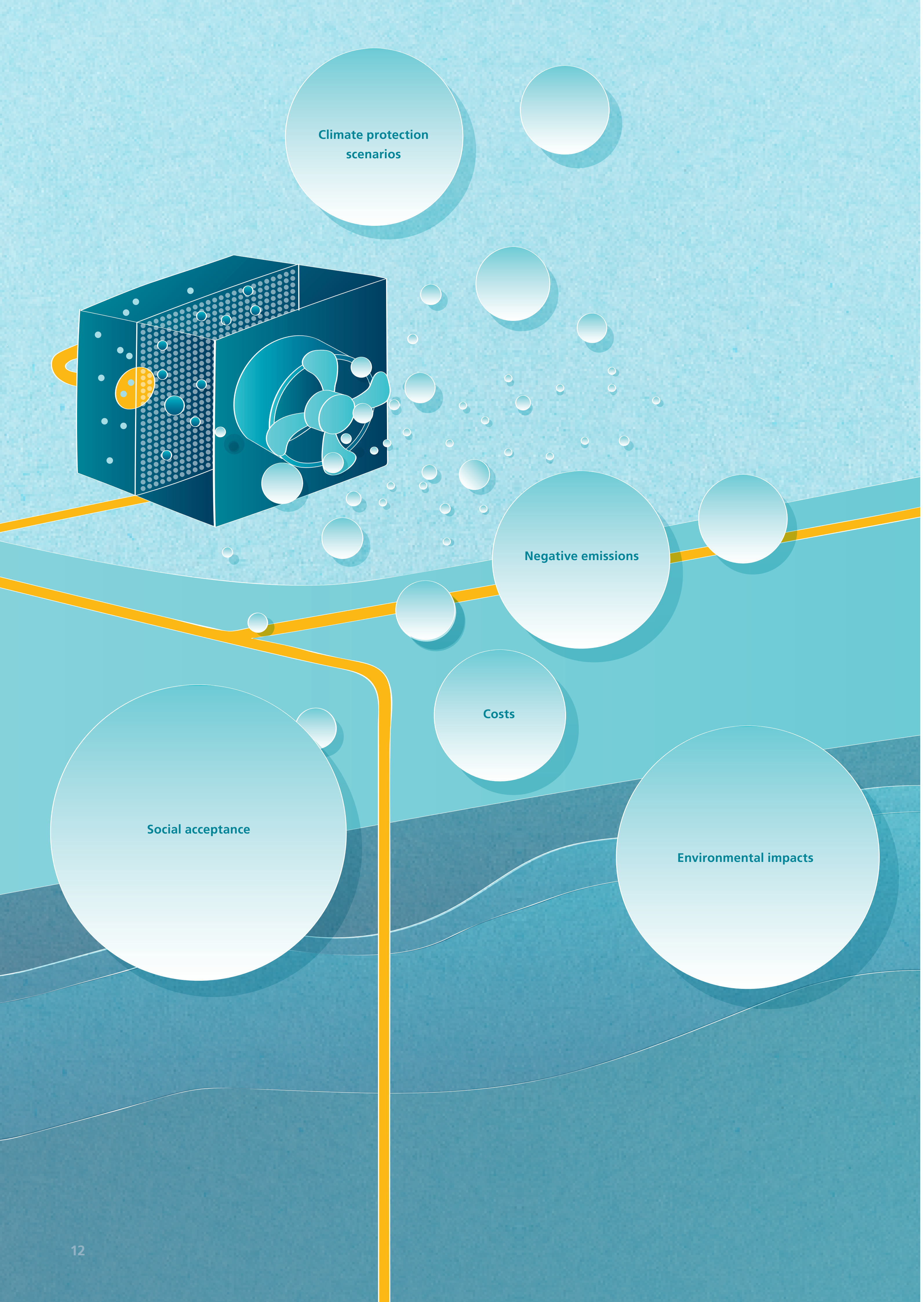
Many social actors have only limited knowledge of DACCs. So far, there have hardly been any public debates concerning its use as a technical option for negative emissions, i.e., long-term removal of CO_2 from the air. Previous attempts to store CO_2, for example, in Germany or other EU countries were often very controversial in the regions concerned, and surveys show that larger sections of the population are still rather critical of CO_2 storage – even if this is not currently taking place in their vicinity. With regard to extracting CO_2, surveys show that there is better acceptance of those options that are perceived as more »natural«, for example, binding CO_2 in plants, and as less »technical«. Broader societal discussion of this technology is required for a more targeted further development of DACCS with regard to regulation and technology promotion, as well as its potential significance for climate protection.
→ More information on page 23

10

What role should DACCS play in a climate protection strategy?

In many climate change mitigation scenarios, DACCS is seen as a possible option for offsetting CO_2 emissions in sectors that are difficult to decarbonize. It also offers the option of realizing negative emissions and, as such, offers some protection against the risk of possibly failing to meet climate protection targets. Nonetheless, using it as such risk protection harbors the associated risk that other necessary emission avoidance measures might be postponed and therefore transformation delayed. This is especially critical if it leads to the emergence of new path dependencies and lock-ins that significantly delay decarbonization. As a result, the development of DACCS requires continuous monitoring and evaluation in order to address undesirable developments and the associated burdens, risks, and opportunities that may be unevenly distributed.

Nevertheless, based on current knowledge, DACCS is one of the more promising technological approaches to achieve negative emissions, even though its deployment is still associated with many open technical, regulatory, economic, environmental, and societal issues and challenges. In this respect, this policy brief concludes that it should be a climate policy goal to further develop DACCS as an option to generate negative emissions, while bearing in mind the time needed for its development and deployment.
→ More information on page 24



The questions in detail

In this long version, we want to address the questions concerning Direct Air Carbon Capture and Storage (DACCS) in more detail, explain the background, and draw attention to those questions that are still unanswered.

01

Why do we need a discussion about Direct Air Carbon Capture and Storage (DACCS)?

To limit the risks to humans associated with climate change, the global community is aiming to keep global warming to 1.5 °C or less. To achieve this goal, many countries are developing strategies with ambitious climate policy targets. These place an emphasis on massively increasing energy efficiency and expanding renewable energy generation or other low-carbon generation technologies. Despite increasingly ambitious greenhouse gas reduction targets, existing climate change mitigation strategies are no longer sufficient and the window of opportunity for achieving greenhouse gas neutrality is shrinking. In addition, there are applications where, despite all efforts, greenhouse gas emissions are very difficult to reduce, such as process-related emissions from the cement industry or agriculture.

For this reason, discussions are increasingly focusing on negative emissions – the removal of CO_2 from the air and its storage – which would reduce the amount of CO_2 accumulated in the atmosphere to a lower level. Various natural and technical processes can be used for this purpose. One of these technical options is Direct Air Capture and Carbon Storage (DACCS). An increasing number of studies recognize that this process will play a relevant role.

Because technological innovations such as DACCS are embedded in complex socioeconomic, technical, and political systems, they evolve under the influence of a variety of social, political, and economic factors. Hence, the possible use of DACCS as a technical solution for emission reductions is not purely a question of techno-economic functionalities, but also a balancing of societal and political factors [2,3].

If DACCS is to play a relevant role in climate protection in the future, the conditions needed for successful market entry must be created through national and international regulations and through societal and political consultation processes. This needs to be done in the near future, as the further development of the technology, and the construction of production capacities and infrastructures for CO_2 transport and storage are time consuming and capital intensive.

The aim of this policy paper is to present in detail and discuss the current scientific understanding of the above-mentioned challenges and to draw important conclusions for decision-makers.

02

What is DACCS?

DACCS is a process by which negative emissions can be achieved. It consists of three process stages: a) the extraction of CO_2 from the air, b) the transport of CO_2 between the extraction point and the storage site, and c) the permanent underground storage of CO_2. If CO_2 is captured and stored at the point source where it is emitted due to the use of fossil fuels, for example, a fossil fuel power plant, instead of being removed from the air, this captured CO_2 is not necessarily considered a negative emission.

CO_2 extracted from the air can also be used to produce chemical base materials and synthetic fuels in industry or transport, and later released back into the atmosphere when these base materials or fuels are used. While this does not result in negative emissions, it does result in a carbon-neutral closed-loop system.

This paper focuses on DACCS's contribution to achieving negative emissions. Its application to provide basic materials for synthetic fuels is not discussed in detail, as this leads at best to a climate-neutral circular economy, but not to a reduction of CO_2 in the atmosphere.

▸ The technology for the extraction of CO_2 from the air by means of DAC requires further technological development

DAC is a process for capturing CO_2 from the air, for example, a process specialized in capturing CO_2 below a very low CO_2 concentration. Various technical processes can be used to separate CO_2 from the air, which share a similar basic procedure: Fans are used to generate an airflow, which moves past a liquid or solid material, the so-called sorbent. The sorbent removes CO_2 from the air by accumulating it on its surface or in its phase. The corresponding chemical processes are also called adsorption or absorption. More and more CO_2 accumulates over time, which then has to be separated from the sorbent again. Depending on the sorbent used, the separation and thus the regeneration of the sorbent takes place by using a membrane, applying a vacuum, or energy in form of heat or electricity.

An important distinguishing feature between the different processes is the temperature [1]. In low-temperature processes (LT-DAC), desorption takes place at around 100 °C, while current high-temperature processes (HT-DAC) often require temperatures of up to 900 °C [2]. Efforts are underway to lower the required temperature in order to be able to integrate renewable, geothermal or solar thermal heat sources or even low-temperature waste heat into the heat supply. Since CO_2 in the air is available everywhere in the same way as a basic resource, DAC plants can be constructed at any location that has a favorable potential in terms of renewable energy, water and/or land and, if required, is close to a possible CO_2 storage site [3].

