China Council for International Cooperation on Environment and Development

CCS-based Carbon Dioxide Removal Technologies

Discussion Paper 2024

Author: Qi ZHENG, International Institute for Sustainable Development

Acknowledgements

The author would like to sincerely thank the following experts for their invaluable input to the outline and comments on earlier drafts of this paper:

Knut H. Alfsen	Special Advisor to CCICED
Qimin Chai	China National Centre for Climate Change Strategy and International Cooperation
Tad Ferris	Institute for Governance & Sustainable Development
Sabine Fuss	Mercator Research Institute on Global Commons and Climate Change Jing Huang, Administrative Center for China's Agenda 21
Injy Johnstone	University of Oxford
Xi Liang	University College London
Olivier Bois von Kursk	International Institute for Sustainable Development
Xuedu Lv	Tencent Carbon Neutrality Institute
Ze Ran	Environment Defense Fund Beijing Representative Office
Felix Schenuit	German Institute for International and Security Affairs
Stephen Smith	University of Oxford
Scott Vaughan	International Chief Advisor to CCICED
Jiutian Zhang	Beijing Normal University

The author would also like to acknowledge the following experts for sharing their insights on carbon dioxide removal:

Noah Deich	Department of Energy, U.S.
Jos Delbeke	European University Institute
Susanne Dröge	German Federal Environment Agency
Oliver Geden	German Institute for International and Security Affairs (SWP)
Veronika Elgart	Federal Office for the Environment, Switzerland
Glen Peters	Centre for International Climate and Environmental Research (CICERO)
Jianyu Zhang	BRI International Green Development Institute
Xian Zhang	Administrative Center for China's Agenda 21

Thanks should also go to Xiao Pang from the Secretariat of CCICED for his assistance in this effort.

** The author of this discussion paper serves in her personal capacity. The views and opinions expressed in this discussion paper are those of the author and do not represent those of her organization and CCICED.*

Summary

Novel carbon dioxide removal (CDR), such as bioenergy with carbon capture and storage and direct air carbon capture and storage, may be needed to achieve China's target of reaching carbon neutrality by 2060, in addition to rapid emissions reductions and conventional land-based CDR. Notable progress is being made to advance these technologies in a number of countries and through voluntary carbon markets. However, uncertainties persist regarding their scalability as well as potential risks and trade-offs with other sustainable development goals. China can build on existing knowledge to expand the country's CDR portfolio based on its domestic context while ensuring emission reduction efforts are not jeopardized. Comprehensive assessments on the performance and impacts of CDR options will be needed to help inform policy decisions. Dedicated research, development, demonstration support, and robust measurement, reporting, and verification systems are critical to accelerate scale-up and bring in private investment.

1.Introduction[1]

1.1 CDR is Necessary to Achieve the Paris Agreement Goals

The latest Intergovernmental Panel on Climate Change (IPCC) report (Babiker et al., 2022) makes clear that in addition to rapid and deep emission reductions, carbon dioxide removal (CDR) is necessary in all scenarios that are compatible with the Paris Agreement temperature targets. Given insufficient climate action, it's almost unavoidable that global warming may temporarily exceed the 1.5°C threshold before being brought down below this level through sustained net-negative emissions in the second half of this century—so-called climate overshoot (Reisinger et Geden, 2023). CDR can play multiple roles in these mitigation pathways: further reducing net carbon emissions in the near term, counterbalancing residual emissions from hard-to-abate sectors to reach net-zero emissions, and eventually achieving net-negative emissions to bring warming back to below 1.5°C (Babiker et al., 2022).

CDR has been gaining political support in recent years. The UN Secretary-General explicitly called for support to develop CDR: "I also encourage scientists and engineers to focus urgently on carbon dioxide removal and storage – to deal safely and sustainably with final emissions from the heavy industries hardest to clean. And I urge governments to support them. But let me be clear: These technologies are not a silver bullet; they cannot be a substitute for drastic emissions cuts or an excuse to delay fossil fuel phase-out" (UN, 2024).

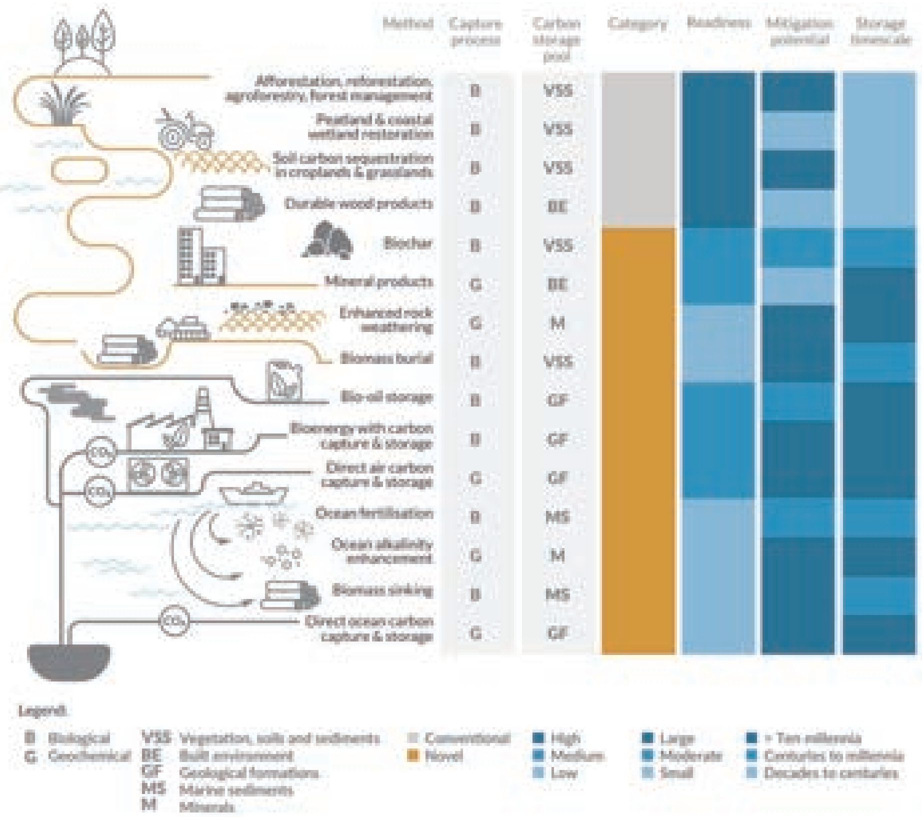

Figure 1. CDR methods and their characteristics

Source: Smith et al., 2024.

[1] All currency is in USD except unless otherwise indicated

1.2 Definitions

CDR refers to human activities that intentionally remove carbon dioxide (CO_2) from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products (Babiker et al., 2022). There is a wide range of different CDR measures, including conventional approaches such as afforestation and reforestation, and so-called novel CDR approaches such as bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), biochar, enhanced weathering, and marine CDR (Geden et al., 2024). In recent years, two CCS-based CDR methods (BECCS and DACCS) have gained increasing attention of policy-makers and investors because of their high durability of carbon storage.

BECCS involves "the combination of natural sequestration of atmospheric carbon by biomass during its growth with the capture and geological storage of CO_2 emitted upon conversion of this biomass to energy. If more CO_2 is captured and permanently sequestered than is emitted over the entire BECCS value chain, this system results in a net removal of CO_2 from the atmosphere" (Fajardy, 2022). BECCS has featured predominantly in most integrated assessment models' scenarios compatible with a "well-below" 2°C target. DACCS refers to chemical processes to capture ambient CO_2 from the atmosphere and store it underground (Babiker et al, 2022). Since the publication of the IPCC 6th Assessment, more recent scenarios start to include DACCS and other novel CDR methods (Gidden et al., 2024). BECCS and DACCS are still at a nascent stage, generating a tiny part of the total amount of removals today (less than 0.1%) (Pongratz et al., 2024).

