Carbon Dioxide Removal

Europe and Germany's Role in Catalyzing a Trillion-Euro Industry

June 2024

BCG + DVNE

Boston Consulting Group partners with leaders in business and society to tackle their most important challenges and capture their greatest opportunities. BCG was the pioneer in business strategy when it was founded in 1963. Today, we work closely with clients to embrace a transformational approach aimed at benefiting all stakeholders—empowering organizations to grow, build sustainable competitive advantage, and drive positive societal impact.

Our diverse, global teams bring deep industry and functional expertise and a range of perspectives that question the status quo and spark change. BCG delivers solutions through leading-edge management consulting, technology and design, and corporate and digital ventures. We work in a uniquely collaborative model across the firm and throughout all levels of the client organization, fueled by the goal of helping our clients thrive and enabling them to make the world a better place.

The German Association for Negative Emissions (DVNE) was founded in July 2023 as the European Union's first national CDR association. DVNE is a multi-stakeholder, industry-led platform to facilitate collaboration and the development of policies conducive to the formation and scale-up of an equitable, world-class carbon dioxide removal industry in Germany to realize net zero by 2045 and net negative thereafter. Our dynamically growing member base includes large corporations as well as start-ups and scale-ups in the CDR sector.

Together with decision-makers from politics and business, we help to translate the standards formulated by the IPCC into concrete action. To this end, we create knowledge, connect stakeholders, and give the CDR sector a voice to support its scaling.

Carbon Dioxide Removal

Europe and Germany’s Role in Catalyzing a Trillion-Euro Industry

Table of contents

Foreword

Dear Readers,

Carbon dioxide removal (CDR) emerges as an increasingly necessary and viable element for combating climate change. To keep the ambition of the Paris agreement within reach, emissions reductions and removals are most crucially needed—supported by massive adaptation efforts to counter the worst effects of global warming.

Efforts to reduce greenhouse gas emissions continue to fall short of what is needed; for a 1.5°C-compatible pathway, we would need to reduce emissions by 7% annually, against a recent trend of a 1.5% annual increase. Similarly, while crucially needed, adaptation alone will be insufficient; we cannot adapt ourselves out of a 3°C world. And any meaningful long-term climate scenario encompasses significant negative emissions to get greenhouse gases in the atmosphere back to acceptable levels.

In this context, the human-made ability to remove carbon dioxide from the atmosphere is becoming a crucial element of any meaningful climate strategy. Beyond its climate impact potential, carbon dioxide removal offers sizable economic potential. In this report, we explore this potential along the value chains of different CDR methods. We spotlight the opportunities for German and European companies and countries and the job potential inherent in scaling the CDR industry.

Realizing the potential identified in this report requires bold and timely action: Policymakers, CDR companies, certificate buyers, and investors must collectively embrace decisive measures. Only then can we unlock this trillion-euro opportunity on our path to net zero and beyond.

Enjoy reading!

Stefan Schlosser
Managing Director, DVNE

Patrick Herhold
MD & Senior Partner, BCG

Contributors

This report was prepared by the German Association for Negative Emissions (DVNE) and Boston Consulting Group (BCG), with special support from several DVNE member companies.

Lead authors

BCG

Patrick Herhold
Johanna Pütz
Karan Mistry
Robin Bierganz
Phillip Spiekermann
Louisa Maier

Co-authors

DVNE

Stefan Schlosser
Sebastian Hanss-Mirodone

LANDWÄRME

Caroline Braun
Sarah-Luise Grimm

Carbonfuture

Nikolaus Wohlgemuth

PYREG

Jörg zu Dohna
Marcel Rensmann

CZR

Magnus Drewelies

TREEO

Johannes Schwegler
Constanze Adolf

e.on

Julia Mühleiß

ZeroEx

Tony Oehm

Acknowledgements

The author team extends their sincerest gratitude for the collaboration and valuable insight provided by the DVNE sounding board:

Name	Organization
Jodok Batlogg	Tree.ly
Mevina Caviezel	CarbonX
Carolin Güthenke	German Biochar
Lisa Mangertseder	Carbon Removal Partners
Sebastian Manhart	DVNE
Dirk Paessler	Carbon Drawdown Initiative
Philipp Rothenberger	Carbon Atlantis
Oscar Schily	Climeworks
Venna von Lepel	Novocarbo

We furthermore acknowledge the invaluable time and knowledge shared by:

Name	Organization
Martin Albicker	Deutsche Energie-Agentur (DENA)
Oliver Geden	Stiftung Wissenschaft und Politik (SWP)
Pascal Hader-Weinmann	Deutsche Energie-Agentur (DENA)
David Keller	GEOMAR

Lastly, we would like to thank Nicole Herold, Elisabeth Harding, and Amy Sims for their support.

Executive summary

Carbon dioxide removal (CDR) is an integral component of climate change mitigation

Carbon dioxide removal is essential for meeting global climate goals - given the divergence between emission reduction targets and our current policies and actual progress, and due to the long-term need for substantial negative emissions. While the Paris Agreement has galvanized global commitment to limit warming to 1.5°C, achieving this requires CDR to neutralize residual emissions that are hard to abate, such as in the cement sector. All IPCC pathways compatible with 1.5°C or 2°C include CDR to achieve a “net zero” emissions world. To meet the 1.5°C pathway, CDR needs to reach approximately 9 gigatons of CO_2 annually by 2050.

CDR methods have a unique combination of advantages, co-benefits and limitations

There are a broad range of CDR methods which can be classified into three categories: nature-based removal (e.g., afforestation), enhanced natural processes (e.g., enhanced (rock) weathering or biochar carbon removal), and technology-based removal (e.g., bioenergy with carbon capture and storage). Each method varies in technology intensity, permanence, scalability, ease of monitoring, and cost. For instance, while most nature-based solutions are immediately implementable and cost-effective, technology-based solutions offer higher durability but are currently more expensive and less technologically mature.

CDR can become a global nearly trillion-Euro industry

The global economic potential of CDR could reach €470-940 billion per year by 2050 in a 2.0°C and a 1.5°C pathway, respectively—at par with today’s global airline industry. This potential hinges on significant cost reductions across CDR methods, driven by technological advancements and economies of scale. For example, costs for direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS) could decrease by 50-60% compared to 2023 levels, while enhanced (rock) weathering (ERW) and biochar carbon removal (BCR) could see reductions of 35-65%. Conversely, nature-based methods might see cost increases due to rising input prices, land competition, and stricter monitoring and reporting requirements.

Europe, and especially Germany can be catalysts for a thriving CDR industry

The EU-27 and Germany, in particular, are uniquely positioned to lead the global CDR market due to their technological prowess, robust industrial base, and progressive climate policies. Germany’s commitment to net-zero emissions by 2045 and its influential role in European climate policy further underline its leadership potential. The European (German) CDR industry could grow to €220B (€70B) per year by 2050, creating up to 670K (190K) jobs.

Bold and decisive measures are needed now across stakeholder groups

As a society, we are currently not on a path to realize the full potential of CDR. While there are clear signs that interest in CDR is constantly growing, much more effort is needed to harness its benefits fully. Achieving the full potential of CDR requires concerted efforts from policymakers, industry, buyers, and investors. A 15-point action plan outlines necessary measures to overcome current roadblocks, such as regulatory uncertainty, high costs, technical challenges, and limited funding to enable large-scale CDR deployment. Actions range from specific policy measures over technological advancements to early, long-term offtake commitments and tailored funding mechanisms that could jointly support the swift uptake of the global CDR industry.

Objectives of this report

This report has three objectives:

- The primary objective is to explore and demonstrate the economic potential of carbon dioxide removal (CDR), specifically for Europe and Germany.
- Additionally, the report aims to provide a comprehensive overview of the quickly evolving CDR landscape while distinguishing CDR from other related concepts.
- Lastly, the report emphasizes the need for swift and decisive action by providing a specific, stakeholder-oriented action plan to realize the economic potential outlined.

The report elaborates on the role of CDR in climate change mitigation and evaluates different CDR methods. It builds on existing climate research and uses four distinct CDR volume scenarios to project possible demand development until 2050 from both a climatic need viewpoint and current trajectories and announced targets.

In the context of carbon offsetting credits, many existing reports have remained at a high level regarding discussing the development of avoidance and removal credits. Others have focused solely on the overall demand for CDR without differentiating between the variety of possible methods it encompasses.

This report examines removal in much more detail. It offers four specific, conceivable CDR portfolio compositions based on cost expectations, regulatory development, and other assumptions.

To make discussions concrete, the report explores a specific combination of required CDR volumes and potential portfolio compositions that illustrate the tangible impacts of CDR globally. It explores the economic potentials for Germany and Europe and discusses job potential driven by the uptake of CDR.

There is no realistically conceivable way to reach our climate goals that does not include a substantial amount of carbon dioxide removal.

1 Carbon dioxide removal (CDR) is instrumental for climate protection

1.1 CDR is an integral component of climate change mitigation

Current climate policies are still far from our required 1.5°C pathway

Since the 2015 Paris Agreement, the ambition to limit global warming to 1.5°C has been the hallmark of good climate policy. While >96%[1] of the world's greenhouse gases are now emitted by countries that have pledged commitment to this ambition, actual policies still do not put the world on a path to reach this target. There is a significant divergence between our current trajectory, nationally determined contributions (NDCs) towards emission reduction, and the pathways compatible with limiting global warming to below 2°C and 1.5°C, respectively.[2] This underscores the urgent need for more political action and a broader set of instruments.

All IPCC pathways include CDR to reach net zero by 2050

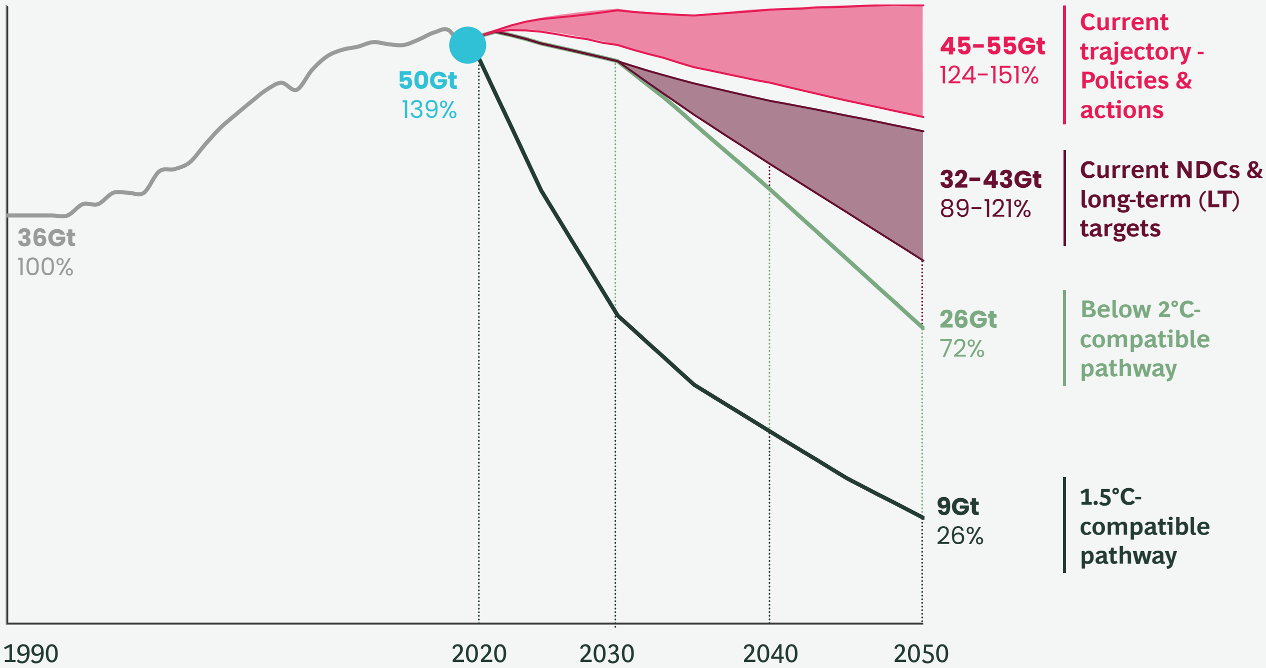
The focus of current climate policy is—and rightly should be—reducing the amount of carbon dioxide and other greenhouse gases that are emitted into the atmosphere. This primarily requires a shift away from fossil fuels in all sectors of the economy, including electricity production, transportation, buildings,

[1] World Resources Institute, March 2023.

[2] Lamb et al., 2024.

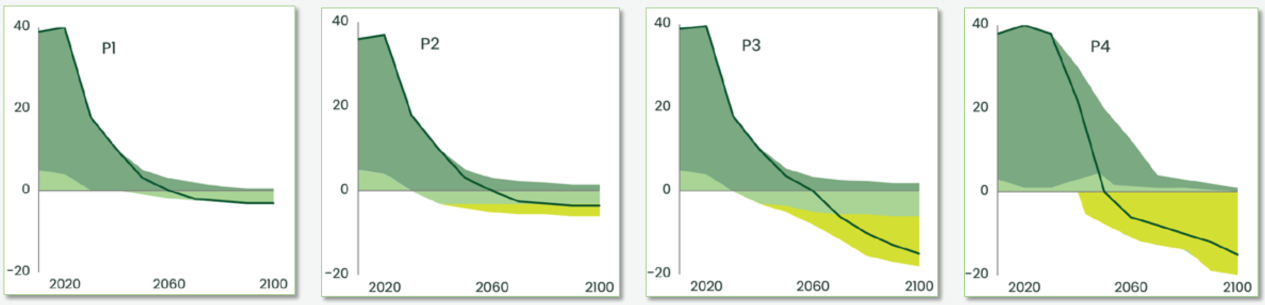
FIGURE 1

Global GHG emissions (Gt CO_2e p.a., indexed to 100% based on 1990 values)



Note: Nationally Determined Contributions (NDCs) are each country's climate action plans to reduce greenhouse gas emissions under the Paris Agreement
Source: IEA; Climate Action Tracker; BCG analysis

FIGURE 2



Pathway 1
Low energy demand, higher living standards; afforestation CDR

Pathway 2
Sustainable consumption patterns, some technical CDR

Pathway 3
Limited demand reduction, increased reliance on CDR

Pathway 4
Resource- and energy-intensive global economy, strong CDR focus

Fossil fuel and industry | Nature-based CDR[1] | Other CDR[2] | Net GHG emissions

- + **Flexible approach** involving a **variety of methods** that are not necessarily tied to industrial processes or locations
- + Can address both **residual emissions** that are still being emitted and CO_2 **historically released** into the atmosphere
- + Combines climate change mitigation with **economic potential and job creation**
- − Should only be considered as a **complementary option** and not used where emission reductions are feasible

1. AFOLU in IPCC 2. IPCC pathways only model BECCS – not further differentiated here
Source: IPCC AR6 Mitigation of Climate Change; IPCC SR15 special report; BCG analysis

The IPCC defines CDR as a deliberate, intentional human activity to remove and store CO_2

“

Carbon dioxide removal (CDR) encompasses a range of technologies, practices, and approaches designed to remove and store carbon dioxide (CO_2) from the atmosphere, preventing it from further contributing to global warming.[3]

CDR is…

… necessary to reverse and stabilize rising atmospheric CO_2 concentrations

… critical for significantly mitigating the impacts of global warming

… imperative for meeting ambitious net-zero emissions targets and goals

and industry. Additionally, reduction could include solutions like point source carbon capture and storage (CCS).