▸ Transporting CO_2 is not a challenge from a technological point of view

Since the storage sites are often not located directly at the CO_2 extraction site, it is necessary to transport the extracted CO_2. Road and rail are the main transport options discussed for short distances and smaller quantities of CO_2. For longer distances, onshore and offshore pipelines are a possibility, as is marine transport. For the latter, ships similar to those transporting liquefied gas can be used. Their capacity is significantly higher than trains. Container-based or existing pipeline-based solutions can usually be converted to transport CO_2 without major problems. These types of transport have been used for many years and are judged to be technologically mature.[9].

▸ Permanent storage of CO_2 is already technologically advanced

Geological storage is particularly suitable for the permanent storage of CO_2 [4]. The most suitable area for this is the porous space of rock at depths of more than 800 meters, where the CO_2 enters a supercritical state due to the pressure and temperature conditions that exist there. There are essentially three storage options for long-term underground storage of CO_2:

- **Saline Aquifere**, in which the CO_2 increasingly dissolves in the brine over time and sinks to the bottom due to its higher density. A small amount of CO_2 mineralizes with the surrounding rock over a very long period of time. Because of their great depth, there is no competition for use with drinking water supply, although there may be competition with hydrogen storage. This type of storage is considered to have the greatest potential both worldwide and in Germany.
- Decommissioned **oil or gas fields** have been well explored, already have infrastructure in place, and are usually leak-proof. This form of storage is still considered to be less technologically mature (TRL 5–8 out of 10)[5], although a few such facilities already exist. In addition, storage in unmineable coal seams is also conceivable, but this is still being researched [6].
- Mineralization (in-situ) involves forcing CO_2 into the pores of **sandstone formations or alkaline rocks** located at depths of 800 meters or more below the seafloor. Depending on the surrounding rock, the CO_2 mineralizes over time. Due to the low level of technological maturity to date and the difficulty in forecasting storage capacities, this form of storage is not yet considered capable of storing the volume of negative emissions required by the climate protection scenarios [5].

A wide range of surveillance and control technologies are available, which show high potential for the further development of comprehensive and cost-effective monitoring of the storage sites in the future [5].

It should be noted that DAC technologies are still at the beginning of their technical application and require significant and rapid development if they are to be used on a larger scale than before. In contrast, the transportation and some geological storage options for CO_2 are relatively mature, although experience with long-term storage is still missing. Moreover, the current commercial development of the existing storage potential is very small compared to potential future demand. In addition, there may be partial competition for the use of CO_2 storage sites, since some could be used for other purposes, such as hydrogen storage.

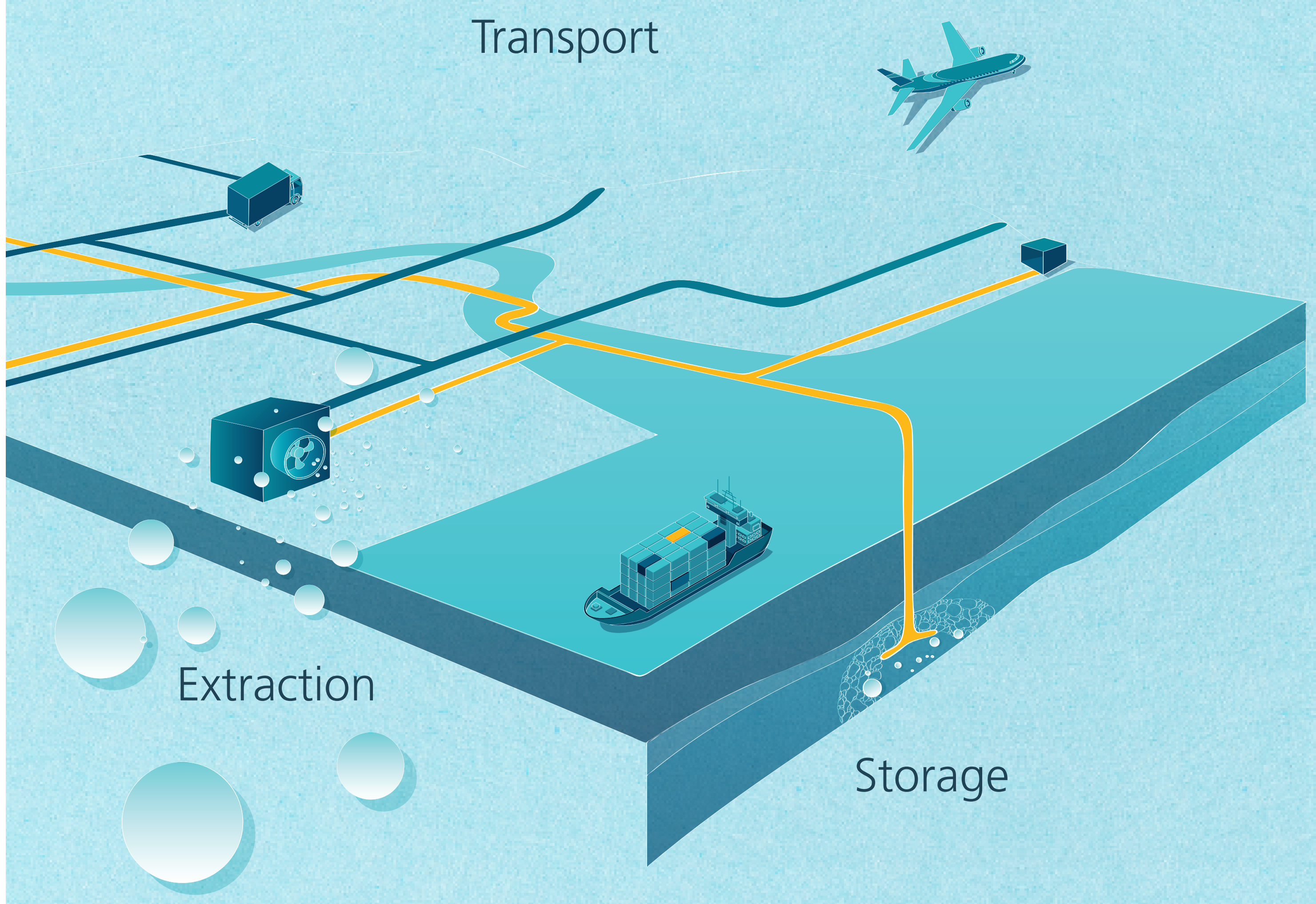


Figure 1 DACCS – from extraction to storage

DACCS

Terms

DACCS
Direct Air Capture and Carbon Storage

DACCU
Direct Air Capture and Carbon Utilization

BECCS
Bioenergy Carbon Capture and Storage

03

Besides DACCS, how can negative emissions be realized?

In addition to DACCS, there are other options for removing CO_2 from the atmosphere and storing it permanently. These different combinations of CO_2 removal and storage are distinguished by how this is done. Generally, CO_2 can be extracted from the air or at a direct emission point such as a power plant or industrial facility (point source)[1]. The binding of CO_2 takes place via a natural process within organic materials by means of photosynthesis or via technical processes binding CO_2 in liquid or solid substances. In the interests of climate protection, sustainable long-term storage of the extracted CO_2 in various forms is required to keep the captured CO_2 out of the atmosphere permanently. These forms include the storage of CO_2 in organic material (biosphere), the storage of CO_2 in geological reservoirs (such as the Earth's crust and part of the mantle), the accumulation of CO_2 in water (hydrosphere), and the storage of CO_2 in long-lasting products such as building materials.[2]

The processes known to date for extracting and storing CO_2 from the air [4,7,8] can be differentiated according to these various forms of extraction and storage and are shown here in Figure 2. The term natural sinks refers specifically to natural CO_2 removal with storage in the biosphere.

In comparison to the other processes, DACCS:

- is technically more advanced compared to enhanced weathering and ocean fertilization,
- is more predictable in terms of storage reliability than natural storage options,
- requires less land, if the energy needed is not taken into account,
- is very flexible with regard to the location of CO_2 extraction,
- and does not differ from BECCS concerning storage issues.

As a result, it is considered a potentially important technical option to achieve negative emissions despite the high costs involved. However, if it is necessary for DACCS to play a role, the use of DAC technologies must be scaled up well beyond their current small-scale deployment (see [9] for a detailed overview of the alternatives).

04

What role does DACCS play in climate scenarios?

▸ The need for DACCS varies significantly between climate scenarios

There are usually several options listed in the climate scenarios to realize negative emissions, such as (re)afforestation, BECCS, and DACCS.

In the 6th IPCC Assessment Report [10], the **global** climate change pathways model the level of negative emissions between 2020 and 2100. Amongst the scenarios likely to achieve the 2.0 °C target or lower, BECCS is considered to play a greater role in achieving negative emissions than DACCS, although the use of DACCS will increase with an increasing level of climate protection ambition. In other global energy system studies (Figure 3), for example, the study by the International Energy Agency (IEA), DACCS contributes about one-third of the negative emissions extracted from the air. This study assumes that the projected geological storage capacities are significantly higher than the required capacities [11]. The projections of the Global Energy and Climate Outlook (GECO) of the Joint Research Centre (JRC) of the European Commission are within a similar range in the 1.5 °C scenarios. DACCS also contributes a smaller share in this study compared to BECCS (14 per cent of the total emission reductions in the scenario). The storage capacities for this are not discussed in detail. However, depleted gas and oil fields are identified as suitable storage sites [12].