Box 1. Distinguishing CDR, CCS, and CCU

It is important to clearly distinguish between CDR and carbon capture and storage (CCS) and carbon capture and utilization (CCU). CCS applied to CO_2 from point-sources of fossil emissions for geological storage cannot reduce the concentration of CO_2 in the atmosphere. CCS can, however, be a component of two CDR methods, such as BECCS and DACCS if atmospheric CO_2 is being captured. With regards to CCU, in contrast to CCS, the captured CO_2 will then be used to produce other products such as synthetic fuels, chemicals, and construction materials. Most CCU products will eventually be combusted, thus re-releasing CO_2 back into atmosphere. CCU can at best delay emissions depending on the lifetime of product and carbon footprint of the process chain (Schenuit et al., 2023). Using captured CO_2 for enhanced oil recovery raises serious concerns over providing oil and natural gas industry the legitimacy to continue their business (Grubert & Talati, 2024).

1.3 China Can Build on Existing Knowledge to Expand CDR Portfolio

For China to achieve its carbon neutrality goal by 2060, important volume of CDR will be needed to compensate emissions from the hard-to-abate industries (He et al., 2022). It is worth noting that CDR is not new to China. The country launched national reforestation/afforestation programs decades ago to address other environmental challenges such as desertification, which were then repurposed as a key climate action. Incentive policy and regulatory frameworks for the forestry sector are established, such as inclusion into its nationally determined contributions (NDC) (UNFCCC, 2021) and the voluntary carbon emission trading system (Schenuit et al., 2024). Currently, China provides the largest conventional CDR volume in the world (close to 400 Mt CO_2/year) (Pongratz et al., 2024). In addition, ocean-based CDR is also explored in China, for example, through the Ocean Negative Carbon Emissions initiative (ONCE, 2024). Blue carbon is also featured in China's NDC as a new measure to achieve the updated goals.

All CDR measures carry both risks and benefits, in particular if deployed at scale. Reforestation/ afforestation can bring co-benefits for ecosystem services and livelihoods but also come with risks such as competition for agricultural land and water resources, shorter durability of carbon storage than geological storage, saturation of storing ability, and reversal due to natural and human disturbances (UNEP, 2023). As the world's biggest carbon emitter, China faces great challenges in accelerating green transition while ensuring development and energy security objectives. It is therefore important to expand the CDR portfolio to meet the scale needed and minimize risks and trade-offs. Although considerable research has been dedicated to novel CDR in China (see chapter 2), there is neither official information nor academic agreement on the specific contribution of novel CDR in China's decarbonization pathways.

1.4 Scope and Purpose of This Discussion Paper

This discussion paper will focus on two novel CDR methods, BECCS and DACCS, for two reasons: 1) important developments have been observed at the international level; 2) CCS and CCU have been gaining increasing attention in China in recent years. The confusion between CDR and CCS and CCU is problematic and necessitates clarification, in particular from a policy perspective. Drawing on existing analyses, this discussion paper will provide a snapshot of the latest policy developments of BECCS and DACCS and bring forward some key challenges and opportunities of scaling these technologies in China.

2.Developments in Policy, RD&D, and Market Activity

2.1 Government Support Growing Fast, Largely in Developed Economies

Policy instruments vary across different countries and include tax credits, public procurement, and regulatory measures, along with investments in research, development, and demonstration (RD&D). Some notable developments are summarized below. A snapshot of these developments can be found in the annex.

United States: In its long-term strategy of reaching net-zero emissions (DOS, 2021), the United States aims to deliver about 1 Gt CO_2 CDR per year by 2050. A range of fiscal and public procurement measures have been introduced to support this, notably increased support from the Inflation Reduction Act to DACCS through the 45Q of the U.S. tax code and significant funding streams from the Infrastructure Investment and Jobs Act into novel CDR (WRI, 2022). The Infrastructure Investment and Jobs Act includes, among others, \$3.5 billion for creating four regional direct air capture hubs (DOE, 2023) and \$115 million for the DAC Technology Prize Competition, \$2.1 billion for CO_2 transport, and \$2.5 billion for carbon storage validation and testing (DOE, 2021).

European Union: The European Climate Law makes legally binding the climate neutrality by 2050 objective and a commitment to net-negative emissions after 2050 (EC, 2021). In February 2024, the European Commission announced its recommendation for the interim 2040 climate target (EC, 2024) and published the Industrial Carbon Management Strategy (EC, 2024), making CDR an important part of the EU decarbonization effort. By 2050, the EU would need to remove about 0.4 Gt CO_2/year to balance residual emissions from hard-to-abate sectors. The Industrial Carbon Management Strategy also lays out the potential policy options and support mechanisms for BECCS and DACCS, including through the EU Emission Trading System, and additional investment needs for CO_2 transport and infrastructure.

Norway: Norway doesn't have a net-zero target. The Climate Change Act (MoCE, 2021) sets a 90%-95% emissions reduction target by 2050 compared to 1990 emissions levels. The development of CCS is a result of a business case created by the Norwegian CO_2 tax on the oil and gas sector which plays a crucial role in the country's economy (GCCSI, 2023). Nowadays CCS is considered critical to helping the country reach its domestic mitigation targets and to sequestering imported CO_2. BECCS and DACCS have gained support provided by the government to CCS. For example, Enova, the state company owned by the Norwegian Ministry of Climate and Environment, has provided the first grant of about \$3.5 million (NOK 36.3 million) to a DACCS project managed by Removr. As part of the government-backed Longship CCS project, the Northern Lights signed an agreement with Danish Ørsted to store 430 kt CO_2/year from a BECCS project (LN, 2023). Two other BECCS projects are the Norcem plant and Hafslund Oslo Celsio. The Norwegian Environmental Agency has proposed incentive instruments for CDR, including a reverse CO_2 tax, offering monetary rewards and integrating CDR credits in the voluntary carbon market (NEA, 2023).

United Kingdom: The United Kingdom released its Net Zero Strategy in 2021, with a target to withdraw 5 Mt CO_2 in engineered removals annually by 2030 on a path to reach 75-81 Mt CO_2/year in removals by 2050 (U.K., 2021). It is committed to using a set of market-based instruments to incentivize greenhouse gas removal deployment. In 2023, the government announced its plans to support engineered removals through the Contract for Difference (U.K., 2023). In 2024, a consultation was launched by the government to seek input on the integration of greenhouse gas removal in the UK Emissions Trading Scheme (DESNZ, 2024).

China: China has included CCS-based CDR (negative emissions technologies) as a critical area for research and development (NDRC, 2021). DACCS is also featured in China-US bilateral dialogue (WRI, 2024). Yet, no comprehensive assessment has been done. Some studies show that it is likely that CCS-based CDR could play a critical role in achieving China's carbon neutrality goal (Chen et al., 2023 ; Fuhrman et al., 2021; Chai et al., 2020). Deng et al. (2024) think that the potential of biochar could satisfy China's need for carbon removals. The central government is promoting the development of CCU and CCS through RD&D and demonstrations. However, these projects are not CDR projects as most of them are associated with fossil CO_2 sources, and the captured CO_2 will be reinjected for enhanced oil recovery (Schenuit et al., 2024).

