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Paving the Way for a European Carbon Market

A framework for initiating the uptake of carbon capture technologies

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With increasing time pressure, it is becoming more and more evident that reducing greenhouse gas emissions alone will not suffice to achieve the EU's ambitious long-term climate targets. Carbon capture solutions, specifically Negative Emission Technologies, offer an opportunity to diversify the existing mitigation portfolio, thus providing a form of technology insurance. With the EU-ETS being firmly established as a separate system, no conflict with emission reduction goals will arise. However, several barriers remain for establishing a European market for captured CO_2. This cepInput analyzes the technical and economic potential of carbon capture and defines key requirements for a future support framework.

► **Specific long-term targets and reliable certification schemes:** As strategical guidance, the EU should formulate legally binding long-term targets for annual carbon removals, complementing the emission reduction targets. These should rest on the requirements defined by the future certification scheme currently being negotiated.

► **EU-wide tendering for carbon contracts specifically involving Negative Emission Technologies:** To initiate a timely uptake of infant but promising technologies like Direct Air Capture, investments in this area should be promoted by two-sided Carbon-Contracts-for-Difference. These should be allocated through competitive EU-wide tender schemes.

► **Harmonized rules for building a cross-border CO_2 infrastructure:** The build-up of a European carbon market promoting spatial specialization requires a coordinated development of CO_2 infrastructure, especially pipelines and long-term storage sites. To this end, a uniform position on carbon storage must be established across Member States as well as common rules for CO_2 transport.

► **A transatlantic CCS research partnership:** The implementation of its own carbon capture strategy must not lead to the EU's splendid isolation. A large part of the global investment dynamics will emanate from the Anglo-American countries in the medium term. The EU should take advantage of this by initiating a transatlantic research partnership. This will allow it to benefit from future research findings and experience gained on the other side of the Atlantic.

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1 Background

The EU's ambitious goal of establishing a climate-neutral economy by 2050 requires access to all technological options that help to improve the greenhouse gas balance. A timely implementation of available options for decarbonizing energy conversion, industrial production, building heating and transport remains key. However, far-reaching decarbonization alone will not suffice to reconcile the transformation to climate neutrality with the other central goal of the EU Green Deal - the establishment of a globally competitive green economy. With feasible solutions for the use of renewable energy sources being increasingly exploited, the costs of avoiding the residual emissions are becoming ever higher. Therefore, standard climate models agree that a cost-minimizing path towards climate neutrality will have to increasingly rely on solutions in the field of carbon capture as time progresses.

First, this will involve investments in carbon capture equipment by those industries where decarbonization is excessively costly or technologically unfeasible. Second, it will rest on the emergence of a new strand of technology solutions removing carbon directly or indirectly (through biomass cultivation and subsequent capture) from the atmosphere. The relevance of these solutions for European climate policies lies in their potential for a negative greenhouse gas balance, and thus in their role as a counterweight to the remaining hard-to-abate emissions. The European Commission assigns Negative Emission Technologies a key role in its long-term climate strategy.[1] As the market ramp-up for these infant technologies will require time, the necessary steps to build up capacities and subsequent value chains must be taken today.

The EU legislative proposal currently being negotiated for a carbon removal certification system is an important first step in this direction.[2] However, certification alone will not be sufficient to initiate rapid development of competitive markets for captured carbon. In addition to creating reliable cross-technology standards for carbon removal, coordination problems in the development of the necessary infrastructure - in particular CO_2 pipelines and storage facilities - and the exploitation of learning potential in capture technologies must be managed as well. Suitable regulatory instruments for this task are already available. However, they must be applied to carbon capture as part of a coherent strategy. This requires close cooperation between the EU and Member States.

This cepInput provides concrete impulses for the development of such a regulatory toolbox. It analyzes state-of-the-art carbon capture technologies, and the potential they offer, from a technological and economic perspective. Based on this analysis, it identifies current economic barriers and regulatory gaps. Using as a case study the particularly promising Direct Air Capture technology, it demonstrates how state support in the form of a guaranteed CO_2 price will interact with expected future learning effects. The extent and timing of current subsidies are thus revealed as decisive parameters for initiating self-reinforcing capacity growth. At the same time, the high sensitivity of growth dynamics to today's price signals entails significant fiscal risks. Limiting these risks requires a funding approach that is open to all reliable technologies and strictly based on fair and competitive mechanisms. Furthermore, it requires regulatory harmonization to establish cost-minimizing EU supply chains for captured carbon.

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[1] European Commission (2021a). Sustainable Carbon Cycles. Communication from the Commission to the European Parliament and the Council. (2021) 800 final.

[2] European Commission (2022). Proposal for a Regulation of the European Parliament and of the Council establishing a Union certification framework for carbon removals. COM(2022) 672 final.

2 Technical potential of carbon capture

2.1 Overview

At the highest level, carbon capture technologies can be divided into natural and artificial methods. Natural forms of carbon capture in the Land Use, Land-Use Change and Forestry (LULUCF) sector are referred to under the term 'carbon farming'. In the broadest sense, this term refers to all land management practices that aim to reduce GHG emissions and/or increase the storage of carbon in organic material.[3] Artificial carbon capture can be defined as the practice of capturing CO_2 using technical and industrial methods. These can be differentiated according to the origin of the captured CO_2. The carbon can be of fossil, mineral or biogenic origin, or taken directly from the atmosphere (Direct Air Capture). Moreover, depending on the method, capture can take place at different points in the production process, for example in the case of fossil fuels both before and after combustion.[4] The fate of the captured CO_2 can differ as well (see Figure 1). It can be fed into air-sealed reservoirs for long-term storage (Carbon Capture and Storage (CCS)). Possible reservoirs are primarily geological formations such as depleted fossil deposits or saline sedimentary rock, both on land and on the seabed. Alternatively, it can be used as a raw material in an increasing number of applications and initiate a form of carbon recycling (Carbon Capture and Use (CCU)).

One focus of the technology debate is on Negative Emission Technologies (NETs). This term covers approaches that aim to remove Greenhouse Gases (GHG) from the atmosphere, i.e. act in the opposite direction to GHG emissions from human and natural activities. This includes established techniques of carbon farming as well as recently researched technologies such as ocean fertilization, the production of biochar, the manipulation of weathering processes and the direct extraction of carbon from the ambient air. This should be distinguished from processes that absorb emissions from the combustion of fossil or mineral resources because the aim is to avoid emissions and thus reach (or at least approach) climate-neutrality.

Despite great ambitions, the global development of CCS capacity has only seen very modest growth in the last ten years (see Figure 2). Technological and regulatory uncertainty with regard to the geological storage of CO_2, coupled with a general lack of clarity about long-term climate policy targets, has hindered market development in the period from 2013 onwards.[5] The operational capture capacities in this period were predominantly projects with the aim of Enhanced Oil Recovery (EOR), i.e., the injection of CO_2 into crude oil reservoirs in order to push the oil to the surface (see Figure 3). From 2019, the formulation of more ambitious long-term climate targets and investment initiatives in individual countries gave a new boost to project plans. However, this has not yet been reflected in a steady growth of operational capacities. The CCUS database of the International Energy Agency (IEA) shows a total global capacity of only about 41 million tonnes of CO_2 p.a. for capture plants in operation in March 2023. This is well below the long-term capacities required for typical mitigation scenarios in climate models (see Subsection 2.2).[6]

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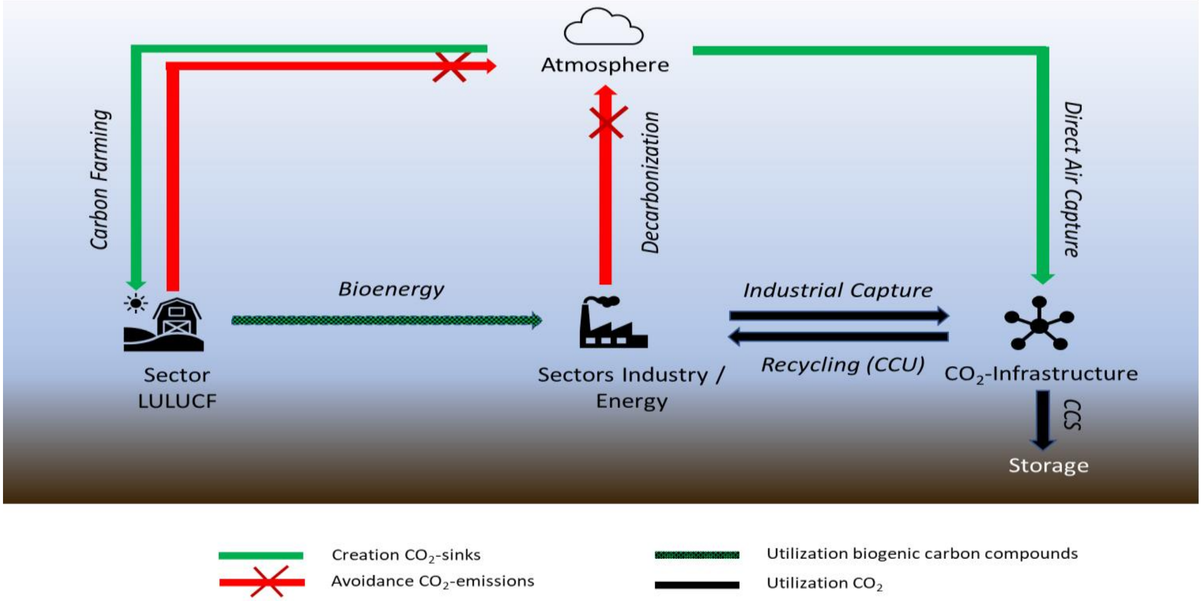
[3] McDonald, H. Frelih-Larsen, A., Lóránt, A., Duin, L., Andersen, S.P., Costa, G., Bradley, H. (2021). Carbon farming – making agriculture fit for 2030. Study requested by the ENVI committee of the European Parliament. November 2021.

[4] Gaurina-Međimurec, N., & Mavar, K. N. (2019). Carbon capture and storage (CCS): geological sequestration of CO2. CO2 Sequestration, 1-21.

[5] Martin-Roberts, E., Scott, V., Flude, S., Johnson, G., Haszeldine, R. S., & Gilfillan, S. (2021). Carbon capture and storage at the end of a lost decade. One Earth, 4(11), 1569-1584.

[6] IEA (2023). CCUS Projects Database. International Energy Agency. Accessed: Nov 16 2023.

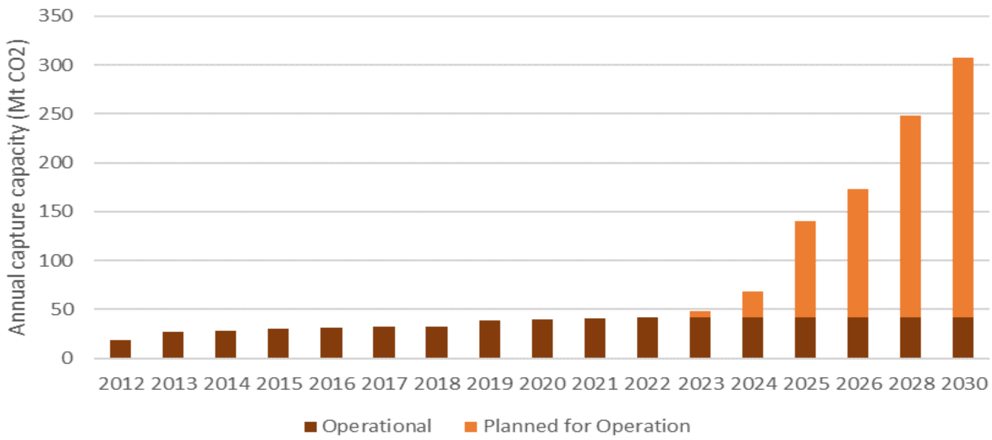
Figure 1: Comparison of different capture technologies in the carbon cycle



Source: own representation.

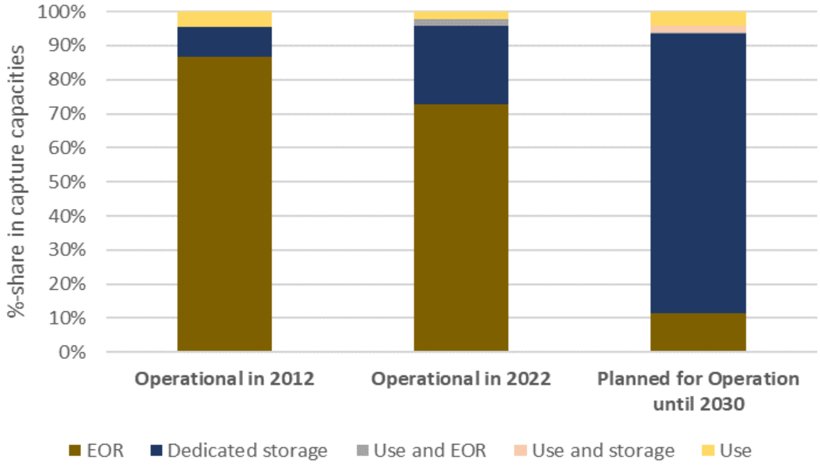
However, a sharp increase in the number of projects currently in planning or under construction suggests that a new dynamic can be expected in the near future. Realization of just the projects currently being planned for the period up to 2030 would already result in an almost exponential increase in global capture capacities over the next few years (see Figure 2) and represent a significant shift in the type of projects from EOR towards dedicated storage solutions (see Figure 3).

Figure 2: Evolution of global capacities for carbon capture



Source: IEA (2023); own aggregation.

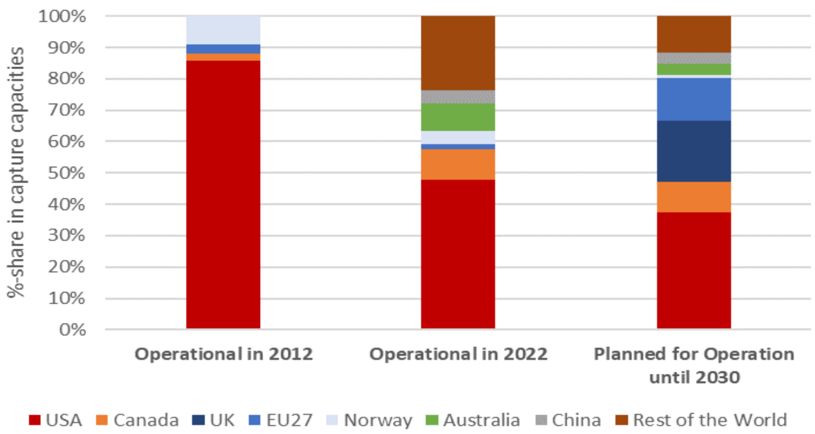
Figure 3: Distribution of global capture capacities by fate of captured CO_2



Source: IEA (2023); own aggregation.

The growing momentum is likely to be accompanied by a major shift in the spatial distribution of capture capacities. In 2022, almost half of all global capacities were located in the USA (see Figure 4). Together with Canada's capacities, North America's global share was almost 60 %. The EU27 only had a share of about 1.5 %. According to the IEA CCUS database, there are currently only five commercial carbon capture plants on European soil, only two of which are located in the EU (Hungary, Netherlands). According to current plans, North America would still be the most important region for CCS globally in 2030 but Europe could catch up considerably. This is due to ambitious investment plans in the EU Member States, but even more so due to the ambitions of the UK, which alone is planning more capacity than the EU27 combined. By contrast, the emission-intensive emerging economies will continue to play a minor role in global capacity expansion up to 2030. China's share in global capacities planned for operation up to 2030 is less than 5 %.

Figure 4: Distribution of global capture capacities by country/region

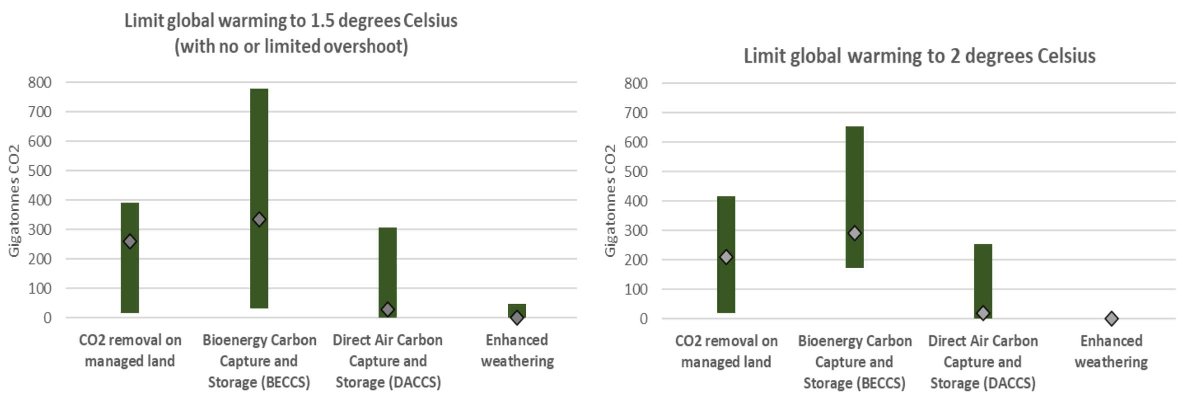


Source: IEA (2023); own aggregation.