At the **European level** in the Diversified Scenario of the Deployment Scenarios for Low Carbon Energy Technologies (LCET), approximately 7 per cent of the total emission reductions in the 2050 scenario are attributed to DACCS [13]. This study points out that the technology still has to be proven on a larger scale. In the JRC scenarios (GECO 1.5 °C) for Europe, about 17 per cent of the total emission reductions in 2050 are attributed to DACCS. This scenario assumes CO_2 is only stored in those countries where it is not legally restricted under current regulations.

At the national level, for example, in Germany,[3] negative emissions [17] are found in three of the »Big 5« climate neutrality scenarios. For example, in the Foundation for Climate Neutrality (SKN)/Agora) study, DACCS accounts for about 27 per cent of total emissions reductions. DACCS is only used in the DENA study if the sink performance of soil carbon storage options is lower than planned. This amounts to about 23 per cent of the total emission reductions in the scenario.

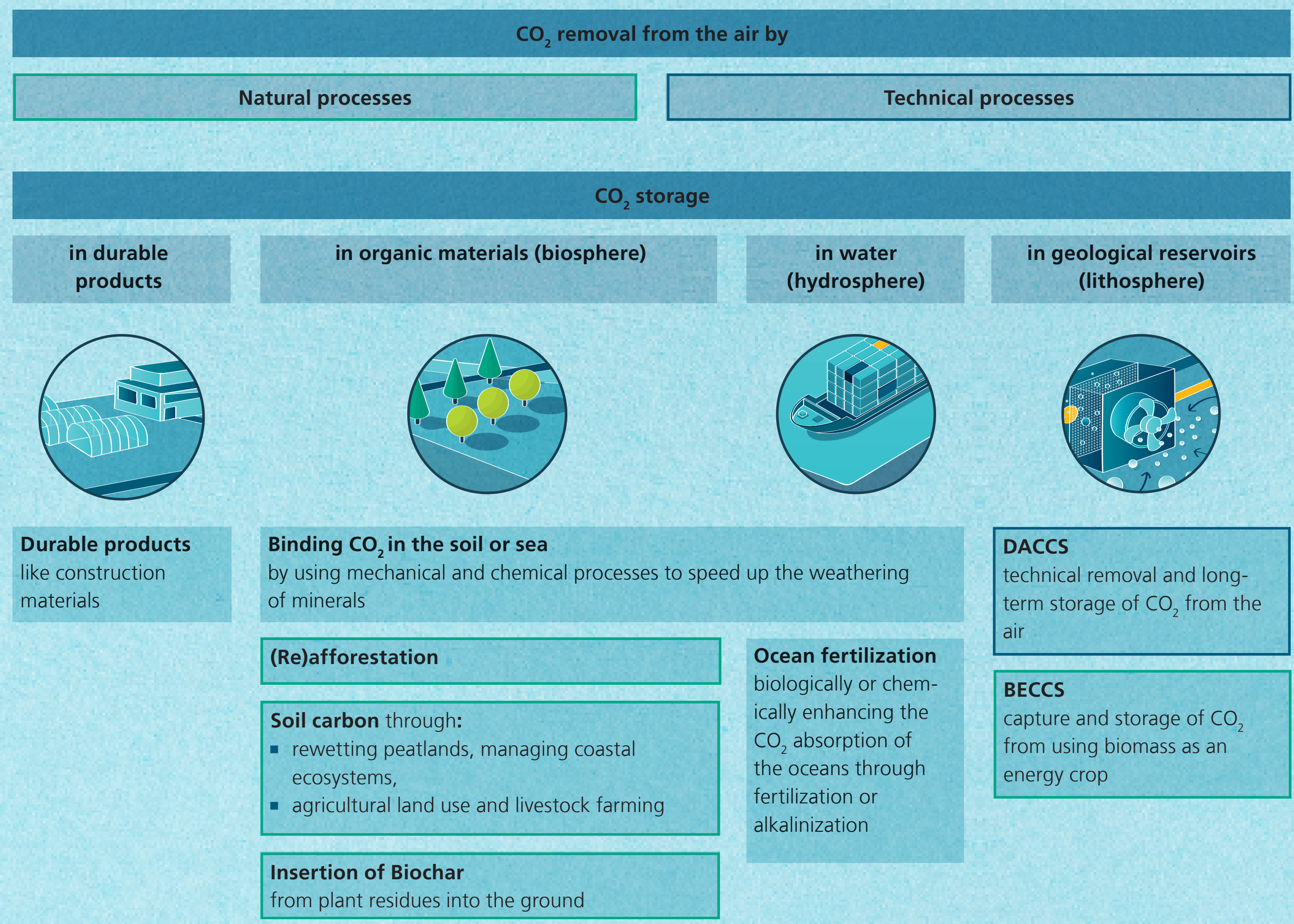


Figure 2 Overview of different options for CO_2 removal and storage

CO_2 removal and storage options

▸ High level of uncertainty about technology and cost development leads to the wide range in the scenarios
In the scenarios, the costs – including environmental impacts and risks – are a key criterion for the choice of extraction option, and since DACCS has not yet been used on a large scale to date, there is a correspondingly high degree of uncertainty regarding the criteria mentioned, which means that there is a high degree of uncertainty regarding the contribution of DACCS to negative emissions in the scenarios. There may also be geopolitical or societal constraints on the use of regional capabilities. It can be seen that, while DACCS is used in many of the IPCC scenarios, it is not used with the same frequency or on the same scale as BECCS, for example. In the 1.5 °C scenario (2021) of the International Renewable Energy Agency (IRENA), DACCS is not included because of the difficulties in quantifying its potential due to its low technical maturity [18].

▸ The upscaling of DACCS in the scenarios is very ambitious when compared to current use
According to the IEA, 18 DAC plants are currently operating worldwide with a capacity of about 0.01 MT CO_2 per year, with more plants under construction and capacity expected to increase 200-fold by 2026 ([19] und [20]). Nevertheless, there is a considerable difference between the capacity increase projected in the IEA roadmap of 60 Mt CO_2 per year in 2030 [11], for example, and the currently expected increase in 2026 of a maximum of 2 Mt CO_2 per year. If the DACCS capacities given in the scenarios are to be achieved, capacity expansion will have to be greatly accelerated [21].

▸ Whether there is sufficient storage potential depends on whether and when the projected geological capacities are commercially developed
With the exception of the IPCC, the majority of studies project the need for DACCS only for the years up to 2050, which is when climate neutrality is to be achieved. During this period, it is not anticipated that geological storage capacities will be exhausted to any great extent. In the IPCC scenarios, the importance of DACCS only increases in the second half of the 21st century, i.e., after 2050. Here, in the pathways below 2 °C, the total use of negative emissions between the year in which net-zero is achieved and 2100 is a maximum of 620 Gt CO_2. The estimated storage capacities of around 14,000 Gt CO_2 would therefore provide sufficient capacity until 2100. However, the proportion of the global storage capacities that have already been commercially developed, around 0.25 Gt of CO_2, falls far short of this figure. It is therefore clear that it will be necessary to greatly accelerate both the extraction capacity using DAC and the storage capacity in order to achieve the pathways from the scenarios.

05

What is the environmental impact of DACCS?

Initial environmental assessments of DAC plants include the direct environmental impacts, i.e., those resulting from the construction, operation, and recycling of DAC plants ([22] and [23]), with the most significant environmental effects resulting from supplying the energy required to operate the plants, water consumption, and land requirements.

Since the concentration of CO_2 in the air is very low at 415 ppm, high **energy consumption** is required to capture it. This is significantly higher than the energy required for CO_2 capture directly at stationary emission point sources, such as power plants or industrial plants [2], because the CO_2 concentration here is almost 100 times higher than in the air [24].

Because of the DAC plant's high energy consumption, the CO_2 intensity of the energy sources used for its operation has a major impact on the life cycle assessment of the DAC itself (cf. Table 1 in [9]). For energy efficiency reasons, extraction from the available point sources, i.e., (off-)gases with higher CO_2 concentrations, should be prioritized over DAC where possible. In the same way, DAC plants should be sited where **low-emission energy sources** are available, because the energy source used has a direct effect on the environmental impact. Thus, plants powered by renewable electricity or heat can achieve more net negative emissions than DAC plants with high shares of fossil-based electricity or heat production [22]. It is a subject of controversial debate in the scientific community whether it makes sense in life cycle assessments to base the operation of a DAC plant exclusively on renewable electricity or renewable heat as long as the electricity mix is still dominated by fossil fuels. However, policy advisors are increasingly of the opinion that the emissions of the (regional) electricity and heat mix should be used to calculate the emissions caused by the plant's operation (see [27–29]). It follows that, even if the DAC plant is powered exclusively by renewable energy sources, emissions from the on-site energy mix must be taken into account.