2.2 Monitoring, Reporting, and Verification is Vital to Scaling Up Novel CDR

Robust monitoring, reporting, and verification (MRV) systems are vital to supporting novel CDR scale-up as they can help governments and private sectors make regulatory and investment decisions. Thus, developing MRV is the first step toward integrating novel CDR into climate policies and markets. Currently, other than for BECCS and biochar, there is no guidance for novel CDR measures. MRV protocols for novel CDR are primarily developed and being applied in the voluntary markets (Schulte et al., 2024).

At the level of the United Nations Framework Convention on Climate Change, ongoing efforts in developing robust accounting rules for CDR, including creating additional guidance for novel methods, are crucial as this will be relevant for potential international carbon trading under Article 6.4 of the Paris Agreement. Another relevant mechanism is Article 6.2, which allows countries to trade carbon emission reduction and removal credits. The IPCC TFI is expected to produce a methodology report on CDR and CCUS by 2027, which will provide guidance on how to include novel CDR into national greenhouse gas inventories (IPCC,2024).

The EU is pursuing establishment of an EU-level certification framework for CDR and will develop tailored certification methodologies for different CDR methods (EC, 2024). In May 2024, the European Commission adopted new templates for climate reporting, allowing member states to report on the volume of BECCS and DACCS (EC, 2024). Compared to the EU, the U.S. government is taking a different approach by prioritizing creating the markets for novel CDR, though some efforts are being taken to advance MRV (Schulte et al., 2024).

With regard to the voluntary market, Schulte et al. (2024) mapped out the existing protocols and state of science on MRV and concluded that both BECCS and DACCS have seen MRV development albeit a knowledge gap exists in relation to the direct air capture and aspects related to biomass.

2.3 Investments in RD&D

It takes on average around 20 years for a novel technology from first commercial deployment to achieve widespread adoption. Thus, to reach a gigaton-scale by 2050 adequate RD&D investment is urgent and critical to lower the cost of DACCS and BECCS in the early stages of their formative phase (UNEP, 2023).

Public funding for CDR RD&D, in particular for novel CDR, has grown, notably through the CDR Launchpad initiative under the Mission Innovation ($100 million in funding for CDR demonstrations and pilot projects by 2025) (MI, 2023) and the Direct Air Capture regional hubs funded by the U.S. federal government ($3.5 billion over 5 years).

Nemet et al. (2024) observed significant growth in private investments for CDR start-ups in recent years, from $4 million for 3 start-ups in 2013 to $1.5 billion for 131 start-ups by 2022. Overall speaking, increased investments are directed to novel CDR startups, in particular to DACCS and biochar. However, compared to the total investment of $1.8 trillion to clean energy in 2023 (IEA, 2024), the investment to CDR is still low. According to a survey conducted by Nemet et al. (2024), these start-ups face challenges of getting access to finance, uncertainties in the voluntary market, as well as scientific uncertainties around MRV.

There is no dedicated public RD&D funding for BECCS and DACCS in China, though the Tencent Carbon X program supports the research and early commercialization of low-carbon technologies including DACCS. The government needs to catch up on RD& D funding towards novel CDR options and stimulate more private funding. In addition, it can be beneficial to collaborate with other countries or regions such as UK, EU and join the CDR Launchpad given China is already a member of the Mission Innovation.

2.4 The Role of Voluntary Market

The voluntary market plays an important role in creating demand and financing this nascent industry. According to CDR.fyi (2023 Year in Review), the purchase volume of novel CDR has grown more than five times every year since 2020. In 2023, CDR purchases grew to 4.5 Mt CO_2, concentrated in BECCS (63%) and DACCS (20%). However this only represents 4% of the total voluntary carbon market in 2023 (110.8 Mt CO_2), which is dominated by emission reduction projects in terms of the volume of carbon credits (Forest Trends' Ecosystem Marketplace, 2024).The average volume-weighted price for novel CDR credits is currently significantly higher than that of conventional CDR: in 2023, the price for afforestation/reforestation was $16/t CO_2, whereas the price for DACCS and BECCS was $715 and $300, respectively.

A survey conducted by CDR.fyi (2024) reveals that the purchasers are primarily from the finance and information technology sectors whose motivation is to help accelerate the scale-up of the industry. A notable example is Microsoft, which plans for a CDR portfolio of more than 5 Mt CO_2/year in 2030 (Microsoft, 2023) and purchased more than 8 Mt , 75% of all novel CDR at the time of writing this report (CDRfyi, 2024).

Fuss et al. (2024) concluded that the voluntary market may not offer sufficient finance for scaling up CDR, compliance markets will likely play a key role in driving future demand. However, in the near term the former can allow novel CDR to be tried out in practice and to develop necessary MRV protocols and in the long term the VCM can still serve as a niche market for CDR to facilitate innovation and experimentation and to supplement climate change mitigation efforts.

3.Key Challenges and Opportunities of Developing BECCS and DACCS in China

Deploying novel CDR at a gigaton scale by mid-century requires a drastic ramp-up of these technologies in the next decade (UNEP, 2023). Some of the key challenges and opportunities can be relevant for China.

3.1 Economic and Technical Feasibility

● While DACCS is technologically feasible, high cost is a major challenge due to the relatively low CO_2 concentration in the atmosphere, which implies high renewable energy inputs and other related costs. There is great uncertainty in cost estimates because of limited real-world experiences to date. NASEM (2019) estimates that the average costs for net CO_2 removed for the solid sorbent-based and liquid solvent-based DACCS are $89-$877/tCO_2 and $156-$506/tCO_2, respectively; whereas the costs for other CDR measures are $45-$100/tCO_2 for soil carbon sequestration, $0-$240/tCO_2 for afforestation/reforestation, $10-$345 for biochar, and $15-$400/tCO_2 for BECCS (Babiker et al., 2022). Some recent studies project that the costs of DACCS will fall substantially by 2050 from their current levels but will remain significant, much higher than the long-term CDR policy target of $100/t$CO_2$ set by the United States government (Shayegh et al., 2021; Sievert et al., 2024).

● In contrast to DACCS, BECCS yields marketable energy products (e.g., electricity, liquid fuel, and hydrogen) which can translate into revenue streams for the BECCS system, in addition to removing CO_2 from the atmosphere (Fajardy, 2022). Some BECCS applications are at presently technologically mature and commercial (e.g., bioethanol production, biomass co-firing in coal-fired plants, pulp and paper mills, cement plants, and steel blast furnaces), and some are still at the prototype or demonstration stage (e.g., biomass for synthetic gasification, CO_2 capture from kilns, and blast furnace off-gas) (IEA, 2024).

● The deployment of BECCS and DACCS is dependent on the existence of CCS infrastructure. The estimates of global geological storage potential seem sufficient to cover the demand for storage. The

United States, EU, and China have great storage potential in proximity to their emission sources which can reduce costs (IEA, 2021), though more investment is needed to develop adequate CO_2 transport and storage infrastructure (IEA, 2024). The fact that CCS is considered largely falling short of expectations after decades of development (Mahjour & Faroughi, 2023) adds to uncertainties that the adequate CCS infrastructure can be built in time. China's efforts in developing CCU/CCS in recent years helped drive down the overall capture cost and capture energy consumption (Yang, 2023). However, gaps in policy and regulatory frameworks for CO_2 geological storage (Yang & Li, 2024) could impede the scale-up of CCS-based CDR.

