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Carbon Capture and Storage

Contribution to the discussion on its integration into national climate action strategies

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With the Paris Agreement, the global community set itself the goal of limiting global warming to well below 2°C and making efforts to stop the temperature increase at 1.5°C if possible. The European Union wants to become the first greenhouse gas-neutral continent by 2050 (Fras 2019) and has set the first steps towards this with the Fit for 55 legislative package. Germany aims to become net greenhouse gas neutral by 2045 (Section 3(2) KSG) and to achieve negative greenhouse gas emissions across all sectors after 2050.

To meet these targets, massive efforts to mitigate greenhouse gas emissions are indispensable. However, even with ambitious implementation of all feasible mitigation options, unavoidable residual fossil emissions will remain in individual sectors, especially in agriculture, but also in individual parts of industry (lime and cement industry) (Purr et al. 2019, Warszawski et al. 2021). This means that the release of unavoidable residual emissions must be offset. Natural CO_2 reservoirs such as forests, peatlands, and also increased wood use are options for this. A possible additional option could be technical measures that have a sink effect. On the one hand, there are measures to prevent the emission of fossil fuels into the atmosphere that have been produced at point sources, to capture and store them, e.g. through carbon capture and storage (CCS). On the other hand, there are technical sinks, where CO_2 is directly removed from the atmosphere (Direct Air Carbon Capture Storage- DACCS) or biogenic carbon is used (Bioenergy Carbon Capture Storage- BECCS) and stored. This balance requires regulatory prioritisation following the criteria of sustainability, nature conservation and risk minimisation.

At the same time, it is becoming apparent at the global level that the 1.5°C target is likely to be missed (“overshooting”) in the 2030s if global CO_2 emissions are not reduced by 48 % by 2030 and by 99 % by 2050, in each case relative to the level of 2019 (IPCC 2023). In addition, various tipping points of the Earth's climate system must also be taken into account in risk management strategies (IPCC 2021). Tipping points that would already be threatened by a warming of more than 1.5°C include, for example, the Greenland and Antarctic ice sheets and the boreal permafrost soils.

Against this background, the question arises as to how quickly measures to mitigate greenhouse gas emissions can be implemented, but also in what form and to what extent natural and technical sinks as well as technical measures to reduce greenhouse gas emissions (CCS) must contribute to a sustainable negative greenhouse gas balance across all sectors. In view of the global trends, it is also a matter of setting the course for investments in sinks and related technologies without undermining the reduction efforts. In order to set priorities for this, weigh up the risks and create predictability for investments and the stakeholders involved, a binding sink strategy is needed – both in Germany and in the EU.

In the coalition agreement 2021-2025 (SPD; BÜNDNIS 90/ THE GREENS; FDP 2021), the governing parties commit themselves to this challenge and, in addition to natural climate protection, also mention technical negative emissions as a necessary supplement. With a "Carbon Management Strategy" (BT- Drs. 20/5145) and the funding guideline for the decarbonisation of industry, the federal government is laying the first foundations, and is also making international agreements on the storage of CO_2 abroad (German-Norwegian cooperation (PM 2023)) and is participating in the debates on the ratification of the London Protocol (Polansky 2023).

The potential, the cost-effectiveness, the climate footprint and the environmental impact of technical sinks are uncertain. Numerous factors, such as the technological development dynamics in this field, the technical and regulatory framework, legislation and greenhouse gas reporting for CCS and engineered sinks, need to be clarified. This paper provides an assessment of the use of CCS and recommendations with regard to these aspects focusing on Germany.

Definition of CCS

Carbon Capture and Storage (CCS) is defined as the capture of CO_2 emissions from the exhaust stream of point sources and their subsequent transport to the storage site, where they are injected into the subsurface. Potential storage sites include partially or fully depleted oil or gas reservoirs or saline aquifers. Storage can take place both terrestrially and in the subsurface under the seabed. If the carbon dioxide is produced during the use of sustainably produced biomass for energy and is "captured" using CCS (BECCS) or CO_2 is extracted directly from the atmosphere, CCS can also cause negative emissions. These applications of CCS then fall into the category of technical sinks.

1 Factors to be considered in the integration of CCS technology

When deciding on the use of CCS, as well as the regulations and incentives for its use, the principles and guidelines for maintaining an ambitious climate protection policy must be taken into account in a differentiated manner. On the one hand, CCS is seen as a necessary part of the global climate policy of the future in order to achieve greenhouse gas neutrality as quickly as possible and making up for previous delays. Reaching the tipping points and the drastic consequences for our ecosystems and societies have to be prevented. On the other hand, the short-term (national and European) focus is being placed on mitigated greenhouse gas emissions by means of CCS and technical sinks, while at the same time GHG avoidance and reduction strategies are nowhere near being exhausted and there is thus a danger of clinging to fossil fuel economic practices and preventing transformation. Furthermore, we should consider how future generations would evaluate today's decisions, also with regard to the restriction of their scope for action. This is because the limited CO_2 storage capacities would already be used and consumed today for avoidable fossil emissions in the case of CCS application, which will be needed on a long-term basis in the future.

The CCS discussion is a balancing act and needs to be carefully evaluated, due to a climate protection policy that is still inadequate. CCS in combination with the adherence to existing fossil technologies, economic models and consumer behaviour would lead to a constant intensification of these challenges. **If CCS is to be integrated into today's climate protection policy, it will require applications that do not exacerbate this dilemma.** In other words, no new fossil energy sources taken from nature should be used, and at the same time the greatest synergies must be exploited, **at the end of a long value chain, combining CCS with thermal waste treatment plants (WACCS).**

Figure 1

Simplified representation of the factors to be weighed up when integrating technical sinks

Source: own illustration, German Environment Agency

2 The potential impacts of CCS: Environment, human health and usage competition

In addition to the aspects of climate action, the capture of CO_2, transport and storage in geological formations have potential environmental impacts on ecosystems, such as the ocean, and on the environmental media of water, soil and air.

Relevant release scenarios and monitoring objectives (see Chapter 5) for assessing environmental risks of CO_2 storage are:

- Borehole leaks (active or old boreholes),
- Releases via geological fault zones and
- Mostly diffuse releases with significant effects on buildings and historical and cultural assets.

Impact of CO_2 storage on water, soil and air are possible

Groundwater near the surface may be contaminated and **salinated** by leakage if CO_2 is stored underground. This can occur due to displaced (highly) mineralised formation waters, the by-products of the gas mixture to be stored, as well as other reaction products and associated process materials (Li et al. 2018).

In the seas, leakage causes CO_2 to be dissolved in the water and contributes to seawater acidification (Cai et al. 2020). The risk of leakage during CO_2 storage increases with the amount injected and the pressure differences this creates in the storage layer. These can impair the sealing function of the cover layer.