Besides energy consumption, **water consumption** also needs to be critically assessed. This depends heavily on the design of the technology (cf. Table 2 in [9]). Low-temperature DAC also extracts water from the air together with CO_2, the amount of which depends on the humidity and the ambient temperature [30]. With regard to the **land needed**, in addition to that used directly by the plant, the land required for renewable electricity generation is also added, where applicable. In some studies, DAC technology performs significantly better than BEECS in terms of land use, as BECCS is assumed to require 100 to

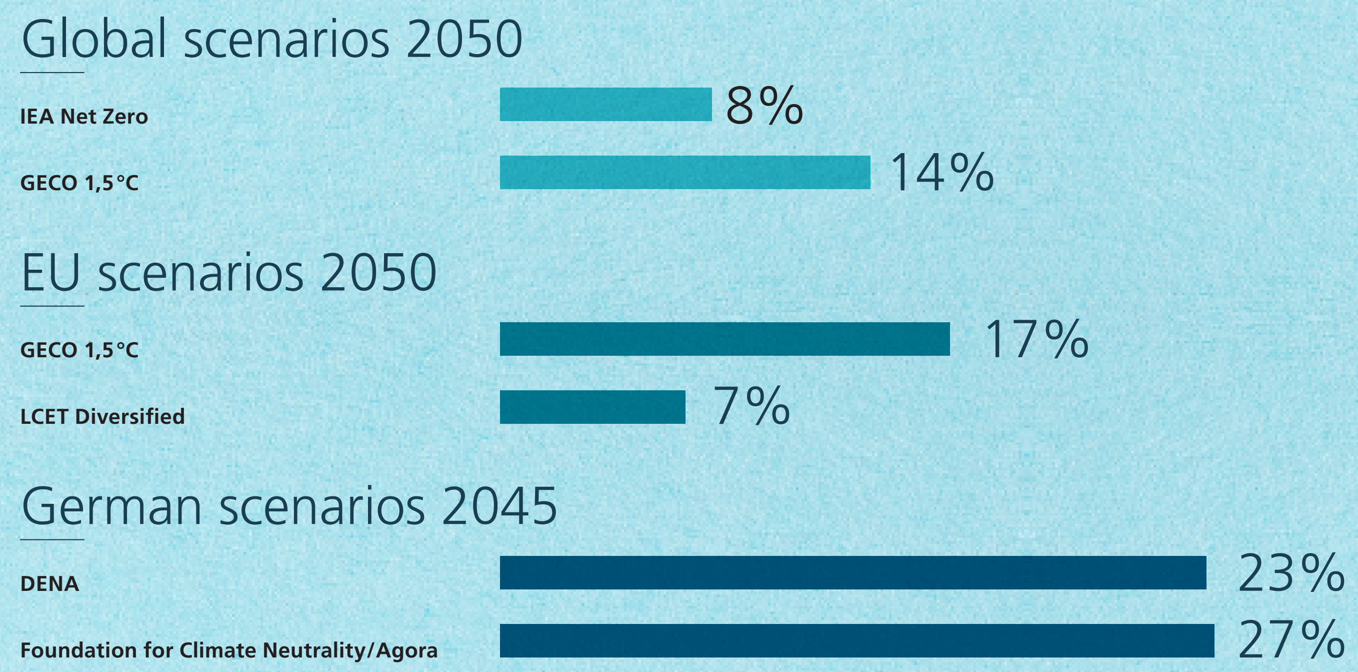


Figure 3 Share DACCS emission sinks in the scenarios in per cent

DACCS scenarios

Example of net negative emissions

For each ton of CO_2 captured from the air using DAC plants, around 0.7 t of CO_2 is emitted just for the fossil-based generation of the energy required (for electricity and heat). Thus, in the worst case, the net negative emissions amount to about 0.3 metric tons of CO_2 (1 metric ton of captured CO_2 minus 0.7 metric tons of emitted CO_2). The CO_2 emissions for electricity and heat are calculated by multiplying the emission factors of the German 2021 electricity mix [25] and natural gas [26] by the electricity and heat requirements of the DAC plant.

50,000 times more land [3]. However, this advantage is limited, as areas for the injection and for monitoring the storage must be considered for DACCS as well as the areas for PV, wind power, etc., where applicable. Another advantage that is emphasized for DAC plants is that they can be located in the vicinity of cost-effective energy generation capacities and close to suitable storage sites, avoiding the need for long-distance transportation of the CO_2 [31].

The **materials** used in the manufacture of DAC plants, as for other industrial plants, are mainly concrete, low-alloy steel, PVC and stainless steel (cf. Table 2 in [9]). Energy is used in upstream chains during their production and, as an indirect effect, CO_2 is also released into the air. These indirect emissions are small relative to the CO_2 extracted over the lifetime of the DAC plant: a one-time emission of about 0.08 Mt CO_2 would be generated by the construction of a low-temperature DAC plant with a capacity of 1 Mt CO_2 per year. Critical raw materials are not used in the process [32].

06

How much does DACCS cost?

In order to achieve the gigatons of CO_2 extraction shown in the scenarios in the future, it will be necessary to install large numbers of DAC plants [31]. Along with the technical scaling of these plants in terms of production, the main challenges are to reduce the investments needed as well as their operating costs. DAC technology is still at the beginning of its development, and therefore at the beginning of the so-called technological learning curve. This curve shows how the costs of a technology decrease as its use increases. These cost reductions result from learning and economies of scale effects in manufacturing the technology and operating the plant, for example, due to efficiency improvements in the use of materials and resources, including energy, and may also vary somewhat depending on the technology. Several authors [7] foresee a significant reduction in costs due to the great scope for further development and potentially high energy savings, which is an important cost factor. In addition to the cost of removing CO_2 from the air, there are also costs associated with transport and storage, but these are relatively low. Consequently, the costs of CO_2 removal are prioritized in this Policy Brief.

▸ Falling costs of CO_2 extraction from the air as DAC technologies become more widely used

The cost per ton of CO_2 captured from the air is calculated based on the operating costs and investments as well as the yield of the plant, which is recorded in tons of CO_2:

- **Capital expenditure** (CAPEX) for the manufacture and construction of the DAC plant. In the literature, estimates of future investments in DAC technology are based on three parameters: a) current level of investment (CAPEX), b) installed capacities over several decades, c) rate of learning. According to this calculation formula, future capital expenditures for the production of DAC plants decrease as their use increases, i.e., as capacity expands.
- **Operating costs** (OPEX) depend on the availability of a low-cost energy source, especially a low-cost heat source, such as waste heat, or low-cost electricity, for example, from PV or wind power plants, as well as on the operating hours of the DAC plants. In addition, new materials for adsorption or absorption can improve resource and process efficiency and contribute to decreasing operating costs.
- Over their lifetime, the **net yields** result from the CO_2 removal from the air minus the CO_2 emissions generated while operating the DAC plant (see section 05). These operational emissions reduce the gross efficiency of the plant, which is determined by its capacity and utilization rate.

The costs per ton of removed CO_2 are calculated based on the cost components outlined by different authors [1,33–38] with differing assumptions. As a result, they vary greatly. For current CO_2 extraction, cost estimates range from 80 to 1,130 EUR/t CO_2 [38]. Many authors regard it as quite possible that pure CO_2 sequestration without storage will cost less than 200 EUR/t CO_2 in the future using LT-DAC technology. In addition to decreasing capital expenditures, cost efficiency in the operation of DAC plants plays an important role here. This cost efficiency is the highest when inexpensive and constantly available energy sources are used (for example, hydroelectric power, natural gas) and the plant is in continuous operation. The use of fluctuating renewable power sources makes it harder for the DAC systems to amortize due to the low utilization rate. As a result, levelized costs of DAC (LCO_{DAC}) tend to be higher with renewables than with constantly available energy sources. Under very favorable conditions (for example, low-cost energy source, significant capacity expansion, high utilization of the plants, technical advances), it is conceivable for some authors that the LCO_{DAC} of separating one ton of CO_2 from the air could be around 90 EUR/t CO_2 using HT-DAC technology and around 40 EUR/t CO_2 using LT-DAC from 2050 onwards [1,38].

▸ Moderate costs for transport and storage

To estimate the cost of DACCS for a ton of CO_2, the costs for transporting and long-term storage of the CO_2 are also relevant in addition to the costs of extracting the CO_2 from the air. Different authors, e.g., [1] and [4], give a short overview of the possible current **costs of CO_2 transport** for different transport routes. Road transport costs (by truck) are the highest at around 15 EUR cent/ton CO_2/km, while ship transport ranges from 1 to 7.5 EUR cent/ton CO_2/km, and pipelines (onshore and offshore) from 0.3 to 5.5 euro cent/ton CO_2/km. The costs for the **capture and storage** of the CO_2 are estimated to be 4 EUR/t CO_2, but can increase to 20 EUR/t CO_2 depending on the storage site (onshore–offshore, gas/oil fields, saline aquifers) [4]. These costs are low in comparison to the cost of CO_2 removal using DAC. Additionally, since the level of technology maturity (the so-called Technology Readiness Level) for transportation and storage is estimated to be significantly higher than for DAC, they have a lower cost reduction potential.

▸ The major cost drivers:

In summary, the cost of DAC (CO_2 capture) is the predominant factor determining the future use of DACCS. In this context, the relevant factors are low prices and good availability of resources, such as energy, water, land and other materials during plant operation, as well as declining capital expenditures driven by high rates of learning in plant operation, manufacturing and development, and strong capacity expansion.

07

How could a CO_2 removal market be designed?

As the level of ambition for emissions abatement increases, so does the importance of negative emissions. This might be accompanied by a further development of the negative emissions market, hereafter referred to as the **CO_2 removal market**. Such a market could also increase the incentives for investing in DAC(CS) facilities.

▸ Currently, there is a small market for CO_2 removal

Although there is currently no market regulation for negative emissions, a small CO_2 removal market already exists, where negative emissions obtained via DACCS are also offered. This includes private companies offering negative emissions as CO_2 offsets for corporate or private air travel at a price of USD 600 to USD 1,000/t CO_2 [31]. Companies such as Microsoft, Stripe and Swiss RE are currently among the customers for such CO_2 offsets. However, the DAC plants currently in operation only remove small amounts of CO_2 from the air and are still a long way from achieving the DACCS quantities required in the scenarios [19].