3.2 Sustainability Barriers

● BECCS deployment is mainly limited by the availability of sustainable biomass feedstock, which raises concerns over competition for agricultural land, water resources, and biodiversity loss from land conversion. Additional greenhouse gas emissions may be generated from biomass production (e.g., use of fertilizer), processing, transport and CCS stages, so conducting a life-cycle assessment over a BECCS value chain to evaluate the climate impact is crucial (Fajardy, 2022; Bloomer et al., 2022)

● Large-scale DACCS deployment requires large volumes of sorbent bulk materials and significant energy input, perhaps representing a quarter to a third of today's global energy production (Gidden et al., 2024). For a whole DACCS facility to be carbon-negative, it has to be powered by renewable energy and therefore can increase the demand for associated raw materials. The location of the DACCS facility requires access to carbon-free electricity. Moreover, the demands for land and water are also important constraints for China. To filter 1 ton of CO_2 out of the air, Climeworks' solid sorbent system requires 1,000 KWh of energy, 36 kg of materials, 3 m^3 of water, and 11,000 m^2 of space annually (Madhu et al., 2021).

● To evaluate the scalability of these technologies in China, it will be necessary to conduct comprehensive assessments for large-scale deployment by taking into account sustainability factors, including energy, land, water, and raw materials.

3.3 Social and Political Barriers

● Moral hazard. One of the major concerns about CDR is the risk of delaying emissions reduction efforts and providing a continued social license for the fossil fuel industry to operate, the so-called moral hazard or mitigation deterrence. An example is the purchase of Carbon Engineering, a DACCS company with a natural gas-reliant process, by Occidental Petroleum (Oxy, 2023), which plans to use DACCS to offset the CO_2 emissions from the industry and produce "net-zero oil" (Oxy, 2022). Some solutions have been proposed to reduce this risk, such as setting up separate targets for emissions reduction and carbon removal, or requiring a tightening of caps in emissions trading schemes as CDR credits are integrated(Hoglund et al., 2023; McLaren et al., 2019).

● Lack of a robust MRV system. Effective and robust MRV regimes are critical to scaling CDR by ensuring integrity of the market and building trust (see chapter 2.4). They need to address additionality, permanence, and sufficiency (Grubert & Talati, 2024). Compared to forest projects, it's more straightforward for BECCS and DACCS to demonstrate additionality as a business-as-usual case would "not removing carbon dioxide from the atmosphere in the first place". However, demonstrating additionality requires a life-cycle analysis to account for additional emissions (e.g., additional energy input, transport and land disturbance, and fertilizer use, etc.). Different CDR methods have different levels of permanence, which has implications for if and how to link CDR with compliance carbon markets since not all CDR credits are interchangeable with CO_2 allowance in terms of their climate impact and cost (Burke et al., 2023). The issue of sufficiency arises because of the asymmetry of climate impacts of removals and emissions at a large scale, which means to compensate for 1 ton of CO_2 emitted, more than 1 ton of CO_2 may need to be removed at a later stage (Chimuka et al., 2023). In 2024, China laid out a plan to strengthen the carbon accounting system which features CCS-based CDR (NDRC, 2024) which is a first step toward to effort.

● Lack of dedicated policy support and innovation. Technology development of DACCS and BECCS is mainly driven by private sector initiatives and net-zero or net-negative pledges through the voluntary markets. Currently, a handful of governments have begun to specify the role of CDR in domestic climate policies (Schenuit et al., 2024). National net-zero strategies and plans need to clarify the anticipated role of CDR, including for DACCS and BECCS. To reduce costs and investment risk, more targeted policy support will be needed, such as tax credits, grants, loans and loan guarantees, RD&D funding, as well as robust carbon-pricing mechanisms (IEA, 2024).

3.4 Advantages and Opportunities

● As mentioned in chapter 1.3, existing regulatory and incentive policy frameworks for conventional CDR lay out the foundation for China to expand the CDR portoflio. Other advantages exist: China is the biggest contributor to CDR research publications (30%) over the last 2 decades, mainly driven by research on biochar and soil carbon sequestration. In terms of patent, China shows a great emphasis on conventional CDR but has recently seen increasing numbers of patents across several CDR methods, including BECCS. The share of CDR patents in China is the same as its global share of climate change mitigation patents. In addition, China has a lot to offer in terms of advancing green technology innovation and driving down costs (Minx et al., 2024).

● China is expanding the compliance market and re-opening the voluntary market, which offers an opportunity to develop and test MRV for novel CDR measures and to support RD&D. This will also allow the country to actively participate in the discussions under Article 6 at United Nations Framework Convention on Climate Change and align national standards with international ones.

● The design of the 15th Five-Year Plan and the upcoming new NDC present opportunities for China to include novel CDR into overall green transition strategies and national research plans for low-carbon technologies.

4.Conclusions

● •In the 15th Five-Year Plan, China may consider developing a roadmap for CDR in the context of the overarching strategy for reaching the country's dual carbon goals. China may also consider, in the updated NDC, indicating its intention of developing a portfolio of CDR to reach net-zero and negative emissiosn thereafter, in addition to rapid emission reductions.

● •Interdisciplinary and comprehensive assessment of CDR options (feasibility and performance, socio-environmental impacts) can be included into national research plans for green technologies, potentially through dedicated funds under the Ministry of Ecology and Environment, Ministry of Science and Technology, and the National Natural Science Fundation of China.

● •China may include novel CDR into more relevant bilateral (e.g., with EU, UK) and multilateral cooperation mechanisms (e.g. the Ministerial on Climate Action). As a member of the Mission Innovation, China may consider joining the CDR mission.

References

(1) Babiker, M., G. Berndes, K. Blok, B. Cohen, A. Cowie, O. Geden, V. Ginzburg, A. Leip, P. Smith, M. Sugiyama, F. Yamba. (2022):

(2) Cross sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working

(3) Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade,

(4) A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi,A. Hasija,G. Lisboa,

(5) S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

(6) doi:10.1017/9781009157926.014

(7) Bloomer, L., Sun X.,Dreyfus, G., Ferris, T., Zaelke, D., Schiff, C. (2022). A call to stop burning trees in the name of climate mitigation.

(8) Vermont Journal of Environmental Law, 94-123.

(9) Burke, J and Schenuit, F. (2023) Governing permanence of Carbon Dioxide Removal: a typology of policy measures. CO_2RE – The

(10) Greenhouse Gas Removal Hub

(11) CDR. fyi. Trending on Track?-CDR.fyi 2023 Year in Review. https://www.cdr.fyi/blog/2023-year-in-review. last access 23 July 2024

(12) CDR.fyi. (2024). 2024 + Market Outlook Summary Report. https://www.cdr.fyi/blog/2024-market-outlook-summary-report

(13) Chai.Q., Fu.S., Wen,X. (2020). Modeling the implementation of NDCs and the scenarios below 2°C for the Belt and Road countries. Ecosystem Health and Sustainability. 6. 1766998. 10.1080/20964129.2020.1766998.

(14) Chen et al., (2023). CCUS Progress In China-A status report. https://www.globalccsinstitute.com/wp-content/uploads/2023/03/CCUS-Progress-in-China.pdf

(15) Chimuka, V. R., Nzotungicimpaye, C.-M., and Zickfeld, K. (2023). Quantifying land carbon cycle feedbacks under negative CO_2 emissions, Biogeosciences, 20, 2283–2299, https://doi.org/10.5194/bg-20-2283-2023

(16) UNFCCC NDC Registry. (2021). https://unfccc.int/NDCREG?field_document_ca_target_id=143

(17) National Reform and Development Commission, China. (2021). Action Plan for Carbon Dioxide Peaking Before 2030. https://en.ndrc.gov.cn/policies/202110/t20211027_1301020.html

(18) Deng, X., Teng, F., Chen, M. et al. (2024). Exploring negative emission potential of biochar to achieve carbon

neutrality goal in

(19) China. Nat Commun 15, 1085. https://doi.org/10.1038/s41467-024-45314-y

(20) Department for Energy Security and Net Zero, U.K. (2024). Integrating greenhouse gas removals in the UK Emissions Trading

(21) Scheme. https://www.gov.uk/government/consultations/integrating-greenhouse-gas-removals-in-the-uk-emissions-trading-

(22) scheme

(23) Department of Energy, U.S. (2021). The Infrastructure Investment and Jobs Act.