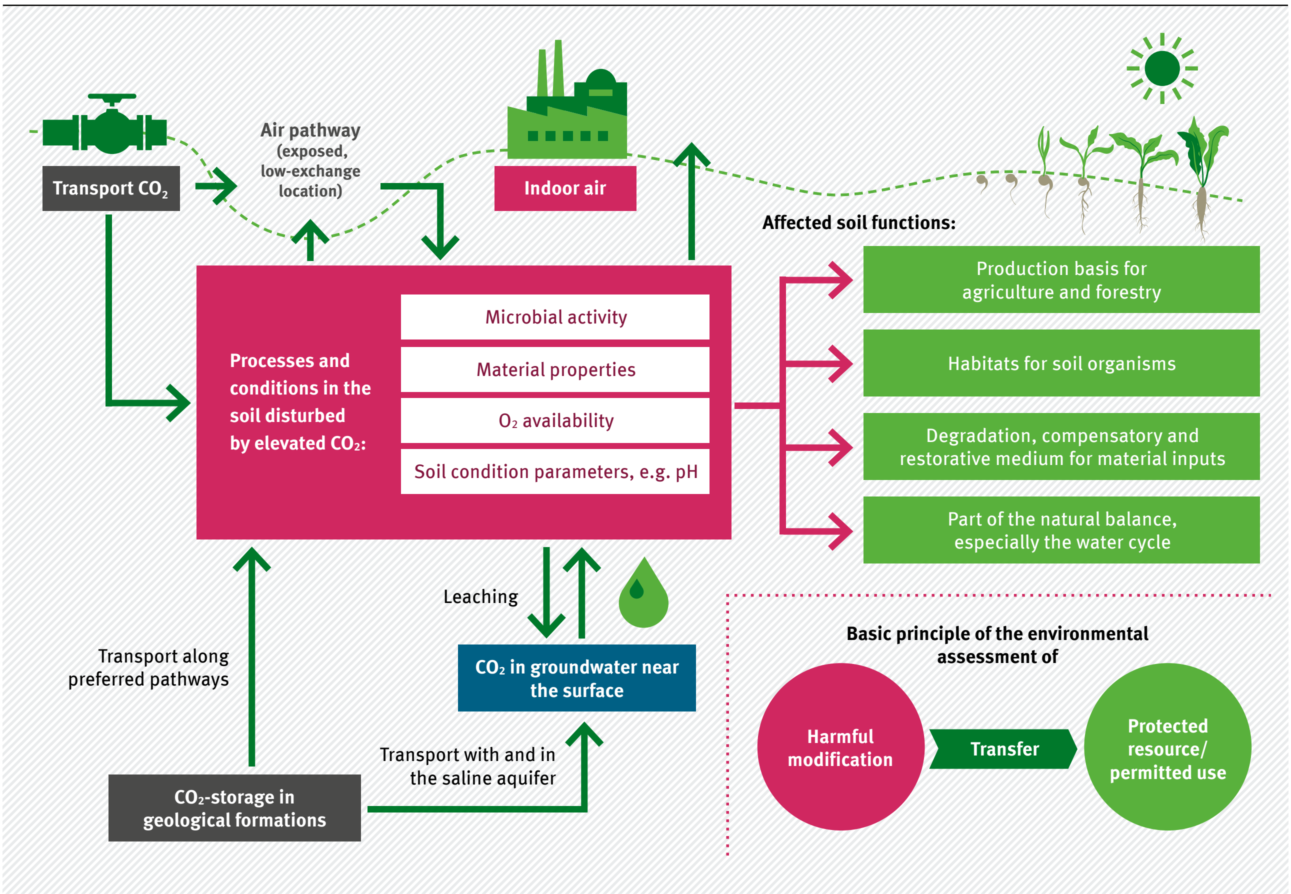
If stored **CO_2 escape**s, significant **impacts on marine ecosystems can occur.** There is an additional danger if toxic substances are mobilised in the saltwater formation by the CO_2 discharge. **Changes in pH and CO_2 concentration in the sea can significantly affect marine algae, fish and other groups of organisms.** The development of deep-sea organisms tends to be slow because their metabolic rates are lower and their lifespan is longer than in other marine layers (IPCC 2005). In the case of major leakages, ecosystems can be severely damaged and are likely to take a very long time to recover (IPCC 2005). There is an urgent need for research into the effects (e.g. of a blow-out as a sudden release of large quantities of CO_2 from storage) on the marine environment.

On land, the oxygen concentration in the near-surface soil layer decreases after CO_2 has escaped from a deeper storage reservoir, and the pH value can drop. This impairs the material balance and the milieu conditions in the soil, can lead to a mobilisation of heavy metals **and also has a negative effect on microorganisms and plant growth.** This has been demonstrated at naturally occurring mofette sites with comparable CO_2 currents (Stange and Duijnis- veld 2013, Maček et al. 2009). For example, an increase of only 0.7 % CO_2 in the composition of soil air as a result of CCS storage leakage leads to signs of significantly reduced root respiration, which successively reduces the yield capacity of agricultural soil use and has a negative impact on microorganisms and soil diversity (Stange and Duijnisveld 2011). This can create obstacles to achieving the EU soil protection targets of healthy soil conditions by 2050.

The spontaneous release of a large amount of CO_2 into the air through leakages of the storage reservoir or in the seal on the surface **cannot be completely ruled out.** If it is connected to the technical installations of the storage reservoirs, it is easily detectable and can be eliminated in a targeted manner. A collapse of the underground storage reservoir can be clearly pinpointed with rock mechanics signals. Repair is generally not possible. Similarly, continuous release of CO_2 may occur due to leakage of the storage reservoir or during transport. These leakages are largely a result of geological anomalies, fault zones, fractures and cracks and can neither be excluded nor immediately detected even with high-resolution exploration and monitoring. As a gas, carbon dioxide is odourless, colourless and heavier than air. **Depending on the local conditions of the leakage, areas of elevated CO_2 concentrations may occur due to displacement of atmospheric oxygen.**

Figure 2

Possible impacts on humans and the environment, in particular on soil, as a protected resource, along the CCS process chain



Source: Federal Institute for Geosciences and Natural Resources (www.bgr.bund.de/)

Potential impacts on human health

CO_2 is heavier than air and **can** escape at ground level into low-lying areas or **accumulate** in zones with low air exchange (e.g. depressions in calm conditions, cellars, closed rooms). **In humans, an increased CO_2concentration** in the air we breathe can cause numerous symptoms which, depending on the concentration, **can lead to unconsciousness or even death.** There are no limits or guideline values for CO_2 concentrations outdoors. For indoor areas, health and hygiene guideline values for CO_2 have been developed for the entire population. In order to reduce residual risks for humans, on-shore CCS storage facilities should not be planned and permitted under settlements. The potential for conflict between CCS storage and simultaneous use as a residential area is so high that both types of use must be strictly separated. In addition, if storage facilities and residential areas were to spatially overlap, considerable acceptance problems would be expected among the affected population.

Damage to material assets cannot be ruled out

Seismic events can occur especially during injection, but also during the subsequent storage of CO_2 (Zoback 2012). A low magnitude would be expected. On land, however, an impact on buildings in particular cannot be completely ruled out.