2.2 Expected contribution to climate change mitigation

CO_2 storage methods play an important role in climate projections, especially when considering long-term mitigation strategies. Simulations by the UN Intergovernmental Panel on Climate Change (IPCC) see extensive storage capacities for the period after 2030 as a prerequisite for having a realistic chance of achieving the 1.5-degree target. Most of the stored CO_2 will need to stem from the application of Negative Emission Technologies. In fact, all modelling scenarios in the 2018 IPCC special report on limiting global warming to 1.5 degrees Celsius rely on the removal of carbon dioxide from the atmosphere. [7] In a recent comprehensive meta-analysis of climate change mitigation forecasts, the IPCC determines a median need for cumulated carbon removals of hundreds of gigatonnes CO_2 over the period 2020-2100 across the range of modelling scenarios, also for achieving the less ambitious 2 degrees target.[8] The combination of bioenergy with carbon capture and storage technologies is in many climate models assigned a key role (see Figure 5). In its Sustainable Development Scenario, which envisages climate neutrality for industrialized nations by 2050, the IEA also identifies a critical contribution from CO_2 storage technologies in the order of gigatonnes.[9]

Figure 5: Cumulative carbon removals 2020-2100 by technology in IPCC scenario comparison



Source: IPCC (2022); own illustration. Upper end bars: 95 % confidence interval. Lower end bars: 5 % confidence interval. Grey rhombus: median level.

At the same time, the IPCC warns against naïve confidence in the sustainability of CCS technologies. Knowledge about their long-term effectiveness and possible climatic and ecological side-effects is still inadequate in many areas. Moreover, processes for storing other important greenhouse gases besides CO_2 are still lacking scientific evidence.[10] The overall suitability of CCS as a climate policy instrument has been the subject of controversial debate for some time. Of the three steps involved in this technology (capture, transportation, storage), the latter in particular has so far only had limited research with regard to long-term sustainability risks. While geological deposits could store CO_2 for many

[7] IPCC (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways. Intergovernmental Panel on Climate Change

[8] IPCC (2022). Climate Change 2022 - Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.

[9] IEA (2021). World Energy Outlook 2021. International Energy Agency.

[10] See IPCC (2022).

centuries, possible side effects such as acidification of groundwater deposits or geological instability need to be monitored.[11]

However, a sustainability assessment also needs to take the positive environmental side effects of CCS into account. By cutting net emissions, CCS reduces the need to expand renewable energies and related downstream technologies on a given path towards climate neutrality. This leads to a system-wide gain in efficiency, as the construction of wind and solar power capacities at locations with low generation potential can be avoided. This is accompanied by material savings, which implies a reduction in environmental damage related to the extraction of raw materials and production of intermediates from a life cycle perspective. As part of a comprehensive environmental life cycle assessment, Shu et al. (2023) compare two scenarios with high and low CCS volumes. The high-volume scenario is predicted to be associated with lower negative environmental impacts in 13 of 16 environmental categories considered. The greatest benefits are predicted for the areas of aquatic freshwater eutrophication, human toxicity cancer effects, and resource use of minerals and metals.[12]

From an incentive perspective, there are widespread fears that the prospect of future carbon removal technologies could counteract current efforts in the area of decarbonization. The expectation that such technologies will become available on a large scale and on favorable economic terms in the long run could be viewed by emitters as a form of climate insurance. This could give rise to a classic moral hazard problem. In this case, it could induce individual emitters to adopt a wait-and-see attitude that is too risky from a societal point of view. The low level of technological maturity of carbon removal technologies exacerbates this problem. It implies that the prospect of future economic viability depends heavily on the realization of learning effects that are uncertain from today's perspective. Relying on future CCS backup technologies as climate insurance could therefore in reality represent a massive gamble that, in the worst case of failing technology improvement, undermines climate change mitigation as a whole.[13] However, this moral hazard problem does not apply to economic areas such as the EU, which have mandatory emissions certificate trading in place. The obligation to reduce emissions in the affected sectors is politically determined by the number of certificates issued. In the current EU trading system, there is no possibility of substituting the need for emission reductions by investments in Negative Emission Technologies. The downside of this dichotomy is that alternative remuneration schemes must be created to incentivize the exploitation of the development potential of carbon removal technologies (see Section 4).

2.3 Current states of development

2.3.1 Industrial carbon capture from fossil fuels

A range of different technologies have been established for the capture of CO_2 released in industrial production processes. They differ initially with regard to their starting point within the industrial process chains. Pre-combustion technologies carry out capture even before the step of burning fossil resources. A classic, long-established process starts with the fossil extraction of hydrogen by means of

[11] Song, Y., Jun, S., Na, Y., Kim, K., Jang, Y., & Wang, J. (2023). Geomechanical challenges during geological CO2 storage: A review. Chemical Engineering Journal, 456, 140968.

[12] Shu, D. Y., Deutz, S., Winter, B. A., Baumgärtner, N., Leenders, L., & Bardow, A. (2023). The role of carbon capture and storage to achieve net-zero energy systems: Trade-offs between economics and the environment. Renewable and Sustainable Energy Reviews, 178, 113246.

[13] Anderson, K., & Peters, G. (2016). The trouble with negative emissions. Science, 354(6309), 182-183.

steam reforming (for natural gas as a source) or gasification (for coal).[14] The fossil fuel is subjected to a chemical reaction to obtain synthesis gas, in the case of steam reforming with steam. The synthesis gas obtained is a mixture of CO, CO_2, H_2 and H_20. In a subsequent step, it is cleaned of impurities and subjected to a water-gas shift reaction in a reactor. Here, the CO contained in the gas reacts with water vapor, which increases the CO_2 content in the mixture. The CO_2 must then be separated, for which various chemical or physical absorption methods are available. The final step is to compress and dehydrate the separated CO_2 for transportation.[15]

Post-combustion processes are initiated after the combustion of fossil resources. CO_2 is separated from the released flue gas. The hot flue gas is first cooled and cleaned of pollutants (e.g., nitrogen oxides, sulphur oxides). It is then fed into a CO_2 absorber containing a CO_2 solvent. The CO_2 solvent is then fed into a CO_2 stripper, where CO_2 is recovered in gaseous form. The final step of compression and dehydration is comparable to the pre-combustion route. A particular challenge of the post-combustion process is the comparatively low initial CO_2 concentration in the flue gases. This implies a high energy input required to achieve the high CO_2 concentration necessary for transport and storage.

With oxyfuel combustion processes, a third technology variant has by now been established. In this setup, the fossil fuel is not burned in the air, but in an environment consisting almost entirely of oxygen and at very high temperatures (> 1,300 degrees Celsius). The resulting flue gas has a very high CO_2 content. The remaining foreign substances (water, pollutants) are then removed. As a result of the high CO_2 concentration obtained, the CO_2 can be separated in a simple way without requiring chemical solvents or physical sorbents. However, a major challenge with this technology is the beginning of the process chain which involves the extraction of almost pure oxygen. The air separation unit required for this process step is characterized by a high energy requirement.[16]

In principle, all three technology variants feature a high degree of technological maturity.[17] One aspect that has promoted the practical use of post-combustion capture to date is the ease with which existing industrial plants can be retrofitted. Unlike the other technologies, no direct adaptation of existing combustion processes is necessary. In addition to these main categories, other technologies have been developed more recently, such as the oxidation of carbon-rich fuels with a solid O_2 carrier such as metal oxides (chemical looping combustion capture). However, these are still at a low level of technological maturity.[18]

Concerning the sectoral distribution of operating industrial CCS facilities, the field of natural gas processing currently dominates globally (see Figure 6). However, the diversity of technological options has also been reflected in the current project plans, which exhibit an increasing range of sectoral applications. In the capacity plans for the period up to 2030, the power and heat sector plays the largest role globally, particularly through the use of carbon capture in coal-fired power plants. The plans to introduce carbon capture in the fossil-based production of hydrogen (blue hydrogen) and its derivatives are also quite ambitious. Carbon capture is also expected to be implemented to a significant extent in

[14] Hong, W. Y. (2022). A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO_2 emissions future. Carbon Capture Science & Technology, 3, 100044.

[15] Osman, A. I., Hefny, M., Abdel Maksoud, M. I. A., Elgarahy, A. M., & Rooney, D. W. (2021). Recent advances in carbon capture storage and utilisation technologies: a review. Environmental Chemistry Letters, 19(2), 797-849.

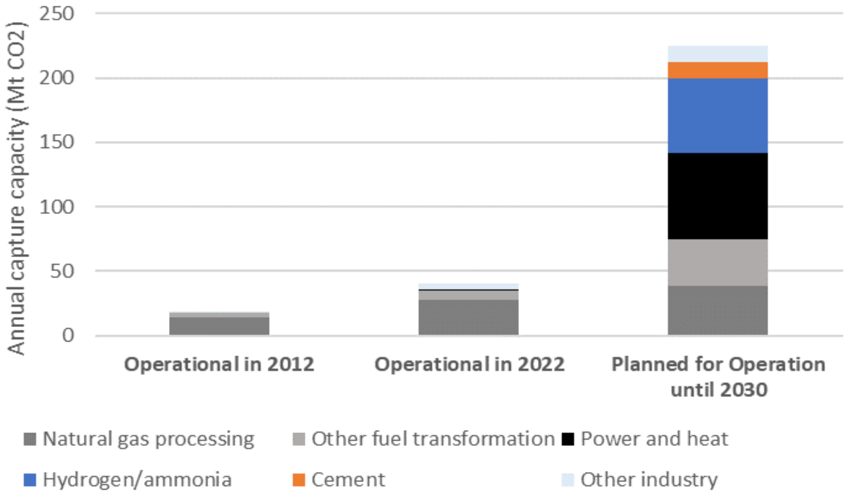
[16] See Hong (2022).

[17] See Hong (2022).

[18] See Osman et al. (2021).

cement production by 2030. The existing capacity plans in the iron/steel sector are negligible in comparison (part of "other industry").

Figure 6: Evolution of global industrial carbon capture capacities by sector



Source: IEA (2023); own aggregation.

2.3.2 CO_2 removal from atmosphere

The removal of CO_2 from the atmosphere must be distinguished from the avoidance of CO_2 emissions. Only direct or indirect carbon removal technologies have the potential for an overall negative greenhouse gas balance. Under these circumstances, they can be referred to as Negative Emission Technologies (NETs). The concrete definition is difficult, as the measured greenhouse gas balance strongly depends on the boundaries of the technology system under consideration. There is no generally accepted convention on this in the scientific literature. One particularly critical aspect is the extent to which indirect emissions from the extraction of inputs required for NETs are included in the assessment.[19]

A wide variety of very different technologies are now being discussed under the umbrella of NETs. The oldest group of NETs can be summarized as technologies that rely solely on natural chemical reactions in ecosystems. These include, for example, afforestation and reforestation measures that utilize the CO_2 storage capacity of forests. The improvement of the absorption capacity of agricultural soils through more sustainable methods of land management (e.g., avoidance of cropping), wetland restoration as well as the strengthening of ecosystems on the seashore should also be mentioned.[20] This is to be distinguished from methods that likewise rely on natural CO_2 reservoirs but aim to strengthen and accelerate the processes involved through targeted chemical interventions. These include, for example, the increased cultivation of CO_2-absorbing phytoplankton in the oceans through the introduction of nutrients (ocean fertilization).[21] Another approach is the acceleration of geological weathering

[19] Tanzer, S. E., & Ramírez, A. (2019). When are negative emissions negative emissions?. Energy & Environmental Science, 12(4), 1210-1218.

[20] NTNU (2021). Negative emissions and carbon dioxide removal. NTNU Energy Transitions. Policy Brief 02/2021.

[21] Strong, A., Chisholm, S., Miller, C., & Cullen, J. (2009). Ocean fertilization: time to move on. Nature, 461(7262), 347-348.

processes through the application of CO_2-binding silicate rock, e.g., on arable land (enhanced weathering).[22]

Natural CO_2 sinks will continue to be indispensable as a balancing instrument within the climate system. However, there are clear limits to their systematic use as a mitigation technology. First, this concerns the limited absorption capacity. For methods that rely on storage in biomass, the temporal restriction of storage to the biological life cycle represents a limitation. The complexity of ecosystem interactions also makes it extremely difficult to predict the actual effectiveness over time. Chemical intervention methods such as ocean fertilization risk having negative effects on diversity and the long-term viability of local ecosystems.[23]

Against this background, technologies that rely on the development of artificial capture and storage processes for atmospheric CO_2 have been at the forefront of the debate in recent years. One of these technologies is the use of bioenergy in combination with carbon capture and storage (BECCS). Carbon is removed from the atmosphere as the biomass grows. The harvested solid biomass can be burned directly. The CO_2 released during the combustion is captured using established industrial technologies (see Subsection 2.3.1) and stored geologically. Alternatively, the harvested biomass can be converted into gaseous or liquid fuels by means of fermentation or digestion, with the CO_2 gained as a by-product being captured and stored.[24] In this way, a negative greenhouse gas balance can be achieved for the overall process. In addition to this indirect form of CO_2 extraction, methods of Direct Air Capture using artificial systems and subsequent geological storage (DACCS) have also been developed. Finally, the production of charcoal as a carbon store by means of pyrolysis of plant material can also be considered part of this group.[25]

In the current climate debate, BECCS and DACCS are seen as high-potential technology classes. At the same time, the question of their sustainability is the subject of much controversy. In the case of BECCS, one critical point is the origin of the biomass. If specific energy-rich plants are cultivated for this purpose (e.g., rapeseed, maize), the CO_2 emissions generated during cultivation and harvesting can worsen the greenhouse gas balance of the overall process. Additional negative effects can result from direct and indirect forms of land use change associated with cultivation (e.g., competition with food production, loss of biodiversity).[26] The assessment is different for biomass in the form of residuals such as plant residues and biogenic household waste. Their incineration in the context of BECCS does not generate additional negative land use effects, and also contributes to better energy recovery from organic waste, in addition to achieving negative emissions. However, if the use of additional arable land is to be avoided, there are limits to the expansion of BECCS capacities in terms of resources. For example, Rosa et al. (2021) estimate a maximum annual capture potential of 200 million tonnes of CO_2

[22] Hartmann, J., West, A. J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D. A., ... & Scheffran, J. (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. Reviews of Geophysics, 51(2), 113-149.

[23] Williamson, P., Wallace, D. W., Law, C. S., Boyd, P. W., Collos, Y., Croot, P., ... & Vivian, C. (2012). Ocean fertilization for geoengineering: a review of effectiveness, environmental impacts and emerging governance. Process Safety and Environmental Protection, 90(6), 475-488.

[24] Consoli, C. (2019). Bioenergy and carbon capture and storage. Global CCS Institute.

[25] Woolf, D., Lehmann, J., Cowie, A., Cayuela, M. L., Whitman, T., & Sohi, S. (2018). Biochar for climate change mitigation. Soil and climate, 219-248.

[26] Hanssen, S. V., Daioglou, V., Steinmann, Z. J. N., Doelman, J. C., Van Vuuren, D. P., & Huijbregts, M. A. J. (2020). The climate change mitigation potential of bioenergy with carbon capture and storage. Nature Climate Change, 10(11), 1023-1029.

for Europe, assuming the exclusive use of residual biogenic sources. Accordingly, only a few European countries can cover their long-term carbon removal needs exclusively via BECCS.[27]

By contrast, the artificial form of carbon removal using DACCS requires significantly less land[28] and water and therefore has a much smaller direct impact on local ecosystems.[29] Ambient air is fed via large fans through a separator containing a chemical CO_2 sorbent. This can be a liquid or a solid sorbent. If a liquid sorbent (e.g. sodium hydroxide, potassium hydroxide) is used, the liquid is then heated to more than 800 degrees Celsius to separate the CO_2 as a gas. When using a solid sorbent (e.g., amine materials, ionic membranes), only heating to 85-120 degrees Celsius is required for separation, as a weaker chemical bond is formed between the CO_2 and the sorbent.[30] However, the technologies with liquid sorbents are technologically more mature. A general challenge for DACCS is the low concentration of CO_2 in the ambient air. This implies high energy and material costs for the capture of concentrated CO_2.[31] Finally, potential environmental risks can also arise from pollutants as by-products in the production of sorbents.[32]

The commercial application of BECCS and DACCS beyond research projects is currently still in its infancy globally. Climeworks Orca in Iceland was the first large-scale DACCS plant to go into operation in 2021. The annual capture capacity of 4000 tonnes of CO_2 is currently still far below the scenarios discussed in the literature for large-scale projects but is to be significantly expanded in 2024.[33] No further DACCS plants are currently listed as operational in the IEA CCUS Projects Database. However, according to the database, the commissioning of a range of new plants has been announced for the period up to 2030. Their geographical focus is the USA and the UK (see Figure 7).[34] Several demonstration projects are underway within the EU, including a DAC plant in south-west Germany with a designated capacity of 1000 tonnes of CO_2 per year.[35] The IEA estimates that BECCS has a global capacity of 2 million tonnes of captured CO_2. Current project plans would imply a capacity of about 50 million tonnes of CO_2 by 2030, which is well below the 190 million tonnes that the IEA assumes in its climate neutrality scenario.

27 Rosa, L., Sanchez, D. L., & Mazzotti, M. (2021). Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. Energy & Environmental Science, 14(5), 3086-3097.

28 Based on literature results, Realmonte et al. (2019) estimate the land use of a BECCS power plant to lie between 270 and 1636 m^2 per tonne CO_2 per year, while the land use of a DACCS plant with liquid sorbent is estimated at 1.5 m^2/tCO_2/year.

29 Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature communications, 10(1), 3277.

30 Gambhir, A., & Tavoni, M. (2019). Direct air carbon capture and sequestration: how it works and how it could contribute to climate-change mitigation. One Earth, 1(4), 405-409.

31 Ozkan, M., Nayak, S. P., Ruiz, A. D., & Jiang, W. (2022). Current status and pillars of direct air capture technologies. Iscience.