However, credible scientific pathways to reach net zero do not rely on emission reduction alone. Emission scenarios by the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and further research institutes stipulate that the removal of carbon dioxide from the atmosphere (or the upper hydrosphere)[4] is urgently required to limit global warming. CDR is essential to neutralize the effect of residual emissions from hard-to-abate sectors like steel, cement, chemcals, and others. Moreover, it can “clean up” historic emissions. This is a decisive benefit as historically emitted carbon dioxide (CO_2) can remain in the atmosphere for multiple centuries.[5] The multitude of available removal methods is elaborated on later in this chapter.

All modeled IPCC pathways that limit global warming to 1.5°C or 2°C include a varying amount and portfolio of CDR, addressing the residual emissions that cannot be eliminated through reduction efforts alone, either due to technical restrictions or prohibitive cost (Figure 2).

3 Adapted definition, based on IPCC AR6 WGIII Factsheet.
4 In the remainder, atmosphere and upper hydrosphere (0-200m) will be considered equivalent for simplicity.

5 Umweltbundesamt, 2022.

GHG emission reduction (CO_2e)	Carbon dioxide removal
Technologies, practices, and approaches that **reduce the amount of CO_2 emitted** into the atmosphere	Technologies, practices, and approaches that **remove CO_2** from the atmosphere **and store it**

1.2 CDR encompasses an array of methods

CDR methods can be categorized based on their technology intensity

As the concept of carbon dioxide removal (CDR) is still nascent, there is no universally accepted classification system for CDR methods, nor is the list of CDR methods exhaustive. This report categorizes CDR methods into three main types: nature-based removals, enhanced natural processes (hybrid), and technology-based removals. Nature-based removals involve natural processes such as protecting, restoring, or managing ecosystems to sequester carbon. Enhanced natural processes can be considered ‘hybrid’ as they involve augmenting natural carbon sequestration mechanisms via technological means or significant human intervention to accelerate the capture and storage of CO_2. Technology-based removals involve the use of man-made technologies to capture CO_2 from the atmosphere and store it permanently. This report focuses on CDR methods that are commonly described in literature such as afforestation, reforestation, improved forest management, biochar carbon removal, or bioenergy with carbon capture and storage.[6]

6 IPCC AR6 Mitigation of Climate Change; The State of Carbon Dioxide Removal, 2024.

FIGURE 3

Conventional

NATURE-BASED REMOVALS

Afforestation, reforestation, improved forest mgmt.
Planting forests & restoring existing ones to absorb CO_2 via photosynthesis (incl. durable wood products[1])

Soil carbon sequestration
Implementing agricultural practices that enhance the capacity of soils to hold carbon

Peatland and wetland restoration
Restoring peat- & wetlands to their natural state to enhance their ability to store carbon

Blue carbon management
Conserving & restoring coastal/ marine ecosystems, like mangroves, salt marshes, and seagrasses

Novel

ENHANCED NATURAL PROCESSES (HYBRID)

Enhanced (rock) weathering
Spreading finely ground silicate rocks over large areas to chemically react with CO_2 and form stable minerals

Biochar carbon removal
Converting biomass residues or other biogenic material into a stable form of carbon, which is used to enhance soils or used in durable products, e.g., asphalt or cement

Biomass burial
Burying organic material to prevent decomposition & carbon release

Biomass sinking
Sinking terrestrial or marine biomass into the ocean to sequester CO_2 at ocean floor

Ocean/river alkalinity enhancement
Adding minerals to oceans/rivers to increase alkalinity and enhance the water's capacity to absorb CO_2

Ocean fertilization[2]
Adding nutrients to oceans to boost phytoplankton growth (which absorbs CO_2 via photosynthesis)

TECHNOLOGY-BASED REMOVALS

Direct air carbon capture and storage
Capturing CO_2 directly from the atmosphere and storing it underground or using it in durable products

Bioenergy with carbon capture and storage[3]
Producing energy or methane from biomass, capturing & storing CO_2 or using it in durable products[1]

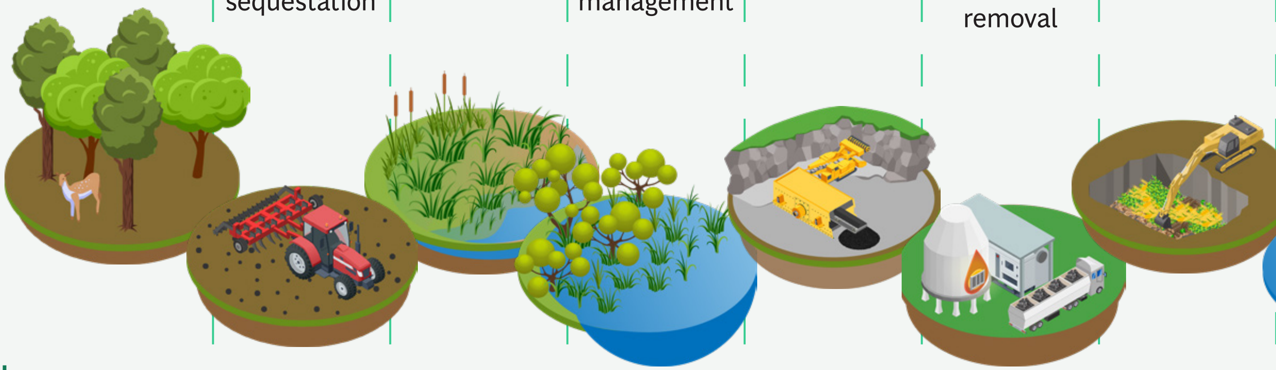
Bio-oil injection
Converting biomass into bio-oil and injecting it into geological underground formations

Direct ocean removal[4]
Energy-powered carbon removal directly from ocean using membrane and electrodialysis technology

1. Durable wood products and mineral products considered as separate CDR methods in other reports – subsumed under use phase of respective CDR methods in this report 2. Includes artificial upwelling 3. The currently emerging broader term "Bio-CCS" includes a variety of implementation options not solely related to capturing CO_2 in energy production – in this study, we use BECCS and subsume Waste-to-energy plants with subsequent CCS and biogas producing facilities with CO_2 capturing, liquefaction and storage 4. Includes Direct Ocean Capture and Electrochemical Ocean Removal
Source: IPCC; Expert interviews; BCG analysis

FIGURE 4

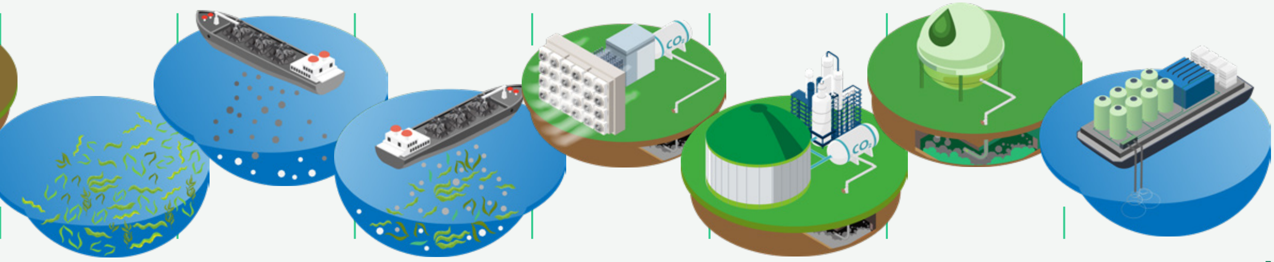
	Conventional						
CDR method	Afforestation, reforestation, improved forest management	Soil carbon sequestration	Peatland and costal wetland restation	Blue carbon management	Enhanced (rock) weathering	Biochar carbon removal	Biomass burial



Method characteristics							
Technological intensity	Nature-based removals				Enhanced natural		
Location	Land	Land	Land	Ocean	Land	Land	Land
Capture process	Biological	Biological	Biological	Biological	Geochemical	Biological	Biological
Carbon storage pool	Biosphere (Vegetation, soils & sediments)	Biosphere (Vegetation, soils & sediments)	Biosphere (Vegetation, soils & sediments)	Hydrosphere (Vegetation, soils & sediments)	Hydrosphere (Minerals)	Biosphere & lithosphere (Vegetation, soils & sediments)	Biosphere (Vegetation, soils & sediments)
Qualitative comparison							
Permanence	Decades to centuries	Decades to centuries	Decades to centuries	Decades to centuries	>10 millennia	>10 millennia[1]	Decades to centuries
CO_2 removal potential	Large	Moderate	Moderate	Small	Large	Moderate	Moderate
Ease of MRV	Medium	Hard	Hard	Hard	Hard	Medium	Medium
Readiness to scale	High	High	High	Low	Medium	High	Low
Cost 2050 (€/ton CO_2)	<100	<100	<100	10 150	50 200	50 160	N.A.

1. Permanence of >10 millennia particularly applies to inertinite biochar
Source: IPCC, DVNE Working Group, expert opinion, Bustamante M et al. (2024), Rhodium Group (Jones et al. 2024), IVL (Bednar et al. 2023); State of CDR (Geden et al. 2024); BCG analysis

Novel							
Biomass sinking	Ocean/river alkalinity enhancement	Ocean fertilization	Direct air carbon capture and storage (DACCS)	Bioenergy with carbon capture and storage (BECCS)	Bio-oil injection	Direct ocean removal	**CDR method**



							Method characteristics
processes (hybrid)			Technology-based removals				Technological intensity
Ocean	Ocean	Ocean	Land	Land	Land	Ocean	Location
Biological	Geochemical	Biological	Geochemical	Biological	Biological	Geochemical	Capture process
Hydrosphere (Marine sediments)	Hydrosphere (Minerals)	Hydrosphere (Marine sediments)	Biosphere (Geological formations)	Biosphere (Geological formations)	Biosphere (Geological formations)	Hydrosphere (Geological formations)	Carbon storage pool
							Qualitative comparison
Centuries to millennia	>10 millennia	Centuries to millennia	>10 millennia	>10 millennia	>10 millennia	>10 millennia	Permanence
Large	Large	Large	Large	Large	Moderate	Large	CO_2 removal potential
N.A.	Hard	Hard	Easy	Easy	Easy	Medium	Ease of MRV
Low	Low	Low	Medium	Medium	Medium	Low	Readiness to scale
N.A.	40 260	50 500	100 400	50 250	N.A.	N.A.	Cost 2050 (€/ton CO_2)

Figure 3 provides a detailed overview of CDR methods in the three categories. An alternative categorization refers to nature-based removals as "conventional" CDR methods while subsuming both enhanced natural processes and technology-based removals under "novel" CDR methods—this categorization is added for reference in Figures 3 and 4 but not used in the remainder of this document.

CDR methods can differ substantially from each other. Each CDR method utilizes a different capturing process and carbon storage pool, has a different technological intensity (see above), and is deployed on land or in an ocean environment. Beyond the fundamental way of functioning, CDR methods each have a unique set of advantages and disadvantages. The main criteria used to describe and compare different CDR methods are:

- **Permanence:** Describes the time scale of CO_2 storage and is an important measure to ensure that CO_2 removal is not reversed.
- **Removal potential:** Describes a method's theoretical global potential to sequester CO_2, e.g., given the earth's geological boundaries.
- **Ease of measurement, reporting, verification (MRV):** Describes the effort required to verifiably measure and track the amount of CO_2 removed by a specific method.
- **Current (technological) readiness to scale:** Describes the maturity of a CDR method, e.g., scalability beyond a laboratory testing environment.
- (**Expected**) **cost per ton of removal:** Describes the cost of creating a verified certificate of one metric ton of CO_2 removal through a respective method.

Figure 4 provides a comprehensive overview of all CDR methods and their rating along these criteria.

1.3 Strong CDR growth anticipated, but current roadblocks delay uptake

All scenarios expect CDR to grow strongly, but the total volume is uncertain

The current market for CDR is tiny, and while projections indicate a solid upward trend, the overall development of CDR volumes remains highly uncertain. Removals accounted for 0.015 Gt of credit retirement volumes in the voluntary carbon market 2023.[7] Given their non-additionality, this study does not include c. 2.2 Gt CO_2 of nature-based removals in countries' national GHG inventories at its starting point.[8] The growth of CDR is contingent on various factors, including technological advancements, policy and regulatory support, public and private sector investments, and infrastructure development for large-scale deployment. Discrepancies in volume projections arise mainly from different temperature targets, varying assumptions about emissions reductions, and diverse methodologies employed in these projections.

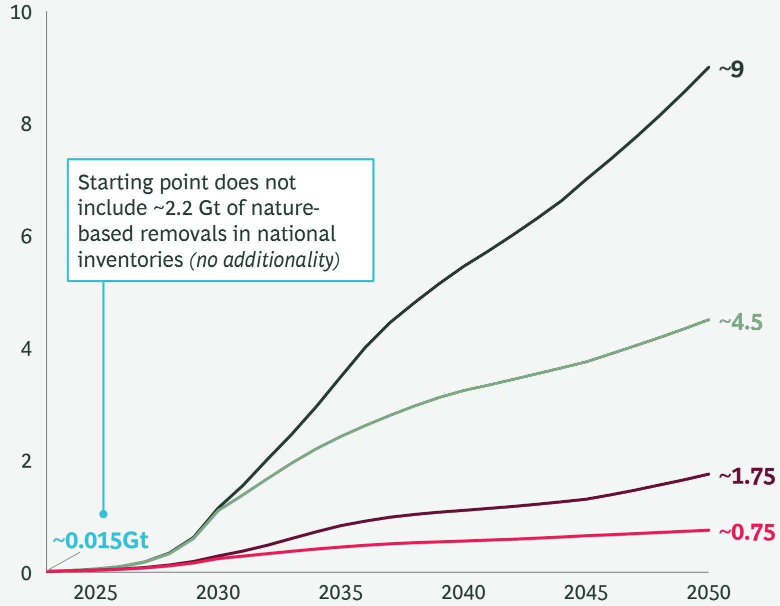
This paper's projections draw from a synthesis of research papers, meta-analyses of mitigation pathways, and international policy commitments.[9] Four distinct pathways can illustrate the potentially required global CDR volume (Figure 5). Their derivation and implications are described in the following section.

1. **Current trajectory**
   Based on existing commitments and pledges, the current trajectory projects a CDR volume of around 0.75 Gt CO_2 p.a. by 2050. This projection draws on global demand forecasts for durable CDR and is extrapolated to include CDR with lower durability.[10]

[7] Voluntary Carbon Market 2023 Review, Climate Focus.
[8] The State of Carbon Dioxide Removal, 2024.
[9] Lamb et al., 2024, Prütz et al., 2023, Fuss et al., 2018, IPCC AR6.
[10] The Time for Carbon Removal Has Come, 2023.