(24) https://www.energy.gov/sites/default/files/2021-12/FECM%20Infrastructure%20Factsheet.pdf

(25) Department of Energy, U.S. (2023). Regional Direct Air Capture Hubs. https://www.energy.gov/oced/DACHubs. last access 14 July 2024

(26) Department of State & Executive Office of the President, U.S. (2021). The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

(27) European Commission. (2021). European Climate Law. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32021R1119. last access 14 July 2024.

(28) European Commission. (2024). Climate actiom: Council and Parliament agreed to establish a EU carbon removals certification fraework. https://www.consilium.europa.eu/en/press/press-releases/2024/02/20/climate-action-council-and-parliament-agree-to-establish-an-eu-carbon-removals-certification-framework/. last access 14 July 2024

(29) European Commission. (2024). Adopted: New templates for Member States' climate reporting. https://climate.ec.europa.eu/news-your-voice/news/adopted-new-templates-member-states-climate-reporting-2024-05-07_en. last access 14 July 2024

(30) European Commission. (2024). Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable , just and prosperous society. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52024DC0063. last access 14 July 2024

(31) European Commission. (2024). Industrial Carbon Management. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2024%3A62%3AFIN&qid=1707312980822. last access 14 July 2024

(32) Fajardy, M. (2022). Bioenergy with Carbon Capture and Storage (BECCS). In B. e. al, Greenhouse Gas Removal Technologies (pp. 80-114). The Royal Society of Chemistry.

(33) Forest Trends' Ecosystem Marketplace. (2024). State of the Voluntary Carbon Market 2024. Washiongton DC: Forest Trends Association. https://www.forest-trends.org/publications/state-of-the-voluntary-carbon-market-2024/

(34) Fuhrman, J. et al. (2021). The role of negative emissions in meeting China's 2060 carbon neutrality goal, Oxford Open Climate Change, Volume 1, Issue 1, kgab004, https://doi.org/10.1093/oxfclm/kgab004

(35) Fuss,S.,Johnstone,I. Höglund, R., Walsh, N. (2024). The voluntary carbon market. in The State of Carbon Dioxide Removal 2024-2nd Edition (eds. Smith, S.M. et al.). http://www.stateofcdr.org, doi:10.17605/OSF.IO/MG3CY(2024).

(36) CDR.fyi (2024). Leaderboards. https://www.cdr.fyi/leaderboards

(37) Global CCS Institute. (2023). Insights and Commentaries. https://www.globalccsinstitute.com/news-media/insights/ccs-commercial-and-regulatory-frameworks-enabling-ccs-progress-in-norway-and-europe/

(38) Geden,O., Smith,S., M.,Cowie,A. (2024). Chapter 1: Introduction. in The State of Carbon Dioxide Removal 2024-2nd Edition (eds. Smith,S.M.et al.).

(39) Gidden, M. J., Roe, S., Ganti, G., Gasser, T., Hasegawa, T., Lamb, W. F., Ochi, Y., Strefler, J., Vaughan, N. E. (2024). Chapter 8: Paris-consistent CDR scenarios. in The State of Carbon Dioxide Removal 2024-2nd Edition. https://www.stateofcdr.org, doi:10.17605/OSF.IO/8XK7H (2024).

(40) Grubert, E., & Talati, S. (2023). The distortionary effects of unconstrained for-profit carbon dioxide removal and the need for early governance intervention. Carbon Management, 15(1). https://doi.org/10.1080/17583004.2023.2292111

(41) He,J., Li,Z., Zhang,X., Wang,H., Dong,W., Du,E., Chang,S., Ou,X., Guo,S., Tian,Z., Gu,A., Teng,F., Hu,B., Yang,X., Chen,S., Yao,M., Yuan,Z., Zhou,L., Zhao,X., Li,Y., Zhang,D.(2021). Towards carbon neutrality: A study on China's long-term low-carbon transition pathways and strategies, Environmental Science and Ecotechnology,Volume 9, 100134, ISSN 2666-4984. https://doi.org/10.1016/j.ese.2021.100134. https://www.sciencedirect.com/science/article/pii/S2666498421000582

(42) Höglund, R., Mitchell-Larson, E., Delerce, S. (2023). How to avoid carbon removal delaying emission reductions. https://carbongap.org/wp-content/uploads/2023/09/carbongap-policybrief-sep23_v2.pdf

(43) International Energy Agency. (2021). The world has vast capacity to sotre CO_2: Net zero means we'll need it. https://www.iea.org/commentaries/the-world-has-vast-capacity-to-store-co_2-net-zero-means-we-ll-need-it

(44) International Energy Agency. (2024). Direct Air Capture. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture#programmes

(45) International Energy Agency. (2024). Tracking Bioenergy with Carbon Capture and Storage. Retrieved from https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage#tracking.

(46) International Energy Agency. (2024). World Energy Investment 2024. https://www.iea.org/reports/world-energy-investment-2024/overview-and-key-findings: International Energy Agency.

(47) IPCC. (2024). PCC agrees on the set of scientific reports for the seventh assessment cycle. https://www.ipcc.ch/2024/01/19/ipcc-60-ar7-work-programme/

(48) Madhu, K., Pauliuk,S., Dhathri, S., Creutzig, F. (2021). Understanding environmental trade-offs and resource demand of direct air capture technologies through comparative life-cycle assessment. Nature Energy. 6. 10.1038/

s41560-021-00922-6.

(49) Mahjour, S. K., & Faroughi, S. (2023). Risks and uncerstainties in carbon capture, transport, and storage projects: A comprehensive review. Gas Science and Engineering, Volume 119, Part A.

(50) Mclaren, D., Tyfield, D., Willis, R., Szerszynski, B., Markusson, N. (2019). Beyond "Net-Zero": A Case for Separate Targets for Emissions Reduction and Negative Emissions. Frontiers in Climate. 1. 4. 10.3389/fclim.2019.00004.

(51) Microsoft. (2023). Microsoft Carbon Removal. https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RW16V26

(52) Minx, J. C., Probst, B. S., Lück, S., Müller-Hansen, F., Toetzke, M., Diaz Anadon, L., Engelmann, T., Greene, J., Hoffmann, V. H., Nemet, G. F., Repke, T (2024). Chapter 2: Research and development. in The State of Carbon Dioxide Removal 2024 - 2nd Edition . doi:10.17605/OSF.IO/4FGHP (2024): https://www.stateofcdr.org.

(53) Mission Innovation. (2021). Joint Mission Statement for the Carbon Dioxide Removal Mission.

(54) https://mission-innovation.net/wp-content/uploads/2021/11/Joint-Mission-Statement.pdf

(55) Ministry of Climate and Environment, Norway (2021). Act on amendments to the Climate Change Act. Retrieved from Ministry of Climate and Enviroment: https://lovdata.no/dokument/LTI/lov/2021-06-18-129

(56) National Academy of Sciences, Engineering, and Medicine (NASEM). (2019). Direct Air Capture. In E. M. The National Academies of Sciences, Negative Emissions Technologies and REliable Sequestration (pp. 189-496).