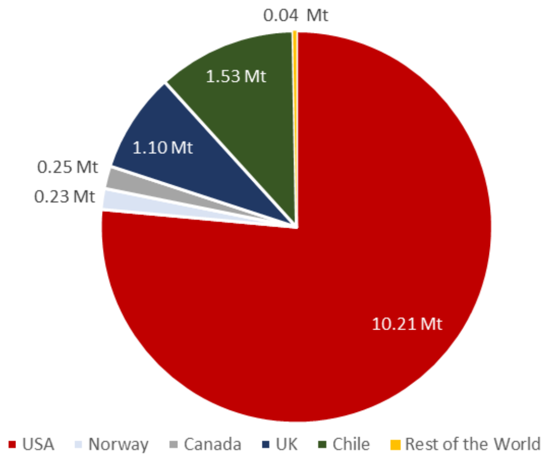
32 See Realmonte et al. (2019).

33 Climeworks (2023). Orca: the first large-scale plant. Climeworks AG.

34 See IEA (2023).

35 ZSW (2023). Etappenziel erreicht: Direct Air Capture Verfahren überzeugt im ZSW-Forschungsbetrieb. Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW). Press release, Oct 4 2023.

Figure 7: Planned annual DAC capacities for 2030 by country



Source: IEA (2023); own aggregation.

2.3.3 CO_2 transport and geological storage

In principle, the injection of CO_2 into geological formations enables a permanent form of storage with only minimal CO_2 leakage potential.[36] For sufficient storage efficiency, the CO_2 must be compressed to more than 100 bar before injection. In order to maintain this density during storage, the reservoir must be located at a depth of at least 800 m.[37] Two types of geological reservoirs have been well tested and are considered particularly suitable: saline formations and depleted oil and gas fields. The technologies required for storage in saline formations are the most mature. Experience has been gained since the 1990s. Since 1996, around 1 million tonnes of CO_2 have been stored annually in saline formations beneath the Sleipner offshore gas fields in the Norwegian part of the North Sea.[38] Storage in depleted oil and gas fields has so far only been realized in the form of demonstration projects but offers particular potential in the medium term in view of the size of the oil and gas deposits in the North Sea.[39]

The theoretical total potential of geological CO_2 storage in Europe is estimated by an EU project at 507 gigatonnes of CO_2, which means that way more than 100 years of EU CO_2 emissions could be stored completely even at current emission levels.[40] However, the practical potential is limited by geological uncertainties and competition for space (e.g., alternative use as hydrogen storage). In addition, offshore storage as the most important part of the European storage potential is still prohibited in some Member States. According to the IEA CCUS Database, only four CO_2 storage facilities are currently operated on a commercial scale in Europe (two in Norway, one in Hungary and one on Iceland), with a total injection capacity of around 1.9 million tonnes of CO_2 per year.[41] These are all integrated (full chain) solutions and not open-source storage facilities.

36 Benson, S. M., & Cole, D. R. (2008). CO2 sequestration in deep sedimentary formations. Elements, 4(5), 325-331.
37 Kearns, D., Liu, H., & Consoli, C. (2021). Technology readiness and costs of CCS. Global CCS Institute. March 2021.
38 See IEA (2023).
39 See Kearns et al. (2021).
40 Poulsen, N., Holloway, S., Neele, F., Smith, N.A., & Kirk, K. (2015). CO2StoP Final Report. Assessment of CO2 storage potential in Europe. European Commission Contract No ENER/C1/154-2011-SI2.611598.
41 See IEA (2023).

Infrastructure development is made more complex by unfavorable geographical conditions in Europe. Suitable geological sinks are on average located at some distance from the currently most important industrial CO_2 point sources.[42] The rapid development of a network for the long-distance transport of captured CO_2 is therefore all the more important. Large quantities of CO_2 are currently transported both onshore and offshore almost exclusively by way of pipelines, the most technically mature form of transportation. For this purpose, captured CO_2 must first be dehydrated and compressed to a dense phase (> 74 bar).[43] At present, the lion's share of the world's CO_2 pipeline network is located in the US. The main reason for transport infrastructure to date has been the use of captured CO_2 for EOR. Within Europe, the Netherlands and Norway already maintain pipeline networks. In Germany, a large-scale pipeline project is being planned to transport CO_2 from industrial centers in the south to offshore storage facilities in the North Sea.[44]

Pipelines are likely to continue to dominate long-distance transportation in the future due to their significant economies of scale. However, transportation by ship could become more important for the offshore sector. This requires the CO_2 to be cooled down to a liquid state for transportation, which generates high fixed costs.[45] Nevertheless, as variable costs (variable ship size) also play a role in ship transportation, the economies of scale are not as pronounced as in pipeline transportation. Ship transportation has the advantage over pipelines of being more easily scalable. As a supplement to offshore pipelines, it could therefore play an increasingly important role in the transport of captured CO_2 from decentral sinks to North Sea storage facilities.

2.3.4 CO_2 as industrial feedstock

Carbon Capture and Use (CCU) as an alternative to the pure storage of captured CO_2 has recently gained attention in the climate policy debate. The use of CO_2 as a raw material not only avoids the limitations and long-term risks associated with storage but can also help to conserve resources by replacing the use of fossil or mineral raw materials in production. Although additional material and energy costs are incurred in the utilization of CO_2, this must be offset against the costs saved by conventional production methods. The time horizon for binding the carbon in the products is crucial for the carbon footprint. The use of CO_2 for products that are characterized by an average long service life or a high degree of reusability or recyclability makes the most sense from a climate perspective. On average, CO_2 is thus kept out of the atmosphere for a relatively long time, and the climate impact comes closest to that of emissions avoidance.

At present, CO_2 is primarily used in two processes: in the production of urea in the chemical industry and in EOR. With regard to future utilization potential, the IEA identifies four product categories: fuels, plastics, building materials and fertilizers.[46] The production of CO_2-based fuels typically requires the complementary use of hydrogen. Given the current state of the technology, this is not price-competitive with fossil alternatives in these fields. If the hydrogen is not produced via electrolysis using green electricity, it also increases the carbon footprint of the CCU system. In the chemical industry, in addition to the established urea production, the use of CO_2 in plastics production is a technically feasible

[42] See Rosa et al. (2021).
[43] See Kearns et al. (2021).
[44] Anderson, P. (2023). Wintershall Dea, Fluxys Mull CO2 Pipeline Network Between Germany, Belgium. Rigzone Staff. March 10 2023.
[45] See Kearns et al. (2021).
[46] IEA (2019). Putting CO_2 to use – creating value from emissions. International Energy Agency.

option. Some of the new polymers produced in this way have favorable material properties. However, the high stability of CO_2 requires a high energy input in the reaction chain, implying that high energy costs are still an obstacle to market ramp-up.[47]

The use of CO_2 in the production of building materials is particularly attractive from a climate perspective given the long life of the products. The technologies currently being researched for this purpose do not require the use of hydrogen as a cost driver. At the same time, they provide sectors that are particularly difficult to decarbonize with an opportunity to recycle captured CO_2 using their own waste products. For example, intensive research is being conducted into the mineralization of CO_2 emissions in the steel industry using steel slag as the basis for the production of building materials. This technology is already classified as market-ready and climate-friendly.[48] In the cement and concrete industry, the use of CO_2 in the curing of concrete based on secondary raw materials is being tested. Injection into this building material offers the potential for particularly long-term storage.[49]

3 The role of CCS in European policies

3.1 Existing EU-wide regulatory framework

In the current regulatory framework of EU climate policies, carbon capture is only present in a few places and often only in indirect form. Since 2009, Directive 2009/31/EC on the geological storage of carbon dioxide has regulated technical aspects related to CCS.[50] It sets requirements for the selection and approval of storage facilities, defines monitoring and reporting obligations and regulates non-discriminatory access to transmission grids and storage facilities. It does not oblige Member States to accept CO_2 storage on their territory. Moreover, it does not contain a support mechanism or other economic incentive instruments. In the case of CCS from fossil sources, such a mechanism is set via the EU Emissions Trading System Directive (EU-ETS).[51] Emissions are defined as the release of greenhouse gases into the atmosphere. The capture and subsequent storage of the CO_2 produced thus reduces the number of certificates that plant operators have to surrender in connection with their emissions activities. This means that every tonne of CO_2 captured generates a monetary benefit in the amount of the certificate price. However, this does not apply to the storage of CO_2 taken directly or indirectly (CO_2 from biogenic sources) from the atmosphere. As no emissions activity covered by the EU-ETS is avoided, no indirect remuneration through reduced certificate requirements applies.[52] Moreover, environmentally friendly technologies in the field of CCS and CCU are classified in the EU Taxonomy

[47] Muthuraj, R., & Mekonnen, T. (2018). Recent progress in carbon dioxide (CO2) as feedstock for sustainable materials development: Co-polymers and polymer blends. Polymer, 145, 348-373.

[48] de Kleijne, K., Hanssen, S. V., van Dinteren, L., Huijbregts, M. A., van Zelm, R., & de Coninck, H. (2022). Limits to Paris compatibility of CO2 capture and utilization. One Earth, 5(2), 168-185.

[49] Liang, C., Pan, B., Ma, Z., He, Z., & Duan, Z. (2020). Utilization of CO2 curing to enhance the properties of recycled aggregate and prepared concrete: A review. Cement and concrete composites, 105, 103446.

[50] European Union (2009). Directive 2009/31/EC of the European Parliament and the Council of 23 April 2009 on the geological storage of carbon dioxide.

[51] European Union (2021). Directive 2003/87/EC of the European Parliament and the Council of 13 October 2003 establishing a system of greenhouse gas emissions trading for the Union. Consolidated version of 1 January 2021.

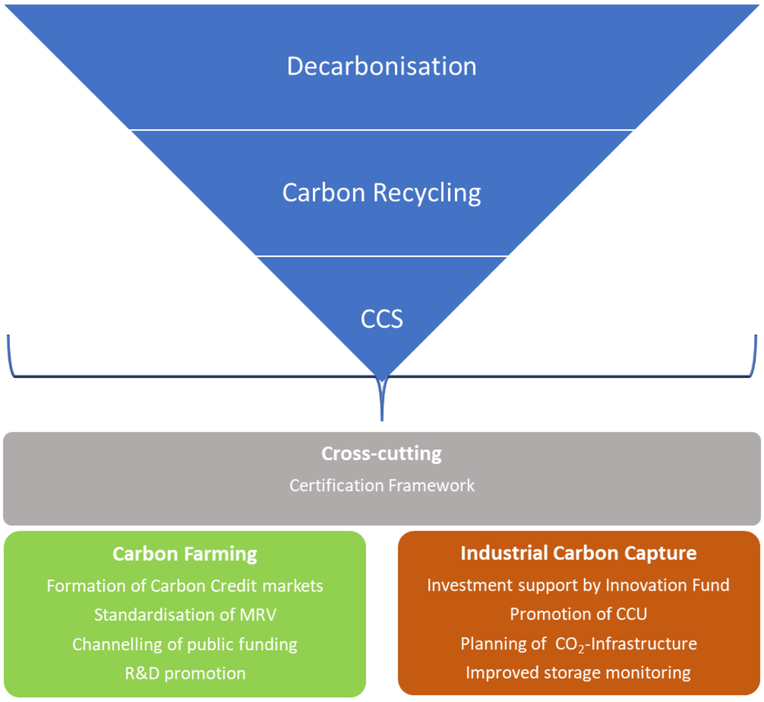
[52] Rickels, W., Proelß, A., Geden, O., Burhenne, J., & Fridahl, M. (2020). The future of (negative) emissions trading in the European Union (No. 2164). Kiel Institute for the World Economy (IfW).

Regulation (2020/852) as economic activities with a significant contribution to climate protection. This gives them access to green financing instruments.[53]

3.2 The EU Sustainable Carbon Cycles Strategy

With its strategy paper "Sustainable Carbon Cycles" published in December 2021, the EU Commission outlined for the first time an overarching plan to develop a common regulatory framework for carbon storage. The Commission divides its strategy into three fields of action that influence carbon cycles in different ways (see Figure 8). The description exhibits features of a hierarchical structure.[54]

Figure 8: Elements of the EU Sustainable Carbon Cycles Strategy



Source: own representation.

The first field of action comprises all measures aimed at decarbonization, i.e. reducing gross emissions by switching to greenhouse-gas-free products and energy sources. This field of action has absolute priority: all potential for decarbonization must first be exploited before measures to offset gross emissions come into play. The second field of action includes measures in the area of carbon recycling. The Commission defines this as activities aimed at replacing the use of carbon from fossil resources with alternative processes that extract carbon directly or indirectly from the atmosphere. The Commission emphasizes that these activities must be limited to those economic sectors for which decarbonization is not an option. The third field of action is the upscaling of solutions for the capture and permanent storage of CO_2 from the atmosphere. This aims to exploit the remaining potential for reducing greenhouse gas concentrations after decarbonization and carbon recycling.

Carbon capture is therefore part of the second and third fields of action of the EU strategy. While the second field aims to (re)utilize the captured carbon, the third field of action refers to permanent

[53] European Union (2020). Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088

[54] See European Commission (2021a).

storage and thus the permanent removal of carbon from its cycle. In both cases, the Commission distinguishes between two basic forms: Carbon farming and industrial carbon capture technologies. The strategy paper brings a variety of instruments into play for their promotion.

- **Regulatory framework for the certification of carbon removals:** In the long term, NETs should be fully integrated into the existing EU climate policy framework with a view to achieving climate neutrality. To this end, transparency must first be created regarding the effective climate impact of a particular technology and the ecological and other risks and side effects associated with its use. As in other cases, the Commission would like to use the instrument of taxonomy and certification to ensure reliability and create trust. This is seen as a prerequisite for the availability of private funding and subsequent market penetration. In view of measurement uncertainties and the large number of possible (positive and negative) side effects of the technologies under consideration, the Commission sees the creation of such a uniform standard as a major challenge. At the same time, the costs of verification for users arising during implementation should be kept within limits.
- **Expansion of support for investments via the EU Innovation Fund:** The EU Innovation Fund for the commercial testing of emission-reducing technologies with an expected total volume of around 25 billion euros for the period 2020-30 also serves to finance CCS projects. The focus here is on funding large-scale lighthouse projects. This funding is to be further expanded in the future. The introduction of Carbon Contracts for Difference (CCfDs) as an additional instrument within the innovation fund will also serve this purpose: By guaranteeing investors in CCS projects a fixed CO_2 price (and thus secure savings) for the emissions saved through capture and storage, the government will create additional incentives for innovation.
- **Promotion of CO_2-based products:** The production of industrial products and energy sources manufactured using sequestered carbon is to be promoted. This includes, for example, the promotion of synthetic fuels for maritime transport and aviation. In the context of emissions trading, double counting of emissions in the production and use of synthetic fuels is also to be ruled out through appropriate allocation.
- **Planning a cross-border CO_2 infrastructure:** In order to prevent potential future bottlenecks in the transportation and storage infrastructure for CO_2, the Commission seeks to identify the medium to long-term requirements in Europe with the broad involvement of stakeholders. The infrastructure is to be planned on a cross-border basis in order to give countries the opportunity to participate regardless of the existence of their own suitable storage locations. In the interests of competition between providers and CCS technologies, the open access principle should apply. In addition, the Connecting Europe Facility will be used to actively promote CCS transport infrastructure.
- **Improving the implementation of the monitoring system:** The EU-wide implementation of the framework developed in the CCS Directive for the monitoring and risk management of storage sites (see Subsection 3.1) is to be improved. To this end, the implementation guidelines are to be updated in light of the new objectives.

3.3 CCS in recent EU legislative initiatives

3.3.1 Effects of EU-ETS reform on carbon capture

The reform of the EU Emissions Trading Scheme (EU-ETS) recently adopted as part of the Fit-for-55 legislative package[55] will have direct and indirect impacts on the future commercial viability of carbon capture projects in several respects. First, this concerns the more ambitious future path for the issuance of emission allowances in the ETS-1, which is relevant for industry and the energy sector.[56] The amount of emission allowances issued is to be reduced by 62 % by 2030 (instead of the previous 43 %). Second, the previous system of free allocation for sectors affected by carbon leakage will be phased out as part of the introduction of the Carbon Border Adjustment Mechanism (CBAM).[57] The general expectation is that the greater scarcity of allowances will lead to a steeper increase in the price of pollution rights which will improve the profitability of current investments in abatement technologies. This applies in particular to industrial CCS technologies, as these tend to lie at the upper end of the cost range of technology alternatives in many sectors (see Subsection 4.1.1).

The reform is accompanied by an enhanced endowment of the Innovation Fund. Around 85 million certificates will be added to the Innovation Fund, with the total volume for the 2021-2030 period estimated at around 40 billion euros. The task of the Innovation Fund is to support innovation in the area of low-carbon technologies, which explicitly includes technologies in the fields of carbon capture, transport, geological storage and utilization. It is not limited to the research and development phase, but also includes the upscaling of technologies. The improved equipment has already been reflected in two new calls for proposals to accelerate the deployment of innovative technologies. One of these calls, with a volume of 4 billion euros in funding, finances projects in several sectors and is also open to carbon capture applications.[58]

The ETS reform makes a direct reference to carbon capture for the first time by recognizing carbon capture and utilization technologies as eligible technologies, provided they are "environmentally safe" and contribute "substantially to mitigating climate change". Funding instruments of the Innovation Fund can thus also benefit CCU projects in future. With regard to the recognition of CCU for emission avoidance, the reform stipulates that utilized greenhouse gases are not counted as emitted if they are permanently chemically bound in a product and can be expected to never re-enter the atmosphere "under normal use". At the same time, the Commission is requested to carry out an assessment of the accounting methods of greenhouse gas emissions in connection with carbon capture and utilization by July 2026, taking into account the role of emissions in the end-of-life stage of products.