Competition between CO_2 storage and other uses

The geological structure used for CCS is permanently occupied, it will no longer be available for other uses in the future. **CCS competes on land with deep geothermal energy,** natural gas storage, renewable methane and hydrogen storage, and heat storage. Impacts of CCS on neighbouring uses (vertical and horizontal) in the subsurface and the previously described impacts on protected resources on the surface must be taken into account.

In the marine environment, there may be competition between the storage of CO_2 and the operation of offshore wind energy plants. Furthermore, the necessary comprehensive monitoring of CCS projects with various measurement methods requires special precautions against other uses of the sea (e.g. fishing, anchoring of ships). Before implementing storage projects, the various sea-bed-related use requirements must be coordinated and prioritised (CDRmare 2023).

3 Guidance for achieving sustainable greenhouse gas neutrality with the integration of CCS

CCS is no substitute for the necessary greenhouse gas mitigation

Avoiding greenhouse gas emissions is the overriding guiding principle for a sustainable climate protection policy based on a precautionary approach. This is also the core message of a special report of the World Climate Council from 2018 (IPCC 2018). **CCS and the retention of greenhouse gases that have already been produced must not be used as a solution for energy-related fossil greenhouse gas emissions. In particular, carbon capture and use policies must not lead to a lock-in effect of fossil technologies.** Instead, comprehensive measures must be taken to mitigate emissions. This requires many fundamental and rapid changes in the economy and society, in the production of goods and also in consumption. Improved efficiency, savings, renewable energies, alternative products and services that produce little or no greenhouse gases, through to sufficiency, are important control mechanisms, the potential of which must be fully exploited.

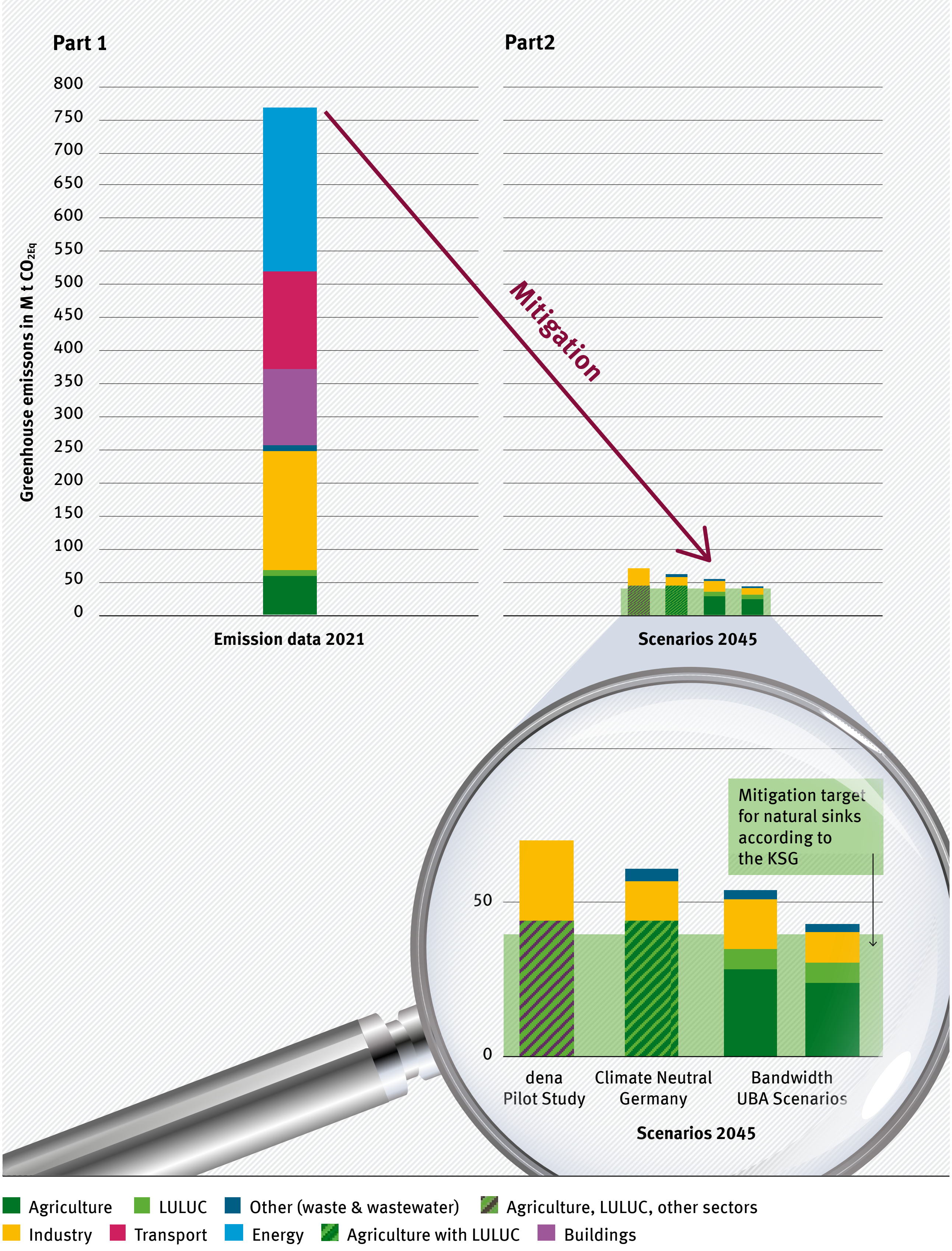
Technical measures (CCS) should therefore only be used for the residual emissions that cannot be avoided in the long term. These unaivoidable residual emissions will remain primarily in agriculture, but also in industry in the processes of lime and cement production as well as waste and wastewater management. Here, it is important to develop technological and social innovations and to constantly push them forward in order to reduce the technical and socially acceptable minimum of unavoidable emissions continuously and in accordance with the most recent knowledge and research. In many areas, alternatives are already available, e.g. in the steel industry by switching to Direct Reduced Iron (DRI) technology or in hydrogen production by using water electrolysis with renewable electricity. In other areas, intensive research and development is still needed, e.g. in the reduction of process-related emissions in the cement and lime industry through measures along the value chain, e.g. alternative binding agents instead of cement, timber construction, modified construction methods, etc. Despite technological development potential, unavoidable emissions will remain in the long term.