FIGURE 5

Required global CDR volume under different scenarios (Gt CO_2 p.a., 2023-50)



1.5°C-compatible removal pathway
Median annual CDR deployment at Net Zero in IPCC AR6 1.5°C-compatible and high overshoot pathways[1]

Below 2°C-compatible removal pathway
Median annual CDR deployment in 2050 in IPCC AR6 below 2°C-compatible pathways[2]

Current NDCs & long-term targets
Based on 111 NDCs (2030) and all long-term strategies for 2050 up to Nov. 23 (COP28)[3]

Current trajectory
Current trajectory based on current commitments and pledges

1. Ruben Prütz et al: Analysis of 83 1.5°C compatible and high overshoot IPCC AR6 WGIII pathways 2. Lamb et al: Analysis of scenarios in categories C1 and C3 of IPCC AR6 scenario database 3. Lamb et al.; Includes assumption that countries without a quantifiable strategy preserve their current levels of conventional CDR on land
Note: Variance of CDR volumes in IPCC AR6 pathways is very high, indicating diverging beliefs in degree of emission reduction
Source: IPCC AR6 WGIII Chapter 12; Ruben Prütz et al. 2023 Environ. Res. Commun.; Lamb et al. 2024, Nature Climate Change; IEA Net Zero Roadmap; BCG CDR Market Model

2. **Current NDCs & long-term targets**
   Anticipated CDR volumes based on 111 existing Nationally Determined Contributions (NDCs) and all long-term mitigation strategies up to November 2023 (COP28) could achieve a volume of around 1.75 Gt CO_2 by 2050.[11]

3. **Below 2°C-compatible pathway**
   To limit temperature increases to below 2°C, a CDR volume of around 4.5 Gt CO_2 p.a. in 2050 could be required. However, substantial uncertainty exists about the exact amount of CDR required to meet below 2°C targets. Analysis of applicable scenarios in the IPCC AR6 scenario database indicates a range of 0.92 to 11 Gt CO_2.[12] Given that the median value of 4.5 Gt CO_2 represents a more than 2.5-fold increase of the expected 2050 volume compared with the projection based on current NDCs and long-term mitigation strategies, achieving it requires significant investments and concerted action from all stakeholders.

4. **1.5°C-compatible pathway**
   For a 1.5°C-compatible pathway, CDR needs to reach approximately 9 Gt CO_2 annually by 2050. The range indicated in different IPCC AR6 scenarios is enormous, ranging from 3.5 to 18 Gt CO_2.[13] The median value of 9 Gt CO_2 indicates a substantial gap between pathways 1 to 3 and the necessary CDR deployment to reach the 1.5°C climate goal. It underscores the need for significant advancements in emission reduction technologies and robust financial and policy support to scale CDR methods effectively.

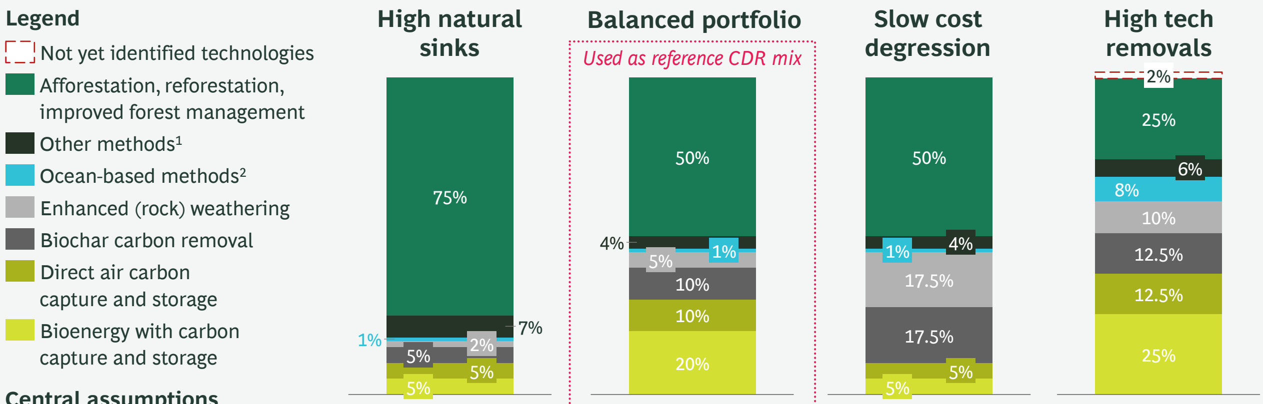
The future volume of CDR, both in total and for individual CDR methods, is highly uncertain. Out of the four scenarios described above, this report focuses on the 1.5°C- and 2°C-compatible removal pathways. The 2°C-compatible removal pathway provides a realistic perspective given historical developments and current roadblocks, while the 1.5°C-compatible removal pathway represents an ambitious target aligned with existing climate policies. This approach balances practicality with the need for bold action to meet stringent climate goals.

11 Lamb et al., 2024.
12 Lamb et al., 2024.
13 Ruben Prütz et al., 2023.

FIGURE 6

CDR portfolio composition (2050 scenarios in % of total volume p.a.)

Global



Central assumptions

	High natural sinks	Balanced portfolio	Slow cost degression	High tech removals
Cost degression of technology-based removals vs. 2023	20-40%	40-60%	20-40%	60-80%
Regulatory enforcement of high-durability CDR	Weak	Moderate	Moderate to strong	Strong
Infrastructure build-out (e.g., CO_2 pipelines, RES)	Slow	Moderate to fast	Slow to moderate	Fast
Credibility improvements, e.g., for MRV-heavy CDR methods	High for afforestation, low for others	Low	High	Medium
Willingness to pay for average CDR portfolio	Low	Medium to high	Medium	High

1. Includes soil carbon sequestration, peatland & wetland restoration 2. Includes ocean alkalinity enhancement, ocean fertilization, blue carbon management, direct ocean removal
Note: Figures rounded
Source: IPCC AR6 WGIII Chapter 12; IEA Net Zero Roadmap; Climate Focus, Voluntary Carbon Market 2023 Review; BCG CDR Market Model

Several long-term scenarios are conceivable for CDR portfolio composition

The volume of CDR is uncertain, as well as the future composition of the global CDR portfolio. Therefore, this report develops four conceivable scenarios (Figure 6). Nature-based removals like afforestation, reforestation, and improved forest management dominate the market, constituting 92% of the CDR portfolio today.[14] This dominance is attributed to their proven readiness to scale and relatively low costs. However, their limited permanence and potential land-use competition with agriculture underscore the need to mature further CDR methods and enable the diversification of the global portfolio. Depending on the overall market demand and how fast novel CDR methods can decrease costs and address MRV challenges, the future CDR method portfolio could be much more diversified.

In the "High Natural Sinks" scenario, reliance on nature-based removals remains high at 75%, emphasizing the advantages of CDR methods like afforestation, reforestation, and improved forest management or peatland and wetland restoration due to their maturity and lower investment needs. However, this scenario faces challenges with low storage permanence, risking the global long-term effectiveness of CDR. Furthermore, it is not conceivably compatible with the high CDR volume required in the below 2°C- and 1.5°C-compatible pathways due to increasing land-use competition and land management costs.

The "Balanced Portfolio" scenario, used as the reference CDR portfolio composition throughout this report, expects a roughly equal proportion of nature-based CDR on the one hand and enhanced natural processes and technology-based methods on the other hand. This scenario expects a 50% share for nature-based CDR, while bioenergy with carbon capture and storage (BECCS) contributes 20%, and biochar carbon removal (BCR) and direct air carbon capture and storage (DACCS) each contribute 10%. This scenario reflects considerable yet limited cost degression of technology-based removals, moderate infrastructure build-out, and an increased willingness to pay for high-quality CDR, among other influencing factors. This 2050 portfolio composition is the reference in this study because it is resilient to the limitations of any single approach, adaptable to changing conditions, and less reliant on emerging technologies and their quick scaling alongside significant cost reductions. Also, it could significantly improve average CDR permanence and reduce dependence on natural sinks while acknowledging that these could remain an essential part of the overall solution.

The "Slow Cost Degression" scenario assumes only limited cost degression of technology-based removals like DACCS and BECCS in conjunction with limitations imposed by slow build-out of required infrastructure such as renewable energy supply or CO_2 pipelines and qualified storage locations. In this scenario, enhanced (rock) weathering (ERW) and BCR are represented more strongly, with a combined share of 35% of the global CDR portfolio, given their ability to scale without significant infrastructure dependence. Assuming a limited cost degression for DACCS and BECCS, the two methods contribute only 5% each.

Lastly, the "High Tech Removals" scenario has the highest levels of CDR from DACCS and BECCS at a combined level of 37.5% and considerably high shares of ERW and BCR. At the same time, nature-based removals take a smaller share compared with other scenarios. This scenario would require high investment, significant technological breakthroughs to reduce these methods' costs, and robust policy support for technological removals. It emphasizes high-durability CDR methods but demands substantial upfront investments.

[14] Climate Focus, 2023; CDR.fyi, 2023.

Several roadblocks currently prevent accelerated growth of the CDR industry

Despite the urgent need for uptake of CDR globally and the tremendous economic potential, several roadblocks currently inhibit its realization.

1. **Unclear policy status** and role of CDR in countries' climate mitigation strategies
2. **High costs,** especially compared to avoidance offsets, and often CAPEX-heavy technologies
3. **Some nascent technologies** with challenges around efficiency, monitoring, and verification
4. **Funding gap,** especially for growth-stage companies, preventing project investment decisions
5. **Complex approval procedures** for plant operation and (cross-border) transport & storage infrastructure

The heavy reliance on partially nascent technologies in both the "Slow Cost Degression" and "High Tech Removal" scenarios makes the "Balanced Portfolio" the chosen reference CDR portfolio composition for 2050 and for the remainder of this report.

To achieve 2°C- or 1.5°C-compatible CDR pathway, yet nascent methods need to reach gigaton scale

Combining CDR's overall required volume development (Figure 5) and the balanced portfolio composition (Figure 6) indicates the absolute volume that may be expected for each CDR method. Achieving the 2°C- or 1.5°C-compatible removal pathway requires scaling several emerging CDR methods to hundreds of megatons or gigatons (see Figure 7). To put this challenge and order of magnitude into perspective, BCR accounted for most (93%) of all CDR certificate deliveries, excluding nature-based removals in 2023 (125,100 tons).[15] This amounts to approximately 116,000 tons of BCR CO_2 removal. BCR could account for 450-900Mt of CDR p.a. by 2050 in the 2°C- and 1.5°C-compatible scenario, respectively, assuming the balanced portfolio composition. This corresponds to an annual growth rate of c. 39-43% per year over the next c. 25 years, higher than the yearly growth rate of the global solar PV industry in a decade less (c. 38% p.a., 2007-22).[16]

Expanding scalable CDR methods, such as nature-based removals, and advancing nascent technologies are crucial to meeting the Paris Agreement's targets. The developments outlined in the following are uncertain, and historical trends of the past decades do not point towards a 1.5°C-compatible pathway (see Figure 1). Additionally, multiple roadblocks currently hinder the outlined development of CDR (see info box on previous page). The report further elaborates on these roadblocks and describes the required actions to overcome them in chapter 5.

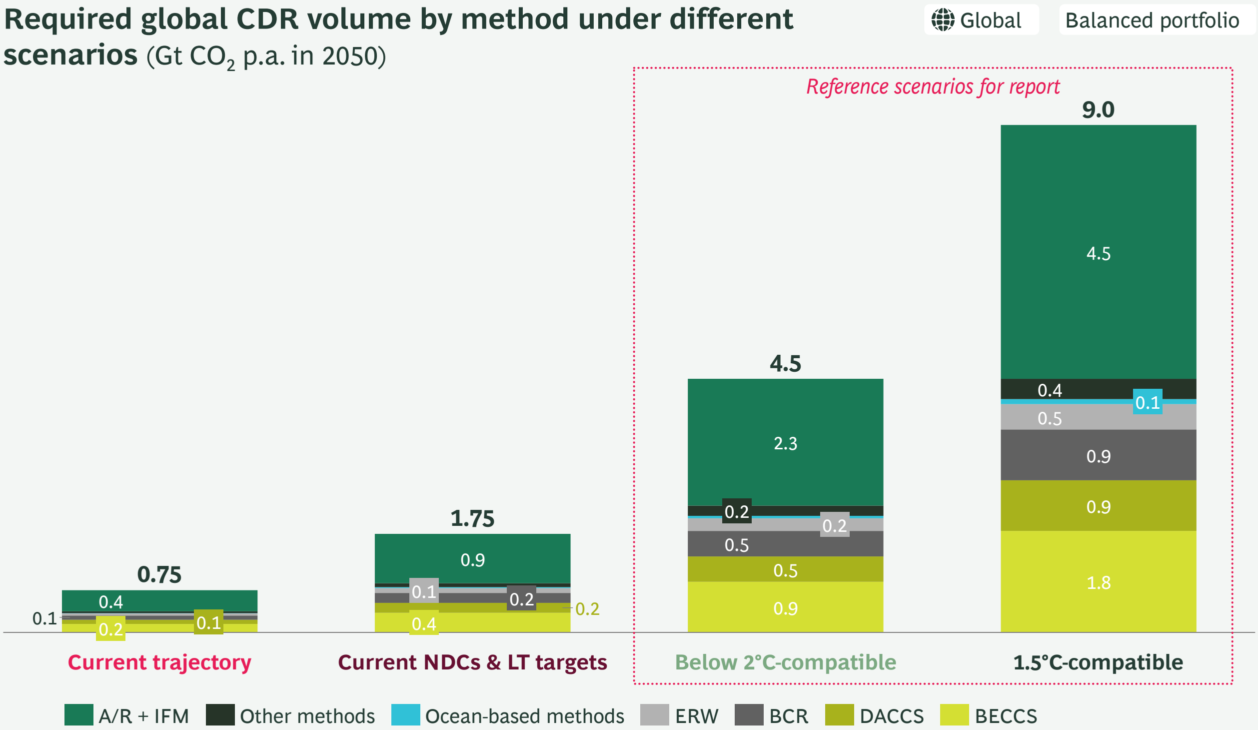
The following chapter delves deeper into selected CDR methods, especially those anticipated to be the main constituents of the global CDR portfolio composition by 2050. These are afforestation, reforestation, improved forest management, enhanced (rock) weathering (ERW), biochar carbon removal (BCR), direct air carbon capture and storage (DACCS), and bioenergy with carbon capture and storage (BECCS).

15 CDR.fyi 2023 Year in Review.

16 Solar Power Europe, 2023.

FIGURE 7

Required global CDR volume by method under different scenarios (Gt CO_2 p.a. in 2050)



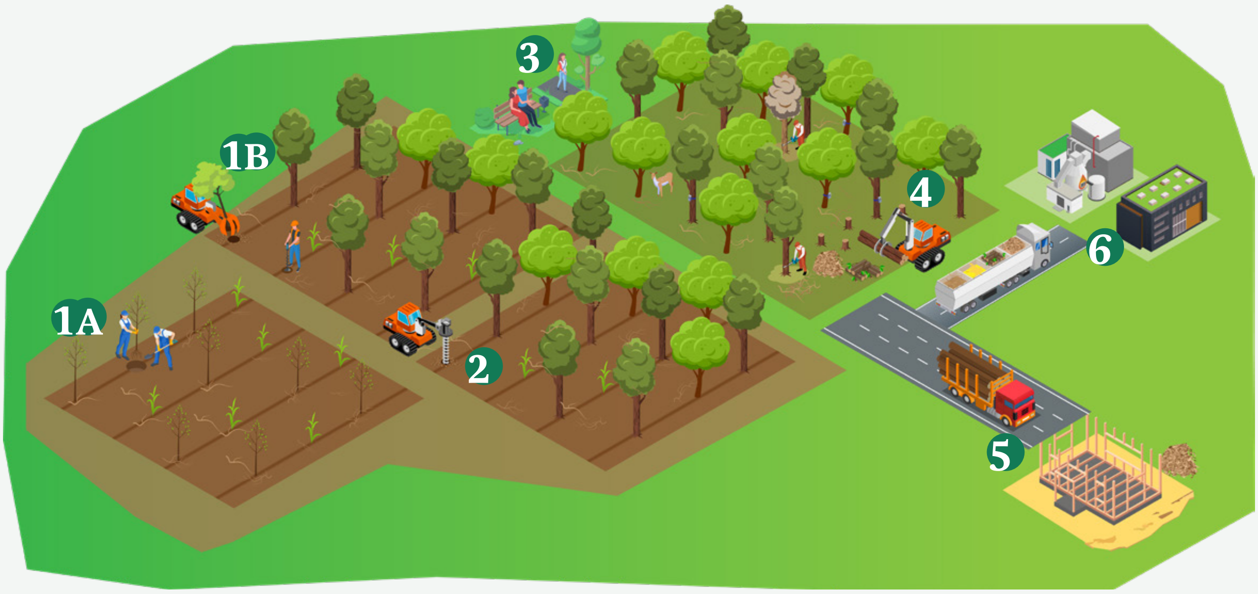
Note: Figures rounded; Numbers <0.1 not shown for readability; CDR volume p.a. defined as delivered CDR
Source: IPCC AR6 WGIII Chapter 12; IEA Net Zero Roadmap; Climate Focus, Voluntary Carbon Market 2023 Review; Ruben Prütz et al 2023 Environ. Res. Commun.; Lamb et al. 2024, Nature Climate Change; BCG CDR Market Model

To meet the immense requirement for carbon dioxide removal, no single method will suffice.