For CCS technologies, it is important to note that emissions in CO_2 transport are recognized not only in the case of pipeline transport, but for all transport technologies (i.e. including ships and trucks). This will ensure the equal treatment of all modes of transport. As a consequence, emissions in CO_2 transport

55 Menner, M. (2022). Trilog-Einigung zu Emissionshandel, „EU-Klimazoll“ und Klimasozialfonds. cepAktuell, Dec 19 2022.

56 European Union (2023a). Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system.

57 European Union (2023b). Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism.

58 European Commission (2023). Innovation Fund announces two upcoming calls for proposals. News Article, Oct 23 2023.

are generally not attributed to the installation which initiates the transport.[59] From the industry's point of view, this reduces the cost burden of carbon capture facilities.

The EU's support for NETs remains very cautious even after the reform. Direct air capture is recognized as an innovative technology worthy of support. However, NETs will not be integrated into emissions trading for the time being. Here too, a mandate is given to the Commission to submit a report by July 2026 on how integration could take place in the long term. At the same time, the legal text makes it clear that the recognition of NETs should not lead to an offsetting of the emissions covered by the ETS, i.e. the obligations of the ETS sectors to reduce emissions must not be reduced as a result.[60]

3.3.2 Carbon capture in the Net Zero Industry Act

The proposal for a Net Zero Industry Act published by the Commission on March 16 2023[61] aims to provide practical impetus for the accelerated development of carbon capture capacities in Europe. Carbon capture and storage technologies are listed as one of a total of eight classes of technologies that are to be classified as strategic net-zero technologies and are subject to special support. An entire separate chapter in the draft (Chapter III) is dedicated to the topic of CO_2 storage. It sets an EU-wide target of an annual injection capacity of at least 50 million tonnes of CO_2 for the year 2030. Extensive reporting obligations are to be imposed on the Member States for monitoring purposes. They are to publish data on areas where CO_2 storage sites can be permitted. In addition, they are to submit annual reports on the development of carbon capture projects in their territory, on their storage requirements and on the CO_2 storage capacities created, as well as on the national support measures implemented to speed up this development. In addition, oil and gas producers will be held particularly accountable. They are to make an individual contribution to the EU-wide storage target, the relative scope of which is based on their individual share of the EU's crude oil and gas production. To this end, they are expected to draw up specific target plans and report annually on the progress made in implementing their storage projects.

CO_2 storage projects on EU territory (for offshore projects: on the continental shelf) that contribute to this goal are recognized as net zero strategic projects, provided they have applied for a permit for CO_2 storage in accordance with the CCS Directive. This gives such projects priority status in the regulatory treatment. This includes a limit of 12 months on the length of approval processes. It also involves additional support from the EU and Member States. They will support the project sponsors in the crowd-in of private investments and provide additional administrative assistance in complying with rules and in increasing public acceptance. In the event of funding gaps, the newly established Net Zero Europe platform will discuss opportunities for additional financial support from private and public sources to close the gaps.

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[59] Borchardt, K.-D. (2023). Carbon Capture Usage and Storage the new driver of the EU Decarbonization Plan? The Oxford Institute for Energy Studies. OIECS Energy Comment.

[60] See European Union (2023a).

[61] European Commission (2023). Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe’s net-zero technology products manufacturing ecosystem (Net Zero Industry Act) (COM(2023) 161 final).

The Industry Committee of the European Parliament is even more ambitious in its position on the Net Zero Industry Act with regard to CO_2 storage.[62] It calls for binding storage targets to be set also for the period after 2030 in order to do justice to the long-term contribution of storage solutions. It wants to extend the scope of application to CO_2 transport in order to address the development of a pipeline infrastructure as an important bottleneck (See Section 2). In addition, fair and open access to CO_2 storage sites is to be guaranteed. The obligations for oil and gas producers are specified by demanding the imposition of penalties in case of non-compliance.[63]

Overall, the Net Zero Industry Act can thus provide a very important impetus for eliminating the storage bottleneck (see Section 2). By setting, for the first time, a legally binding target for CO_2 storage capacities it defines a clear roadmap at the political level and makes the importance of CCS as an indispensable component of climate policy legally clear. The concrete obligations envisaged for oil and gas producers send a clear signal that the EU is serious about building capacity. The extension to CO_2 transport proposed by Parliament may also serve as an impetus for the development of a legal framework for an internal market for captured CO_2. However, its provisions must go well beyond the instruments provided for in the Net Zero Industry Act (see Section 5).

3.3.3 Proposal for a Carbon Removal Certification Framework

As part of its Sustainable Carbon Cycles Initiative (see Section 3.2), the Commission proposed a Regulation in November 2022 to create a legal framework for a harmonized voluntary certification scheme for carbon removals.[64] To this end, quality criteria are defined as requirements for carbon removal projects and rules for the process of verification and certification of removals are laid down. Emissions covered by the EU-ETS are unaffected by this in order to avoid double promotion of industrial carbon capture.

One necessary quality criterion is the quantification of a net carbon removal benefit. This calculation will also include the direct and indirect GHG emissions associated with the implementation of the carbon removal activity. Another criterion is the additionality of a measure: it will go beyond existing legal requirements and be encouraged by the certification. Project operators will also demonstrate that their activity is aimed at the long-term storage of the removed CO_2. Finally, the activities must not have a negative impact on the EU's existing sustainability goals in the climate and environment sector. The methodology used to certify compliance with the criteria is to be defined by the Commission in subsequent delegated acts.

Public criticism of the proposals focused primarily on the vagueness of the formulated quality criteria and the lack of clarity regarding possible uses of the certificates.[65] The European Parliament adopted its position on the proposal on November 20, 2023.[66] Among other points, it calls for a fundamental differentiation of the quality criteria for different activities (carbon farming, carbon storage in products and permanent carbon removals). Transparency is to be increased through additional detailed

[62] European Parliament (2023). MEPs back plans to boost Europe's Net-Zero technology production. Press release Oct 25, 2023.

[63] CATF (2023). Parliament votes on key measures to support the role of carbon capture and storage in industrial decarbonization. Oct 25, 2023.

[64] See European Commission (2022).

[65] Bellona Europa (2023). The CRFC is not yet fit-for-purpose. Policy Brief, March 2023.

[66] European Parliament (2023). Carbon removals: MEPs want EU certification scheme to boost uptake. Press release Oct 24, 2023.

information on storage media and the expected duration of storage, which is to be published in a public register. Carbon stored in products will only be certified as long-term carbon storage if it is either permanently chemically bound or stored for at least five decades, which limits the spectrum of applications to wood products and construction material. Overall, the Parliament's position demonstrates a fundamental skepticism towards CCU and a preference for the long-term geological storage of captured CO_2.

3.3.4 State aid guidelines for carbon capture

In specific guidelines, the Commission has explained the conditions under which it considers national aid to projects in the areas of climate, environmental protection and energy to be compatible with the internal market and the general EU state aid rules.[67] The basic requirements are that the projects encourage economic activities, incentivize an action that brings environmental benefits in line with the Green Deal objectives and do not harm competition and trade. Carbon capture technologies are recognized by the EU as strategically important technologies for the transition to a zero-emission economy. The conditions that define the guidelines for projects in the area of reduction and removal of greenhouse gas emissions are also applicable to these projects. Investment aid for CCS and CCU projects is considered compatible with the internal market by the Commission, provided that a number of specific criteria are met.

The first criterion is the necessity of the aid. The Member State must demonstrate that the support measure is necessary to incentivize the investment against the background of the existing political framework. The criterion of eligibility requires that, in the case of support for projects that only relate to certain types of activities (e.g. only carbon capture with specific utilization of CO_2), the Member State must provide objectively comprehensible reasons why such a restriction is meaningful. The guidelines also provide examples of circumstances in which the Commission does not consider such a restriction to be a distortion of competition. Among those, the potential to make an important and cost-effective contribution to long-term decarbonization could play a role as a relevant circumstance with regard to carbon capture. As a rule, the allocation of aid should take place via a competitive bidding process, which should in principle be open to all eligible beneficiaries. In addition to direct grants, support can also take the form of tax incentives. In this case, no competitive bidding process is required, but such incentives must be granted equally to all suitable actors in the same economic sector.

Another key criterion is the existence of a positive environmental impact. Aid for the decarbonization of industrial activities should lead directly to a reduction in emissions. The reduction effect must also be of a macroeconomic nature, i.e. emissions must not simply be shifted from one sector to another. To create transparency, an estimate of the amount of subsidy per tonne of CO_2 emissions avoided must be provided. The avoided emissions must be recorded on a net basis and from a life cycle perspective. Finally, aid that aims to cover operating costs should only be used if this results in a more environmentally friendly form of operation.

[67] European Commission (2022). Communication from the Commission - Guidelines on State aid for climate, environmental protection and energy 2022. 2022/C 80/01.

3.4 Policy initiatives at country level

Within Europe, Norway, a non-EU country, has been the biggest supporter of carbon capture for some time. Back in 2005, the Norwegian government founded a state-owned company, Gassnova, which is responsible for researching and implementing CCS in the country.[68] CCS received a particular boost in Norway in 2020 thanks to government support for the Longship Project worth EUR 1.6 billion. The aim of the project is to establish a central offshore storage hub in the North Sea. To this end, CO_2 will be transported by ship from major emitters in the North Sea coastal region (and beyond) to a spot on the Norwegian coast, from where it will be piped to an offshore storage facility in the North Sea.[69] In this way, the initiative can also become a magnet for the development of new carbon capture projects within its broad geographical catchment area. The UK government also injected new momentum into international market development in 2020. With the Carbon Capture and Storage Infrastructure Fund (CIF), it launched a new financing mechanism for CO_2 supply chains (primarily the transport and storage parts) worth GBP 1 billion. In addition to traditional investment funding, the fund also serves to set up new revenue schemes for various players in the supply chains. While the operators of the capture systems are funded in the form of CCfDs, a regulated tariff is provided as a source of income for infrastructure operators, similar to the electricity and gas grids.[70]

Within the EU, only the Netherlands, Denmark and Sweden have so far shown comparable determination. In the Netherlands, CCS was added to the list of technologies eligible for funding under the Sustainable Energy Transition Subsidy Scheme in 2020. In this scheme, projects bid in a competitive process for the amount of expected funding per tonne of abated CO_2.[71] The CCS projects financed by this fund are subject to a volume cap of 9.7 million tonnes of CO_2 per year. This allows large-scale projects such as Porthos in the port of Rotterdam and Aramis in the North Sea to be covered. [72] In Denmark, the development of CCS capacities was first enshrined as a goal in the Climate Act of 2020 and a funding pool of EUR 2.14 billion was set up.[73] This was followed in 2021 by an explicit CCS strategy, which aims to drive forward the development of CO_2 storage capacities in the oil and gas extraction fields that will be completely abandoned by 2050. One result of these efforts is a EUR 1.1 billion support scheme that was recently approved by the Commission.[74] Sweden has distinguished itself by being the first country to launch a support scheme for BECCS, and thus for a negative emissions technology. In reverse auctions, BECCS projects bid for the lowest cost at which they can capture and store CO_2 using BECCS technology.[75]

The biggest EU countries have long been rather cautious in their stance towards CCS. In Germany, the EU CCS Directive was only implemented to a very limited extent, with concerns about the environmental and climate risks of CO_2 storage dominating over a protracted period. This changed in 2019, when

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68 Gassnova (2023). Gassnova – Norwegian state enterprise for CCS industrial. Gassnova SF.
69 Northern Lights (2023). About the longship project. Northern Lights JV DA.
70 UK.Gov (2022). The Carbon Capture and Storage Infrastructure Fund: an update on its design (May 2021). Updated 16 December 2022. Policy Paper.
71 DNV (2022). Dutch industrial decarbonization policy effectively supports CCS, but needs further push on low-carbon and green hydrogen to meet climate targets. DNV AS.
72 CATF (2022). A European Strategy for Carbon Capture and Storage. Clean Air Task Force.
73 State of Green (2023). Denmark’s new plan for carbon capture and storage.
74 European Commission (2023). State aid: Commission approves €1.1 billion Danish scheme to support roll-out of carbon capture and storage technologies. Press release, 12 January 2023.
75 IEA (2023a). Support scheme for bio-CCS. International Energy Agency.

the CCS technology was included in the national decarbonization plan.[76] CCS technologies are also included in the CCfD support scheme currently being launched.[77] Furthermore, the German government has announced a national industrial carbon management strategy for the near future. In July 2023, the French government presented a draft national Carbon Capture, Storage and Utilization Strategy.[78] Here, too, CCfDs are to be used as a central support tool for the scale-up of CO_2 supply chains. The government would also like to explore possibilities for the development of CO_2 storage capacities domestically. This could provide a significant impetus for onshore storage in Europe, in addition to the large-scale projects in the North Sea mentioned above. In Italy, the Ravenna hub, a huge CCS project, is currently under development. Starting in 2026, the plan is to create an annual injection capacity of 4 million tonnes of CO_2 in the Adriatic Sea by 2030.[79]

4 The economics of carbon capture

4.1 Literature insights

4.1.1 Investments in industrial CCS deployment

The sharp rise in global momentum in the creation of CCS capacities is reflected in a rapid increase in investment volumes. According to estimates by BloombergNEF, a total of USD 6.4 billion was invested globally in CCS in 2022, which represents an almost three-fold increase compared to the previous year. The stimulus provided by US policy leads analysts to expect further significant increases in the coming years.[80] Nevertheless, a number of economic challenges remain from the perspective of industrial companies.

The first key challenge is the long-term nature of the investment in a carbon capture system. Studies usually assume an economic lifetime in the range of 20-25 years. Not only is there a high initial outlay for setting up the necessary infrastructure, there are also persistently high operating costs in connection with maintenance and energy consumption.[81] This results in a long amortization period for the systems. Against this backdrop, regulatory uncertainty is a major obstacle. Abdulla et al. (2021) undertook an expert-based assessment of the main reasons for success or failure of CCS investment projects in the US in past years. They identified the credibility of project revenues as one crucial factor besides capital costs and technological readiness. Specifically, the credibility of policy incentives, i.e. the stability of the policy design, was identified by the experts as the single most important factor.[82] Strategic changes in climate policy could lead to lock-in effects. In addition, there is uncertainty about the long-term reliability of storage and the resulting cost risks. There is also uncertainty on the revenue side, in

76 Bundesregierung (2022). Integrated National Energy and Climate Plan. Pursuant to the Regulation of the European Parliament and of the Council on the governance of the energy union and climate action.

77 BMWK (2023b). Richtlinie zur Förderung von klimaneutralen Produktionsverfahren in der Industrie durch Klimaschutzverträge. Entwurf (abgerufen 04.04.2023). Bundesministerium für Wirtschaft und Klimaschutz.

78 Davies, C. (2023). France backs CCS. Carbon Capture & Storage Europe.

79 Eni (2023). Ravenna CCS project. eni / snam joint venture.

80 BloombergNEF (2023). Carbon Capture Investment Hits Record High of $6.4 Billion. BloombergNEF Blog. February 15, 2023.

81 Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., ... & Fennell, P. S. (2014). Carbon capture and storage update. Energy & Environmental Science, 7(1), 130-189.

82 Abdulla, A., Hanna, R., Schell, K. R., Babacan, O., & Victor, D. G. (2020). Explaining successful and failed investments in US carbon capture and storage using empirical and expert assessments. Environmental Research Letters, 16(1), 014036.

this case about the long-term development of the CO_2 price. A low price level on the EU-ETS has in the past also contributed to the sluggish progress of CCS expansion in Europe.

Individual technology variants cannot be described as more or less expensive across the board. Costs depend heavily on the fuel source and the conversion processes. At the same time, existing studies point to significant cost differences between carbon capture in various industrial processes. Production processes in which the capture of concentrated CO_2 streams is integrated from the outset have an advantage. This applies, for example, to natural gas processing, ammonia production and bioethanol production. Other emission-intensive industries, whose technologies do not provide for corresponding equipment, are confronted with significantly higher conversion costs.[83] However, as the relevant processes concern the production of basic materials, which typically account for only a small value share in consumer products, consumers are little affected by CCS costs. Emanuelsson and Johnsson (2023) estimate that even with a full cost-pass through to consumers, a complete retrofit of installations in the EU cement, pulp, waste-to-energy and refinery industries with CCS appliances would only cause price increases for end products in a range of 0.3–3.3 %.[84]

The level of transportation and storage costs depends on the geography and structure of the respective economic area. A sufficient number of suitable geological storage sites and the broadest possible spatial distribution of emission sources are decisive factors for short transportation distances and thus low costs in connection with pipeline construction and transportation losses. Regions with a strong industrial base, especially in the oil and gas processing sectors, therefore have an advantage when it comes to building CCS capacities.[85] Storage projects require risky pre-construction investments, particularly for first-mover projects with uncertain demand.[86] A general source of uncertainty in the existing cost estimates are the unknown ecological side effects of long-term storage and the resulting liability risks. In addition to possible CO_2 leakage, these can include the risk of acidification of groundwater and geological instability, depending on the location. In this respect, offshore storage can have a cost advantage due to its greater distance from inhabited areas.[87]

The Clean Air Task Force (CATF) has published estimates of the total costs of implementing CCS (including transport and geological storage) for all current large-scale carbon point sources in the EU. Figure 9 shows an example of the range of estimates by sector for a long-term scenario assuming that existing geological storage potential has been exhausted. The range is considerable in some sectors. However, no option is estimated to cost less than EUR 100 per tonne of captured and stored CO_2. CCS investments would thus not pay-off at the current price level on the EU-ETS. In the medium term, however, analysts expect prices on the EU-ETS to rise significantly, assuming a recovery from the short-term weakness of the EU economy. This is further nourished by the latest ETS reform and its more ambitious target path for reducing the quantity of allowances issued. In a recent forecast, the GMK Center predict that the average price level will rise to EUR 147 per tonne of CO_2 by 2030.[88] This means that the monetary benefit from reduced certificate requirements would for most sectors and

83 Irlam, L. (2017). Global costs of carbon capture and storage. Global CCS institute, 16.

84 Emanuelsson, A. H., & Johnsson, F. (2023). The Cost to Consumers of Carbon Capture and Storage—A Product Value Chain Analysis. Energies, 16(20), 1-23.