With a very ambitious climate protection policy in all sectors in Germany as well as a very ambitious biodiversity protection policy, the natural sinks can largely compensate for the residual emissions in 2045. Depending on the level of effort, scientific studies show a wide range of unavoidable emissions for Germany of 43 to 70 million tonnes of CO_{2eq} (Purr et al. 2019, dena 2021). In contrast, the binding sectoral target in the area of LULUCF of at least -40 million t CO_{2eq} in 2045, which is enshrined in the Federal Climate Change Act, is available for offsetting across all sectors (Figure 3). **Accordingly, under ideal conditions, the need for technical sinks and the use of CCS could be very low or even reduced to zero.**

However, the potential of natural sinks is just as limited as that of technical sinks. The implementation of successful climate protection measures is currently not keeping pace with the requirements and the legal targets – see, for example, the projection report of the German Federal Government (UBA 2021), the Greenhouse Gas Emission Inventory (UBA 2023a) or the assessment of the Expert Council on Climate Issues (ERK 2022). **A robust sink strategy is therefore needed that takes into account and weighs up the (societal and political) environmental and climate impacts and the necessary compensatory techniques for sustainable negative emissions.**

Figure 3

Greenhouse gas emissions in 2021 and scenarios for 2045 for Germany



Source: own illustration, German Environment Agency

Even with CCS, conventional and fossil processes cannot become greenhouse gas neutral

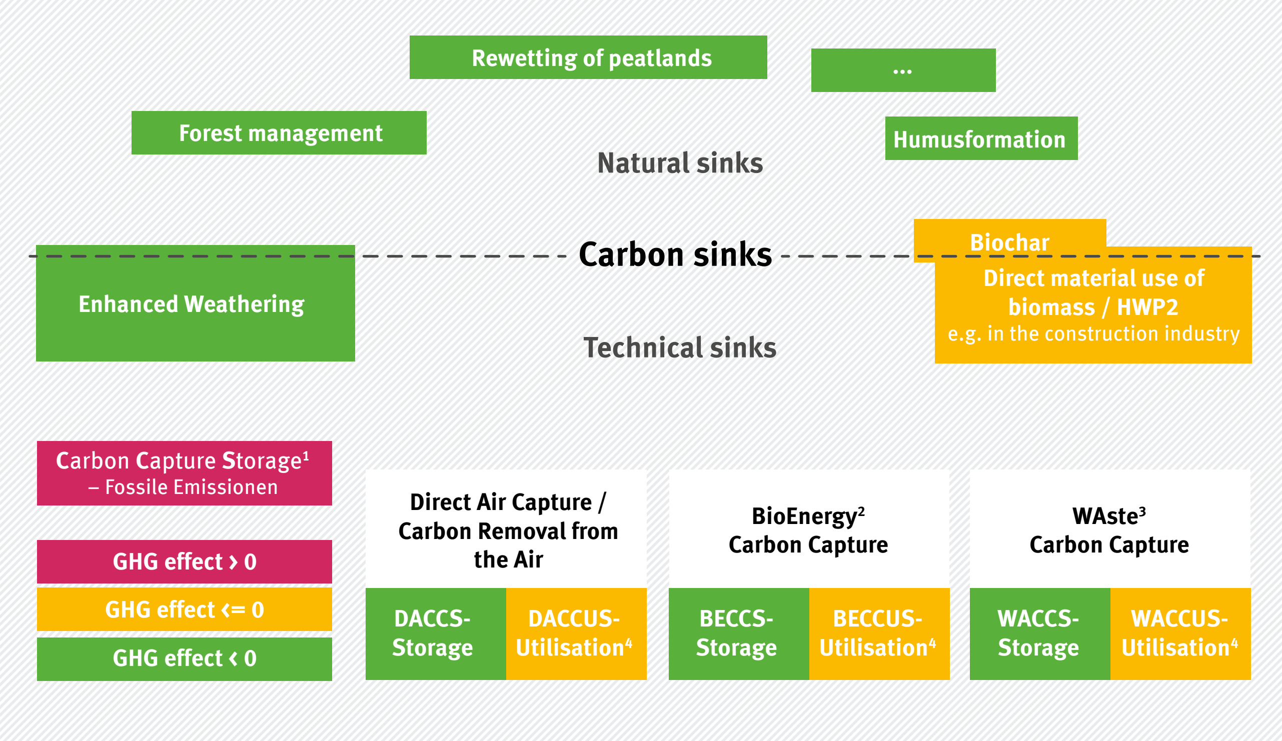
In the current debates on industrial and climate policy, CCS often appears to be a beacon of hope that could master both the challenges of unavoidable emissions and the transformation of the fossil economy. Although CCS is used in the gas and oil industry to enhance oil recovery ("enhanced oil recovery", EOR), it has hardly been tested in large-scale projects (Harvey & House, 2022). Plausible or detailed cost calculations for CCS without EOR are not publicly available. **With regard to the process chain, it is clear that CCS in combination with fossil energy carriers,** e.g. blue hydrogen produced from natural gas, **or CCS with process-related greenhouse gas emissions at industrial plants,** e.g. in the cement industry, **cannot be implemented in a completely greenhouse gas-neutral way.**

Additional energy costs arise along the process chain: during capture, compression, transport, storage of CO_2 as well as during the construction and operation of infrastructure on land and at sea. If renewable energies are not used for this purpose, CO_2 emissions will increase. Further greenhouse gas emissions occur in the upstream chain, for example in the extraction of natural gas for blue hydrogen, which is directly associated with diffuse methane emissions.

But even assuming that only renewable energies are used and unavoidable emissions are to be stored, it is not possible to achieve greenhouse gas neutrality in the economy in the case of process-related emissions. **In carbon capture processes, part of the carbon dioxide cannot be captured. Capture rates of around 85 % are achieved, so that about 15 % of the CO_2 continues to be released into the atmosphere (Bisinella et al. 2021).** Furthermore, in addition to leakages during non-conventional operation, emissions also occur during regular operation along the process chain: through leakages during handling and transport of the CO_2. If, on the other hand, CCS is combined with atmospheric carbon from ambient air (DACCS) or sustainably produced biomass (BECCS), CO_2 is temporarily removed from the atmospheric carbon cycle and "negative emissions" can be achieved (see Figure 4). **The capacities for storing carbon dioxide are limited and should be used sensibly.** Even after precise preliminary exploration of a potential storage complex, considerable deviations from the projected storage capacity can occur in the operational phase (IEEFA 2023), which means that storage capacities are subject to great uncertainties. **In the event that natural sinks cannot contribute sufficiently or permanently to compensating for unavoidable emissions, these storage capacities should be retained as an option and not wasted on avoidable fossil emissions.**

Figure 4

Simplified overview of different types of carbon sinks and their greenhouse gas impact when only renewable energy is used



[1] CO_2 emissions cannot be fully sequestered and stored.
[2] Use of sustainably produced biomass / biogenic residues.
[3] Use of non-recyclable biogenic and fossil wastes.
[4] CO_2 use for durable products.