A diverse portfolio is essential, as each approach brings its unique set of strengths, co-benefits, and limitations.

2 CDR method overview

2.1 Afforestation, reforestation, improved forest management



Afforestation, reforestation, and improved forest management enhance carbon sequestration by restoring and managing forest ecosystems. Afforestation involves planting new forests on non-forested lands, reforestation restores degraded forests, and improved forest management optimizes carbon storage in existing forests. These methods support biodiversity, water regulation, and climate resilience.

Key process steps:

1. Planting of trees
   1a. In areas previously not covered by trees: Identification and selection of suitable land previously barren or used for other purposes. Soil testing, land clearing, and layout planning for new forests.
   1b. In previously destroyed forest land or existing forests: Focus on degraded or deforested areas within existing forests. Assessment of forest condition, selection of appropriate tree species, and strategic planting to restore density and support wildlife.
2. Replanting of tree seedlings based on forest condition: Regular monitoring of forest conditions on-site and via software, assessment of tree growth, health, survival rates, and increased stored CO_2. Replanting of seedlings where needed, protecting young trees from pests.
3. Use of protective forests for biodiversity, non-timber forest products, and leisure: Designation of areas for biodiversity support, providing habitats and non-timber forest products like fruits and medicinal plants.
4. Harvesting of productive forest wood: Employment of sustainable harvesting practices like selective logging to extract wood without compromising forest health.
5. Use of harvest wood products for construction and other durable products: Harvested wood is processed into durable goods such as high-quality construction materials, sequestering carbon long-term.

FIGURE 8

Illustrative value chain for afforestation/reforestation

6. Use of waste wood products in other CDR methods and chemical industry: Repurposing of residual wood and waste products for biochar production, BECCS, and chemical industries, maximizing biomass utility, reducing waste, and enhancing carbon sequestration potential.

The value chain begins with selecting suitable seedlings and sourcing fertilizers like biochar-based substrates to enhance soil quality tailored to local climate and soil conditions. The choice of seedlings impacts both cost and environmental benefits. While monoculture plantations of trees like eucalyptus or acacia may be cheap, they can harm biodiversity—the more diverse and local the tree species selected, the higher the economic return. The site selection and project development phase involves assessing such environmental impacts, biodiversity benefits, community impact, and long-term land use, alongside negotiating supplier contracts to ensure a steady supply of necessary inputs.

Site preparation and planting require detailed planning of access roads, water management systems, and optimal tree spacing. This is followed by the physical planting of trees and compliance monitoring to ensure environmental standards and regulations adherence. Maintenance and replanting are crucial for sustained forest health; this includes regularly monitoring tree growth, soil health, biodiversity, and stored CO_2 via digital tools. Replanting is carried out where seedlings have not thrived, with adaptive management practices implemented to address challenges such as invasive species and wildfires. The planting and maintenance activities typically rely heavily on manual labor, especially in projects in the global South. While machinery and equipment may play a more prominent role in the future, the development of labor costs could be a determining factor for project costs.

Forests are managed for multiple uses in the CO_2 transport and storage phase. Protective forests support biodiversity, non-timber forest products, and recreational opportunities. Productive forests are sustainably harvested for construction and industrial use, with residual wood repurposed for biochar, BECCS, and other applications.

Advantages:

- Immediately available for implementation
- Cost-effective and CAPEX-light
- Easily scalable based on available land

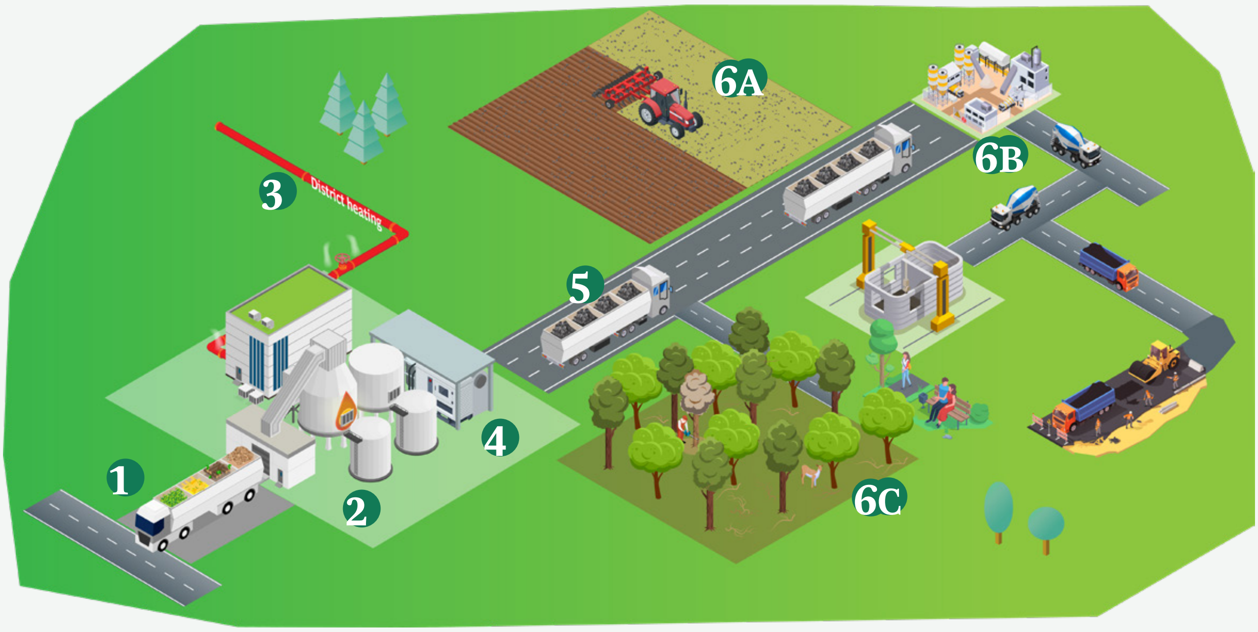
Co-benefits:

- Improved biodiversity of the surrounding ecosystem
- Enhanced soil carbon and nutrient recycling
- Supportive for circular economy concepts, e.g., sustainable building sector
- Enhanced water management
- Additional income for rural population

Limitations & risks:

- Land competition, limiting land for biodiversity & food
- Credibility risk given recent scandals due to insufficient monitoring
- Potentially reversible, e.g., through wildfires, browsing damage, or shifting climate zones causing tree mortality

2.2 Biochar carbon removal (BCR)



Biochar carbon removal (BCR) uses pyrolysis to turn biomass into biochar. For commercial BCR, most of this biochar consists of so-called inertinite, a highly durable and stable form of carbon. Pure inertinite biochar can persist for more than 10 millennia.[17]

Key process steps:

1. Transport of biomass residues to factory/pyrolysis plant: Collection and transport of biomass residues, such as agricultural and forestry waste, to a pyrolysis plant.

2. Operation of biochar production unit (BPU) to convert biomass residues into biochar: Operation of the BPU under controlled conditions to convert biomass residues into biochar through pyrolysis. This process occurs mainly in the absence of oxygen, resulting in stable carbon sequestration.

3. Production of renewable heat as a by-product: Capturing and utilizing heat generated as a by-product during the pyrolysis process, e.g., for district heating.

4. Processing of biochar: Processing of produced biochar to enhance its properties, making it easier to handle, transport, and apply in various use cases.

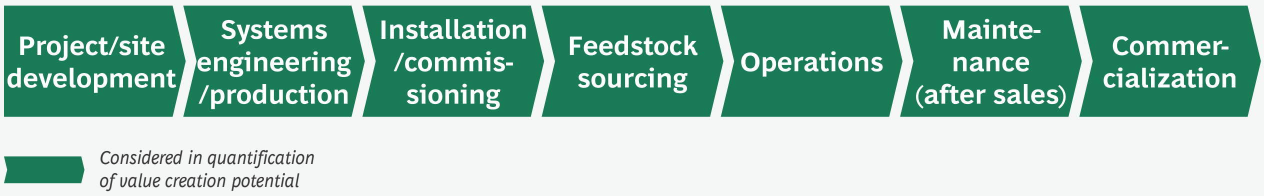
5. Transport of biochar to destination in trucks or other vessels: Transport of processed biochar to its destination, such as agricultural fields or industrial sites.

6. Use of biochar
   6a. For application to agricultural fields as soil conditioner: Application of biochar to agricultural fields to improve soil health, water retention, and nutrient availability, potentially enhancing crop yields and promoting sustainable farming practices.
   6b. As supplementary input in construction materials: Biochar is used as an additive in construction materials like concrete, asphalt, or polymers. It helps sequester carbon in long-lasting products, reduces the carbon footprint of construction projects, and potentially improves the performance of construction materials.
   6c. In municipal/urban green areas in the built environment

[17] Sanei et al., 2024.

FIGURE 9

Illustrative value chain for biochar carbon removal



The value chain for biochar carbon removal starts with identifying and preparing suitable sites for biochar production units (BPUs) located near sources of biogenic residues or near heat off-takers and securing necessary environmental permits. Systems engineering and production follow, involving the mechanical, electrical, and software engineering of BPUs, including their manufacturing, assembly, and facility acceptance testing to ensure readiness for installation.

BPUs are integrated into client sites during installation and commissioning, with mechanical and electrical systems fine-tuned and units commissioned. On-site team training ensures effective operation. Feedstock sourcing collects suitable biomass residues such as forestry and crop waste, industry residues, biosolids, and food residues, serving as raw inputs for biochar production.

In the operations phase, BPUs convert biomass residues into biochar under controlled conditions to maximize carbon content and durability. Different process technologies lead to varying degrees of permanence of the biochar, with key factors being the temperature and oxygen levels in the reactor and the type of biomass used. While previous studies, including IPCC publications, have qualified BCR's permanence as centuries to millennia, this report builds on the most recent research and qualifies BCR as above 10 millennia.[18] This is valid for pure inertinite biochar, which, according to recent research, makes up more than 75% of commercial biochar.[19] Standards define minimum thresholds for pyrolysis temperature and other parameters. The biochar is then processed for agricultural or industrial applications. Regular planned and unplanned maintenance is crucial to prevent equipment breakdowns and ensure continuous, reliable production.

Finally, the commercialization phase involves applying biochar to agricultural fields as a soil conditioner or supplementary material in concrete, asphalt, or other construction-related use cases. Surplus thermal and electrical energy produced during the carbonization process can be sold, enhancing the operation's economic viability. It should be noted that the economic potential of surplus energy (heat/electricity), as well as improved agricultural yields, has not been quantified (see system boundaries in chapter 3).

18 IPCC AR6 Mitigation of Climate Change.
19 Sanei et al., 2024.

+ Advantages:

- Flexibly scalable depending on varying demand
- Decentralized availability, integration into existing sites
- Uses low-cost input (crop residues, etc.)

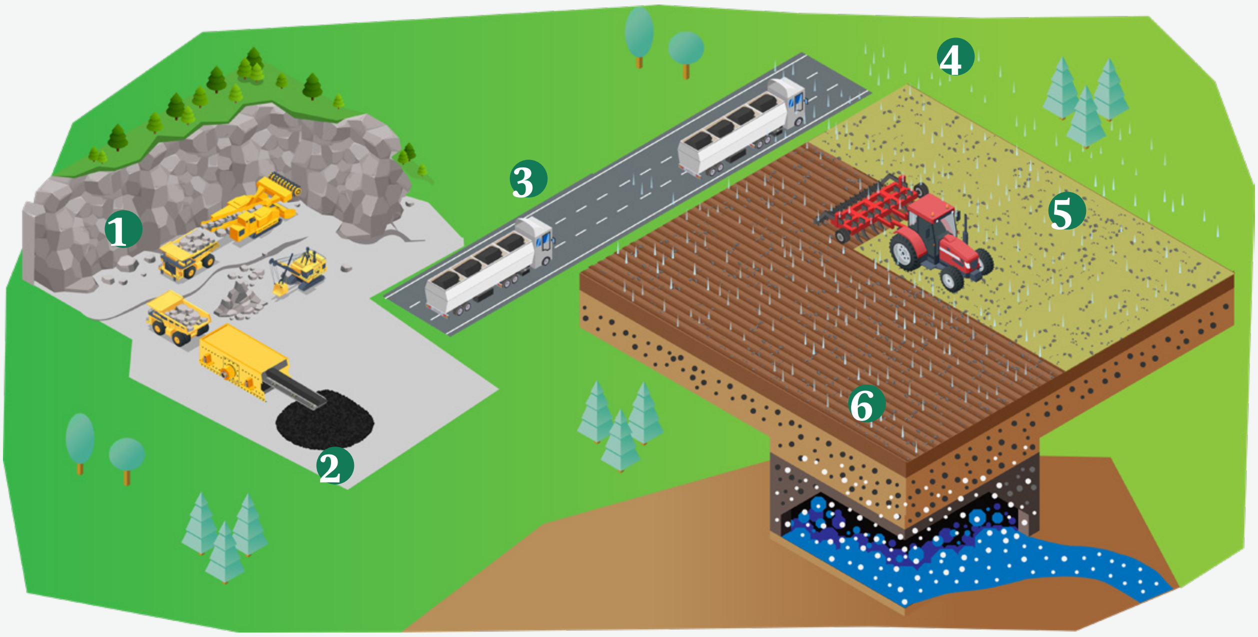
+ Co-benefits:

- Increased soil health, water- and nutrient retention
- Production renewable energy while removing CO_2
- Elimination of excess crop/ biomass residues
- Reduction of emissions in CO_2-intensive industries by replacing fossil carbon; prevention of rotting, composting, and incineration (release of CO_2)

− Limitations & risks:

- Potentially local competition for feedstock
- Complex approval procedures for biochar plant operation

2.3 Enhanced (rock) weathering (ERW)



Enhanced (rock) weathering (ERW) accelerates the natural process of mineral weathering to capture CO_2. Finely ground silicate rocks, such as basalt, are spread over land, where they react with rainwater to form stable carbonate minerals. This method sequesters CO_2 and improves soil fertility, making it a scalable and environmentally beneficial approach. Industrial by-products such as slag from iron and steel production can be utilized as feedstock as an alternative to rock powder. However, rock powder is predominantly used and is considered exclusively for this study.