▸ Current emission reduction systems could be linked to a CO_2 removal market via the CO_2 price

Similar to the emissions trading scheme to reduce greenhouse gas emissions, further developing the CO_2 removal market could set market-driven incentives to monetize the emissions offset by DACCS. Such a market would be directly related to the climate goals of the European Union and its member states and thus also to the existing emission reduction systems of the European Union (EU markets for emissions). For such a CO_2 removal market to be linked to these systems, the rules in the respective emission reduction systems would have to be adapted in a next step:

- **European Emissions Trading Scheme** (EU ETS): The EU ETS regulates combustion plants in the energy industry, plants in energy-intensive industries, and intra-European air traffic. Currently, the use of GHG capture technologies does not exempt plant operators from their compliance obligations under the EU ETS. However, the reform proposal published as part of the EU's Green Deal stipulates that, in future, plant operators will not have to submit allowances for captured greenhouse gas emissions that are permanently sequestered. Whether these reforms will also include the crediting of negative emissions by means of DACCS is currently an open question. It would be conceivable that plant operators who offset their greenhouse gas emissions with the help of negative emissions would also be exempted from compliance obligations, or that companies that acquire negative emissions could have them credited against their compliance obligations (see [39]).
- **Effort Sharing Regulation** (ESR): The ESR sets greenhouse gas emission reduction targets for member states in transport, buildings, agriculture, non-EU ETS industry, and other smaller sectors. It is conceivable that, in the future, allowances from a removal market for negative emissions could also be used to help member states achieve their targets. Member states could then purchase negative emissions on the CO_2 removal market and credit them to their ESR targets. Alternatively, similar to the EU ETS, negative emissions could be offset in the planned emissions trading system for the buildings and transport sectors. In this case, private stakeholders would acquire negative emissions and not the member states.
- **Land use and forestry regulation** (LULUCF): The LULUCF regulation sets greenhouse gas emission targets for land use and forestry. In a similar way to the ESR targets, if the regulation were to be adapted, member states could have negative emissions credited to their targets in the future.

The three systems mentioned above already represent emission mitigation solutions with market-based elements. However, at present they only apply to specific sectors or areas and differ in their market participants: in the EU ETS, these are companies; in the ESR and LULUCF, these are currently only the EU member states.

If the CO_2 removal market were linked to these emission avoidance systems, the linking element would be the price of CO_2 certificates. Certified negative emissions would be purchased on the market as soon as their price dropped below the cost of other CO_2 prevention options[4] or allowances of the respective system. However, the current comparatively high cost of DACCS suggests that, in the event of a large-scale CO_2 removal market, it would not be competitive at present and would therefore be unlikely to be used (e.g., [39]) . In general, due to the limited availability and uncertainties of storage capacity, the principle of »reduction first« must be considered, i.e., emission avoidance before negative emissions. This avoids lock-ins in CO_2 intensive processes.

▸ A long-term CO_2 removal market is conceivable under certain framework conditions

The basic condition for creating such a long-term CO_2 removal market is an institutional framework, with a monitoring system that works and ensures that the certified CO_2 is really and fully removed from the atmosphere and that this is a net removal (see section 05). This leads to another requirement, namely certification and monitoring. The European Commission's certification proposal (in November 2022) to remove carbon from the atmosphere laid a vital foundation for this. Based on this proposal, companies will be able to trade negative emissions and offset their emissions and enhance their image in doing so, but not to reduce their obligations on carbon markets such as the EU ETS. Therefore, the European Commission's proposal envisages a CO_2 removal market on its own to start with and separate from existing systems. Further aspects of market design would be the crediting of negative emissions from countries outside the EU and considering the »reduction first« principle, i.e., emissions avoidance should be prioritized over negative emissions.

A market ramp-up of DAC technologies requires a broader, regulated CO_2 removal market on which negative emission certificates can be traded. Without special support for DAC technologies, the high costs involved mean that completely integrating the CO_2 removal market into existing emission reduction systems would not stimulate the market ramp-up of DAC technologies. Market integration could be possible in the long term, but at the same time would then involve the risk of lock-ins to technologies that are not climate friendly.

08

Are subsidization and regulation needed for DACCS to take off in the market?

The establishment of a CO_2 removal market (section 07) requires a tight regulatory framework with regard to the production, transport and storage of CO_2 in conjunction with the targeted promotion of DACCS.

▸ The need for regulation of CO_2 extraction, transport and storage

So far, there is no regulatory framework for **CO_2 extraction** using DAC technology, for example, with regard to site selection, plant specifications, product properties or the certification of net negative emissions.

The European Commission's **CCS Directive** [40] provides a regulatory framework for the **transport and storage** of CO_2 that addresses leakage, environmental risks, health and safety hazards, and ensures permanent storage. This framework is currently being revised. In addition to this, regulations in the member states are necessary to close gaps in European legislation, especially on how to deal with liability in the event of leakage. The majority of EU member states have so far only implemented the actual wording of the CCS Directive. The leaders in this respect are the Netherlands, the UK and Norway – countries in which the timely development of CCS infrastructures is a clear political objective.

The **EU ETS Directive** also stipulates that both CO_2 transport by pipeline and its storage are activities subject to European emissions trading. Accordingly, obligations to pay levies arise in the event of leakage for transported and stored CO_2. It is expected that other modes of CO_2 transport will be included as part of the revision of the EU ETS Directive. Despite the planned revisions at the EU level, there will still be a need for further shaping transport and storage requirements at the member state level. In addition, there may be a need to revise existing regulation even in those countries where the CCS Directive has already been implemented in a more concrete way. In particular, this applies to cases in which storage has been significantly restricted in the past, limited to an evaluation phase as in Germany, or completely prohibited.

The **London Protocol** is also of relevance for the case of offshore storage of CO_2. This regulates the handling of waste and other materials for disposal or incineration at sea worldwide and also addresses the transport and disposal of CO_2 (Art. 6). So far, CO_2 transfer from one country to another for disposal at sea is only possible under an exemption clause if the two countries have ratified the amended Article 6 for this purpose and reached a bilateral agreement. Only a few countries in Europe have done this so far. As a result, exporting CO_2 for offshore storage [5] is currently only possible to a very limited extent.

The combination of the London Protocol and implementation of the CCS Directive at national level means that, in some countries (including Germany), there is currently no possibility of setting up CO_2 storage projects.

▸ The need for regulation in the trading of certificates

When establishing a **CO_2 removal market**, the appropriate market regulation would need to specify, the certified tradeable products, the pricing mechanisms, market access, and the interplay with existing targeting schemes described in section 07. This market regulation should build on existing regulations such as the CCS Directive or regulation under the EU ETS. The first draft of a regulatory framework to establish a negative emissions system, published at the end of 2022 (see section 07), represents a first step in this direction, but is not sufficient to ensure net negative emissions and thus a functioning market.

▸ Subsidizing DACCS is necessary at least in the short term, but market integration should be the goal in the long term

Several governments have approved R&D funding, for example, USA, Australia, Canada, Japan and the United Kingdom, but many other countries are still reluctant. In contrast, the funding of storage infrastructures for CO_2 can be found especially in those countries that have clear political objectives for CCS (Netherlands, Great Britain, Norway). In Germany, projects to capture and store CO_2 in industry are being funded as part of an open-technology research program (BMWK – CO_2 Capture and Utilization in Industry). However, the first round of funding is explicitly directed at research projects that aim to fill existing research gaps. Pilot and demonstration plants will only be supported in a second round of funding. Funding DAC technologies or DACCS would also be conceivable in principle as part of the decarbonization of industry research program. European funding is available for CO_2 storage through the Innovation Fund, but there is no specific regulation or funding focus on DACCS and its market integration to date.

In order to achieve the scale-up rates outlined in the scenarios, there is a need to promote and fund the expansion and application of DACCS. This is particularly necessary due to the comparatively high costs for DACCS (up to 1,000 EUR/ton CO_2), which cannot be covered by the currently obtained CO_2 prices, for example, 85 EUR/t CO_2 in the EU ETS at the end of December 2022 [41].

One possible instrument for market-integrated support along the lines of the support for renewable energies or hydrogen is a concept based on a CfD or CCfD – (Carbon) Contract for Difference – similar to climate protection contracts for the decarbonization of industry. The CO_2 certificate price could be used as a market signal, whilst at the same time absorbing high investment risks. This instrument is closely linked to the CO_2 removal market from the outset by setting a time limit on the subsidy and a corresponding repayment mechanism in the event of sufficiently high market prices.

09

What is the state of the social debate on DACCS?

Even though DACCS has appeared in climate scenarios as an important option for generating negative emissions for some years (see section 04), there is hardly any current social debate about the use of DACCS. The public's general knowledge and awareness of DACCS is classified as low [42]. It is therefore unclear what the future level of acceptance of DACCS will be and this calls for a process of societal negotiation . The research findings that exist so far indicate that there are a few important parameters that could be critical for acceptance:

One critical aspect is the **geological storage** of CO_2 in the seabed or underground on land, which was viewed with skepticism in the past [43] or rejected outright [44], especially in regions suitable for CO_2 sequestration[45], so that storage projects in Germany and other countries were even abandoned [46].

Recently, it can be observed that the rejection of this concept has been declining [43,47], influenced by the framework conditions under which CO_2 removal, use or storage takes place: For instance, **utilizing the CO_2** instead of storing it, is usually assessed more positively, even if this does not achieve negative emissions. In the same way, **storing CO_2 from energy-intensive processes in industry** or combined with biomass use is viewed slightly more positively than storing the CO_2 captured from coal-fired power generation [48]. Although there are still only limited research results available on the other options for negative emissions (such as BECCS or **afforestation** or reforestation) (e.g., [42]), interim results show that approaches like afforestation tend to trigger more positive reactions among the population than measures perceived as very technical in the sense of not natural or complex [42,45,49–51]. A slightly higher level of acceptance can be seen in countries with more advanced development of CCS, e.g., [52], although an initial study indicates that storing **imported CO_2** is viewed negatively [53]. This and **further conditions and processes** that are relevant for local acceptance or opposition include: 1) local characteristics, 2) project characteristics, 3) specific behavior of different actors as well as the degree of trust in them, 4) participation and communication process, (5) cost-benefit considerations as well as (6) the wider socio-political context [42,54,55].