Source: own illustration (revised), German Environment Agency

The contribution of CCS and technical carbon sinks should be aligned with natural carbon sinks

In addition to the climate crisis, we are facing major challenges in many areas of environmental and health protection. In the interests of sustainability and in order to meet these urgent challenges, synergies must be considered, exploited and prioritised from the outset. Natural sinks can provide these co-benefits for biodiversity and ecosystem protection (Reise et al. 2019). In addition to carbon sequestration, they can contribute to species conservation and to improving the microclimate (near the ground) and the water balance. **Any contribution of technical sinks to the reduction of greenhouse gas concentrations in the atmosphere or CCS for the retention of greenhouse gases should therefore be oriented towards the prioritised and ambitious development of natural sink capacity.**

This requires a concept for dealing with CO_2 emissions that does justice both to the priority of reducing the production and release of greenhouse gases and to integral environmental protection. In this regard, there is a proposal published by the German Environment Agency in 2022 "Technical Negative Emissions: Is the Federal Government's Climate Policy Target Architecture Fit for Purpose?" (Voß-Stemping et al. 2022). **In addition to the clear identification and limitation of residual emissions** – free from the particular interests of individual sectors and actors – **cross-sectoral mechanisms must be developed to link safe and long-lasting CDR measures on the one hand and producers of unavoidable greenhouse gas emissions on the other.** Currently, instruments and considerations are singular and sectoral, e.g. to promote CCS in industry or measures for natural climate protection.

The architecture of climate change policy must be based on a clear hierarchy and be designed in a robust way

Despite the urgency for successful climate protection, there are still many unanswered questions and a need for research with CCS regarding technical measures and negative emissions. This is already starting with the clear identification and limitation of unavoidable emissions as well as how to address them through instruments. For planning certainty, reliability and acceptance by businesses and in society, a well-founded concept should be developed before CCS is implemented and a clear political commitment to the implementation of this concept should be made on the basis of scientific findings.

For political credibility and an ambitious climate protection policy, reduction and avoidance in CO_2 generation must be separate from sink targets. In a first step, a legal definition, quantity determination and regular follow-up is required regarding which and what quantities of emissions are considered unavoidable emissions and for which the use of CCS to mitigate emissions **is permitted.** Furthermore, regular monitoring is required to determine which and what quantities of negative emissions are to be targeted at which point in time.

This is reflected in the further developed target architecture, which defines: 1) the GHG mitigation targets (without CCS) in the individual sectors of energy, industry, buildings, transport, agriculture and waste management as well as others; 2) the targets for natural carbon sequestration; and 3) the targets for technical carbon sequestration and reduction of CO_2 emissions. Separating the different goals is helpful for transparency and success control.

In order to integrate technical sinks into our economic system, a social and political weighing-up process is necessary in advance on the environmental and climate consequences as well as societal consequences of an increase of more than 1.5°C in human-induced greenhouse gas emissions compared to those of compensatory techniques. CO_2 storage and the final disposal of national residual emissions are very regionally limited. The burdens of risks and consequences are therefore strongly concentrated locally. It is therefore of particular importance for social acceptance to organise the necessity and choice of CO_2 storage in a transparent and comprehensible way.

Clear communication on terminology and its hierarchy in climate action

Avoiding a misleading use of climate policy terms is essential. Communication should be accurate, targeted, and promote acceptance. For example, the commonly used term "mitigation" can be understood and used in different ways: it can refer to emission reduction, the reduction of greenhouse gas concentrations in the atmosphere (in which case it also includes carbon dioxide removal (CDR), as in the use of the term "mitigation" by the IPCC), or the mitigation of the impacts of climate change (in which case it might even include the highly problematic solar radiation management (SRM)). In accordance with the precautionary principle, climate policy measures must be prioritised at the beginning of the impact chain and be aimed at preventing the generation of greenhouse gases. Secondary measures are those that should merely delay or prevent the release of existing fossil emissions into the atmosphere (Carbon Capture and Utilisation, CCU for short, and Carbon Capture and Storage – CCS). Finally, there are measures that aim to reduce the concentration of greenhouse gases by removing them from the atmosphere (DACCS, BECCS) (Markus et al. 2021). Where collective terms are used, such as the term "climate neutrality", this gradation and hierarchy must be clearly communicated and guaranteed so that priority measures cannot be arbitrarily replaced or "offset" by secondary measures.

4 Guidelines for technical integration and promotion of technology of CCS

WACCS – CCS at thermal waste treatment plants occurs at the end of the value chain, causes low lock-in effects and offers potential for negative emissions

A possible introduction of CCS should take place where the least lock-in effects are caused and where there is no competition for substitution with renewable energies or alternative processes. This is particularly the case with thermal waste treatment, where non-recyclable waste is energetically recovered at the end of a long utilisation cascade. Although it is known in industry which processes are associated with unavoidable process-related greenhouse gas emissions (cement and lime industry), fossil fuels are still used in this sector. **If CCS technology is introduced here, fossil avoidable emissions will inevitably also be captured and stored.** In the lime and cement industry, about one third of CO_2 emissions are currently fossil and energy-related. Furthermore, there is a risk that alternative developments will be blocked, for example along the value chain in the construction sector (see Chapter 3).

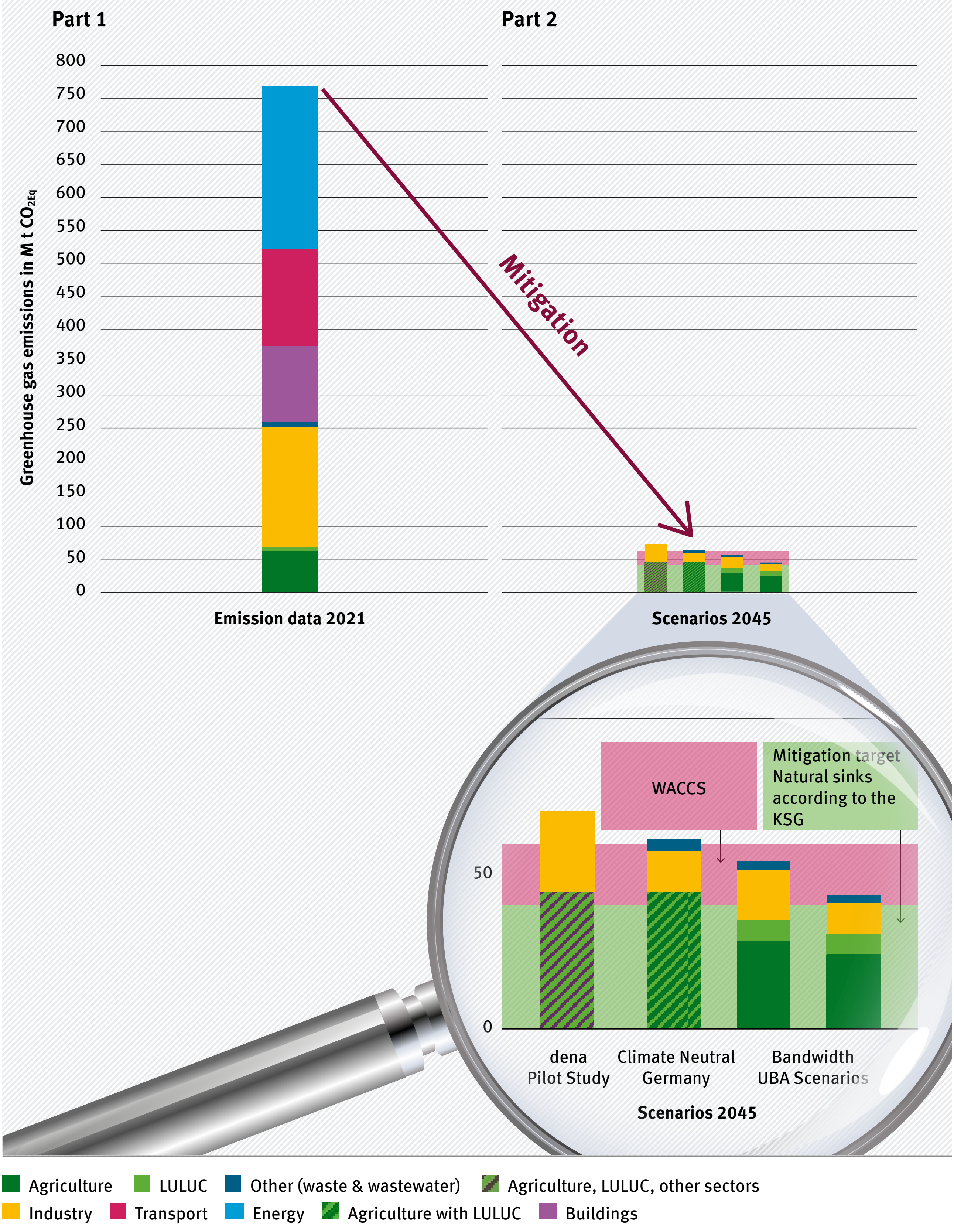
In thermal waste treatment, hardly any additional and newly extracted fossil fuels are used.[1] In 2021, around 20.5 million t CO_2 from household waste (10.3 million t CO_2 biogenic and 10.2 million t CO_2 fossil) were emitted during waste-to-energy processing in Germany (UBA 2023b). **The capture of CO_2 emissions at thermal treatment plants and their storage (Waste Carbon Capture and Storage, WACCS) could already lead to negative emissions today** (under the conditions described in Chapter 3). With the transformation of the chemical industry, green polymers will also replace petroleum-based polymers at the end of long life cycles over a very long period of time. These are then likely to be produced based on atmospheric carbon and can thus continue to contribute systemically as negative emissions following thermal waste treatment. **Thus, in this use case, the long-term availability of CCS for technical sinks can be verified and preserved for a robust sink strategy with negative emissions.**