Key process steps:

1. Procurement of rock or "mining dust" from quarries: Sourcing of silicate minerals, typically basalt, from quarries, incl. identification of suitable quarries and environmental impact assessments to ensure minimal disruption to ecosystems.

2. Processing of extracted rock into fine powder: Crushing and grinding of extracted rock into a fine powder to increase surface area, enhancing the chemical weathering process when applied to soil.

3. Transportation of rock powder to surrounding fields: Transport of finely ground rock powder to agricultural fields or other application sites.

4. Application of rock to fields by farmers: Standard agricultural equipment, like spreaders, is used to apply rock powder to farmers' fields. This ensures even distribution across the soil surface.

5. Reaction of water with rock powder to form carbonates: Reaction of applied rock powder with water and CO_2 in the soil, forming stable bicarbonate ions. This chemical reaction sequesters carbon in a stable form.

6. Washing of dissolved carbonates into rivers and eventually oceans: Dissolved bicarbonates are carried by groundwater into rivers and eventually the oceans, where the carbon is permanently stored for millennia and helps mitigate ocean acidification.

FIGURE 10

Illustrative value chain for enhanced (rock) weathering

The value chain for enhanced (rock) weathering begins with quarry exploration and selection. This involves identifying suitable quarries based on geological and climatic criteria and conducting environmental impact assessments to ensure minimal ecosystem disruption. Basalt, for instance, is a common industrial by-product from mining operations and is particularly suitable for enhanced (rock) weathering.

Farmer and field selection is the next step, which involves engaging with farmers near quarries, typically aided by farmers' associations. Once fields are selected based on their alkalinity, soil, crop type, and other factors, contractual agreements between the ERW operator and farmers can be established.

Following this, rock procurement and crushing occur, extracting rock from quarries and processing it into fine powder. By-product rock dust is often readily available. Otherwise, raw rock is crushed to create the powder. The rock powder is then transported from the quarry to the surrounding fields. This involves route planning and coordination to ensure efficient delivery of rock powder.

Before the rock powder can be spread, soil samples must be taken to establish a baseline for measuring its impact on CO_2 sequestration. Farmers then spread the rock powder using standard agricultural equipment, ensuring uniform coverage to maximize the effectiveness of the weathering process. If farmers lack the capacity to spread the rock powder, contractors may be hired at a slight premium.

Finally, repeated sampling for certification is conducted, taking soil and water samples to quantify the absorbed CO_2. This step is crucial for verifying the effectiveness of the enhanced (rock) weathering process and ensuring compliance with carbon sequestration standards. Samples are typically taken over a period of a decade at intervals of 1 to 2 years. The samples are sent to laboratories for analysis, inducing a significant cost. The complexity of removal measurement and the lack of a standardized measurement, reporting, and verification (MRV) methodology are currently driving costs for ERW players. Once a standardized methodology is established and the requirements for sampling are eased, e.g., through sensor-based or simulation-based MRV, the costs of ERW removal could be reduced significantly.

Advantages:

- Enables partial substitution of chemical fertilizers
- Broad applicability across various types of land
- Complementary to standard agricultural practices
- Use of mining by-product otherwise backfilled

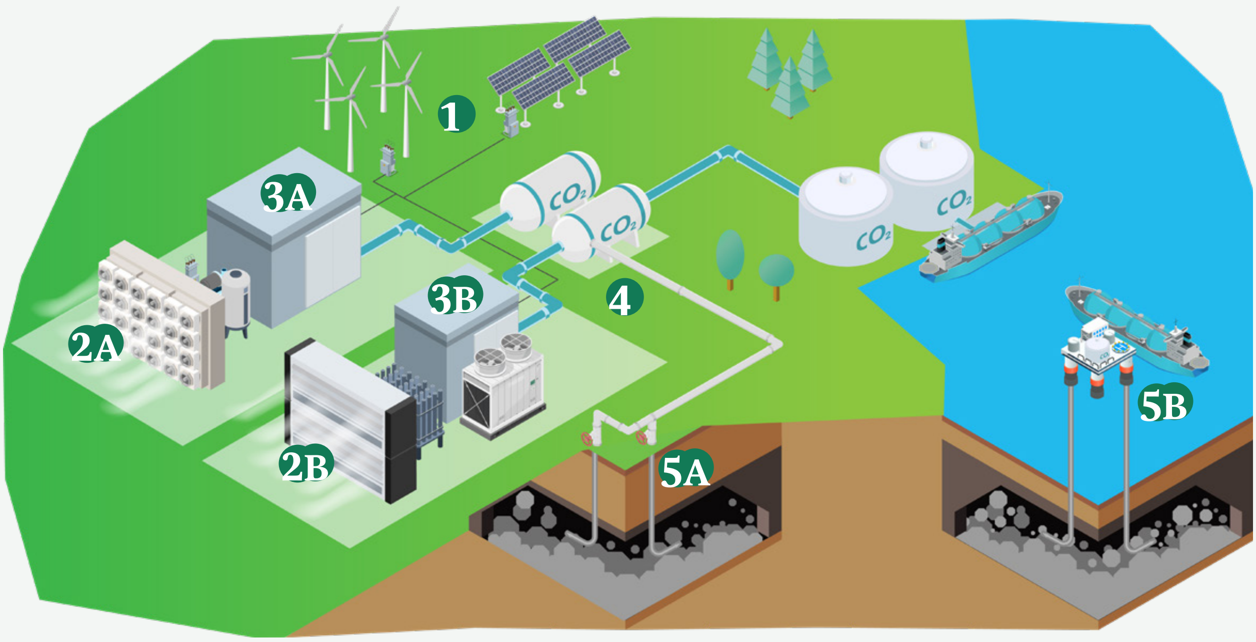
Co-benefits:

- Enhanced plant growth and yield (e.g., pH regulation & nutrients)
- Reduced erosion through soil aggregation
- Improved soil water retention
- Lowering agricultural greenhouse gas (GHG) emissions by replacing CO_2-intensive time applications for pH control

Limitations & risks:

- Negative mining impacts if by-products are not available, e.g., soil erosion
- Air quality impacts of rock dust when spreading on soil
- Slow reaction rates to sequester CO_2 and complex MRV
- Potential heavy metal accumulation

2.4 Direct air carbon capture and storage (DACCS)



Direct air carbon capture and storage (DACCS) involves capturing CO_2 directly from the ambient air using chemical or physical processes. The captured CO_2 is stored underground in geological formations for long-term storage or used in durable products. This technology is highly effective for reducing atmospheric CO_2 levels for hard-to-abate sectors.

Key process steps:

1. Provision of electricity via renewable energy sources: Renewable energy sources, such as wind or solar, generate the electricity required to power the DAC system.

2. Inflow of ambient air:
   2a. Liquid-solvent DACCS: Ambient air is pulled into the air contactor system (a vertical inlet is also possible in other configurations).
   2b. Solid-sorbent DACCS: Ambient air is pulled into the air contactor system via adsorption fans (usually horizontal inlet configuration).

3. Reaction of CO_2 with sorbent and regeneration of sorbent:
   3a. Liquid-solvent DACCS: Reaction of CO_2 with a chemical solvent in the absorption process, regeneration of solvent through an electrochemical cell.
   3b. Solid-sorbent DACCS: Saturation of solid sorbent with CO_2, sorbent regeneration in a vacuum steam chamber.

4. Concentration & compression of CO_2 stream: The captured CO_2 is compressed and prepared for transport or storage.

5. Storage of CO_2 in underground geological formations:
   5a. On-site/near-site storage of compressed CO_2 in underground geological formations.
   5b. Pipeline transport of CO_2 to central storage hub, potentially with subsequent shipping and storage in deep ocean geological formations.

The value chain for DACCS begins with sourcing specific materials and components required for each type of system. There is a large variety of different DAC processes. Alongside other technical criteria, they can be predominantly categorized by the capturing mechanism (type and material of sorbent), the sorbent regeneration mechanism (e.g., different temperatures, vacuum conditions, moisture, etc.), and the sorbent cycling style. They also may require

FIGURE 11

Illustrative value chain for DACCS (solid sorbent and liquid solvent)

different operating feedstocks like acids, bases, or alkaline solids. This study uses two specific examples: (1) solid-sorbent DACCS, using amine-functionalized or other porous substrates, regenerating in a vacuum environment with 80-100°C steam, and (2) liquid-solvent DACCS with sodium hydroxide (NaOH) or potassium hydroxide (KOH) solvent, and electrochemical sorbent regeneration without heat input. The choice of technological approach impacts the cost of chemical media, the required temperature and energy intensity for capture, and the resulting process waste.

Next, engineering and sourcing components for CO_2 capture are undertaken. Solid-sorbent DACCS needs adsorption fans, air contactors, vacuum pumps, steam generators, and auxiliary equipment. Liquid-solvent DACCS requires absorber housing, packing materials, pumps, plant auxiliaries, and electrochemical cell stack components. The assembly phase involves constructing adsorption units and desorption vacuum chambers for solid-sorbent DACCS or absorber units and electrochemical cell stacks for liquid-solvent DACCS. This is followed by site development and plant construction, connecting key components with media supplies, and adding the appropriate sorbent or solvent to the system.

During the operations and maintenance phase, the daily operation of CO_2 capture systems is managed to ensure they run at full capacity and efficiently absorb CO_2. This includes load control, operations software, looping back CO_2-lean solvent, and regular maintenance to prevent downtimes. Logistics for compressed CO_2 delivery to long-term storage sites, such as saline aquifers or depleted oil wells, are also handled, including managing the necessary injection machinery.

CO_2 transport involves the logistics of delivering compressed CO_2 for long-term storage, which includes preparing pipeline networks or on-site storage solutions based on the proximity to suitable geological formations.

In the CO_2 storage phase, drilling and preparing storage sites ensure the geological formations are suitable for long-term storage. This may involve connecting to CO_2 pipeline networks or using on-site storage solutions. The captured CO_2 may also be utilized in producing durable products, such as mineral products, plastics, or even algae cultivation, contributing to a broader circular economy (not in focus here).

Advantages:

- Large-scale potential in a variety of locations
- Can be integrated with existing industrial processes (e.g., use of excess heat)
- Modularity and comparably small land footprint

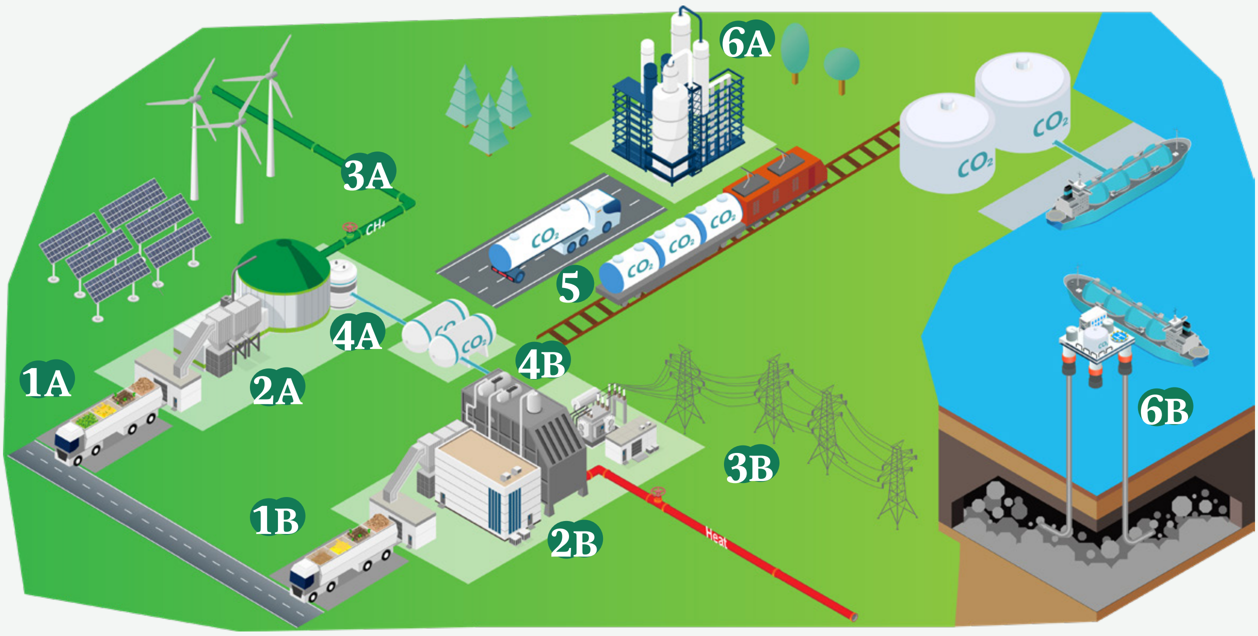
Co-benefits:

- Utilization of non-arable land due to flexible installation
- Utilization of captured CO_2 in other industrial processes

Limitations & risks:

- CAPEX-intensive and sensitive to "grey emissions"
- High water use (only for liquid solvent)
- Availability of sufficient (grid-based) renewable electricity given (currently) tremendous energy requirements
- Limited technological readiness, e.g., not tested at a significant scale

2.5 Bioenergy with carbon capture and storage (BECCS)



Bioenergy with carbon capture and storage (BECCS) combines a variety of processes and can be applied in different industries like energy, cement, or pulp & paper. This study differentiates between two routes under the term "BECCS": (1) biogas upgrading to produce biomethane while capturing CO_2 from exhaust gas streams, subsequently referred to as "biomethane" and (2) conversion of biomass into energy (electricity and heat) from both combined heat and power (CHP) bioenergy plants (BECCS in the narrower sense) as well as waste to energy plants with carbon capture and storage (WACCS). This second route is subsequently referred to as "BECCS incl. WACCS." In both routes, the captured CO_2 is stored permanently.

Key process steps:

1. Transport of biomass to anaerobic digester or plant: Delivery of biomass, e.g., agricultural or forestry residues, waste wood, municipal waste, or energy crops[20] for processing.
   1a. Biomethane: Transport of biomass to an anaerobic digester.
   1b. BECCS incl. WACCS: Transport of biomass or organic waste to a plant.

2. Production of biogas or heat and electricity: The biomass undergoes different processes depending on the route.
   2a. Biomethane: Anaerobic digestion of biomass to produce biogas and subsequent upgrading to biomethane.
   2b. BECCS incl. WACCS: Combustion of biomass or waste to produce heat and electricity.

3. Distribution: Heat and electricity are distributed via existing grids:
   3a. Biomethane: Distribution of produced biomethane via natural gas grid.
   3b. BECCS incl. WACCS: Distribution of electricity and heat via electricity grids and district heating networks, and provision as process heat for industrial off-takers.