(57) National Development and Reform Commission (NDRC).(2024).Further strengthen the consctruction of a standard measurement system for carbon peak and carbon neutrality. https://zfxxgk.ndrc.gov.cn/web/iteminfo.jsp?id=20424. Last access 12 August 2024

(58) Norwegian Environment Agency. (2023). Industrial carbon removal potential, costs and possible policy instruments. https://www.miljodirektoratet.no/aktuelt/fagmeldinger/2023/mars-2023/industrien-kan-fjerne-co_2-med-virkemidler/. last access 14 July 2024

(59) Nemet, G. F., Edwards, M. R., Greene, J., Dayathilake, L., Thomas, Z. H., Surana, K., Kennedy, K. M., Zaiser, A., Probst, B. S. (2024). Chapter 3: Demonstration and upscaling. in The State of Carbon Dioxide Removal 2024- 2nd Edition. doi:10.17605/OSF.IO/DPKSB: https://www.stateofcdr.org.

(60) Northern Lights. (2023). Northern Lights enters into cross-border transport and storage agreemetn with Ørsted. https://norlights.com/news/northern-lights-enters-into-cross-border-transport-and-storage-agreement-with-orsted/. last access 14 July 2024

(61) Ocean Negative Carbon Emisions (ONCE): https://once.xmu.edu.cn/about/History.htm. Last access on 12 July 2024

(62) Oxy. (2022). Occidental, SK Trading International sign first agreement for net-zero oil created from captured atmospheric carbon dioxide. News Release: https://www.oxy.com/news/news-releases/occidental-sk-trading-international-sign-first-agreement-for-net-zero-oil-created-from-captured-atmospheric-carbon-dioxide/. last access 14 July 2024

(63) Oxy. (2023). Occidental Enters into Agreement to Acquire Direct Air Capture Technology Innovator Carbon Engineering. News Release: https://www.oxy.com/news/news-releases/occidental-enters-into-agreement-to-acquire-direct-air-capture-technology-innovator-carbon-engineering/. last access 14 July 2024

(64) Pongratz, J., Smith, S. M., Schwingshackl, C., Dayathilake, L., Gasser, T., Grassi, G., Pilli, R. (2024). Chapter 7: Current lelves of CDR. in The State of Carbon Dioxide Removal 2024-2nd Edition (eds.Smith,S.M.et al.). https://www.stateofcdr.org,.

(65) Reisinger, A., & Geden, O. (2023). Temporary overshoot: Origins, prospects, and a long path ahead. Science Direcct, 6(12), 1631-1736.

(66) Schenuit, F., Boettcher, M., Geden, O. (2023). "Carbon Management": Opportunities and risks for ambitious climate policy. https://www.swp-berlin.org/publications/products/comments/2023C29_CarbonManagement.pdf

(67) Schenuit, F., Buck, H., Geden, O., Hofbauer, V., Odeh, N., Schell, K., Sugiyama, M., Zheng, Q. (2024). Chapter 5: Policy and governance. in The State of Carbon Dioxide REmoval 2024-2nd Edition. doi:10.17605/OSF.IO/4EGUH (2024): https://www.stateofcdr.org.

(68) Schenuit,F., Brutschin,E., Geden, O., Guo,F., Mohan,A., Fiorini,A., Saluja,S., Schaeffer, R., Riahi,K. (2024). Taking stock of carbon dioxide removal policy in emerging economies: developments in Brazil, China, and India, Climate Policy, DOI: 10.1080/14693062.2024.2353148

(69) Schulte, I., Burke, J., Arcusa, S., Mercer, L., Hondeborg, D. (2024). Chapter 10: Monitoring, reporting and verification. in The State of Carbon Dioxide Removal 2024-2nd Edition. doi:10.17605/OSF.IO/ADHP2 (2024).: https://www.stateofcdr.org.

(70) Shayegh, S., Bosetti, V., Tavoni, M. (2021). Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey. Frontiers in Climate. 3. 630893. 10.3389/fclim.2021.630893.

(71) Sievert,K., Schmidt, T.S., Steffen, B. (2024). Considering technology characteristics to project future costs of direct air apture. Joule. 8. 10.1016/j.joule.2024.02.005.

(72) Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024)

(73) Tencent. (2024). Tencent Announces Winners of Flagship CarbonX Program to Combat Climate Change. https://www.tencent.com/en-us/articles/2201846.html. last access 20 July 2024.

(74) UK Government (HMG). (2023). Greenhouse Gas Removals: Update on the design of the Greenhouse Gas Removals (GGR) Business Model and Power Bioenergy with Carbon Capture and Storage Business Model. https://assets.publishing.service.gov.uk/media/6581851efc07f3000d8d447d/ggr-power-beccs-business-models-december-2023.pdf

(75) UK Government (HMG). (2021). Net Zero Strategy: Build Back Greener. https://www.gov.uk/government/

publications/net-zero-strategy. last access 14 July 2024

(76) United Nations. (2024). Secretary-General's message on World Environment Day. https://www.un.org/sg/en/content/sg/statement/2024-06-05/secretary-generals-message-world-environment-day-scroll-down-for-french-version#:~:text=It%27s%20time%20to%20break%20free,and%20reverse%20deforestation%20by%202030. last access on 12 July 2024

(77) United Nations Environment Program. (2023). Emissions Gap Report 2023: Broken Record-Tempratures hit new highs, yet world fails to cut emissions (again). United Nations Environment Programme. Nairobi: United Nations Environment Programme.

(78) World Resources Institute. (2024). The status of CCUS development in the U.S. and China. Briefing Paper - Carbon Management. https://files.wri.org/d8/s3fs-public/2024-07/2024-carbon-management-briefing-EN.pdf

(79) World Resources Institute. (2022). Carbon Remoal in the Bipartisan Insfrastructure Law and Inflation Reduction Act: https://www.wri.org/update/carbon-removal-BIL-IRA

(80) Yang, X. (2023). China continues to advance CCUS in 2023. Global CCS Institute: https://www.globalccsinstitute.com/news-media/insights/china-continues-to-advance-ccus-in-2023-learning-by-doing-after-launch-of-first-integrated-megaton-project-underscore-momentum/

(81) Yang, X., & Li, X. (2024). A gap analysis of China's regulatory framework for CO_2 geological storage. https://www.globalccsinstitute.com/wp-content/uploads/2024/04/CCS-in-China-15-April.pdf: Global CCS Institute.

Annex

1. A non-exhaustive list of DACCS projects

Plant, capacity	Plant location	Operation time	Developer	Application	Source:
Oerlikon plant	Switzerland	2016	Climeworks	Power to Methane	Howard Herzog, Director Catpure, Chapter 6, Greenhouse Gas Removal Technologies, Royal Society of Chemistry, 2022
Hinwil plant (900 t CO_2/yr)	Switzerland	2017	Climeworks	Greenhouse fertilization	https://www.mcc-berlin.net/en/news/information/information-detail/article/filtering-a-tonne-of-co_2-from-the-air-burns-a-thousand-kilowatt-hours-of-energy.html
Arctic Fox (50t CO_2/yr)	Iceland	2017	Climeworks	Geothermal plant	Arctic Fox: Climeworks first direct air capture plant.
Plant in Troia (150 tCO_2/yr)	Italy	2018	Climeworks	Power to methane	Howard Herzog, Director Catpure, Chapter 6, Greenhouse Gas Removal Technologies, Royal Society of Chemistry, 2022
Plant in Hinwil (600 tCO_2/yr)	Switzerland	2019	Climeworks	Beverage carbonation	Howard Herzog, Director Catpure, Chapter 6, Greenhouse Gas Removal Technologies, Royal Society of Chemistry, 2023
Orca (4000t CO_2/yr)	Iceland	2021	Climeworks	Geothermal plant	Orca is Climeworks' new large-scale carbon dioxide removal plant
Mammoth (36kt CO_2/yr)	Iceland	2022	Climeworks	Geothermal plant	Climeworks announced the groundbreaking of Mammoth in June 2022
Silverstone (25kt CO_2/yr)	Iceland	2025	Carbonfix OHF	Geothermal power plant	Silverstone: mimicking nature's way to transform CO_2 into stone - European Commission (europa.eu)