With the sectoral target of -40 Million t CO_2 in the LULUCF sector, the combination of thermal waste treatment plants results in a potential sequestration volume of around 60 Mt CO_2.[2] These are mainly negative emissions (LULUCF and BECCS in the waste sector). Nevertheless, it must be taken into account that the CO_2 emissions of thermal waste treatment plants will be reduced by 2045 compared to 2021 with the strengthening of the circular economy and increasing recycling quotas. In the long term, however, similarly large CO_2 quantities can be assumed. It should be borne in mind that carbon is needed as a raw material and should be used several times, so that there is a fundamental competition between the storage and use of CO_2 . Looking at the range of unavoidable emissions in climate protection scenarios for Germany presented in Chapter 3 (Purr et al. 2019, dena 2021), it becomes clear that robust net greenhouse gas neutrality can be achieved, see also Figure 5. Scenarios at the upper end, with less ambitious implementation of climate protection policy, require further compensation. In 2021, around 21.9 million t. CO_2 was produced from the use of solid biomass (primarily waste and residual wood) for energy purposes (UBA 2023b). With a view to increasing sustainability, a potential increase in cascade use and a carbon cycle economy, this potential may decrease. And yet, in the long term, there will also be potential to realise further offsetting of unavoidable emissions or negative emissions.

1 Fossil fuels are used in auxiliary firing.
2 Without taking biogas plants or the use of firewood into account.

Figure 5

Greenhouse gas emissions in 2021 and scenarios for 2045 for Germany as well as the integration of BECCS and CCS in waste management



Source: own illustration, German Environment Agency

Nevertheless, it should be noted that net greenhouse gas neutrality can only be achieved and maintained in the long term if all elements of a sustainable transformation are implemented. Cross-sectoral approaches to efficiency, lifestyle change and the conservation and safeguarding of natural carbon sinks combined with the expansion of wood product storage and green polymers in the chemical industry (see Purr et al. 2019) are indispensable building blocks for this.

One of the major challenges is social acceptance of the integration of technical sinks. This can probably be achieved more quickly and by a majority if, in addition to the transparent risk assessment (see Figure 1), the adherence to the precautionary principle and an ambitious climate protection policy is credibly demonstrated.

Promoting techniques for carbon extraction from the atmosphere

Even in a defossilised economy, carbon dioxide is permanently needed as a raw material source for synthetic fuels, greenhouse gas-neutral chemistry or negative emissions. A considerable proportion of this must be obtained from the atmosphere (Purr and Garvens 2021). The availability and large-scale application **of direct air capture plants required in the future must be achieved today through research, development and demonstration and pilot projects** in order to ensure this in the medium and long term.

Providing support for carbon storage in a broad-based and technologically open way

In the debates to date, the storage of carbon dioxide has played a dominant role. The associated challenges for humans and the environment are outlined in the following chapters 2 and 5. It is precisely this permanent and long-term challenge that requires broad-based and technologically open further development. **The safest carbon reservoirs are those that are not taken from nature in the first place.** Here, too, nature should be used as a model for re-storage, and new processes should be researched, tested and developed to generate solid synthetic carbon compounds. In general, the conversion of CO_2 into a solid aggregate state offers increased safety during storage.

In the last decade, the focus of climate policy was on the energy transition, and the need for synthetic energy sources was to be established where renewable electricity cannot be used directly. It is important to build on this and pave the way for (complex) solid synthetic carbon compounds (e.g. carbon powder, graphite, etc.) with atmospheric carbon for the coming decades. This is already being taken up in some research (Göbelbecker 2022).

Other research activities focus on the safe storage of carbon by means of accelerated mineral carbonation in basaltic rocks (Snæbjörnsdóttir et al. 2020, CDRmare 2023). However, further research is needed on the environmental integrity of the transformation processes and on the availability of storage rocks. Basaltic rocks are widespread worldwide, but in Germany there are only very small deposits, most of which are already being used for other purposes.

Overall, it is important to invest broadly and openly in research on the conversion of CO_2 into a solid aggregate state in order to overcome the disadvantages and challenges of the permanence of carbon dioxide storage.

5 Guidance – for monitoring and risk precautions as basic preconditions for permanent CO_2 storage

Close monitoring must be carried out along the entire CCS process chain, as CO_2 can escape into the atmosphere during capture, transport and storage. A suitable monitoring strategy must take into account both the relationship to protected resources (impacts on the environment and health) and the relationship to the overall situation (national greenhouse gas inventories and emissions trading), while also taking into account administrative and technical requirements.

Legal requirements for CCS – the high level of protection of environmental media in the Carbon Dioxide Storage Law must be urgently maintained!