85 Martin-Roberts, E., Scott, V., Flude, S., Johnson, G., Haszeldine, R. S., & Gilfillan, S. (2021). Carbon capture and storage at the end of a lost decade. One Earth, 4(11), 1569-1584.

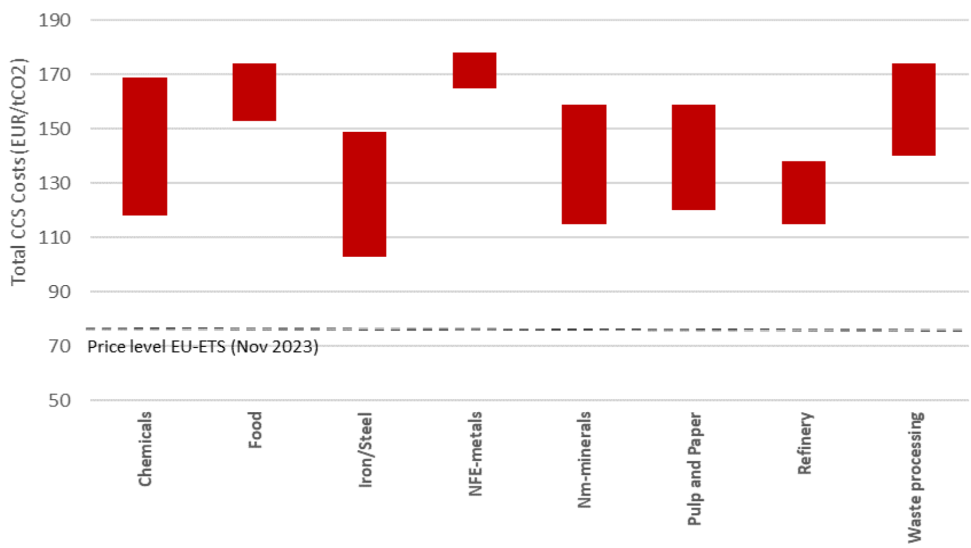
86 CATF (2023). Map of CO2 sources and abatement costs. Clean Air Task Force.

87 Schmelz, W. J., Hochman, G., & Miller, K. G. (2020). Total cost of carbon capture and storage implemented at a regional scale: northeastern and midwestern United States. Interface focus, 10(5), 20190065.

88 GMK Center (2023). Carbon price in EU ETS may achieve €147/t in 2030. October 17, 2023.

installations be of the same magnitude as the costs of CSS implementation in the CATF long-term scenario. Given the long-term nature of the capital commitment, these price forecasts play a decisive role in the individual profitability of CCS investments.

Figure 9: Ranges of CCS costs per tonne of captured CO_2 for German industries



Source: CATF (2023); own Illustration.

For an efficiency assessment of CCS, the cost estimates must be compared with the avoidance costs of technological alternatives with a comparable climate impact. Decarbonization, i.e. the switch to carbon-free energy sources and raw materials, is superior to investment in CSS technologies in some areas, not only in terms of independence from fossil sources, but also from an efficiency perspective. However, not all sectors of the economy in which high CO_2 emissions occur can be completely decarbonized in the near future at an acceptable cost. This applies above all to sectors in which a high level of process emissions is generated, i.e. CO_2 emissions resulting from the processing of raw materials in the production process. This holds true, for example, for the cement industry and waste incineration. As emissions in these sectors are partly inherent to the technology, decarbonization would require a complete restructuring of production processes.

From a welfare perspective, there is no immediate reason to promote industrial carbon capture based on its positive climate impact. Its contribution to emission reductions is already rewarded through the existing emissions trading system, specifically through the reduced need for emissions certificates that investments in new CCS-based production chains or CCS retrofits entail for industrial companies. However, it is not only the price of emission certificates that is vital for investment decisions in CCS systems, but also the future costs and revenues arising from the further utilization of the captured CO_2. These are still governed by a significant degree of uncertainty, both with regard to CO_2-transport (geography and costs of a pipeline infrastructure) and final utilization (availability and costs of geological storage, development of CO_2 feedstock markets). Conversely, with respected to the expected volume of captured CO_2, this concerns the future operators of transportation networks and storage facilities just as well. Since the emergence of liquid markets for captured CO_2 in turn depends on the development of a CO_2 infrastructure, this coordination problem cannot be solved by means of scarcity prices. It thus has the character of a coordination externality comparable to the challenges in the development of European hydrogen supply chains.[89]

One way of dealing with this coordination externality is the simultaneous planning and construction of entire CO_2 supply chains under the umbrella of full chain projects. Such large-scale projects are currently being launched in numerous EU Member States, usually in conjunction with direct state funding (see Subsection 3.4). Such projects are indispensable for the necessary rapid scaling of CCS capacities. However, a one-sided focus of state funding policy on full chain projects also harbors risks. For instance, infrastructure development tailored to the needs of project-internal CO_2 producers and consumers (e.g. size and location of storage sites) can conflict with the idea of establishing an open-source CO_2 infrastructure that is competition-neutral and compatible with the principles of the internal market. In the worst case, it can lead to path dependencies in market formation, which hinders the realization of more cost-effective solutions for CCS supply chains in Europe. The EU is therefore called upon to design more neutral support instruments to mitigate the effect of coordination externalities, including for small and autonomous CCS projects.

4.1.2 Greenfield investments in NETs

Investments in carbon removal capacities differ significantly from industrial CCS in terms of their revenue and cost profiles. In contrast to emissions avoidance, the removal process itself does not yet generate any direct economic returns (e.g. through the sale of surplus emissions certificates). Instead, the revenue potential depends on the market value of the captured CO_2. This can lie in its use as an industrial feedstock or in the certification of long-term storage and the sale of such certificates (carbon removal certificates as a sustainability signal). Both types of markets are currently still in the development phase. Markets for voluntary carbon offsets have experienced significant growth at a global level in recent years. However, due to the lack of uniform global standards, current market platforms are characterized by significant price fluctuations, low transparency and strong fragmentation,[90] which entails high revenue risks.

The costs of carbon removal are highly technology-dependent. The markets focus on two types of technology classes as investment objects: DACCS and BECCS. According to estimates by Bloomberg NEF, global investments in DAC alone amounted to more than USD 1 billion in 2022. As a result of the incentives provided by the US Inflation Reduction Act and the global increase in climate policy ambitions, investment in carbon removal projects is expected to multiply.[91] The extent to which DACCS or BECCS will prevail as the leading technology will be largely determined by the differences in the cost structure. These reveal clear trade-offs.

A key cost advantage of BECCS is that it is based on a combination of already established technologies: the combustion, fermentation or digestion of biomass and the subsequent application of industrial carbon capture technologies. The higher technological readiness compared to DACCS facilitates upscaling and also allows for a more flexible construction of plants depending on the individual sales opportunities for the bioenergy obtained. A further advantage of this set-up is the fact that the

[89] Wolf. A. (2023). A bank to boost renewable hydrogen. cepInput No.13/2023.

[90] Dawes, A., McGeady, C., Majkut, J. (2023). Voluntary carbon markets: A review of global initiatives and evolving models. CSIS Brief. Center for Strategic & International Studies.

[91] Bloomberg NEF (2022). Global Carbon Capture Capacity Due to Rise Sixfold by 2030. Blog Post, October 18 2022.

bioenergy produced provides a second direct source of revenue, which can also be used to diversify CO_2 market price risks. In direct terms, BECCS plants are therefore net energy suppliers and their activities help to reduce the scarcity problem for renewable energies. However, if the energy expenditure for cultivation and harvesting of the biomass is included, this advantage is reduced.[92] There are also limits to this form of climate technology in terms of the capacity of suitable land. When bioenergy is obtained from food and fodder crops, there is also competition for land with the food sector. Currently, around 20 % of bioenergy in Europe (in energy units) is obtained from agricultural sources. The industry association expects this proportion to increase significantly in the future in connection with the growth of the bioenergy market.[93] This can result in new economic dependencies. Simulations show that a significant build-up of BECSS capacities can lead to strong price correlations between carbon and agricultural markets. A long-term rise in the price of CO_2 can thus be reflected in rising food prices.[94] For an appropriate assessment of the climate impact, greenhouse gas emissions from the production of biomass that are not recorded in the EU-ETS should also be taken into account (as far as measurable), for example in connection with fertilizer use (N_2O emissions) or the long-term carbon footprint of direct or indirect land use changes. This in turn increases the costs of carbon accounting and monitoring. Moreover, biogenic carbon compounds cannot (yet) replace fossil fuels in all industrial applications.

Like BECCS, DACCS can lead to genuine negative emissions, but avoids the food competition resulting from the use of biomass. Land consumption is also significantly lower with comparable capacity. The CO_2 net-balance of the process is much easier to measure, as there is no need to account for a variety of agricultural carbon sources and sinks in the calculations. However, the lower level of maturity compared to other capture technologies still stands in the way of a rapid roll-out.[95] This applies first and foremost to the high energy consumption, a consequence of the low concentration of CO_2 in the atmosphere. It not only affects the economic viability of the technology, but also potentially has a massive impact on its carbon footprint, depending on the electricity mix.[96] In addition to the high direct energy requirement for filtering and concentrating CO_2, the availability of sorbents also poses a problem of scarcity in the long term. They are produced at a high energy intensity and have so far been partly obtained as by-products. A strong increase in demand triggered by DAC could change this role and thus lead to market disruptions and a further surge in energy use for such chemicals.[97] At the same time, however, the comparatively low maturity of DAC technologies offers the prospect of particularly strong learning curve effects to reduce input intensities in the future.[98]

From a welfare perspective, these specific features results in additional sources of market failure for NETs compared to industrial CCS. In addition to coordination externalities, this includes the positive climate externality that results from permanent carbon removal. Unlike emissions avoidance through industrial CCS, this externality is not already internalized via the EU-ETS. A future growing market for carbon removal certificates could provide such internalization. However, this will depend heavily on

[92] Creutzig, F., Breyer, C., Hilaire, J., Minx, J., Peters, G. P., & Socolow, R. (2019). The mutual dependence of negative emission technologies and energy systems. Energy & Environmental Science, 12(6), 1805-1817.

[93] Bioenergy Europe (2021). Bioenergy Europe Statistical Report 2021 Biomass Supply.

[94] Muratori, M., Calvin, K., Wise, M., Kyle, P., & Edmonds, J. (2016). Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). Environmental Research Letters, 11(9), 095004.

[95] Breyer, C., Fasihi, M., Bajamundi, C., & Creutzig, F. (2019). Direct air capture of CO2: a key technology for ambitious climate change mitigation. Joule, 3(9), 2053-2057.

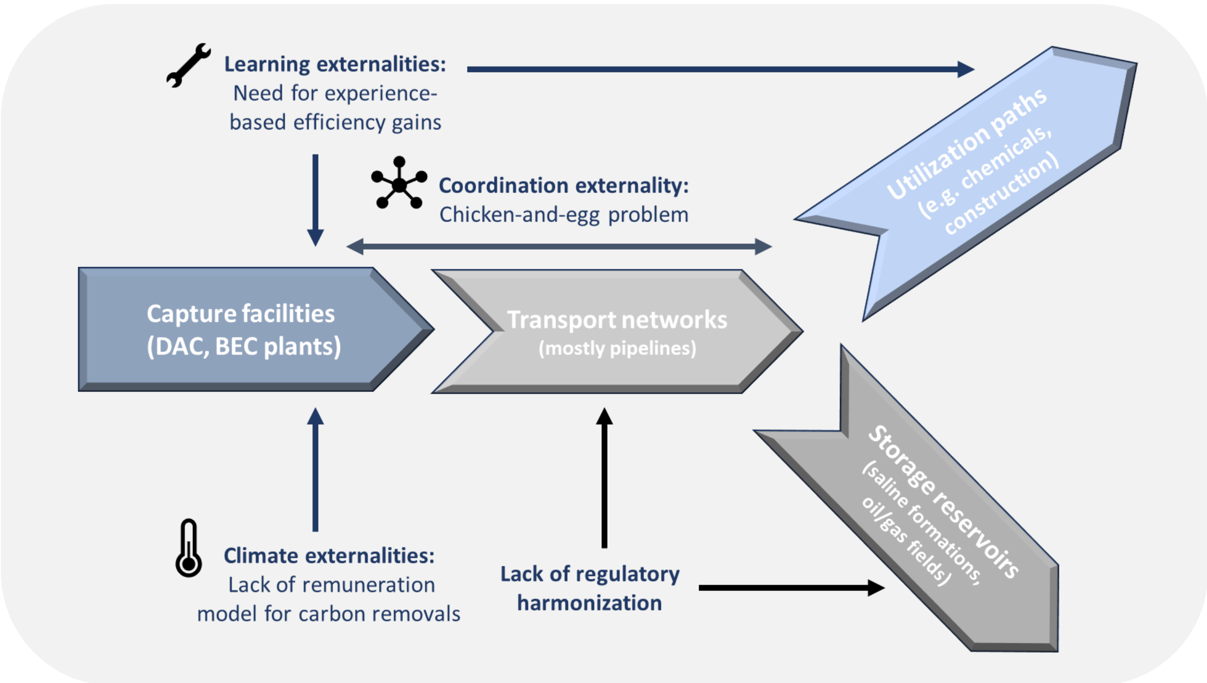
[96] Terlouw, T., Treyer, K., Bauer, C., & Mazzotti, M. (2021). Life cycle assessment of direct air carbon capture and storage with low-carbon energy sources. Environmental Science & Technology, 55(16), 11397-11411.

[97] See Realmonte et al. (2019).

[98] Lackner, K. S., & Azarabadi, H. (2021). Buying down the cost of direct air capture. Industrial & engineering chemistry research, 60(22), 8196-8208.

very uncertain parameters such as the development of demand and the willingness to pay for the corresponding certificates. The possession of carbon removal certificates only represents a value for companies if they can use them as a positive signal to their customers or partners in the supply chain. A sufficient market volume will thus only be achieved if consumers have strong sustainability preferences and trust in the reliability of NET technologies. Finally, the learning effects that result from the increasing operation of NET facilities also represent a form of externality. This is because investors in individual facilities do not consider the positive knowledge effects of their accumulation of operating experience for the industry as a whole, unless they result in private income streams (patenting revenues etc.). This is particularly relevant for DAC technologies, given their potential of large learning curve effects. In the following, we will illustrate the significance of this effect by means of a case study.

Figure 10: Inefficiencies in the development of CO_2 supply chains



Source: own representation

4.2 Case study: policy support for Direct Air Capture

4.2.1 Cost structure

As a young technology, DAC is currently still very cost-intensive. This applies to both capital costs and operating expenses. However, the structure of the costs differs depending on the specific processes. At the top level, it is important to distinguish between processes with liquid and processes with solid sorbents (see Subsection 2.3.2). Due to their different heat requirements, the former are also referred to as high-temperature processes and the latter as low-temperature processes. High-temperature processes exhibit a higher technological maturity. Typical capital costs are estimated to be lower than for low-temperature processes.[99] The main components include the costs of the air contactor (attraction of air and bonding of CO_2) and the calciner (CO_2 purification and gas release), in addition to other parts of the equipment. Due to the high heat requirements of the calciner (900 degrees Celsius), operating

[99] See Ozkan et al. (2022).

costs in the form of energy costs are also particularly high. In addition to the heat for the calciner, significant amounts of electrical energy are required for the air contactor and for CO_2 dehydration and compression.[100]

Besides energy intensity, the choice of the energy source is crucial for the net CO_2 balance of the process, and therefore also for the costs per net tonne of CO_2 stored. The market pioneer *Carbon Engineering* in North America uses electricity from renewable sources and natural gas as a heat source for its DAC plants.[101] Alternatively, the energy requirement could also be met entirely from renewable sources in the future. The use of electricity-powered electrode boilers and, in the future, renewable hydrogen are already being investigated as alternatives in the literature.[102] Particularly in the case of a complete electrification (electrode boilers as heat source), significant differences in costs are to be expected in a spatial comparison, depending on the regional availability of renewable energy sources (see our analysis below).

For low-temperature processes, available data is considered less reliable, due to the earlier stage of development. The largest cost item in the equipment is the solid sorbent. In principle, a wide range of basic materials can be used, roughly divided into physical, chemical and physicochemical mixed sorbents.[103] Estimates of the cost contribution per tonne of CO_2 vary widely, depending on the substance and scientific source. On average, however, significantly higher capital costs are assumed than for high-temperature processes. At the same time, however, the lower heat requirements result in lower energy costs than with high-temperature processes. Under certain conditions, the use of waste heat as a heat source for CO_2 extraction is sufficient.[104] Direct external energy requirements arise mainly in the form of electricity for the fans and for CO_2 compression/dehydration.