The questions in detail

A social opinion-forming process is therefore necessary. This should focus on three main aspects: a) the design and application of DACCS and its alternatives for negative emissions, b) the development and implementation of a flexible communication and participation strategy adapted to the respective circumstances, and c) a prudent and participatory implementation of the projects. It is important that such an opinion-forming process is supported by politics, business and science.

10

What role should DACCS play in a climate protection strategy?

Various reports, such as the World Energy Outlook (IEA), the Emission Gap Report of the UNEP and the UN Climate Change Report indicate that »we are not on track« to meeting the climate goals. It is questionable whether the transformation of key areas of society can be achieved on time and to the extent needed to comply with agreed climate targets. In many areas, this transformation is not happening quickly enough at present. For example, renewable energy expansion in Germany in recent years has fallen well short of what is required, especially for wind power. In order to be able to meet the 80 per cent target for renewables in German electricity generation by 2030, given the 49 per cent achieved in 2022, substantial increases in production capacities are necessary, permit issuing procedures have to be accelerated and the skilled workers needed must be trained and provided. Growth dynamics must also be significantly increased in other areas as well, in some cases well above the levels reached in the past. These areas include building renovations, expanding the electricity grid, deploying electric mobility, reducing primary energy consumption, expanding hydrogen production and transport capacities, and transforming processes in industry, for instance, in the iron and steel industry or in basic chemicals. All this has to take place in an environment already facing several challenges including the energy crisis, partially interrupted value chains, a shortage of skilled workers and rising national debt. Furthermore, the war in Ukraine has affected prices and energy availability and this could have a negative impact on the speed of transformation in some areas and further widen the gap between the transformation needed and its actual implementation. On a global level, climate protection is already accorded high priority, but the corresponding transformation of the (energy) industry is overshadowed by very different types of crisis and power games.

▶ Positive effects of DACCS on the economy and climate protection

Against this background, from a climate policy perspective, the use of DACCS technology seems a possible solution to close or at least to narrow the widening gap between the emission target trajectories and the current development of emissions. In addition to this, it might be easier for some industries to implement the use of DACCS rather than pursuing CO_2 avoidance strategies, because DACCS does not require changes to processes or production methods. This could, if necessary, circumvent transformation risks that might restrict production processes, at least in the short term [35]. In addition, the growth impulses and new jobs triggered by DACCS represent possible positive effects that could foster the acceptance of climate protection measures and make them easier to enforce in groups that have so far shown little willingness to transform, such as employees in sectors that will undergo major structural change due to the energy transition, or parts of the population that stand to benefit from DACCS locations.

▶ DACCS reinforces the fossil path dependencies of the energy industry and therefore jeopardizes sustainability goals

A critical aspect of using DACCS from the viewpoint of sustainability is the risk of path dependencies if these delayed the decarbonization of industry and the phase-out of fossil fuels on a global level in the energy sector [2]. It is precisely this turning away from fossil fuels and avoiding the so-called »Carbon lock-in«, i.e., fossil path dependencies that is regarded as one of the major challenges of the energy transition [56]. The use of DACCS could be counterproductive to this. For example, competitive DACCS technologies would mean less pressure placed on established energy (supply) companies to carry out the energy transition, because climate change could be combated in the short term by using DACCS. Accordingly, DACCS is not perceived as promoting the sustainable use of resources and is seen as a threat to implementing the UN Sustainable Development Goals, SDGs (among others [56] or [57]).

▶ Transformation is hindered by DACCS instead of efficiency measures in long-term renovation cycles

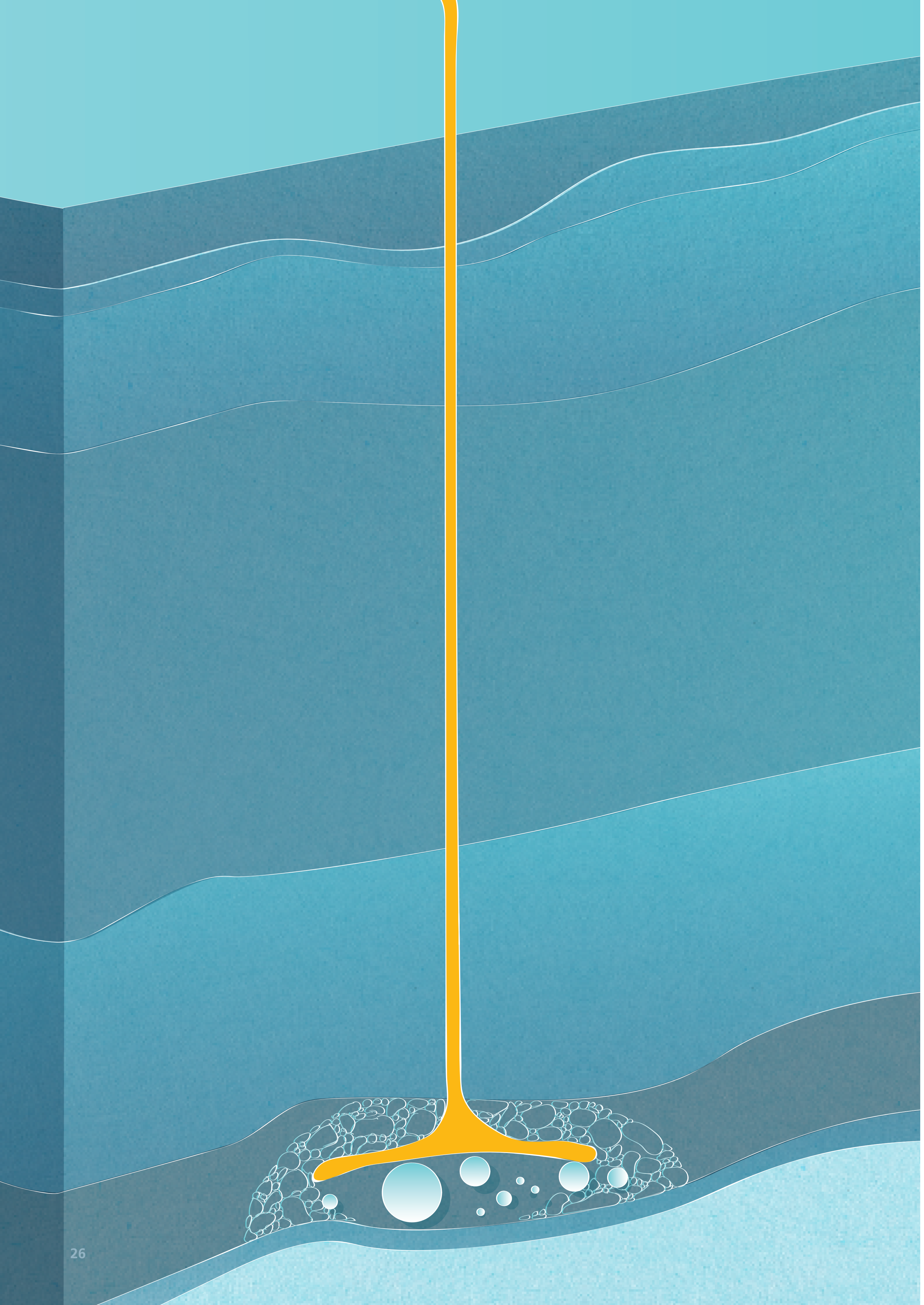
Some sectors have very long investment cycles, for example between 30 and 50 years for buildings. If efficiency measures are not realized during refurbishments because of DACCS options, this would greatly postpone the decarbonization of this sector, as it is usually very uneconomical to implement energy efficiency measures outside of these renovation cycles. This also applies to a number of other transformation processes in industry and in the field of infrastructure, which means that investing in decarbonization should be done at the end of the useful life of production plants and infrastructures wherever possible. Postponing measures to avoid GHG emissions because of DACCS as »a beacon of hope« would be an extremely risky strategy as DACCS capacities may not be sufficient to achieve greenhouse gas neutrality. This risk of exceeding the temperature goal in an unplanned way is quantified with up to 0.8 °C [2]. Moreover, delaying transformation would curtail the options of future generations to protect the climate (intergenerational equity). As a result, the IPPC Status Report points out that DACCS and other carbon removal options should only be used in combination with other measures and not as a substitute for them [10].

▶ DACCS calls for fair and widespread public participation

It is still unclear to what extent giving the public opportunities to participate in the expansion of DACCS will lead to more or less inequality and equitable distribution, especially in light of the high capital requirements and risks of the market roll-out, but this should be considered when developing the DACCS market. This also includes dealing with different preferences between different social groups: While some are ready for radical and rapid change and for a reduction in consumption, for others, only a slower transformation is conceivable or feasible, which is then likely to need negative emissions to a greater extent.[6] In general, there must be a social debate addressing the topic of DACCS to understand the key aspects that can be decisive for how such a technology is handled by society.

▶ DACCS as an instrument to mitigate the risk of failing to meet the target

For reasons of economic viability, sustainability and technical feasibility, it is currently still unclear whether, and if so, to what extent DACCS could contribute to reducing GHG emissions in the future. Nevertheless, or perhaps because of this, the conclusion that can be drawn from this discussion is that, from a climate policy viewpoint, DACCS should be further developed as one option for achieving negative emissions, since it is very likely that these will be needed to achieve greenhouse gas neutrality. In this way, DACCS can be used as an instrument to mitigate the risk of a possible failure to meet the target. Based on the current state of knowledge, DACCS is one of the more promising approaches to achieve negative emissions, even if the actual use of the technology is still linked to many unresolved technical, regulatory, economic, environmental and societal questions and challenges. It is critical that DACCS is not pushed at the expense of other climate protection measures and does not result in new path dependencies.