For CCS in the sea, requirements were agreed by the London Protocol 2006 and by OSPAR 2008 (stands for “Oslo” and "Paris" and is an international treaty for the protection of the North Sea and the North-East Atlantic). Accordingly the injection of CO_2 into geological formations in the seabed is permissible, but storage in the water column is not. The legal basis in the EU and in Germany is the EU CCS Directive of 2009 (EU Directive 2009/31/EC) and the German Carbon Dioxide Storage Law of 2012. According to the latter, only trial and demonstration projects up to a certain volume are permitted. Corresponding applications should have been submitted by the end of 2016, but this did not happen, mainly due to public opposition. As a result of the expiry of the deadline, no testing or demonstration projects may currently be carried out in Germany.

The Carbon Dioxide Storage Law contains appropriate control procedures for CCS to ensure a high level of protection for humans and the environment; this should not be reduced under any circumstances:

- Initially, only testing and demonstration projects should be allowed.
- The permanent and complete retention of CO_2 in a storage facility is a prerequisite for the approval and operation of the storage facility.
- The measures are determined by the state of the art in science and technology.
- Negative environmental impacts must be avoided.
- Rigorous monitoring is required, especially with regard to the legal framework in emissions trading.
- The involvement of the Federal Institute for Geosciences and Natural Resources and the German Environment Agency in the approval procedures ensures the inclusion of expert knowledge.

Independent, accurate and continuous state-of-the-art monitoring of CO_2 storage is required

Long-term and accurate monitoring of the leak-tightness of storage facilities is the basis for legally compliant clarification of the operators' regulatory obligations and liability issues in the event of accidents and leaks. Sufficiently meticulous monitoring in accordance with the above-mentioned requirements is not feasible. **Storage safety (no leakage of CO_2 from the storage complex) can only be determined indirectly via the non-detection of leakages,** since the total amount of CO_2 in a geological storage site can only be determined very imprecisely. When monitoring storage facilities and quantifying possible leakages, it is essential to observe the legal requirements in the emissions trading system.

Continuous monitoring takes into account possible impacts on humans and the environment in the vicinity of the storage complex. An analysis of the impact of carbon dioxide storage on the various protected resources, based on monitoring data, must be a decisive element in an environmental assessment. The use of tracers can facilitate a clear identification of sources and makes it possible to distinguish between CO_2 background concentrations in order to detect and attribute leaks even several kilometres away from storage facilities.

Monitoring must also be continued beyond the decommissioning and aftercare phase and continuously adapted to the latest state of the art. In view of the responsibility within the framework of climate protection, the monitoring of storage safety should be regulated as a sovereign task. The costs for this should be covered at the time of storage.

Long-term storage security is not predictable

In the storage of CO_2 there is great uncertainty about the extent of the release of CO_2 into the environment due to the extraordinarily long storage periods. The storage of CO_2 takes place in geological structures, so far almost exclusively under very high pressure in a supercritical state of aggregation, i.e. in fluid form. Underground storage is possible on land and under the sea. Saltwater-bearing rock strata or depleted gas and oil fields can be used for storage. **The choice of a suitable location is of central importance for storage safety.** The overburden of a CO_2 storage facility must function as an effective barrier, and leakage risks cannot be excluded. **A leakage of CO_2 can occur through the overburden along fault zones or boreholes.** Appropriate pressure management in the storage reservoir and the maintenance of large safety reserves can limit the release quantities and thus the consequences of a possible blow-out in which there is no possibility of intervention. Safety reserves should therefore always be taken into account and generously calculated when choosing a site.

The long-term impermeability of old wells in the hydrocarbon industry cannot be assumed with certainty. This also applies to boreholes planned for carbonic acid resistance, because **“no empirical values are available for requirements for safe storage over a period of more than 1,000 years”** (von Goerne 2010). Current experience with CO_2 storage does not prove storage safety, as the processes involved are very slow and a few decades are not a sufficient observation period for the long-term safety of a storage facility. **Simulations, which also serve as a basis for the approval of a storage facility, predict that carbon dioxide will remain in geologically suitable storage facilities for a period of about 10,000 years. At the same time, the lack of empirical data** on the behaviour of CO_2 and on the long-term behaviour of abandoned wells as a possible escape path for CO_2 **represents the greatest uncertainty for forecasting storage impermeability** (Alcalde et al. 2018).

Despite many years of experience, the long-term safety of the Norwegian CO_2 storage facility Sleipner, for example, has not been proven. From a geological point of view, very young “loose sediments” are used as storage layers, which have a high risk of leakage. Measurements to determine the amount of CO stored at Sleipner can only detect approx. 80 to 85 % of the stored CO_2 and mathematical models cannot compensate for this inaccuracy.

Thinking globally and across generations for carbon storage

In view of the global and communal task of climate protection, the move towards technical sinks while at the same time continuously destroying the global natural sink potential and removing CO_2 from the ground in the form of fossil energy sources must be questioned. An overall systemic solution for globally sustainable climate protection must be sought.

The storage of carbon dioxide outside Germany, which is currently favoured in the political debates on CCS, and the associated shifting of all challenges and problems abroad do not absolve Germany of its responsibility. Particularly since there might be a long distance to the storage site, which would increase costs and reduce feasibility (IPCC 2022). In dealing with the storage of German residual emissions abroad, the high requirements of the national level of protection in accordance with the Carbon Dioxide Storage Law must therefore also be guaranteed there, for example through additional binding agreements with the partner countries.

Little consideration has been given in the political debates to date to the social acceptance on site of CCS projects per se, and even less to the storage residual emissions abroad. In the case of the projects in Germany, there has been great local resistance both from citizens of the region and from representatives of various social groups (BT-Drs. 19/6891). The sixth assessment report of the IPCC also points out that respondents who were provided with neutral information on CCS preferred other climate protection measures such as renewable energies and energy efficiency measures (IPCC 2022). For a robust sink strategy, it is therefore imperative to critically consider societal acceptance.

With a view to the long-term future and the lasting effects of anthropogenic unavoidable greenhouse emissions, it is also important to preserve degrees of freedom for future generations and not to waste possible storage potentials on easily avoidable fossil emissions.

Long-term responsibility for CO_2 storage involves considerable risks – these must be taken into account from the outset

Under current regulations, responsibility for a storage facility and its subsequent decommissioning as well as a 40-year expiry period is transferred to the respective federal state if “according to the state of the art in science and technology, the long-term safety of the carbon dioxide storage facility is given and the operator has made an aftercare contribution…”. (§ 31 para. 2 KSpG). Hence, the **duration of the operator's responsibility is very short in relation to the total period of storage. Potential risks, however, can only be adequately assessed after a long period of time has elapsed, are then borne by the general public and entail considerable uncertainty for future generations, e.g. financial remediation risks.** These risks must be taken into account at an early stage in the development and licensing process, and the possible costs for future generations must be taken into account as a price component of the storage costs.

6 Summary

The hopes that some actors harbour for CCS technology can conceal, but not repair, climate policy failures. There is a danger that the potential of CCS will be significantly overestimated, that alternatives will be neglected and that the other tasks and challenges in climate protection that transcend generations will be underestimated.