From a static perspective, the cost-minimizing choice of technology is therefore essentially a trade-off between capital costs and operating costs. As today's choice of technology determines the potential for future learning effects, this trade-off has a decisive influence on future cost reduction paths. The expected capacity utilization rates and the individual costs of the energy sources are decisive parameters. In the following, we first provide an overview of the cost conditions of the technologies in the EU. To this end, we combine current literature estimates on investment needs, fixed operating costs and energy intensities with sources on the regional distribution of renewable energy costs in the EU. Specifically, we assume a scenario in which both direct electricity demand and heat demand of the DAC plants are completely covered by the purchase of regionally generated electricity from additional renewable sources, as also investigated by Fasihi et al. (2019)[105] and Lux et al. (2023)[106], among others. Such a scenario promises the best congruence of DAC with the general objectives of EU climate policy. It maximizes the net yield of captured CO_2 for a given gross capacity while reflecting the scarcity and competitive situation in the use of renewable energies, comparable with the EU requirements for

[100] Kiani, A., Jiang, K., & Feron, P. (2020). Techno-economic assessment for CO2 capture from air using a conventional liquid-based absorption process. Frontiers in Energy Research, 8, 92.

[101] Carbon Engineering (2023). Our technology.

[102] See Abdulla et al. (2020).

[103] Leonzio, G., Fennell, P. S., & Shah, N. (2022). A comparative study of different sorbents in the context of direct air capture (DAC): evaluation of key performance indicators and comparisons. Applied Sciences, 12(5), 2618.

[104] See Abdulla et al. (2020).

[105] Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. Journal of cleaner production, 224, 957-980.

[106] Lux, B., Schneck, N., Pfluger, B., Männer, W., & Sensfuß, F. (2023). Potentials of direct air capture and storage in a greenhouse gas-neutral European energy system. Energy Strategy Reviews, 45, 101012.

renewable hydrogen.[107] As a spatial resolution, we consider the level of the EU NUTS-2 regions, for which estimates of the regional electricity yield from PV and wind power are available.[108]

Table 1: Overview on parameter choices for our DAC cost estimations

Parameter	Value	Source
General		
Discount rate	8 %	Kiani et al. (2020)
Exchange rate USD/EUR	1.08 USD/EUR	Average 2022
Electricity sources		
PV plants: lifetime	25 years	IRENA (2022)
PV plants: CAPEX	697,000 EUR/MW	IRENA (2022)
PV plants: OPEX (O&M)	15,000 EUR/MW/year	IRENA (2022)
PV plants: capacity factors	region-specific	JRC (2023a)
Wind power plants (onshore): lifetime	25 years	IRENA (2022)
Wind power plants (onshore): CAPEX	1,425,000 EUR/MW	IRENA (2022)
Wind power plants (onshore): OPEX (O&M)	31,000 EUR/MW/year	IRENA (2022)
Wind power plants (onshore): capacity factors	region-specific	JRC (2023b)
DAC (high-temperature (HT) + low-temperature (LT))		
HT process: lifetime plant	20 years	Kiani et al. (2020)
HT process: investment expenditures	592 – 769 USD/tCO_2	Abdulla et al. (2020)
HT process: fixed OPEX (labour & maintenance)	28.3 – 37.3 USD/tCO2/year	Abdulla et al. (2020)
HT process: electricity intensity	6.6 – 9.9 GJ/tCO_2	Ozkan et al. (2022)
LT process: lifetime plant	20 years	Kiani et al. (2020)
LT process: investment expenditures	812 – 2,170 USD/tCO_2	Abdulla et al. (2020)
LT process: fixed OPEX (labour & maintenance)	11.9 – 23.3 USD/tCO2/year	Abdulla et al. (2020)
LT process: electricity intensity	3.5 – 6.6 GJ/tCO2	Ozkan et al. (2022)
CO_2 transport and storage		
Costs pipeline transport	region-specific	CATF (2023)
Costs geological storage	region-specific	CATF (2023)

Source: own representation

Table 1 summarizes our data sources. We utilize capacity factors from the EU *ENSPRESO* database as a source for the regional electricity generation potential. They indicate the average expected annual yield per MW of installed PV[109] and wind power[110] capacity in the respective regions. By combining these with estimates of capital and fixed operating costs per MW by IRENA (2022)[111], as well as with figures on electricity intensities from the DAC literature, we can estimate the average regional energy costs per tonne of captured CO_2. In doing so, we assume producers in the specific regions to choose the less costly of the two considered renewable energy sources. For the other cost components in the

107 See Wolf (2023).

108 Given the pioneering role of Norway for general CCS uptake in Europe, a consideration of Norwegian NUTS-regions would have been desirable. However, neither regional cost estimates for wind nor for hydropower as the dominant local renewable source are available for Norwegian NUTS regions.

109 JRC (2023a). ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. ENSPRESO - SOLAR - PV and CSP dataset. Joint Research Centre of the European Union.

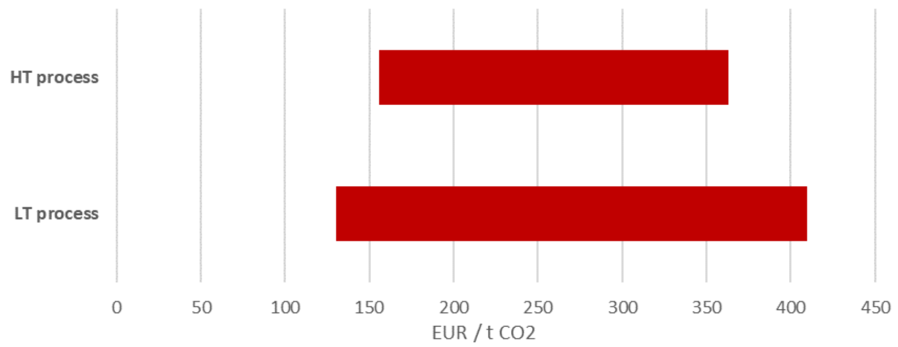
110 JRC (2023b). ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. ENSPRESO – Wind-onshore and offshore dataset. Joint Research Centre of the European Union.

111 IRENA (2022). Renewable Power Generation Costs in 2021. Abu Dhabi: International Renewable Energy Agency.

capture process, we do not differentiate between regions but assume homogeneous pricing on supra-regional markets for DAC equipment and sorbents.

Figure 11 compares the range of our regional cost estimates for the two technology variants under consideration. There is a large overlap between the technologies, with greater overall uncertainty for the low-temperature technology. As this higher uncertainty also concerns future cost paths[112], we restrict our case study in the following to the more mature high-temperature technology. Figure A1 in the Appendix depicts the spatial pattern of capture costs for the high-temperature process, using average values for capital costs and fixed operating costs. It shows a wide range of region-specific costs, ranging from EUR 180 to over EUR 300 per tonne of captured CO_2. As to be expected, comparative cost advantages are evident for coastal regions with high potential for local power generation from wind plants.

Figure 11: Simulated cost ranges for HT- and LT-DAC technologies in the EU



Source: own representation

Focusing exclusively on the costs of the capture process is insufficient for the presentation of regional competitive advantages in DAC. Regional differences in utilization options of the captured CO_2 will be relevant as well. Utilization via sale (or own use) as industrial feedstock (see Subsection 2.3.4) represents a promising avenue both from a climate and an economic perspective. It creates a direct source of revenue for DAC operators. However, the extent and regional distribution of future sales potential cannot be reasonably estimated at present, as they depend on a large number of supply chain decisions in the basic industries concerned. In any case, in order to guarantee a significant long-term climate impact, the permanent geological storage of considerable quantities of captured CO_2 will be indispensable.[113] In our setup, we therefore consider transportation to a geological CO_2 storage facility as the dedicated downstream activity.

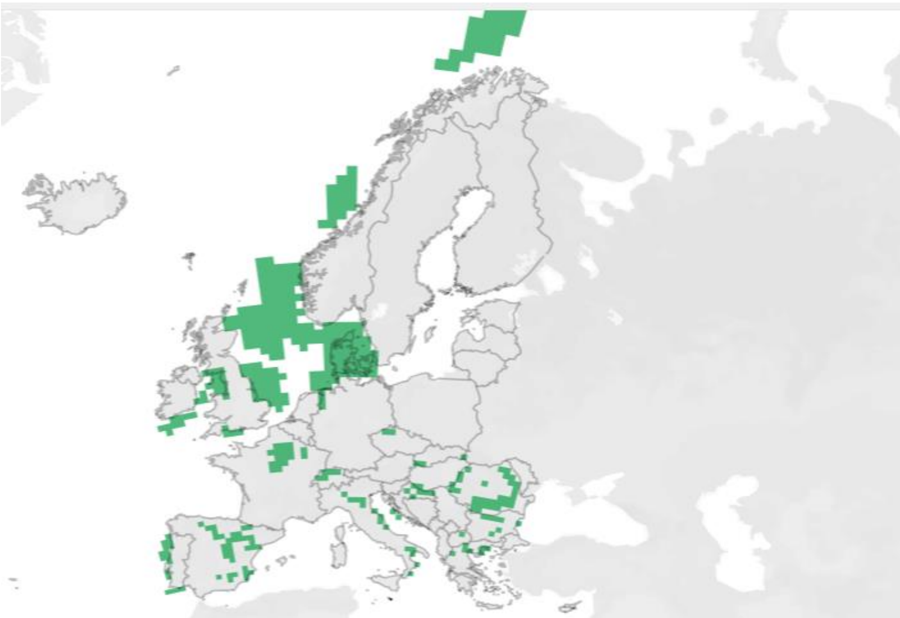
Data on the expected development of geological CO_2 storage in the coming years is currently still subject to great uncertainty for Europe, primarily due to the unresolved regulatory issues at EU level and in the Member States (see Section 3). For our analysis, we assume a storage expansion in Europe based on the distribution of actual geological potential. To this end, we draw on data from the *Clean Air Task Force (CATF)*, which has commissioned the firm *Carbon Limits* to simulate an optimal long-term storage and pipeline infrastructure for Europe based on existing findings on the spatial distribution of

[112] See Ozkan et al. (2022).

[113] CATF (2022). The gap between carbon storage development and capture demand. Clean Air Task Force.

theoretically achievable storage capacities.[114] Figure 12 shows the storage locations assumed for this purpose. From this, spatially differentiated estimates of the level of transport and storage costs per tonne of CO_2 were derived and made publicly available by CATF in a mapping tool (heatmap).[115] We assigned the estimated values to the individual NUTS-2 regions on the basis of the official spatial boundaries.[116] We use the long-term scenario for our purposes, taking new pipelines into account. As a conservative estimate, we apply the provided high estimates in all cases.

Figure 12: Pattern of storage sites underlying the CATF transport and storage cost estimates



Source: CATF (2023). Green areas: considered storage sites.

Figure A2 in the Appendix shows the estimates of the current total costs of a DACCS system (capture, transport and storage) per tonne of CO_2 based on high-temperature technology in the NUTS-2 regions. This magnitude is broadly in line with recent global literature estimates.[117] It is only slightly higher than the costs of the capture part. Compared to regional differences in pure capture costs (see Figure A1), there are also only minor shifts in the spatial pattern. This underlines the crucial importance of capture technology and its energy requirements for future DAC deployment in Europe. Overall, a major conclusion is that DAC would not be profitable in any region, neither at prices for carbon offset certificates comparable to those currently paid for emission certificates in the EU[118], nor at ETS price levels expected for the near-term future (see Subsection 4.1.1). This provides the motivation for a targeted support policy to internalize learning externalities to be expected for the future.

4.2.2 Policy analysis

A comparison of our simulations of current DAC costs with existing cost estimates for industrial CCS (see Subsection 4.1.1) suggests that CO_2 obtained from DAC is unlikely to be competitive on CO_2 feedstock markets with industrially captured CO_2 without further financial support. Our welfare analysis

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114 Information on estimation methods is provided by CATF in a documentation.

115 https://www.catf.us/2023/02/mapping-cost-carbon-capture-storage-europe/

116 In those cases where a NUTS-2-region stretches across more than one cost area, the lower cost level was assigned, reflecting cost-minimizing intra-regional location decisions.

117 See Fasihi et al. (2019).

118 EMBER (2023). Carbon price tracker.

above has stressed the societal dimension of this problem. A carbon removal technology with particularly high long-term mitigation potential would not have the chance to establish itself in the foreseeable future. This would also leave potential for future cost-cutting learning effects untapped, which will be crucial for reaching a cost-minimizing path towards climate neutrality.

Against this background, we examine the impact of a support instrument that directly addresses the current cost disadvantage: a state-guaranteed (inflation-adjusted) price for CO_2 captured through DAC. This can take the form of a legally fixed minimum price or two-sided CCfDs. By now, a specific NET support like this only exists in one Member State, which is Sweden, in the form of a support scheme for BECCS (see Subsection 3.4). To be effective, such a guaranteed carbon price must be set well above the current price level in the EU-ETS. In this way, it ensures that the long-term climate effect of a timely build-up of carbon removal capacities is explicitly rewarded, in contrast to industrial CCS, which merely supplements current fossil production structures. The question of the appropriate level of such a carbon price depends largely on expectations about the extent of future productivity increases, the quantitative restrictions on capacity expansion and the burden on state budgets. We examine these factors below in the form of a scenario analysis.

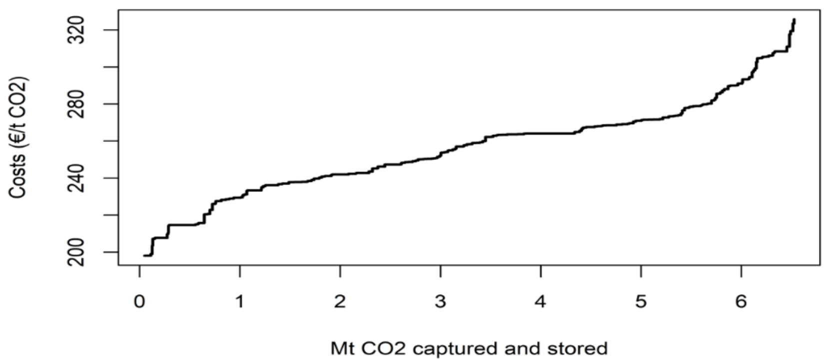
A central and frequently applied parameter to illustrate the expected extent of future cost-relevant learning effects for young technologies is the learning rate. It indicates the percentage cost reduction that can be expected if the cumulative volume of production doubles. This is based on the notion of a cost curve that is convex over time: The gain in experience leads to relatively strong cost reductions in the initial build-up phase. As maturity increases, the scope for further cost reductions becomes smaller and smaller. The actual level of the learning rate is uncertain. In the literature, a value of 10 - 15 % is commonly assumed for DACCS. Fasihi et al. (2019) consider the choice of a value of 10 % to be a conservative approach. We adopt this value for our benchmark simulations and analyze the impact of this choice later on.

To calculate the resulting cost reductions, information on the expected period-specific quantities of CO_2 captured by DACCS is required as well. According to our analysis of cost structures above, two types of volume restrictions are of potentially high relevance: limits on the availability of renewable energy and the capacity limits of CO_2 storage facilities. The former restriction could play a prominent role in the long term, when the EU's land potential for wind and solar power reaches its limits due to continuous progress in electrification of production activities. The capacity limits of CO_2 storage, on the other hand, are likely to take effect already in the initial phase, given the current gap that can be observed between capture and storage projects (see Section 2). In the following, we treat the level of annual injection capacities of CO_2 storages in the EEA (i.e., including the important European players Norway and Iceland) as a technical quantity restriction for DACC capacities and compare the effects of different potential growth rates for the total EEA injection capacity.

The resulting quantity restrictions at the regional level (in our analysis: NUTS-2 level) depend on the access options for DAC projects in different regions to the EU-wide storage capacities. The future mechanisms for the storage allocation of CO_2 from different sources and for the pricing of storage services are currently still unclear. For the sake of simplicity, we assume that (1) the practical allocation follows the principles of completely non-discriminatory access as prescribed by the CCS Directive and (2) the expansion of storage capacities occurs in a spatially homogeneous manner, based on the potential storage sites underlying the CATF transport and storage cost estimates (see Figure 12 in Subsection 4.1.1). Under these conditions, DAC projects at all locations receive equal access to the nearest storage facilities at the location-specific costs (CATF estimates). The shares of the EU-wide annual injection capacities attributable to individual NUTS-2 regions - and thus the maximum regional DACCS capacities - are then simply derived from the relative area sizes (in km^2) of the NUTS-2 regions.

Combined with the estimates of the levelized costs of DACCS from Subsection 4.1.1, this results in period-specific cost-volume combinations for each NUTS-2 region, which can be aggregated to an EEA-wide supply curve for DACCS. In analogy to the terminology used for electricity wholesale markets, one could speak of a merit order of DACCS supply across regions. Figure 13 shows such an estimated merit order curve across all NUTS-2 regions, based on the cost estimates from Figure A2 and the expected EEA storage capacities for 2025 from the IEA CCS Database.

Figure 13: Estimated initial supply curve of DACCS in the EU27



Source. own representation

Such supply curves provide information on the extent of DACCS investments associated with different expectations for long-term CO_2 price levels. In the following, we use this concept to estimate the investment impulse from guaranteeing a time-fixed CO_2 price to DAC-facilities. Starting in 2025, we carry out annual simulations over the following 16 years. In each year, the levelized costs decrease proportionally across regions as a result of the increase in industry-wide experience. The extent of the period-specific cost reduction is determined via a learning curve featuring a learning rate of 10 % (see above). We implicitly assume a free flow of knowledge gains within the EEA and full utilization of the created regional DACCS capacities. Moreover, we assume an exogenous increase in EEA storage capacities in each period.[119] To reflect the significant uncertainty about the level of current capital costs and fixed operating costs (see Subsection 4.1.1), we treat the initial values of these parameters as random variables and determine these by means of a Monte Carlo simulation.[120] On this basis, we obtain for each CO_2 price level a bundle of conceivable time paths for the development of DACCS capacities in the EEA.