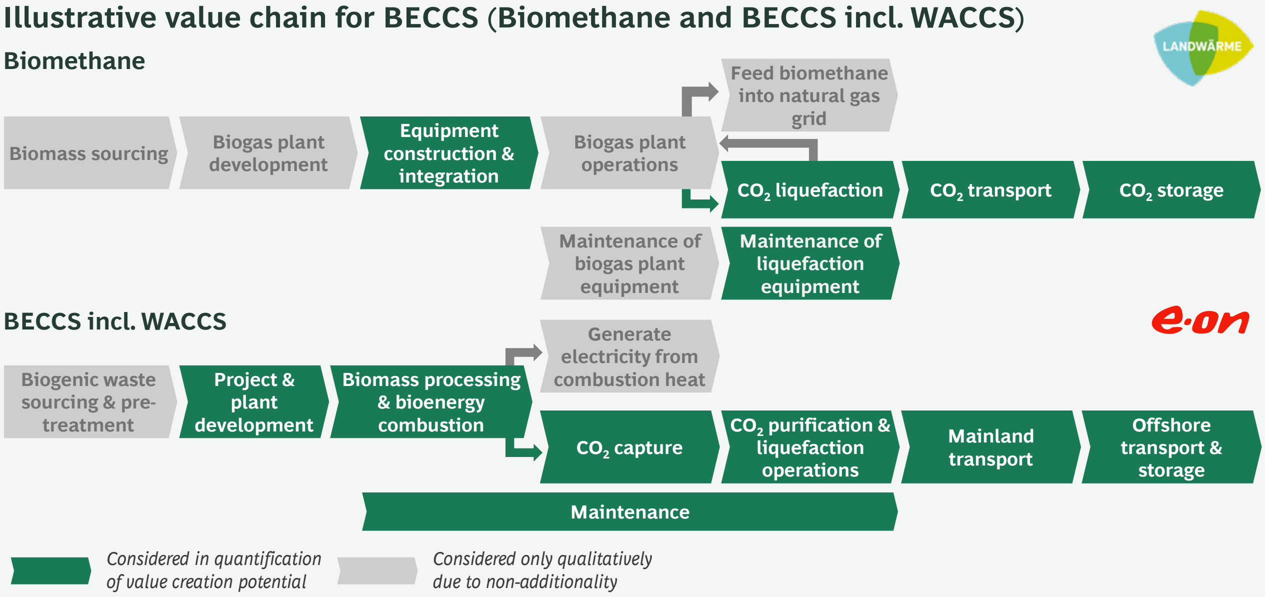
4. Capturing and liquefaction of CO_2:
   4a. Biomethane: Capturing of CO_2 and refinement to remove trace impurities. This is followed by liquefaction on a smaller scale for transportation and storage.
   4b. BECCS incl. WACCS: Cleaning CO_2 from combustion (primarily) via amine scrubbing and other technologies to remove impurities, followed by compression and liquefaction for transportation and storage.

5. Transport of CO_2 to storage site by truck or train: Transport of captured CO_2 to a plant or port by truck, train, or ship. Alternatively, CO_2 could be transported via pipelines, e.g., feeding into a larger central storage hub.

[20] Not deployed by companies in this example, but partially used in the industry.

FIGURE 12

Illustrative value chain for BECCS (Biomethane and BECCS incl. WACCS)



6. Use or storage of CO_2:
   6a. The captured CO_2 is used in the production of durable products
   6b. or it is stored geologically. It is injected and stored in underground geological formations or deep saline aquifers and depleted oil and gas reservoirs.

The value chain for BECCS starts with sourcing sustainable biomass, such as agricultural residues, waste wood, municipal waste, or energy crops, which is then transported to the appropriate processing facility.

For the biomethane route, biomass is transported to a digester for biogas production. Daily operations manage the fermentation process and upgrade the biogas to biomethane. The captured CO_2 is then liquefied and prepared for transport, requiring the integration of both capturing and liquefaction equipment.

In the BECCS incl. WACCS route, biomass is collected and pre-treated to enhance combustion efficiency and reduce emissions. It is then transported to a plant for high-temperature thermal treatment, generating heat and electricity. The CO_2 generated from combustion is captured via amine scrubbing and purified for storage using flue gas cleaning technologies. Excess heat from combustion is utilized to lower operational costs.

The captured CO_2 is liquefied and transported to storage sites, involving logistics for compressed CO_2 delivery through multi-modular transport, depending on the location and infrastructure. Currently, transport costs make up a significant amount of BECCS removal costs. These costs can be drastically reduced if a CO_2 pipeline infrastructure is built, expanded, and accessible to BECCS operators.

Besides permanent on- or offshore storage, captured CO_2 may also be utilized in producing durable products, such as mineral products, plastics, or even algae cultivation, contributing to a broader circular economy (not in focus here).

BECCS integrates bioenergy production with carbon capture and storage, contributing to negative emissions and renewable energy generation. This method is compatible with various biomass feedstock types and offers large-scale potential worldwide.

Advantages:

- Compatible with various biomass feedstock types
- Large-scale potential in a variety of locations
- High CO_2 concentration after biomethane separation

Co-benefits:

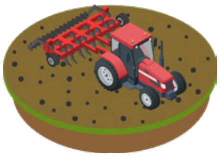
- Support of energy sector decarbonization by producing bioenergy while removing CO_2
- Elimination of excess crop/biomass residues
- Avoidance of methane emissions in the atmosphere
- Reuse of fermentation residues as fertilizer

Limitations & risks:

- High water and energy requirement
- High initial CAPEX for infrastructure
- Competition for land and water to grow feedstock (only for energy crops)

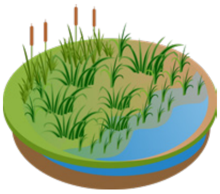
2.6 Other CDR methods including ocean-based CDR

This study analyzes other CDR methods beyond those described in previous sub-chapters at a high level. These include further land-based methods like soil carbon sequestration, peatland and wetland restoration, biomass burial, and bio-oil injection, as well as ocean-based methods like blue carbon management, ocean/river alkalinity enhancement, ocean fertilization, direct ocean removal, and biomass sinking. These methods were not examined individually due to their limited current implementation and the need for more reliable data regarding their execution and effectiveness.



Soil carbon sequestration

This method enhances soil carbon storage through practices like no-till farming, cover cropping, and organic amendments. It can significantly improve soil health and boost agricultural productivity. However, its feasibility is challenged by permanence issues due to new development on farmland, the reversal of no-till practices, and soil carbon release caused by global warming.



Peatland and wetland restoration

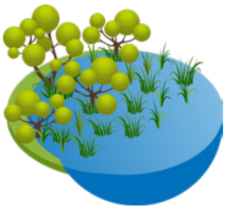
This approach involves re-wetting degraded areas by re-establishing natural water regimes and installing water control structures to promote moss growth and subsequent vegetation development, enhancing carbon storage, biodiversity, soil, and water quality. However, high restoration costs, possible land ownership issues, and the limited feasibility of long-term monitoring pose considerable challenges.

Biomass burial

Biomass burial refers to collecting and burying organic materials (e.g., crop residues and wood) and is primarily in the experimental stage. Despite its low cost and scalability, challenges requiring further research include potential decomposition if the burial environment is not appropriately maintained, logistical issues in collecting and transporting biomass, and potential land use conflicts or adverse impacts caused by excessive deployment. The method is being debated regarding its credibility and is indirectly subject to several environmental regulations like the Landfill Directive or special permitting requirements.

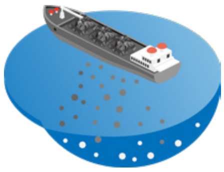
Bio-oil injection

This approach converts biomass into bio-oil through pyrolysis and injects it into deep geological formations. There, it provides a permanent, large-scale carbon sequestration solution. This method is still in its early stages. It faces high bio-oil production and injection costs, technological and regulatory hurdles, and limited co-benefits, raising concerns about potential adverse environmental impacts.



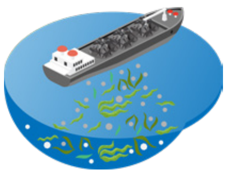
Blue carbon management

Management of blue carbon refers to the restoration and conservation of coastal and marine ecosystems like mangroves, seagrasses, and tidal marshes, which naturally capture and store large amounts of carbon. This enhances biodiversity, improves water quality, and protects against weather-related impacts. However, challenges such as land use competition, limited funding, and the need for particular and limited implementation opportunities hinder scalability. There could be some potential for ecosystem engineering, i.e., creating new coastal vegetated ecosystems, but this could be prohibitively costly.



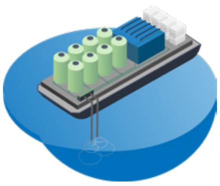
Ocean/river alkalinity enhancement

This method can increase the ocean's capacity to absorb and store CO_2 by adding alkaline minerals to seawater. While approaches based on electrochemistry (e.g., electrodialysis) face exceptionally high costs, mineral-based approaches like spreading olivine on beaches are unlikely to scale significantly. There is no proven, scalable approach; research on suitable synthetic minerals is only evolving. Additional hurdles include logistical issues and regulatory challenges.



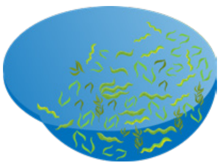
Ocean fertilization

Disperses nutrients like iron sulfate into the ocean to stimulate phytoplankton growth, which absorbs CO_2 during photosynthesis. However, this method faces significant challenges, including the risk of harmful algal blooms and disruptions to marine ecosystems. Additionally, regulatory and scalability issues and the time-consuming and expensive logistics further complicate its implementation. Other implementation methods, like artificial upwelling, have yet to reach commercial scale successfully and are scrutinized for adverse side effects.



Direct ocean removal

This approach directly extracts CO_2 from seawater, e.g., via electrochemical methods or membrane-based technologies. Despite its high theoretical CO_2 removal potential due to the high volumetric CO_2 concentration in the ocean, this method is currently in the early research stages. It faces significant technical and measurement challenges, high energy requirements, and potential ecological impacts. These factors make large-scale deployment difficult.



Biomass sinking

Biomass sinking involves cultivating marine seaweed or terrestrial plants and sinking them into the deep ocean for long-term carbon storage. While it has significant climate mitigation potential, further research is needed on its effectiveness, feasibility, and ecological impact. Additionally, terrestrial biomass projects risk competing with existing uses or altering land practices.

2.7 Measurement, reporting, verification (MRV) & intermediaries

Effective implementation and scaling of CDR methods require robust measurement, reporting, and verification (MRV) systems and the involvement of intermediaries. MRV ensures accurate CO_2 removal quantification, transparency, and accountability through precise measurement, systematic reporting, and rigorous verification. Intermediaries include brokers, traders, resellers, exchanges, platforms & marketplaces, and registries. They bridge the gap between suppliers and buyers and ensure transparency in the evolving CDR credit market by offering transaction handling and portfolio management services.

The value chain for MRV begins with the measurement phase. This involves installing sensors and data collection tools to measure production across diverse relevant areas. Systematic and continuous production data collection uses real-time measurement and remote sensing technologies.

In the monitoring and reporting phase, measurement data is compiled and standardized to ensure comparability through advanced data analytics. The amount of carbon sequestered is calculated using approved methodologies, and the emissions data is compiled into standardized reports detailing the outcomes and methods used in carbon sequestration projects.

Verification involves an independent third-party review of the reported data and methodologies to ensure accuracy and compliance with established standards.

The project is verified to comply with all relevant standards and regulations in the standard and registration phase. Certifications are obtained, and carbon removal credits can eventually be issued.

The final phase is the market transaction, where carbon credits are sold to individuals or companies looking to compensate for their carbon emissions. Carbon credit inventory is also managed, and reports on carbon offset portfolios are maintained according to regulatory and voluntary standards.

MRV process and maturity differ considerably across CDR methods

MRV systems vary significantly across CDR methods due to their unique characteristics. For DACCS, effective MRV necessitates precise, continuous CO_2 capture and storage monitoring. BECCS needs to track type and quantity of biomass input and CO_2 emissions throughout the process. MRV for both is comparably simple, as the amount of CO_2 that is captured and stored can be easily measured. MRV for BCR is also straightforward, with a mature approach and established methods for measuring biochar stability.

FIGURE 13

Illustrative value chain for MRV

Considered in quantification of value creation potential

In contrast, MRV for ERW is highly complex due to the lack of a standardized methodology and extensive soil sampling requirements. Nature-based methods like afforestation, reforestation, and improved forest management require continuous monitoring due to ecosystem variability. Remote sensing and field surveys, with single-tree monitoring, guarantee maximum transparency. Ocean-based CDR methods, like ocean/river alkalinity enhancement, face significant MRV challenges due to their developmental stage and the complexities of the marine environment.

Advancements in MRV are a crucial prerequisite for CDR uptake

Enhancing MRV precision and reliability is crucial for transparency and accountability in carbon markets. Significant challenges include high costs, technical difficulties in reliably measuring CO_2 removal, and the lack of standardized protocols, limiting CDR project comparability and scalability. However, the future of MRV in CDR is promising, with advancements in remote sensing and AI improving accuracy and efficiency. Simulation-based MRV could enable significant cost reductions, e.g., by making frequent soil sampling obsolete. MRV systems can become more robust as international standards evolve, fostering greater trust and investment in CDR initiatives.

Transaction hurdles are still considerable

Navigating the CDR market presents several transaction hurdles. Unclear tax schemes surrounding the cross-border trade of carbon removal credits create uncertainty, e.g., due to the lack of a unified legal definition or different treatment across jurisdictions. The complex transaction setup, exacerbated by a lack of standardized contracting, further adds to this. Efforts to screen and understand the global supply of CDR credits are substantial due to a lack of harmonized market understanding and data. Furthermore, the parallel existence of multiple non-regulatory and regulatory quality frameworks complicates the identification of suitable credits for corporate portfolios. Lastly, limited tooling for sustainability teams to manage CDR credits, often held in multiple accounts, further challenges efficient market participation.

The global CDR industry could reach an annual economic potential of €470-940B by 2050, which is as large as today's global airline industry.[21]

[21] 2024 forecast for global passenger and cargo revenues, IATA, 2024.

3 CDR can become a global €470-940B industry

3.1 Global economic potential of CDR could reach €470-940B p.a. by 2050

The total economic potential of CDR, i.e., the value creation (revenues) that players in CDR-related sectors may expect based on required CDR volumes, crucially depends on the development of the costs to generate CDR credits and the distribution of these costs along the value chain.

The modeling of the CDR-induced economic potential involves a multi-step approach, incorporating multiple variables. As detailed in Chapter 1.3, CDR volumes and CDR portfolio compositions were each estimated across four scenarios. CDR-induced economic potentials were derived by multiplying the required CDR volumes by the respective CDR method shares and assumed costs. Economic potentials are based on cost estimates and not on price forecasts to avoid the uncertainty of supply and demand effects, thus making the long-term projection more reliable. Additionally, cost better represents actual value creation regardless of excess profits. The economic potential is modeled for a balanced CDR portfolio in the below 2°C- and 1.5°C-compatible pathways (i.e., 4.5 and 9 Gt CO_2 p.a. in 2050, respectively).

The system boundaries applied in calculating the economic potentials by CDR method include all value chain steps directly involved in generating and marketing a removal certificate. This encompasses supply, MRV, and intermediary services to enable market transactions. The value chain is modeled to the point where a certain amount of CO_2 is stored or utilized in a durable product. Only economic potential induced by CDR is included, avoiding double counting. For example, feedstock for BECCS is not included, as it is required for energy production regardless of carbon capture. However, all enabling infrastructure, such as CO_2 transport infrastructure and plant component supply, is included. Co-benefits for other industries, like increased agricultural yield rates through biochar or enhanced rock weathering, are not quantified.

The following section explains the assumed cost development in the balanced portfolio composition before discussing the CDR-induced economic potentials.