Plant, capacity	Plant location	Operation time	Developer	Application	Source:
Plant in Calorado (over 1000t CO_2/yr)	US	2022	Global Thermostat		Global Thermostat unveils one of the world's largest units for removing carbon dioxide directly from the air
Tracy facility in California (1000 tCO_2/yr)	US	2021	Heirloom	DAC to concrete storage	Heirloom Blog - Heirloom unveils America's first commercial Direct Air Capture facility (heirloomcarbon.com)
Project Cypress DAC Hub in Louisiana (more than 1Mt CO_2/yr	US	?	Heirloom Climworks, Battelle		Microsoft Signs One of the Largest-Ever Permanent Carbon Removal Deals - ESG Today
DAC1 in the Permian Basin (from 0.5MtCO_2/yr initially to reach 1.0Mt CO_2/yr	US	2024	1PointFive, created by Oxy Low Carbon Vendures		DAC 1 – CCUS around the world in 2021 – Analysis - IEA
Removr (300t CO_2/year in 2024 to 30kt CO_2/yr by 2027)	Norway	2023	Removr		Norway backing Removr's efforts to industrialise DAC - TCM (tcmda.com)
Carbon Removal in Øygarden (0.5-1Mt CO_2/yr)	Norway	?	Carbon Removal, Carbon Engineering, Nordic DAC Group		www.carbonremoval.no

2. A non-exhaustive list of BECCS projects

Plant, capacity (BECCS/ BECCU)	Location	Operation	Developer	Technology	Source:
Decatur plant (1MtCO_2/yr)	US	Operational since 2018	Archer Daniels Midland	Bioethanol +CO_2 capture	Hossain et al., Deployment of BECCUS value chains in the United States, IEA Bioenergy, 2023. https://www.ieabioenergy.com/wp-content/uploads/2023/03/BECCUS-1.0_US-Case-Study_final_update.pdf
Kansas Arkalon (0.2Mt CO_2/yr)	US	Operational	Booker and Farnsworth Oil	Bioethanol +CO_2 capture	Mathilde Fajardy, Chapter 5 Bioenergy with Carbon Capture and Storage (BECCS), Greenhouse Gas Removal Technologies, Royal Society of Chemistry, UK, 2022
Bonanza CCU(0.1Mt CO_2/yr)	US	Operational	Stewart Oil	Bioethanol +CO_2 capture	Mathilde Fajardy, Chapter 5 Bioenergy with Carbon Capture and Storage (BECCS), Greenhouse Gas Removal Technologies, Royal Society of Chemistry, UK, 2023
Husky Energy (250t CO_2/day)	Canada	Operational	Kushburn and Tangleflags oil	Bioethanol +CO_2 capture	Mathilde Fajardy, Chapter 5 Bioenergy with Carbon Capture and Storage (BECCS), Greenhouse Gas Removal Technologies, Royal Society of Chemistry, UK, 2024
Farnsworth (0.2Mt CO_2/yr)	US	Operational	Farnsworth oil field	Bioethanol +CO_2 capture	Mathilde Fajardy, Chapter 5 Bioenergy with Carbon Capture and Storage (BECCS), Greenhouse Gas Removal Technologies, Royal Society of Chemistry, UK, 2025
Red Trail Energy (180kt CO_2/yr)	US	Operational since 2022	Red Trail Energy LLC	Bioethanol +CO_2 capture	Red Trail Energy CCS | University of North Dakota (undeerc.org)
DRAX and C-capture (1tCO_2/day)	UK	Operational	Drax (UK)	bioelectricity plant+ post-combustion amine CO_2 capture	Mathilde Fajardy, Chapter 5 Bioenergy with Carbon Capture and Storage (BECCS), Greenhouse Gas Removal Technologies, Royal Society of Chemistry, UK, 2026

Plant, capacity (BECCS/ BECCU)	Location	Operation	Developer	Technology	Source:
Mikawa power station (640 t CO_2/day)	Japan	Demonstration since 2020	Toshiba ESS	Bioelectricity plant+ post-combustion CO_2 capture	Kitamura et al. CO_2 Capture Project integrated with Mikawa Biomass Power Plan, 2022
Klemetsrud plant (0.4 Mt wastes/ yr)	Norway	Planning		Waste-to-energy	Mathilde Fajardy, Chapter 5 Bioenergy with Carbon Capture and Storage (BECCS), Greenhouse Gas Removal Technologies, Royal Society of Chemistry, UK, 2026
Norcem cement plant in Brevik (0.4 Mt CO_2/yr)	Norway	Planning		Cement plant with 30% biomass	Mathilde Fajardy, Chapter 5 Bioenergy with Carbon Capture and Storage (BECCS), Greenhouse Gas Removal Technologies, Royal Society of Chemistry, UK, 2027
ARV Duiven (0.8tCO_2/yr)	Netherland	Operational since 2019	AVR	Waste-to-energy	PRESS RELEASE First tons of CO_2 captured from residual waste supplied to greenhouse horticulture - AVR - Too good to waste
Stockholm Exergi	Sweden	To be operational by 2026	Exergi	Biomass-based combined heat and power plan	Our pilot facility - Beccs Stockholm
Nordbex	Sweden	?	Nordbex	Biomass-based power plant	"www.nordbex.com"
Ørsted Kalundborg Hub (0.43 Mt CO_2/yr)	Denmark	Operational in 2025	Ørsted	Biomass-based power plants in Western Zealand and the Greater Copenhagen area	Ørsted awarded contract – will capture and store 430,000 tonnes of biogenic CO_2 (orsted.com)
Heartland (200 kt waste/yr, 0.185 Mt CO_2/yr)	Canada	2027	Varme	Waste-to-energy	Projects | Varme Energy
Hams Hall (0,15 Mt waste/yr, 0.195 Mt/CO_2/yr)	UK	2027	Varme	Waste-to-energy	Projects | Varme Energy

Plant, capacity (BECCS/ BECCU)	Location	Operation	Developer	Technology	Source:
Innisfail (0.15 Mt waste/yr, 0.135 Mt CO_2/yr)	Canada	2028	Varme	Waste-to-energy	Projects | Varme Energy
CO2 Energy AG in Nesselnbach (3 Kt CO_2/yr)	Switzerland	Operational	C2G Energy AG	CO_2 separated from methane and then liquefied for use	Regionalwerke Baden: "The pilot project opens the door for Swiss bioenergy with Carbon Capture ("BECCUS") (ascoco$_2$.com)
Karbonwerke (94 t CO_2/day)	Switzerland	Operational	Karbonwerke	capture and liquefy CO_2 from biogas or biorefineries for storage	Carbon Removal at Scale for Companies | Karbonwerke
Plant in Oslo (0,2Mt CO_2/yr)	Norway	Set on hold in 2023 due to higher cost	Hafslund Oslo Celsio	waste-to-energy	Carbon capture projects at the plant of Hafslund Oslo Celsio (ccsnorway.com)