References

[1] **M. Fasihi, O. Efimova, C. Breyer**: Techno-economic assessment of CO_2 direct air capture plants, Journal of Cleaner Production 224 (2019) 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086.

[2] **G. Realmonte, L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A.C. Köberle, M. Tavoni**: An inter-model assessment of the role of direct air capture in deep mitigation pathways, Nat. Commun. 10 (2019) 3277. https://doi.org/10.1038/s41467-019-10842-5.

[3] **B.R. Sutherland**: Pricing CO_2 Direct Air Capture, Joule 3 (2019) 1571–1573. https://doi.org/10.1016/j.joule.2019.06.025.

[4] **Prognos AG**: Technische CO_2-Senken: Techno-ökonomische Analyse ausgewählter CO_2-Negativemissionstechnologien. Kurzgutachten zur dena-Leitstudie Aufbruch Klimaneutralität, 2021.

[5] **Bundesregierung**: Evaluierungsbericht der Bundesregierung zum Kohlendioxid-Speicherungsgesetzt (KSpG): [Evaluation of the regulation on CCS of the Federal Government of Germany], Berlin, 2022.

[6] **Europäisches Exzellenznetzwerk CO2GeoNet**: Geologische CO_2-Speicherung – was ist das eigentlich?, 2010.

[7] **M. Erans, E.S. Sanz-Pérez, D.P. Hanak, Z. Clulow, D.M. Reiner, G.A. Mutch**: Direct air capture: process technology, techno-economic and socio-political challenges, Energy Environ. Sci. 15 (2022) 1360–1405. https://doi.org/10.1039/D1EE03523A.

[8] **P. Smith, S.J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R.B. Jackson, A. Cowie, E. Kriegler, D.P. van Vuuren, J. Rogelj, P. Ciais, J. Milne, J.G. Canadell, D. McCollum, G. Peters, R. Andrew, V. Krey, G. Shrestha, P. Friedlingstein, T. Gasser, A. Grübler, W.K. Heidug, M. Jonas, C.D. Jones, F. Kraxner, E. Littleton, J. Lowe, J.R. Moreira, N. Nakicenovic, M. Obersteiner, A. Patwardhan, M. Rogner, E. Rubin, A. Sharifi, A. Torvanger, Y. Yamagata, J. Edmonds, C. Yongsung**: Biophysical and economic limits to negative CO_2 emissions, Nat. Clim. Chang. 6 (2016) 42–50. https://doi.org/10.1038/nclimate2870.

[9] **Fraunhofer ISI**: Direct Air Carbon Capture and Storage – Rolle für den Klimaschutz: Langfassung, Karlsruhe, 2023.

[10] **IPCC**: Climate Change 2022 Mitigation of Climate Change – Summary for Policymakers: Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Working Group III, 2022.

[11] **IEA**: Net Zero by 2050 – A Roadmap for the Global Energy Sector, fourthth revised Version, 2021.

[12] **K. Keramidas, F. Fosse, A. Diaz Vazquez, P. Dowling, R. Garaffa, J. Després, P. Russ, B. Schade, A. Schmitz, A. Soria-Ramirez, T. Vandyck, M. Weitzel, S. Tchung-Ming, A. Diaz Rincon, L. Rey Los Santos, K. Wójtowicz**: Advancing towards climate neutrality: Taking stock of climate policy pledges after COP26 and the corresponding energy-economy implications, Publications Office of the European Union, Luxembourg, 2021.

[13] **W. Nijs, C.P. Ruiz, Tarvydas, D., T. I., A. Zucker**: Deployment Scenarios for Low Carbon Energy Technologies, Luxembourg, 2018.

[14] **JRC**: Advancing towards climate neutrality: Taking stock of climate policy pledges after COP26 and the corresponding energy-economy implications, Publications Office of the European Union, Luxembourg, 2021.

[15] **J. Serpa, J. Morbee, E. Tzimas**: Technical and Economic Characteristics of a CO_2 Transmission Pipeline Infrastructure, Luxembourg, 2011.

[16] **DENA**: dena-Leitstudie Aufbruch Klimaneutralität. Abschlussbericht, 2021.

[17] **M. Gierkink, J. Wagner, B. Czock, A. Lilienkamp, M. Moritz, L. Pickert, T. Sprenger, J. Zinke, S. Fiedler**: Vergleich der »Big 5«-Klimaneutralitätsszenarien, 2022.

[18] **IRENA**: World Energy Transitions Outlook. 1.5 °C Pathway. Abu Dhabi, 2021.

References

[19] D.W. Keith, G. Holmes, D. St. Angelo, K. Heidel, A.: Process for Capturing CO_2 from the Atmosphere, Joule 2 (2018) 1573–1594. https://doi.org/10.1016/j.joule.2018.05.006.

[20] Global CCS Institute: Global Status of CCS 2021, 2021.

[21] C. Beuttler, L. Charles, J. Wurzbacher: The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. Front. Clim. 1, 10 (2019) https://doi.org/10.3389/fclim.2019.00010.

[22] T. Terlouw, K. Treyer, C. Bauer, M. Mazzotti: Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources, Environ. Sci. Technol. (2021). https://doi.org/10.1021/acs.est.1c03263.

[23] Y. Qiu, P. Lamers, V. Daioglou, N. McQueen, H.-S. de Boer, M. Harmsen, J. Wilcox, A. Bardow, S. Suh:
Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100, Nat. Commun. 13 (2022) 3635. https://doi.org/10.1038/s41467-022-31146-1.

[24] T. Fröhlich, S. Blömer, D. Münter, L.-A. Brischke: CO_2-Quellen für die PtX-Herstellung in Deutschland – Technologien, Umweltwirkung, Verfügbarkei, 2019. https://www.ifeu.de/fileadmin/uploads/ifeu_paper_03_2019_CO2-Quellen-f%C3%BCr-PtX.pdf.

[25] UBA: Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990–2021, 15th edition, Dessau, 2022.

[26] M. Memmler, T. Lauf, K. Wolf, S. Schneider: Emissionsbilanz erneuerbarer Energieträger, 2017.

[27] Agora: Batteriestandort auf Klimakurs – Perspektiven einer klimaneutralen Batterieproduktion für Elektromobilität in Deutschland: Endbericht, 2021.

[28] B. Marmiroli, M. Messagie, G. Dotelli, J. van Mierlo: Electricity Generation in LCA of Electric Vehicles: A Review, Applied Sciences 8 (2018) 1384. https://doi.org/10.3390/app8081384.

[29] M. Wietschel, K. Biemann, S. Link, H. Helms: Schwerpunktstudie „Nachhaltige Mobilität". Los 2: Langfristige Umweltbilanz und Zukunftspotenzial alternativer Antriebstechnologien: für die Expertenkommission Forschung und Innovation, Karlsruhe, 2021.

[30] O. Zelt, G. Kobiela, W. Ortiz, A. Scholz, N. Monnerie, A. Rosenstiel, P. Viebahn: Multikriterielle Bewertung von Bereitstellungstechnologien synthetischer Kraftstoffe. Teilbericht 3 (D2.1) an das Bundesministerium für Wirtschaft und Energie (BMWi), Wuppertal, Stuttgart, Saarbrücken, 2021.

[31] IEA: Direct Air Capture: A key technology for net zero, (2021, 2022). https://www.iea.org/reports/direct-air-capture; https://www.iea.org/reports/direct-air-capture-2022.

[32] F. Marscheider-Weidemann, S. Langkau, S.-J. Baur, M. Billaud, O. Deubzer, E. Eberling, L. Erdmann, M. Haendel, M. Krail, A. Loibl, F. Maisel, M. Marwede, C. Neef, M. Neuwirth, L. Rostek, J. Rückschloss, S. Shirinzadeh, D. Stijepic, L. Tercero Espinoza, M. Tippner: Rohstoffe für Zukunftstechnologien 2021 (2021). https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-50.pdf?__blob=publicationFile&v=4.

[33] C. Breyer, M. Fasihi, A. Aghahosseini: Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling, Mitig Adapt Strateg Glob Change 25 (2020) 43–65. https://doi.org/10.1007/s11027-019-9847-y.

[34] H. Azarabadi, K.S. Lackner: A sorbent-focused techno-economic analysis of direct air capture, Applied Energy 250 (2019) 959–975. https://doi.org/10.1016/j.apenergy.2019.04.012.

[35] R. Hanna, A. Abdulla, Y. Xu, D.G. Victor: Emergency deployment of direct air capture as a response to the climate crisis, Nat. Commun. 12 (2021) 368. https://doi.org/10.1038/s41467-020-20437-0.

[36] N. McQueen, K.V. Gomes, C. McCormick, K. Blumanthal, M. Pisciotta, J. Wilcox: A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, Prog. Energy 3 (2021) 32001. https://doi.org/10.1088/2516-1083/abf1ce.

[37] F. Sabatino, A. Grimm, F. Gallucci, M. van Sint Annaland, G.J. Kramer, M. Gazzani: A comparative energy and costs assessment and optimization for direct air capture technologies, Joule 5 (2021) 2047–2076. https://doi.org/10.1016/j.joule.2021.05.023.

[38] R. Chauvy, L. Dubois: Life cycle and techno-economic assessments of direct air capture processes: An integrated review, Intl J of Energy Research 46 (2022) 10320–10344. https://doi.org/10.1002/er.7884.