Significant cost decreases of 35-85% can be expected for most CDR methods until 2050

The baseline costs for CDR methods were derived from studies and discussions with stakeholders within the CDR ecosystem. Core factors influencing future costs for each CDR solution were identified, and assumptions were made on their development over time. These future cost projections were cross-checked with the Intergovernmental Panel on Climate Change (IPCC) estimates on cost potentials and numerous studies. Recognizing the significant uncertainty in future costs, this variability is reflected in the 2050 cost ranges shown in Figure 14. Current baseline costs may also vary significantly depending on process technology, location, and other factors.

By 2050, enhanced natural processes and technology-based removals are projected to achieve substantial cost reductions. These cost reductions can be expected, especially in processes that heavily rely on plant technology and equipment, where economies of scale and experience rates significantly impact reducing costs. Cost degressions could also be achieved in operations and maintenance, but more constant (and partially volatile) costs are expected for energy, feedstock, and other inputs. Methods that could face competition for land or other natural limitations could even experience cost increases, e.g., for permits.

Bioenergy with carbon capture and storage (BECCS) could see cost reductions of around 50%, driven by scale effects and expansions in transport and storage infrastructure, which can reduce the average cost per ton of CO_2 transported. The cost also heavily depends on sequestered CO_2 volumes: The cost per removed ton decreases with increasing CO_2 concentration in the feedstock. Therefore, biogas upgrading plants can achieve lower specific costs per ton of CO_2 removed than WACCS.

Based on scale effects and typical experience rates, direct air carbon capture and storage (DACCS) could achieve even higher cost reductions of 60%. DACCS would also benefit from improvements in storage infrastructure. The cost range per removed ton of CO_2 is similarly extensive for DACCS compared to BECCS and heavily depends on the capture method. Operators typically use a liquid solvent or a solid sorbent, although other DACCS process variations exist. Furthermore, removal costs strongly depend on the energy requirements determined by the regeneration mechanism and, ultimately, location-specific energy costs.

Similarly, enhanced (rock) weathering (ERW) could experience a cost reduction of approximately 65%. The realized cost reduction mainly depends on developments in measurement, reporting, and verification (MRV). A standardized methodology, larger-scale lab sampling, and sensor- or simulation-based monitoring approaches could lead to significant cost reductions.

Biochar carbon removal (BCR) could also see up to 35% cost reductions. BCR already has high technological readiness today but could still benefit from scale and experience effects as the pyrolysis process is further enhanced. Industrializing production from current batch manufacturing could further decrease unit costs for pyrolysis.

Though still in the early stages, ocean-based removals could also benefit significantly from cost decreases of between 35% and 85%. Such a decrease could be realized if feedstock sourcing and distribution costs decline with scale and if prevalent MRV challenges can be resolved. However, this is still highly uncertain.

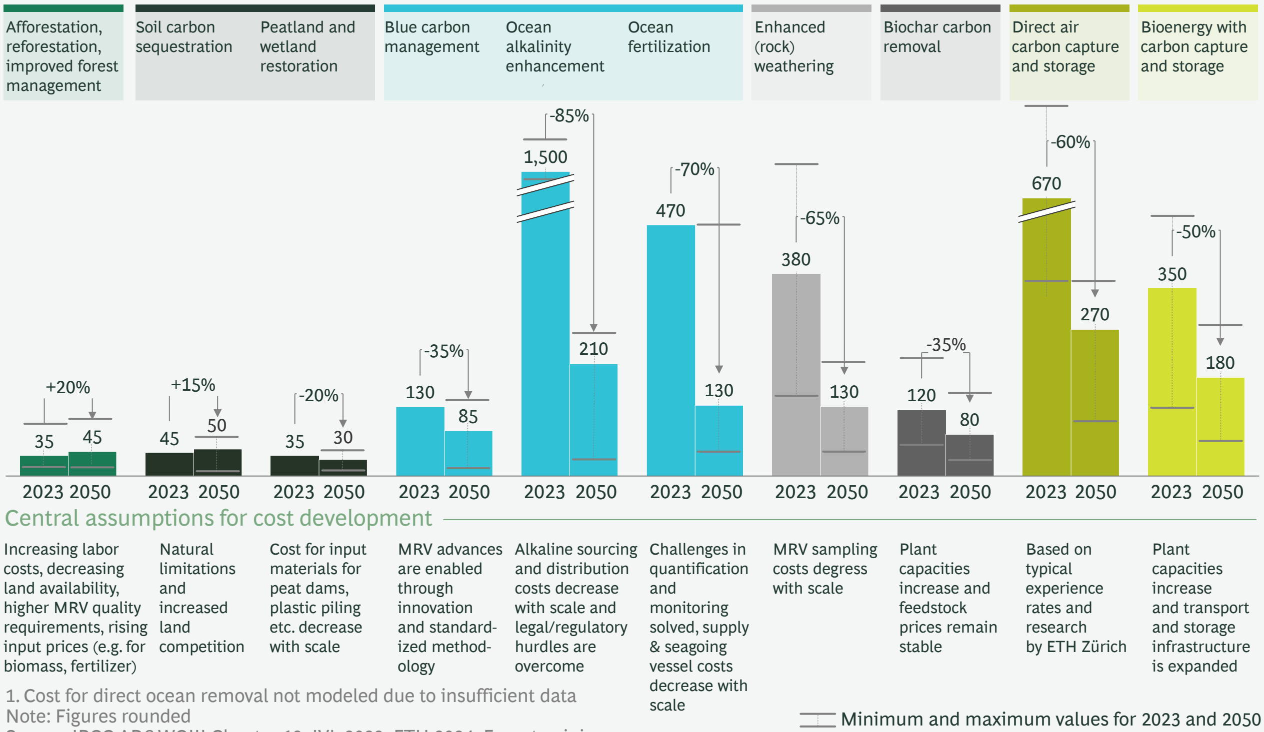
Conversely, nature-based removals such as afforestation, reforestation, improved forest management, and soil carbon sequestration might encounter cost increases of 20% and 15%, respectively. Rising input prices, labor costs, and land competition would primarily drive these potential increases. An increased emphasis on precise monitoring and quality assurance could further drive up costs.

Costs for carbon dioxide removal from forestry projects can vary significantly already today, ranging from below €10 up to €100 or more. The cost heavily depends on the choice of seedlings, country-specific

FIGURE 14

Anticipated CDR cost trends by 2050[1] (€ per tCO_2)

Global | Balanced portfolio



1. Cost for direct ocean removal not modeled due to insufficient data
Note: Figures rounded
Source: IPCC AR6 WGIII Chapter 12; IVL 2023; ETH 2024; Expert opinion

labor costs, and the quality and intensity of monitoring. The Verified Carbon Standard (VCS), the largest certifier of voluntary carbon offsets, recently released a new methodology prohibiting monoculture projects. Combined with stricter monitoring requirements such as single-tree monitoring, premium projects could see costs of up to €100, but on average, need to be much less expensive to achieve the necessary scale. The balanced portfolio assumes an average cost of €45 per ton of removed CO_2 in 2050.

The anticipated cost reductions for most methods are crucial for making CDR technologies more viable and scalable, enabling them to play a significant role in global decarbonization efforts. As mentioned, however, there is substantial uncertainty regarding cost potentials. Much depends on realized scale and experience curves, stability of input prices, and advancements in MRV.

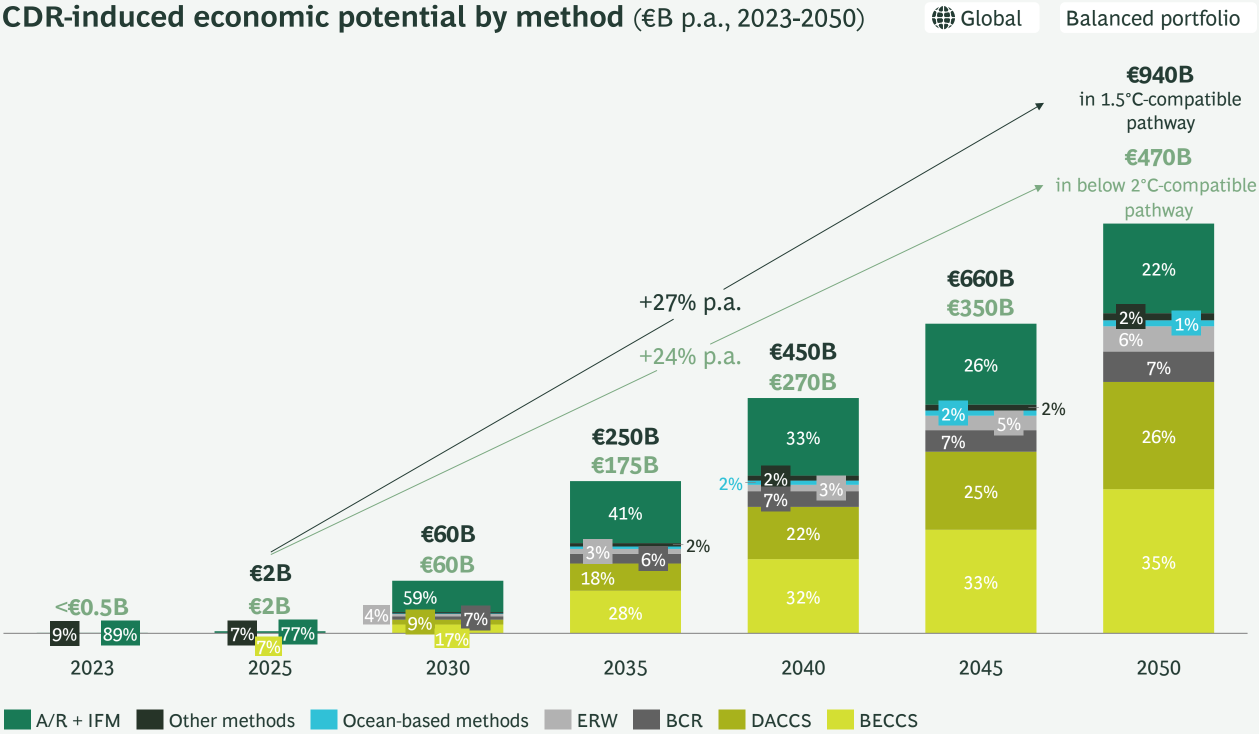
The global economic potential of CDR could reach up to €940 billion

The global CDR-induced economic potential could experience rapid growth under below 2°C- and 1.5°C-compatible scenarios, reaching €470-940 billion in 2050, respectively. The projected economic potentials for CDR illustrate varying levels of ambition and technological advancement in decarbonization efforts but do not constitute an upper limit.

As illustrated in Figure 15, the economic potential could see substantial growth until 2030, reaching €60 billion p.a. in both scenarios. After 2030, growth could accelerate further, driven by cost reductions in CDR methods and strengthened commitments to decarbonization. Under the below 2°C- and 1.5°C-compatible scenarios, the economic potential could reach €175-250 billion p.a. by 2035 and €270-450 billion p.a. by 2040. This period might witness the emergence and scaling of technological methods such as DACCS and BECCS, which could form a significant portion of the CDR-induced economic potential together.

FIGURE 15

CDR-induced economic potential by method (€B p.a., 2023-2050)



Note: Figures rounded; Note: Shares <1% not shown for readability
Source: IPCC AR6 WGIII Chapter 12; Climate Focus, Voluntary Carbon Market 2023 Review; 2024 State of Voluntary Carbon Market Report; BCG CDR Market Model

After 2040, the economic potential of CDR could grow further, eventually reaching €470-940 billion p.a. by 2050. A slightly declining compound annual growth rate (CAGR) would be expected in a maturing market, where early exponential growth transitions to steadier, sustained expansion as CDR technologies become more established. A more diversified portfolio of CDR methods, including ERW and BCR approaches, could contribute to continued growth towards mid-century and beyond. Notably, BECCS and DACCS are expected to be significant contributors, making up 35% and 26% of the economic potential by 2050 based on the balanced portfolio.

The required growth under below 2°C- and 1.5°C-compatible scenarios aligns with historical trends in solar PV and wind power growth, assuming similar adoption rates and technological advancements. Developing the entire CDR method portfolio is critical to achieving these projections and requires significant cost degression and scaling of novel methods.

3.2 Economic potential differs significantly per CDR method

CDR-induced economic potential is aggregated along 6 value chain steps

Each CDR method's economic potential over time is broken down across six value chain steps. These steps include:

- **Plant technology and equipment,** covering suppliers of necessary technologies and capabilities for plant design and construction, such as component manufacturers and engineering suppliers;
- **Feedstock and other inputs,** including providers of essential materials like fertilizer, seedlings, and rock powder;

- **Operations and maintenance,** which encompasses services necessary for the continuous operation and maintenance of removal projects, including site and project development and energy supply from utilities;

- **CO_2 transport and storage,** including infrastructure providers for transporting and storing CO_2, such as rail and truck operators and offshore storage facilities;

- **MRV,** covering organizations that measure, report, and verify carbon removal, like large-scale laboratories, software providers, and auditors;

- **Intermediaries,** which facilitate market transactions and trading of credits, including registries, marketplaces, exchanges, brokers, and resellers.

While plant technology and equipment and CO_2 transport and storage are driven mainly by CAPEX, the other value chain steps are driven only or at least mainly by OPEX. The breakdowns of economic potential are based on illustrative value chains and can differ between specific plant configurations, applications, or locations.

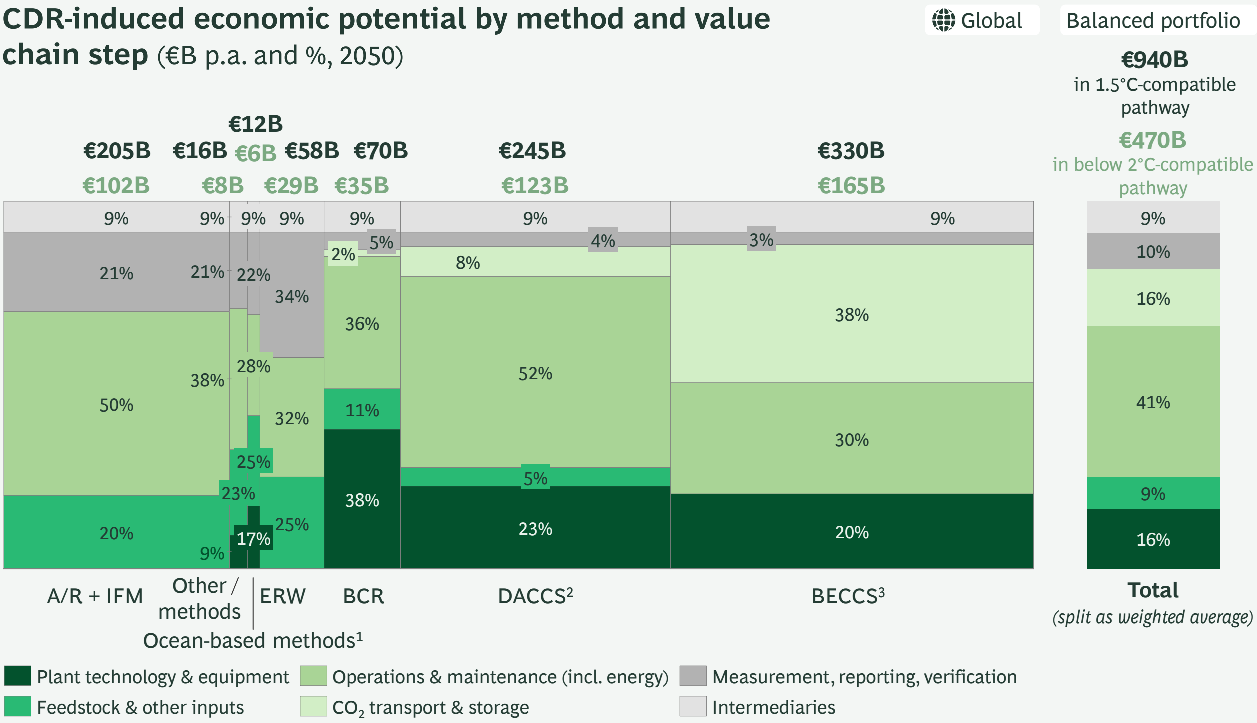
To assess the economic potential, value pools for each value chain step are aggregated according to the modeled volumes for each CDR method. This method of breaking down the economic potential allows to identify the unique economic contributions of each CDR method, highlighting the specific roles played by equipment suppliers, input providers, operational service providers, and other key players.