Therefore, the potential contribution of CCS to greenhouse gas sequestration or as a technology for technical sinks to mitigate greenhouse gas concentrations in the atmosphere (CDR) should be aligned with an ambitious climate protection policy and an ambitious development of natural sink capacity.

With an ambitious cross-sectoral climate protection policy, CCS will only be needed to a small extent or not at all in Germany in the coming decades, but it may well become relevant in the long term as a building block in the balancing of residual emissions and negative emissions. Nevertheless, in view of the current speed of implementation in climate protection with the danger of "overshooting" and the approaching global tipping points, the debates on negative emissions and technical sinks will have to be conducted intensively. Germany can make a constructive contribution to this.

Principles for maintaining an ambitious climate protection policy

- Reducing the production and release of greenhouse gases must remain the top priority. This also reflects the recommendations of the Intergovernmental Panel on Climate Change (IPCC 2023). In the best case, natural and technical sinks can absorb 4 gigatonnes of CO_2 globally in 2050. The remainder of the annual CO_2 emissions, currently ten times the amount of about 40 Gt CO_2]must be prevented from the outset. Technically avoidable emissions must therefore not be undermined by seemingly generous compensation options (CCS capacities). It also follows that CCS cannot act as an alternative to phasing out fossil energies due to the limited storage potential.
- Remaining unavoidable emissions from agriculture and industry must primarily be offset by maintaining, securing and expanding natural sinks. CCS and technical sinks should only be used as a supplement and limited to unavoidable process emissions.

Principles for integrating CCS and technical sinks into climate policy

- CCS is no substitute for greenhouse gas mitigation measures: Technical measures to reduce greenhouse gas emissions and technical sinks can be understood as part of climate protection, the use of which must be targeted and planned, as their availability is scarce and provision is costly. CCS can be integrated as a building block in climate protection to the extent that residual emissions have to be compensated for in addition to emission mitigation and natural sink capacity. Lock-in effects, adherence to fossil energies and fossil fuel-based economic patterns, as well as reduced incentives for substitution by alternative processes and products along the value chain must be prevented.

- Separate target recording: The legislation requires separate recording of sectoral targets for reduction and avoidance in CO_2 generation as well as of natural and technical sink targets. This is not only necessary for greenhouse gas neutrality, but also with a view to targets for negative emissions after 2050. The target triad is as follows: 1. GHG mitigation targets (without CCS) for the sectors of energy, industry, buildings, transport, agriculture, and waste, wastewater management and others, 2. targets for natural carbon sequestration, and 3. targets for technical carbon sequestration and reduction of residual CO_2 emissions. The principle of separate recording of these targets must also be observed in the design of climate policy instruments. This target architecture must enable transparent monitoring of the success of mitigation policy in natural climate protection and the integration of technical sinks.

- Defining unavoidable emissions: A clear definition of unavoidable emissions is needed to determine the necessity of offsetting these residual emissions. This must be regulated by law, for example in the Federal Climate Change Act. In light of the constant progress in research findings, the regulation must be regularly adjusted to take account of technical progress.

- Carbon storage: Possible storage capacities for carbon dioxide should be used effectively for negative emissions. Carbon storage should not only focus on carbon dioxide, as has been the case up to now, but should also include (more complex) solid carbon compounds, e.g. synthetically bound carbon, in a broad-based and technologically open way.

- Competition for the best solution: Cross-sectoral mechanisms should be developed to ensure linkage between safe and long-lasting natural and technical sinks on the one hand and emitters of unavoidable greenhouse gas emissions on the other. There needs to be competition for the best ecological and economic solution for offsetting with residual emissions. Integrated climate protection, i.e. the exploitation of synergies with other environmental objectives, must always be pursued. A joint tendering model for natural and technical sinks could, on the one hand, enable the dynamic orientation of technical measures subordinate to natural sinks and, on the other hand, enable the reliable achievement of the greenhouse gas neutrality target.

- Develop a legal framework: A “licensing roadmap” is needed that guarantees the adaptation of the legal framework for licensing, responsibility and liability as well as success control for climate protection, safety & plant technology along the process chain of CCS (capture, transport and storage).

Proposals for national integration of CCS

- “Use Case” WACCS: CCS should be integrated where no new fossil energy sources taken from nature are used and the greatest synergies are leveraged. This is the case at the end of a long value chain and where large quantities of negative emissions are already generated today, but potentially also in the long term – at thermal waste treatment plants (WACCS). The resulting lock-in effects are small and are not associated with the adherence to fossil energies and fossil economic patterns.

- Testing: CCS should be tested at thermal waste treatment plants in the near future. In this use case, the long-term availability of CCS for technical sinks can be verified and preserved for a robust sink strategy with negative emissions. Since the climate impact in particular has to be verified with special consideration of permanent storage, possible leakages and the energy input, very long observation periods have to be planned.

- Order of magnitude: In combination with the national LULUCF sector target of 40 Mt CO_2 for 2045, this results in a possible sequestration perspective in the order of approx. 60 Mt CO_2 (including negative emissions). With intensification of the circular economy and increasing recycling rates, CO_2 emissions from thermal waste treatment plants could be lower by 2045 compared to today. In the long term, however, similar orders of magnitude can be assumed.

- Protection standards: The high protection standard of existing regulations in the European CCS Directive (EU Directive 2009/31/EC) and the German Carbon Dioxide Storage Law (KSpG) must be maintained in order to be able to safely exclude negative effects on people and the environment. The prohibition of CO_2 transfer into the water column of the oceans according to the London Protocol and OSPAR is reasonable and necessary, because permanent storage in the water is not guaranteed. Careful preliminary exploration and effective long-term monitoring (monitoring and storage accounting) must be an integral part of CCS implementation. Continuous monitoring of possible impacts on people and the environment in the vicinity of the storage site is required. The monitoring should be carried out independently by the authorities and should be continued beyond the decommissioning and aftercare phases.

- Storage abroad: Environmental and climate policy challenges must not be shifted abroad. The requirements for safe and environmentally fair carbon storage must also apply to storage sites for residual German emissions abroad.

- Storage management: Pressure management in the storage facility must be designed in such a way that large safety reserves remain, since in the event of a blow-out there will no longer be any immediate possibilities for intervention. For the actual monitoring during operation, suitable site-specific characteristic parameters must be determined, by means of which migration, significant irregularities or leakages can be detected beyond doubt. In this context, not only carbon dioxide or its minor components and the displacement of formation fluid have to be monitored, but also the formation of new substances and possible other secondary effects. For monitoring related to the protected area, the initial state must be recorded over a large area in advance.

- Liability: There is a need for clear regulation of liability issues and a conservative calculation of the costs of CCS. Monitoring and, if necessary, measures in the event of an accident along the process chain and for the entire storage period must already be factored in as a price component of CO_2 storage. For compensation payments of CO_2 quantities that cannot be detected in the long term in the storage reservoir, the costs at the time of the possible leakage are to be applied.

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