[39] W. Rickels, A. Proelß, O. Geden, J. Burhenne, M. Fridahl: Integrating Carbon Dioxide Removal Into European Emissions Trading, Front. Clim. 3 (2021) 690023. https://doi.org/10.3389/fclim.2021.690023.

[40] J. Burke, A. Gambhir: Policy incentives for Greenhouse Gas Removal Techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework, Energy and Climate Change 3 (2022) 100074. https://doi.org/10.1016/j.egycc.2022.100074.

[41] European Commission: Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological of storage carbon dioxide: Amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006, 2009.

[42] EEX: Preise CO_2-Emissionsrechte, 2023. https://www.eex.com/de/marktdaten/umweltprodukte/eu-ets-auktionen.

[43] M. Jobin, M. Siegrist: Support for the Deployment of Climate Engineering: A Comparison of Ten Different Technologies, Risk Anal. 40 (2020) 1058–1078. https://doi.org/10.1111/risa.13462.

[44] K. Arning, J. Offermann-van Heek, A. Linzenich, A. Kaetelhoen, A. Sternberg, A. Bardow, M. Ziefle: Same or different? Insights on public perception and acceptance of carbon capture and storage or utilization in Germany, Energy Policy 125 (2019) 235–249. https://doi.org/10.1016/j.enpol.2018.10.039.

[45] D. Schumann, E. Dütschke, K. Pietzner: Public perception of CO_2 offshore storage in Germany: Regional differences and determinants, Energy Procedia 63 (2014) 7096–7112. https://doi.org/10.1016/j.egypro.2014.11.74

[46] C. Braun, C. Merk, G. Pönitzsch, K. Rehdanz, U. Schmidt: Public perception of climate engineering and carbon capture and storage in Germany: survey evidence, Climate Policy 18 (2018) 471–484. https://doi.org/10.1080/14693062.2017.1304888.

[47] E. Dütschke, D. Schumann, K. Pietzner: Chances for and limitations of acceptance for CCS in Germany, in: A. Liebscher, U. Münch (Eds.), Geological Storage of CO_2 – Long Term Security Aspects // Geological storage of CO_2 – long term security, Springer, Cham [Germany], 2015, pp. 229–245. https://doi.org/10.1007/978-3-319-13930-2_11.

[48] A. Linzenich, K. Arning, J. Offermann-van Heek, M. Ziefle: Uncovering attitudes towards carbon capture storage and utilization technologies in Germany: Insights into affective-cognitive evaluations of benefits and risks, Energy Research & Social Science 48 (2019) 205–218. https://doi.org/10.1016/j.erss.2018.09.017.

[49] E. Dütschke, K. Wohlfarth, S. Höller, P. Viebahn, D. Schumann, K. Pietzner: Differences in the public perception of CCS in Germany depending on CO_2 source, transport option and storage location, International Journal of Greenhouse Gas Control 53 (2016) 149–159. https://doi.org/10.1016/j.ijggc.2016.07.043

[50] A. Corner, N. Pidgeon: Like artificial trees? The effect of framing by natural analogy on public perceptions of geoengineering, Climatic Change 130 (2015) 425–438. https://doi.org/10.1007/s10584-014-1148-6.

[51] C. Bertram, C. Merk: Public Perceptions of Ocean-Based Carbon Dioxide Removal: The Nature-Engineering Divide? Front. Clim. 2 (2020) 594194. https://doi.org/10.3389/fclim.2020.594194.

[52] A. Corner, N. Pidgeon: Geoengineering, climate change scepticism and the ‚moral hazard' argument: an experimental study of UK public perceptions, Philos. Trans. A Math. Phys. Eng. Sci. 372 (2014). https://doi.org/10.1098/rsta.2014.0063.

[53] L. Whitmarsh, D. Xenias, C.R. Jones: Framing effects on public support for carbon capture and storage, Palgrave Commun 5 (2019). https://doi.org/10.1057/s41599-019-0217-x.

[54] C. Merk, Å.D. Nordø, G. Andersen, O.M. Lægreid, E. Tvinnereim: Don't send us your waste gases: Public attitudes toward international carbon dioxide transportation and storage in Europe, Energy Research & Social Science 87 (2022) 102450. https://doi.org/10.1016/j.erss.2021.102450.

[55] C. Oltra, P. Upham, H. Riesch, et al.: Public Responses to CO2 Storage Sites: Lessons from Five European Cases, Energy & Environment 23 (2012) 227–248. https://doi.org/10.1260/0958-305X.23.2-3.227

[56] **B.K. Sovacool, C.M. Baum, S. Low, C. Roberts, J. Steinhauser**: Climate policy for a net-zero future: ten recommendations for Direct Air Capture, Environ. Res. Lett. 17 (2022) 74014. https://doi.org/10.1088/1748-9326/ac77a4.

[57] **W. Carton, A. Asiyanbi, S. Beck, H.J. Buck, J.F. Lund**: Negative emissions and the long history of carbon removal, WIREs Clim Change 11 (2020). https://doi.org/10.1002/wcc.671.

[58] **D. Otto, M. Gross**: Stuck on coal and persuasion? A critical review of carbon capture and storage communication, Energy Research & Social Science 82 (2021) 102306. https://doi.org/10.1016/j.erss.2021.102306.

[59] **M. Honegger, M. Poralla, A. Michaelowa, H.-M. Ahonen**: Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies, Front. Clim. 3 (2021) 672996. https://doi.org/10.3389/fclim.2021.672996.

[60] **P. Healey, R. Scholes, P. Lefale, P. Yanda**: Governing Net Zero Carbon Removals to Avoid Entrenching Inequities, Front. Clim. 3 (2021) 672357. https://doi.org/10.3389/fclim.2021.672357.

[61] **M. Honegger, C. Baatz, S. Eberenz, A. Holland-Cunz, A. Michaelowa, B. Pokorny, M. Poralla, M. Winkler**: The ABC of Governance Principles for Carbon Dioxide Removal Policy, Front. Clim. 4 (2022) 884163. https://doi.org/10.3389/fclim.2022.884163.

[62] **S. Asayama**: The Oxymoron of Carbon Dioxide Removal: Escaping Carbon Lock-in and yet Perpetuating the Fossil Status Quo? Front. Clim. 3 (2021) 673515. https://doi.org/10.3389/fclim.2021.673515.

[63] **L. Schneider**: Fixing the Climate? How Geoengineering Threatens to Undermine the SDGs and Climate Justice, Development 62 (2019) 29–36. https://doi.org/10.1057/s41301-019-00211-6.

Endnotes

1 In the case of capture directly at an emission point, i.e., so-called point source capture, as is the case in some industrial (for example, in the production of steel, cement, lime or ammonia) or energetic processes (for example, coal-fired power plant), the captured CO_2 can also be stored (PSCCS). The technology used here is similar but not directly comparable to DAC technology. In the case of **utilization** of CO_2, of the term point source carbon capture and utilization (PSCCU) is also used, which, depending on the source of the CO_2, can lead to an enrichment of CO_2 in the atmosphere. However, it can be assumed that these point sources will decline over the course of the decarbonization of industry and the energy sector.

2 If the sequestered CO_2 is used as a carbon source (Carbon Capture and Utilization, CCU), for example, for industrial processes and non-durable products, the CO_2 is released again. In this case, CCU is not an option for negative emissions. If, on the other hand, the sequestered CO_2 is stored in long-lasting products, this creates negative emissions.

3 The »Big 5« climate neutrality scenarios are the dena (German Energy Agency) lead study »Aufbruch Klimaneutralität«; »Klimaneutrales Deutschland 2045 (Climate Neutral Germany 2045)«, published by the Foundation for Climate Neutrality (SKN), Agora Energiewende and Agora Verkehrswende; »Klimapfade 2. 0 (Climate Paths 2.0),« published by the Federation of German Industries (BDI); the "Long-term Scenarios for the Transformation of the Energy System in Germany 3,« published by the Federal Ministry of Economic Affairs and Climate Action (BMWK); and »Germany on the Road to Climate Neutrality« from the Ariadne research project.

4 For example, switching to climate-friendly production routes, energy efficiency measures, using renewable energies.

5 The storage sites currently under development in Europe in the Netherlands, Great Britain and Norway are all offshore storage sites.

6 Cf. the summary regarding public support and different positions of environmental associations in the evaluation report on Germany's Carbon Capture and Storage Act (KSpG). [5].

Imprint

Fraunhofer-Institut
for Systems and Innovation Research ISI
Breslauer Strasse 48
76139 Karlsruhe

Contact
Dr. Barbara Breitschopf
Competence Center
Energy Policy and Energy Markets
Phone +49 721 6809-356
barbara.breitschopf@isi.fraunhofer.de

Authors
Barbara Breitschopf, Elisabeth Dütschke, Vicki Duscha, Michael Haendel, Simon Hirzel, Anne Kantel, Sascha Lehmann, Frank Marscheider-Weidemann, Matia Riemer, Josephine Tröger, Martin Wietschel

Graphic design
Sabine Wurst

Image credits
- shutterstock.com/Aekkasit
- shutterstock.com/VikaSuh

Print
Kern GmbH, 66450 Bexbach

This Policy Brief is printed climate-neutrally on 100 % recycled paper Circleoffset Premium White.

Klimaneutral
Druckprodukt
ClimatePartner.com/11531-2106-1083

Fraunhofer ISI

The Fraunhofer Institute for Systems and Innovation Research ISI analyzes the origins and impacts of innovations. We research the short- and long-term developments of innovation processes and the impacts of new technologies and services on society. On this basis, we are able to provide our clients from industry, politics, and science with recommendations for action and perspectives for key decisions. Our expertise lies in a broad scientific competence as well as an interdisciplinary and systemic research approach.