3. A non-exhaustive list of policy developments

	Legislation and strategy	Fiscal incentives (Subsidy; tax credit)	Public procurement	Market-based (carbon pricing and markets)	Regulatory frameworks (MRV, fungibility)	R&D
US	The long-term strategies of the United States to Net Zero GHG Emissions by 2050, 2021. Projects the to deliver 1Gt CO_2 per year by 2050 through both land-based and novel CD	Tax credit: 45Q Enhancement in the Inflation Reduction Act. Incentives increase from \$50 to \$180/ ton for storage from DAC. For DAC facilities, required amount of CO_2 from 100,000 captured/yr to 1,000 ton/yr.	DOE's Carbon Dioxide Removal Purchase Pilot providing up to \$ 35 million in awards to CDR credits providers	In March 2024, the Government proposed Voluntary CDR Purchase Challenge to catalyze voluntary purchase of high-quality CDR credits	No comprehensive MRV standards or regulations being introduced. The CDR Purchase Pilot Prize has official rules requesting a clear description of the CDR activities and MRV process, including a whole life cycle assessment, forecasted costs, an overview of the anticipated durability and permanence	Bipartisan Infrastructure Law provides funding streams into novel CDR, in total of \$12 billion, including in particular \$3.5 billion for building four regional DAC hubs and \$ 115 million for the DAC Technology Prize Competition. \$2.1 billion for CO_2 transport and \$2.5 billion or carbon storage validation and testing

	Legislation and strategy	Fiscal incentives (Subsidy; tax credit)	Public procurement	Market-based (carbon pricing and markets)	Regulatory frameworks (MRV, fungibility)	R&D
EU	The European Climate Law set a target of climate neutrality objective by 2050. The EU adopted the Industrial Carbon Management Strategy, making novel CDR (BECCS and DACCS), an important part of the EU decarbonization effort.	None	None	The Industrial Carbon Management Strategy lays out the potential policy options and support mechanisms for BECCS and DACCS including through the EU ETS, and additional investment needs for CO_2 transport and infrastructure	The European Commission reached a provisional political agreement on the Carbon Removal Certification Framework, a voluntary regulatory framework for the certification of permanent carbon removals, carbon farming and carbon storage in products. It also updated the reporting templates allowing member countries to report on BECCS and DACCS	The Innovation Fund Call for 2023 opened on 23 November 2023 with a total budget of EUR 4 billion. Certain carbon removal projects can benefit from IF funding through the category of CCS and CCU but CDR is not explicitly listed as a targeted area. in 2023, Stockholm Exergi's BECCS Stockholm project was awarded an IF grant of EUR 180 million and Carbfix's Silverstone project was awarded EUR 3.8 million.

	Legislation and strategy	Fiscal incentives (Subsidy; tax credit)	Public procurement	Market-based (carbon pricing and markets)	Regulatory frameworks (MRV, fungibility)	R&D
UK	The Net Zero Strategy 2021 set objective of removing 5MtCO_2/yr by 2030.	None	None	In July 2023 the government confirmed its position that the UK Emissions Trading Scheme (ETS) will be an appropriate long-term market for GGRs. The UK ETS Authority is expected to carry out a further consultation on GGR inclusion in the UK ETS, which will consider market design, eligibility requirements, and the timing of inclusion.	Commissioned by the UK government, A Review of Engineered Greenhouse Gas Removal (GGR) Standards and Methodologies was published in 2023. Based on the findings, the government indicated its intention to define its own methodologies for GGR projects supported under the business model, ensuring alignment with its MRV policy principles and creating consistency across existing government standards,	In 2020, UKRI provided £100 million for research, development and demonstration of GGR across multiple programmes. This funding includes allocations for a central hub for carbon removal and five land-based CDR demonstrator projects including enhanced weathering and biochar. It also includes a competition on Direct Air Capture and other Greenhouse Gas Removal technologies. This programme aims to produce several operational pilot plants by 2025

	Legislation and strategy	Fiscal incentives (Subsidy; tax credit)	Public procurement	Market-based (carbon pricing and markets)	Regulatory frameworks (MRV, fungibility)	R&D
Switzerland	The Swiss National Long-Term Strategy set net zero GHG emissions by 2050, quantifying a need for CDR of 7MtCO_2/year by 2050, 5Mt of which to be achieved domestically through BECCS, and 5Mt to be achieved abroad, mostly through DACCS.	Establishment of a national working group on CCS/CDR with the involvement of relevant offices and private sector. Governmental support for the Swiss Carbon Removal Platform launched by the Risk Dialogue Foundation	KLIK Foundation is required by the Swiss CO_2 Act to purchase certified CDR to compensate about 10% of Swiss emissions	The CCS and CDR Roadmap aims to create the legal framework at the national and international levels for CDR to scale, including creation of precedents through requirements in bilateral treaties, establishment of NET certificates on the international CO_2 market and their recognition under the Paris Agreement, ISO standards and life cycle assessment (LCA) databases, etc.).	Being active in setting the legal framework at the national and international levels for CDR to scale, including creation of precedents through requirements in bilateral treaties, establishment of NET certificates on the international CO_2 market and their recognition under the Paris Agreement, ISO standards and life cycle assessment (LCA) databases, etc.).	The CCS and CDR Roadmap set several support mechanisms for the development of CDR.

	Legislation and strategy	Fiscal incentives (Subsidy; tax credit)	Public procurement	Market-based (carbon pricing and markets)	Regulatory frameworks (MRV, fungibility)	R&D
Switzerland	The Climate Change Act (MoCE, 2021) sets a 90%-95% emission reductions target by 2050 compared to 1990 emissions levels. CCS is playing a pivotal role in Norway's efforts to deliver on national mitigation target and store imported CO_2 from abroad.	The Norwegian Environment Agency proposed tax reverse, rewards, and integration of CDR into voluntary market in the Industrial carbon removal-potential, costs and possible policy instruments	None	Norway signed an agreement with Switzerland to launch pilot activities aiming at testing transactions and reporting CDR.	None	Norway's CLIMIT Programme has supported a limited number of DACCS and BECCS projects. The Longship CCS project consists of three parts: Northern Lights provides storage location for domestic use and other countries (Netherlands, Denmark, Switzerland)

	Legislation and strategy	Fiscal incentives (Subsidy; tax credit)	Public procurement	Market-based (carbon pricing and markets)	Regulatory frameworks (MRV, fungibility)	R&D
Canada	Canada's Carbon Management Strategy 2023 recognizes the important role of BECCS and DACCS in reaching Canada's net zero target, and sets out a number of support policies and regulations	Tax credit rates: 60% for DAC; 50% for capture equipment in all other projects; 37.5% for transportation, storage, and utilization.	Canadian Greenhouse Gas Offset Credit System was approved in 2022. Bioenergy carbon capture and sequestration (BECCS) has been identified as a project type under consideration for future protocol development	The price on carbon pollution started at $20/t in 2019 and increased by $10/t per year to $50/t in 2022. Starting in 2023, the price will increase by $15/t each year to reach $170/t in 2030. The carbon pricing system recognizes storage in deep saline aquifers and depleted oil reservoirs, which provides an incentive to invest in carbon management technologies with permanent storage.	By 2030, Provincial and federal regulatory frameworks are in place to enable re-use and removal of CO_2, along with safe and permanent CO_2 storage.	Budget 2021 committed $319 million/7 years to support RD&D to improve the commercial viability of carbon management technologies—including CO_2 capture, DAC, and CO_2 utilization, transport, and storage across a broad range of sectors.