Figure 14 depicts the spectrum of DAC capacity paths obtained for CO_2 prices in the range of EUR/t 180 - 210, assuming a linear growth of storage capacities in line with the medium-term EU goals.[121] It

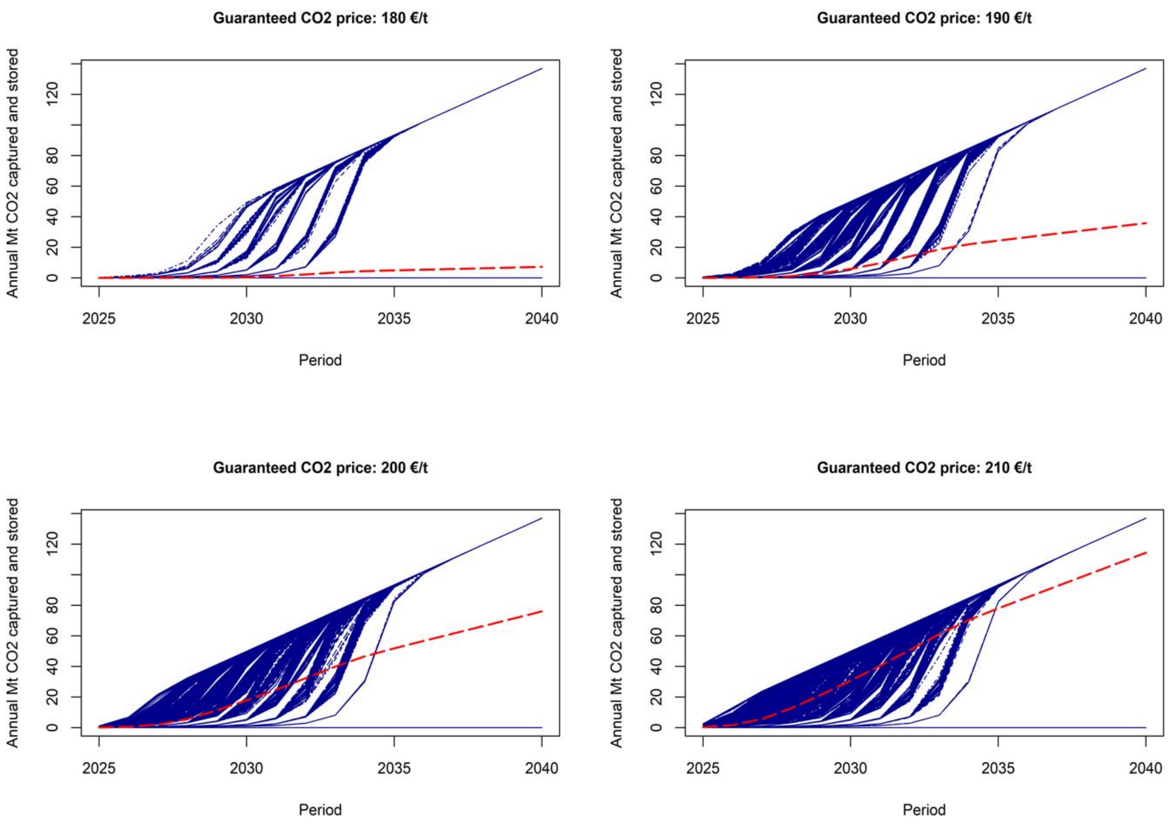
[119] The period-specific supply curves thus shift downwards over time (lower unit costs) and simultaneously become broader.

[120] We assume uniform distributions for capital costs, fixed operation costs as well as the electricity intensity, with maximum and minimum values reflecting the ranges presented in Table 1 (see Subsection 4.2.1). In each draw, numbers are chosen stochastically from these distributions and combined to an initial DAC unit cost. The total number of draws is equal to 10,000. Thus, we create a total of 10,000 potential paths for DAC capacity expansion, differing by the level of initial costs.

[121] The IEA CCUS Database currently predicts for the starting year 2025 a CO_2 storage capacity of 6,525,000 t in the EEA (excluding full chain projects). Starting from this value, we assume a linear growth of storage capacities such that the EU goal of 50,000,000 t capacity in 2030 (see Subsection 3.3.2) is exactly matched. This linear path is assumed to continue for the time after 2030. Given the likely boost to storage investments by future public promotion, this can be understood as a quite conservative assumption for the longer term.

documents a high dynamic sensitivity of the exact CO_2 price level offered to investors through support schemes. At a price of EUR 180 per tonne CO_2, the realization of initial DAC costs at the very low end of the cost spectrum reported by the literature would imply an early uptake of DAC technology. This, in turn, would enable learning effects that unleash dynamic capacity growth through cost reductions, implying that total DAC capacities soon reach the technical maximum path (as determined by the storage restrictions). However, with initial DAC costs at a higher level within the spectrum conceivable, EUR/t 180 are too low to stimulate any DAC investments in the EU, implying that learning effects would not be realized and a technology uptake will not occur. In our Monte Carlo Simulations, this concerns 94 % of all draws obtained at this price level. As a consequence, the estimated average annual capacity for 2040 only amounts to 7.8 Mt CO_2. For the other price levels reported, such a scenario is likewise not precluded, but it is becoming increasingly unlikely with higher guaranteed prices. At a price of EUR/t 210, the technical maximum path is in the majority of all cases reached already before 2030. The no-uptake scenario merely occurs in 16 % of all draws, the estimated average annual capacity equals already 3.1 Mt for 2030 and 114.4 Mt CO_2 for 2040. In cumulated terms, this would result in an average CO_2 capture potential through DAC in a magnitude of 900 Mt CO_2 over the period 2025-2040 (see Figure A3 in the Appendix), i.e., about a quarter of the total annual greenhouse gas emissions (in CO_2 equivalents) of the EU27 in 2022.[122] Given that likely cross-cutting impulses on storage investments are not considered in these micro-simulations (see discussion below), this value should be interpreted as a rather conservative estimate.

Figure 14: Simulated paths of DAC capacity growth for different levels of guaranteed CO_2 prices



Source. own representation. Blue lines: results of single draws (n=10,000), red dots: expected values.

[122] Eurostat (2023). Greenhouse gas emission statistics - air emissions accounts.

The discrepancies in capacity growth are mirrored by the extent of learning effects and resource use. The CO_2 price level of EUR/t 210 is simulated to cause an average cost reduction for DAC of 30 % by 2030 compared to today. At EUR/t 180, due to the low likelihood of any DAC uptake, the expected cost reduction induced only amounts to 1 % by 2030. A major component of resource use is electricity consumption. At EUR/t 210, direct electricity use for DAC in the EU27 (i.e. including compression for transport, but excluding transport itself, storage and production of DAC intermediates) is simulated to reach an average level of 10.0 TWh in 2030. Reaching the maximum capacity path would entail an annual consumption level of 62.7 TWh in 2040. When viewed in relation to current estimates of the overall technical potential for wind, solar PV and hydropower electricity in the EU27 (more than 10,000 TWh per year)[123], this does not appear to be an impressive number. However, as the period of technology uptake will simultaneously witness strong electrification trends in many sectors of the European economy, this would add further pressure on capacity expansion and efficiency improvements in the field of renewables. Moreover, as stressed in the previous subsection, availability of materials, especially sorbents, could become a limiting factor for DAC in the longer term as well.

The level of public expenditures associated with the CO_2 price guarantees are more difficult to gauge, as it directly depends on the future evolution of prices at the EU-ETS. Qualitatively, the strong CO_2 price sensitivity of investments implies that already small adjustments to price support in the spectrum considered can have drastic consequences for overall support volumes. This fact further stresses the benefits of two-sided carbon contracts (CCfDs) as a tool to avoid an over-subsidization in intertemporal terms. A successful stimulus of investments causing high state expenditures in the short-term is then met by correspondingly large repayments in the longer term, when ETS prices have exceeded the level of contractually agreed CO_2 prices. Given the current uncertainty about actual DAC costs, CCfDs thus also act as a partial shield for taxpayers against the risk of overestimating the fiscal stimulus needed for immature climate technologies to prosper. This risk can be further reduced by integrating dynamic components in such a contract, e.g. automatic adjustments of the (real) carbon price over time based on expected or realized average cost reductions. However, the distributive impacts of such dynamic adjustments must be carefully weighed against the risk of nourishing a wait-and-see attitude on the side of investors.

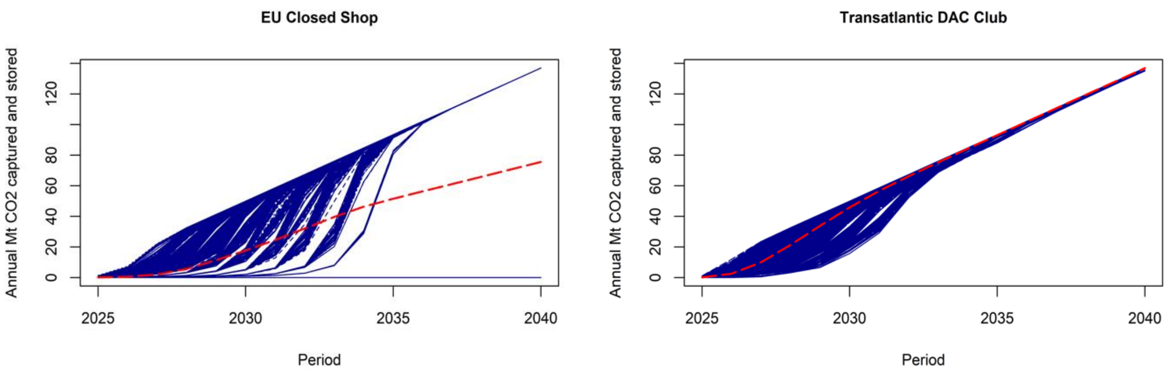
A sensitive factor in every future-oriented technoeconomic simulation is the size of the expected learning rate. Figure A4 in the Appendix highlights this aspect by comparing outcomes for alternative learning rates within the spectrum to be found in the literature. Current uncertainty on learning further adds to the risks for both investors and public budgets. Besides the impact of own learning, another relevant factor is the extent of potential spatial knowledge spillovers. In our simulations, we so far only covered learning from the accumulation of EU-internal experience. In reality, the fate of a European DAC sector will also depend on its ability to access technology improvements resulting from learning elsewhere in the world. This will be even more important given the ambitious global plans for CCS uptake, especially in North America and the UK (see Subsection 2.1). In the following, we illustrate this point briefly by comparing our previous “EU Closed Shop” scenario with an alternative scenario “Transatlantic DAC Club”. In the latter scenario, cost reductions are not just the outcome of EU-internal experience, but the sum of DAC volumes in the EU27, UK, US and Canada over time. This is supposed to reflect the impact of a continuous knowledge exchange on DAC technologies between these countries.

[123] Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., & Jäger-Waldau, A. (2021). Green hydrogen in Europe–A regional assessment: Substituting existing production with electrolysis powered by renewables. Energy Conversion and Management, 228, 113649.

For DAC capacity growth in the UK, US and Canada, an exogenous and linear growth path is assumed. Its slope is determined based on capacity plans for already announced DAC projects according to the IEA CCUS Database. Hence, it represents a conservative estimate of long-term capacity growth in these countries.

Figure 15 compares the simulated time paths for these scenarios, at an exemplary guaranteed CO_2 price of EUR/t 200 and a general learning rate of 10 %. A key feature of the “Transatlantic DAC Club” scenario is that the risk of a no-uptake of DAC in the EU disappears from the spectrum of potential paths. That is, even with initial costs at the highest end of the distribution, the EU27 DAC capacities will sooner or later reach a growth phase that will finally guide them to full utilization of storage potential. As a consequence, average capacity estimates converge to the technical maximum and are thus way higher than in the “EU Closed Shop” scenario in the longer term. The reason for this is the presence of knowledge spillovers from experience-based learning by club partners, which allows the EU to benefit from cost reductions even with low own initial capacities. Faster cost reductions also imply lower long-term support needs. Hence, the efforts of institutionalizing such a DAC partnership are likely to pay off also in fiscal terms over the course of time.

Figure 15: Comparison of DAC capacity growth with and without transatlantic knowledge spillovers



Source. own representation. Blue lines: results of single draws (n=10,000), red dots: expected values.

Finally, it is important to stress that our simulation results are the outcome of an intentionally restricted micro-perspective on DAC. This could in some aspects overestimate future capacity potential, for instance, regarding long-term restrictions on the availability of sorbents and electricity from renewables for the DAC process. In more fundamental aspects, however, it could represent an underestimation. Foremost, the growth of CO_2 transport and storage capacities in Europe will not occur in an independent fashion, but with increasing importance of DAC be directly (DACCS full chain projects) or indirectly (storage pricing) stimulated by the path of DAC uptake. Given the current absence of more detailed and site-specific data on cost structures of CO_2 storage, the analysis of this interaction will remain a task for future research. Moreover, with increasing capacity build-up, DAC capacities in Europe are likely to become subject of a spatial agglomeration process, with a few big facilities centred in strategic points with particularly favourable access to both storage sites and renewable energy supply. The perspectives for such a specialization can only be analysed in an economy-wide projection framework, taking regional industrial restructuring (industrial CCS) and the local needs for investments into electricity transmission capacities into account. At last, future efficiency improvements in PV and wind power will likewise be vital for DAC uptake by reducing electricity costs, thus creating a positive interplay between learning effects in electricity generation and carbon capture.

5 Requirements for a future support framework

Based on our preceding analysis, we propose five key points of action necessary to ensure that CCS in the EU can exploit its climate change mitigation potential.

1. **Agreement on a transparent and differentiated certification scheme for carbon removals**

   The current EU legislative proposal to develop a voluntary certification scheme for carbon removals should be adopted as soon as possible. At the same time, development of the technical certification methodology should also be driven forward. This would allow the EU to take on a global pioneering role and provide an important impetus for the development of transparent international carbon markets. The trilogue negotiations should take up the Parliament's demands for more transparency and a clear differentiation of technologies based on differences in the permanence of storage. In particular, the certification of carbon farming practices should clearly and transparently differentiate them from more easily controllable methods of carbon removals such as industrial capture and DAC with subsequent geological storage, both with respect to the uncertainty of net CO_2 balances and the expected time windows of storage. A regular future updating of monitoring obligations in the certification requirements, on the basis of scientific progress, is essential. It should also be possible to certify carbon removal activities outside the EU on the basis of the same rules and information requirements, in order to strengthen the role of the EU as a global standard setter.

2. **Formulation of EU long-term targets for carbon removals**

   Like the long-term targets in the area of emissions reduction, the EU should also define legally binding targets (in tonnes of permanently removed CO_2) for the medium-term expansion of carbon removal activities in the EU. These should be derived from feasibility studies that are congruent with the definitions for permanent carbon removals set out in the Carbon Removal Certification Scheme and the targets for CO_2 storage capacities contained in the Net Zero Industry Act (see Subsection 3.3.2). If possible, they should be formulated as staged targets and thus serve as a benchmark and indicator of success for the promotion of NETs in the EU. In order to maintain the fundamental difference between emissions avoidance and carbon removals in the climate change mitigation strategy, carbon removals should be regarded as an autonomous component of the EU Green Deal strategy rather than being mixed up with the emissions targets. In view of the very heterogeneous siting conditions for CCS in Europe, Member States should not be obliged to formulate their own national targets.

3. **Introduction of EU-wide carbon removal support based on two-sided carbon contracts**

   In addition to the existing EU funding options for CCS projects in general (e.g. Innovation Fund, Connecting Europe Facility), a targeted funding instrument for capacity building of infant carbon removal technologies is needed. This is necessary to realize economies of scale in a timely manner and expand the technology portfolio to combat climate change. Our case study on DACCS in Europe has demonstrated that the guarantee of an above-market carbon price for a transitional period can provide an important impetus for capacity building and the realization of cost reduction potential. To uphold the principle of reciprocity, it should take the form of two-sided Carbon Contracts for

Difference (CCfDs). Projects receive periodic payments in the amount of the difference between a contractually fixed CO_2 price and the price level prevailing in the EU-ETS for each (net!) tonne of CO_2 removed. In this way, NET-projects are compensated for the cost disadvantage they face in the early phase when competing on CO_2-feedstock markets or for access to CO_2 storage sites. The awarding of CCfDs and the level of contractual prices should be the subject of EU-wide auctioning processes, carried out under the umbrella of the Innovation Fund. Such an EU-wide funding competition would reduce the risk of the emergence of a spatially sub-optimal CO_2 infrastructure provoked by heterogeneous funding policies in the Member States. The avoidance of minimum size requirements and the application of the pay-as-bid principle are recommended to give even very immature technologies the chance to receive appropriate funding. However, compliance with the certification criteria of the EU Carbon Removal Certification Scheme must be a central prerequisite for the right to receive funding, and to ensure a level playing field between different types of NETs in the tender.

4. **Harmonization of rules to create an internal market for captured CO_2**

In addition to EU-wide project funding, the development of cross-border markets for captured CO_2 requires common rules for project and infrastructure development. To this end, the last Member States should abandon their negative attitude towards geological CO_2 storage and allow the construction of storage sites on their territory, in compliance with transparent standards compatible with the CCS Directive 2009/31/EC. At the same time, the Member States should prioritize the acceleration of approval procedures for strategic CCS projects prescribed by the Net Zero Industry Act, e.g., by creating sufficient administrative capacities. Moreover, additional legislation is needed at EU-level, to create joint rules for the development and operation of a future CO_2 pipeline infrastructure, similar in its objectives to the recent revision of the internal gas market legislation.[124] This should include uniform quality standards for CO_2 transport (temperature, pressure, purity) and rules on the form of cross-border cooperation for future Europe-wide network planning, as well as common principles for the levying of network charges when transporting CO_2 from external sources. The common objective of all rules must be the fast development of CO_2 transport in the EU with as few barriers as possible. This will create a margin for the realization of an economically cost-optimizing pipeline geography and of scale economies in large storage reservoirs.

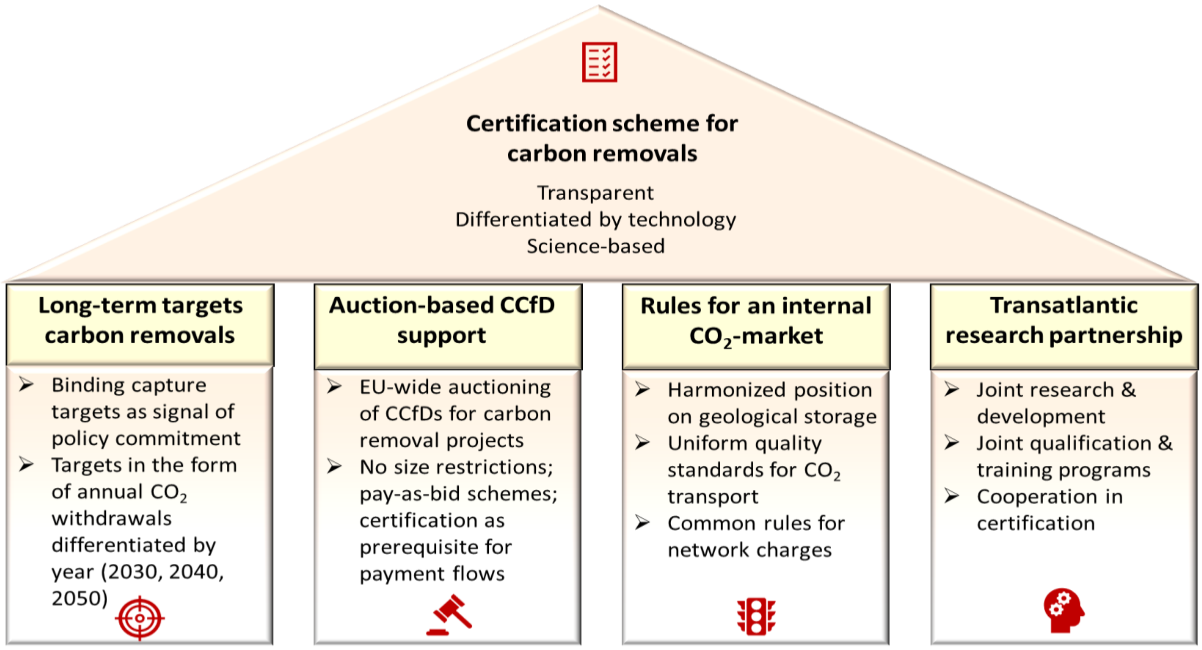
5. **Establishment of a transatlantic CCS research partnership**

The USA is currently the most important player in the global deployment of CCS technologies and will remain so for the foreseeable future (see Section 2). In particular, the North American region will play a key role in the upscaling of the high-potential carbon removal technologies DACCS and BECCS, given its ambitious funding policies and good starting conditions. The experience gained from the implementation of these technologies will initially primarily benefit US companies for future innovation activities. The countries of the European Economic Area should not lament this fact, but rather take advantage of it by promoting a transatlantic CCS research partnership. By establishing joint research & development programs, joint qualification and training initiatives as well as cooperation in the standardization and further development of CCS certification methods, Europe can participate directly in future learning effects achieved overseas. In return, it offers its own

[124] European Council (2023). Gas package: Council and Parliament reach deal on future hydrogen and gas market. Press release, December 8 2023.

significant expertise in the fields of certification and basic research. In addition to all EEA members and the USA, such a partnership should ideally include the UK and Canada, who are also pursuing ambitious CCS projects of their own. This initiative could meaningfully complement other recent attempts at institutionalized supply chain cooperation like the envisaged Critical Raw Materials Club.[125]

Figure 16: Fields of action for promoting carbon capture in the EU



Source: own representation

6 Conclusion

While Europe continues to debate the right mix of mitigation policies, the climate clock ticks on remorselessly. As the toolbox of policy instruments for accelerating decarbonization becomes increasingly exhausted, there is a growing realization that reducing emissions alone cannot achieve the necessary slowdown in mean temperature growth. This puts the spotlight on carbon removal technologies, especially those which offer the potential for a significant net CO_2 withdrawal from a lifecycle perspective. Indeed, when looking at global investment figures, Negative Emission Technologies are likely to gain momentum in the coming years. However, for realizing their full potential within the time frame dictated by the climate goals, several obstacles must be eliminated. These technologies offer an opportunity to diversify the existing mitigation portfolio, thus providing a form of technology insurance for society. With the EU-ETS being firmly established as a separate system, no conflict with emission reduction goals will arise.

This cepInput analyzes the potential and the economic challenges of carbon capture in the EU, with special emphasis on Direct Air Capture (DAC) as an infant, but particularly promising, solution. It argues that market uptake hinges on the timely application of a policy mix promoting investments in all stages of future supply chains for captured CO_2. This starts with instruments for stimulating the capacity growth of capture plants. Our case study on DAC illustrates that both the timing and extent of policy

[125] Europe Table (2023). Critical Raw Materials Club: first meeting before year's end. Table Media.

impulses are highly critical for the future uptake of this infant technology. Under these conditions, offering CO_2 price guarantees above medium-term ETS prices to investment projects could initiate a dynamically self-reinforcing process resulting from the realization of scale economies. Only by initiating this process today can we ensure that sufficient capacities will be in place tomorrow. Thus, early investors in carbon removal projects will at least be partially rewarded for the positive externalities of industry-wide learning and climate change mitigation caused by their impetus. These guarantees should be implemented in the form of two-sided contracts (CCfDs) and allocated through open tender schemes, to reduce long-term fiscal risks and to ensure fair competition among technology solutions.

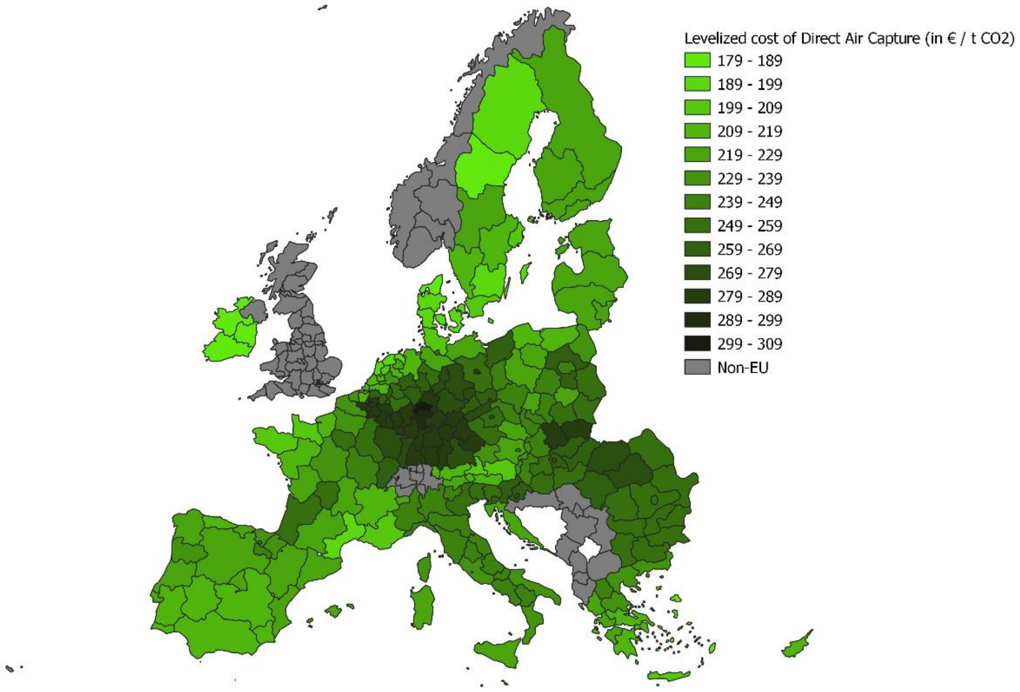
Moreover, CO_2 supply chain policies need to address the additional obstacle of coordination externalities in the simultaneous build-up of capture facilities, pipelines, utilization solutions and geological storage sites. In this respect, the impulse set by CCfDs for capture solutions is also helpful as a signal since it improves demand expectations for transport and storage. In order to ensure the formation of a vibrant and fair internal market for captured CO_2, however, it must be accompanied by efforts to achieve regulatory harmonization and cooperation across Member States. This starts with establishing a common legal position on geological storage. It also needs to involve agreements on physical standards for transported CO_2, a joint framework for the future regulation of network charges and a European approach to long-term infrastructure planning. The recent reform of the internal gas market rules might serve as a role model for some of these aspects.

At the same time, in pushing for a European solution the EU must not be tempted to ignore the dynamics in the rest of the world. In the area of carbon capture, this applies in particular to the Anglo-American countries, who are predicted to manage the bulk of global CCS investments in the years to come. In view of the global nature of the climate problem, this is not a threat, but a welcome opportunity for the EU. By establishing a transatlantic research and development partnership in the field of CCS, involving joint innovation activities in relation to both technical and regulatory issues, the EU can benefit from the practical experience of the technology already gained in these countries. With its own pioneering role in certification, it can act as a self-confident partner in this relationship.

Finally, implementing and monitoring this policy mix over the coming decades requires strategic guidance. For emission reductions, legally binding quantitative targets have proven to be effective political steering signals, as demonstrated by the comprehensiveness of the Green Deal strategy. Comparable targets should be established for the annual tonnage of CO_2 (directly or indirectly) removed permanently from the atmosphere. These should be differentiated by target year and scientifically substantiated according to the requirements determined by long-term climate simulations. A prerequisite for monitoring these goals over time is a clear common understanding of the terms “carbon removal” and “permanent carbon removal”. The EU should therefore bring the current legislative process on carbon removal certification to a successful conclusion as quickly as possible. The priority task for developing certification criteria will be to establish a life cycle view on climate effects and a methodology for an all-round comparison of the environmental impacts of the technology options.

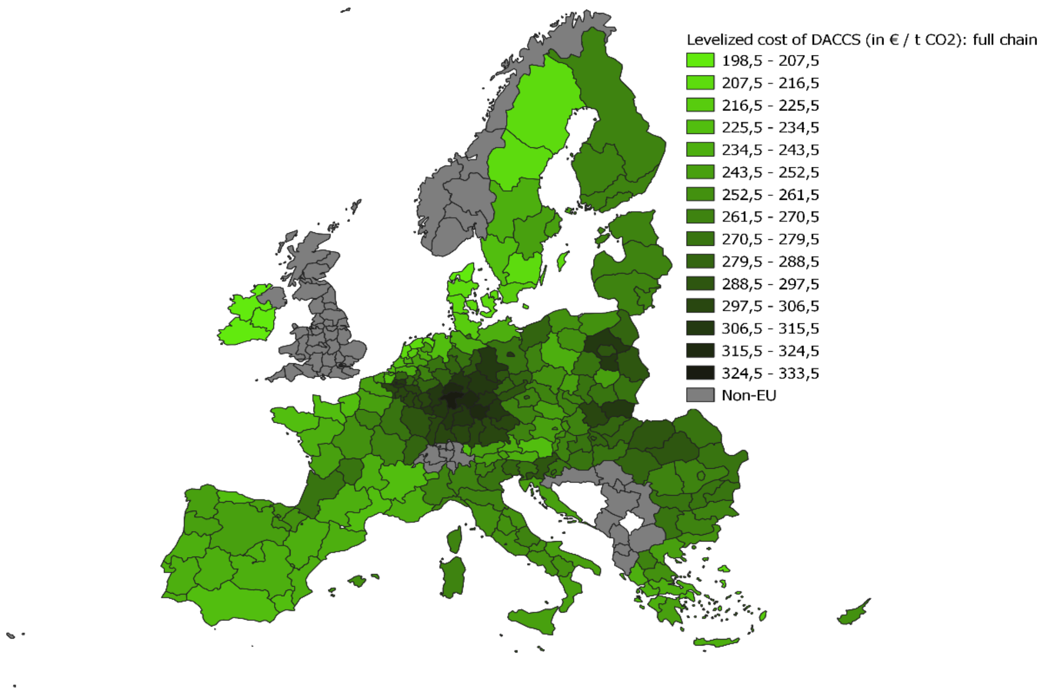
7 Appendix

Figure A 1: Regional comparison (NUTS-2 level) of estimated present DAC costs (only capture)



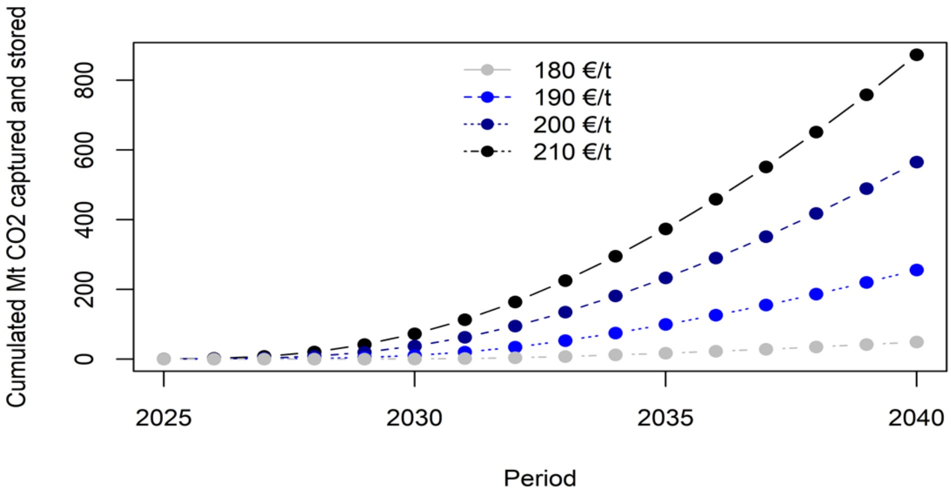
Source: own representation

Figure A 2: Regional comparison (NUTS-2 level) of estimated present DACCS costs (full chain)



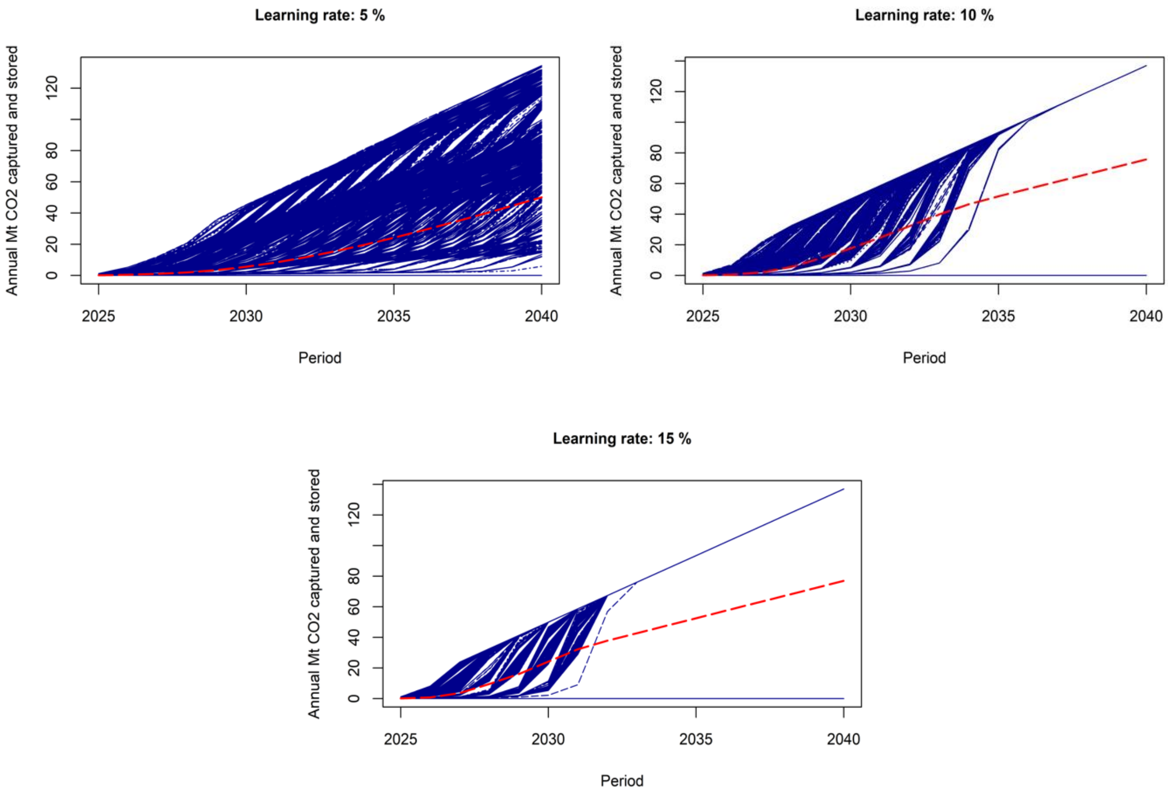
Source: own representation

Figure A 3: Cumulative carbon removals through DAC by level of guaranteed CO_2 price



Source: own representation

Figure A 4: Sensitivity of DAC capacity growth to size of the learning rate (CO_2 price: 200 €/t)



Source. own representation. Blue lines: results of single draws (n=10,000), red dots: expected values.

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