Economic potential along the value chain differs notably across CDR methods

The economic potential along the CDR value chain varies notably across different methods. Figure 16 illustrates the share of economic potential by value chain step in 2050, showcasing the unique economic contributions of each CDR method. The width of each column indicates the global economic potential of each CDR method in billion Euro under the below 2°C- and 1.5°C-compatible scenarios.

FIGURE 16

CDR-induced economic potential by method and value chain step (€B p.a. and %, 2050)



1. Cost for direct ocean removal not modeled due to insufficient data 2. DACCS sub-categories equally weighted 3. BECCS biomethane weighted 20%, other BECCS weighted 80%
Note: Figures rounded; Only additional economic potential induced by CDR included in modeling
Source: BCG CDR Market Model

The most considerable potential for afforestation, reforestation, and improved forest management comes from operations and maintenance, driven by the required labor for site preparation, planting, and maintenance activities. Additionally, rising fertilizer costs due to increased demand and limitations on natural fertilizers contribute to the substantial share of feedstock. MRV plays a notable role due to the need for continuous and precise monitoring and is especially important in premium projects with single-tree monitoring. Acknowledging increasing pressure from environmental organizations and tightening regulatory requirements, demand for premium projects could see more robust growth in the future. However, this is yet highly uncertain.

ERW presents a unique profile with a significant share of MRV due to the extensive soil sampling and laboratory analysis required for verification. By 2050, MRV costs could decrease significantly, mainly due to increased scale, the expected development of a standardized MRV protocol, and the potential deployment of simulation-based MRV methods. As the total cost for ERW removal decreases over time, operations and maintenance, as well as feedstock and other inputs, could have more prominent shares of its economic potential. These encompass the costs of rock procurement, crushing, transport, and spreading, which are expected to decrease with scale, albeit at a lower rate than MRV cost.

BCR is characterized by high contributions from plant technology and equipment, as well as operations and maintenance. While plant technology & equipment costs could decrease with larger plant capacity and scale, feedstock prices could increase moderately, especially in Europe. A small share of economic potential is assigned to CO_2 transport and storage. However, it is essential to note that this potential is not directly comparable with the transport and storage potential for DACCS and BECCS. For BCR, this instead refers to the cost of commercializing the biochar and transporting it to the final user (e.g., farmers or construction companies).

DACCS is marked by substantial contributions from operations and maintenance, as well as plant technology and equipment, in 2030 and 2050. This reflects the intensive operational requirements, especially energy use, and the need for advanced technology inherent to this method. Over time, the share of plant technology & equipment decreases, driven by typical experience rates and research advancements.

BECCS shows significant economic potential in operations and maintenance, as well as plant technology and equipment. This highlights the comprehensive infrastructure and maintenance needs of BECCS. The share of CO_2 transport and storage costs could decrease significantly over time, driven by both scale and infrastructure investments. The feedstock cost is not included to avoid double counting its economic potential: The feedstock is required for bioenergy plants regardless of post-combustion carbon capture. Thus, there is no (or minimal) additional economic potential for sourcing feedstock induced by the growth of CDR.

Overall 2050 operations and maintenance account for the largest share, e.g., driven by considerable energy requirements. Plant technology and equipment, as well as feedstock and other inputs also represent significant shares, highlighting the essential role of infrastructure, machinery, and raw materials in the different CDR processes. MRV and intermediaries could contribute up to 20% of the economic potential, emphasizing the need for compliance, accuracy in tracking carbon removal, transparency, and efficiently facilitating market transactions.

Technology suppliers could see massive growth through CDR – mainly driven by enhanced natural processes and technology-based removal

While there could be potential across the full value chain for German and European players, the economic potential of plant technology and equipment is particularly relevant given Europe and Germany's historical strength in this sector. After elaborating on the global opportunity in plant technology and equipment in this section, the potentials for Germany and Europe are detailed in the next chapter.

The economic potential for CDR-related plant technology and equipment could experience significant growth, with an estimated annual increase of 15% to 19% from 2030 to 2050 under below 2°C- and 1.5°C-compatible removal pathways, respectively. This growth trajectory is depicted in Figure 17, which outlines the expansion of economic potential under both scenarios from €5 billion in 2030 to €76-152 billion by 2050. Technology-based removals, such as DACCS and BECCS, could be key contributors to this growth alongside BCR.

BCR's high technological readiness for scaling could significantly drive economic potential in plant equipment and technology over the next few years. By 2030, BCR could contribute 32% of the economic potential, with the remaining two-thirds coming from DACCS, BECCS, and other methods. Over the following decades, DACCS and BECCS are expected to take up larger shares of the economic potential as they scale more rapidly. By 2050, DACCS and BECCS could contribute 36% and 44% of the economic potential in plant technology and equipment, respectively, while BCR could account for 17% in a balanced CDR portfolio.

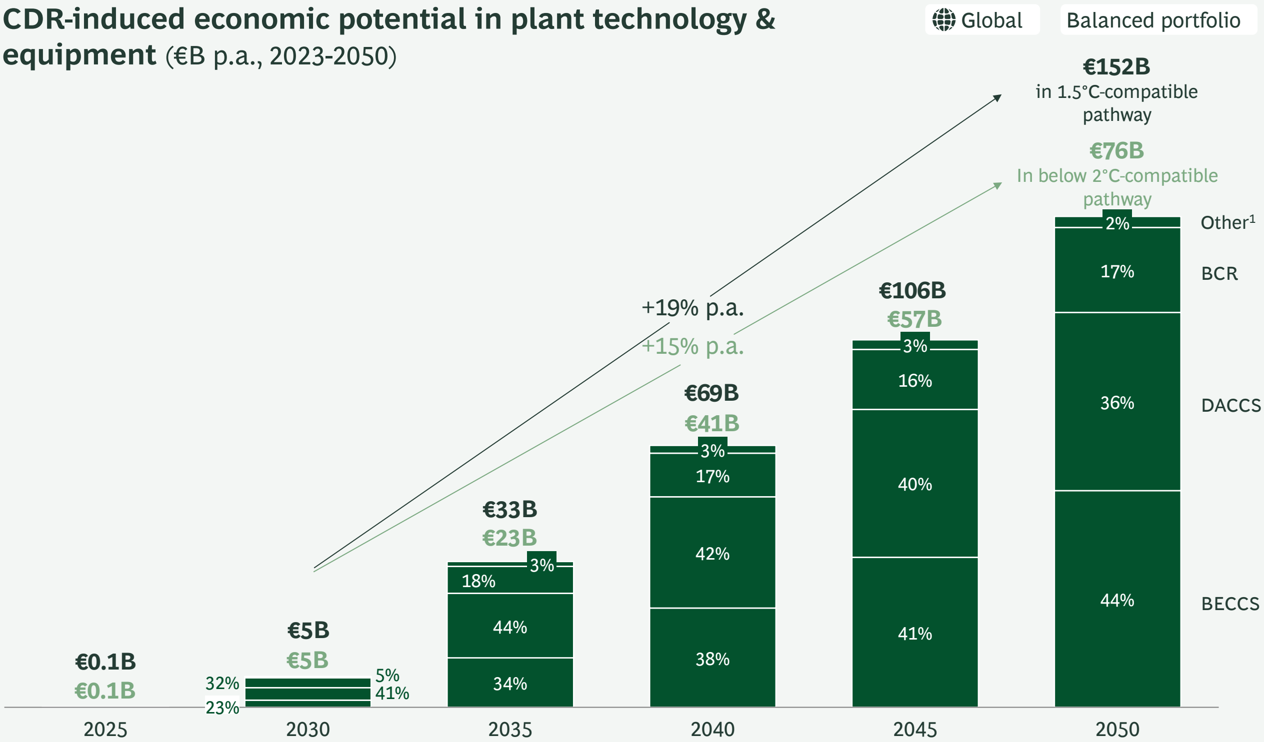
While all technology-based CDR methods require some form of instrumentation equipment (e.g., temperature, pressure, flow) and process control systems (e.g., programmable logic controllers or small distributed control systems), key components differ between methods like DACCS, BECCS, and BCR. DACCS, among other components, and dependent on the specific configuration, requires high-temperature heat pumps, vacuum pumps, or electrochemical cell stacks. BECCS (biomethane or BECCS incl. WACCS) requires a flue gas conditioning unit, cryogenic cooling system, gas compressors, and other critical components. BCR requires fewer critical components but depends on high-quality fabrics and alloys. The steady supply of these components and materials at outstanding quality and competitive cost is essential for efficient and cost-effective carbon dioxide removal.

For technology suppliers, this presents a significant opportunity to innovate and support scaling global CDR operations in the coming years. The demand for advanced equipment and technologies to scale CDR methods could drive economic growth and job creation within the sector. The increased adoption of these technologies is essential in meeting global decarbonization targets, making plant technology and equipment suppliers one of the critical enablers of reaching climate targets.

European players could play a significant role in this evolving market, given their significant investments and proven competitive advantage in sectors like mechanical engineering and component manufacturing. Chapter 4 further investigates the economic potential for German and European suppliers and its implications for job potential.

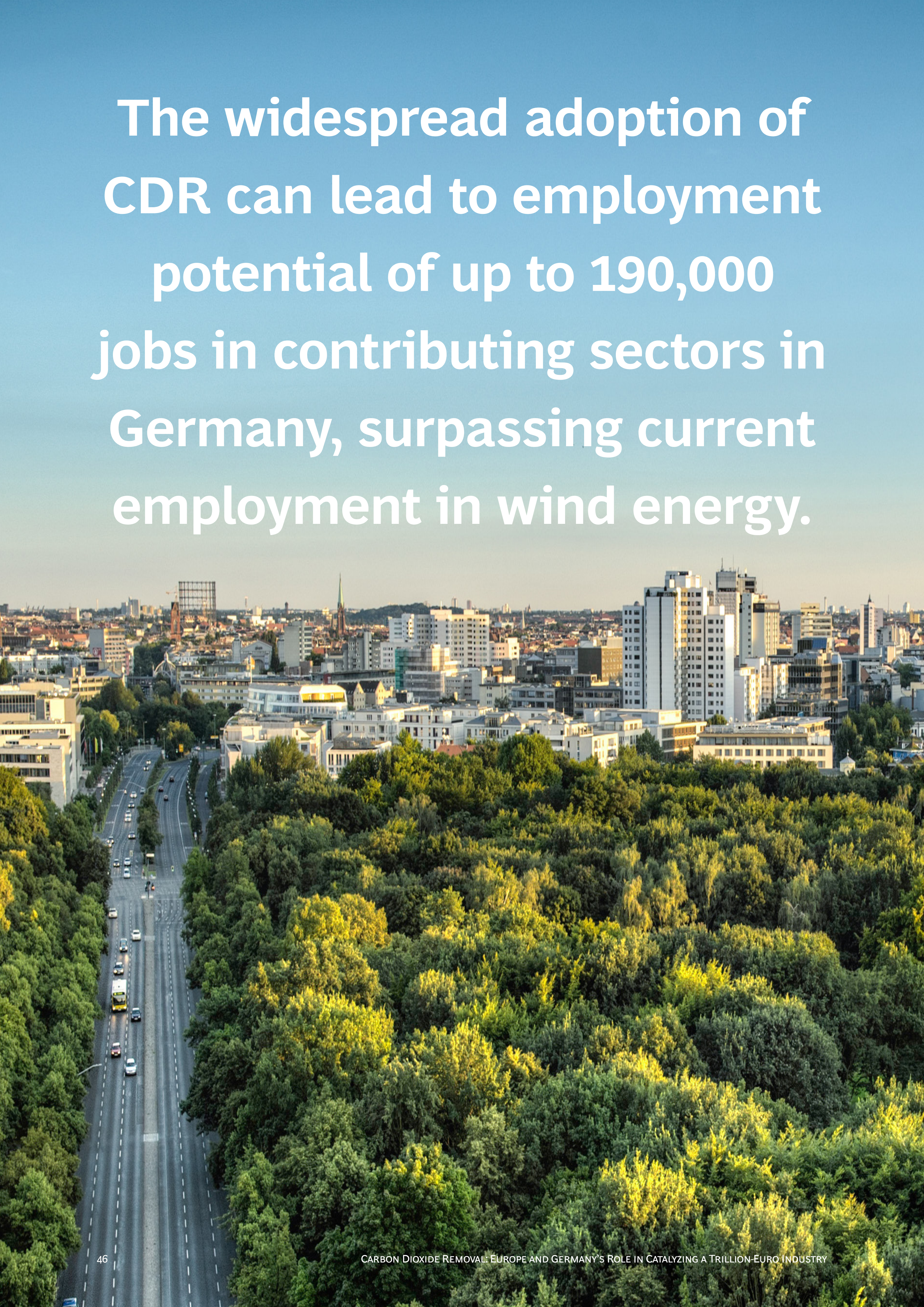
FIGURE 17

CDR-induced economic potential in plant technology & equipment (€B p.a., 2023-2050)



1. Other methods include enhanced (rock) weathering, soil carbon sequestration, peatland and wetland restoration, and ocean-based methods
Note: Figures rounded
Source: BCG CDR Market Model

The widespread adoption of CDR can lead to employment potential of up to 190,000 jobs in contributing sectors in Germany, surpassing current employment in wind energy.



4 Europe and Germany can shape CDR value chains

4.1 A €110–220B opportunity for Europe and Germany

Europe and Germany's competitive advantage lies predominantly in technology

Given the massive economic potential that is induced by CDR, the question presents itself how this might be distributed across regions and countries globally. Competitive advantage plays a decisive role here. The actual installations of CDR will happen in areas with the right natural conditions (e.g., available land) and lowest operations and maintenance costs (e.g., energy and labor). However, the technology supplied to these installations and the software developed to quantify their impact and market the resulting credits could come from anywhere in the world.

Europe and Germany's competitive advantage stems from its technological prowess. Germany is the third-largest machinery producer in the world, and German mechanical and plant engineering is considered a leading export and innovation industry.[22] Software and financial services are also of great importance to the European economy. However, due to Germany's (currently) unfavorable electricity prices, it is uncertain whether it will host a significant share of installations for DACCS or BECCS (except biomethane), despite recent studies indicating potential.[23] Also, given Germany's limited area and coastlines, it is unlikely to see many afforestation or ocean-based projects. BCR may be the

[22] BMWK, 2024.
[23] Helmholtz, TU Berlin, 2024.

exception, given that it produces surplus thermal and electrical energy, and higher energy prices increase the economic viability of such installations.

Europe, more broadly, faces similar spatial limitations, which means that the bulk of these installations and projects could likely be located in regions with more available land, such as the Global South. Therefore, the largest potential for Europe and Germany lies in supplying components and engineering services and providing location-agnostic services required for carbon removal.

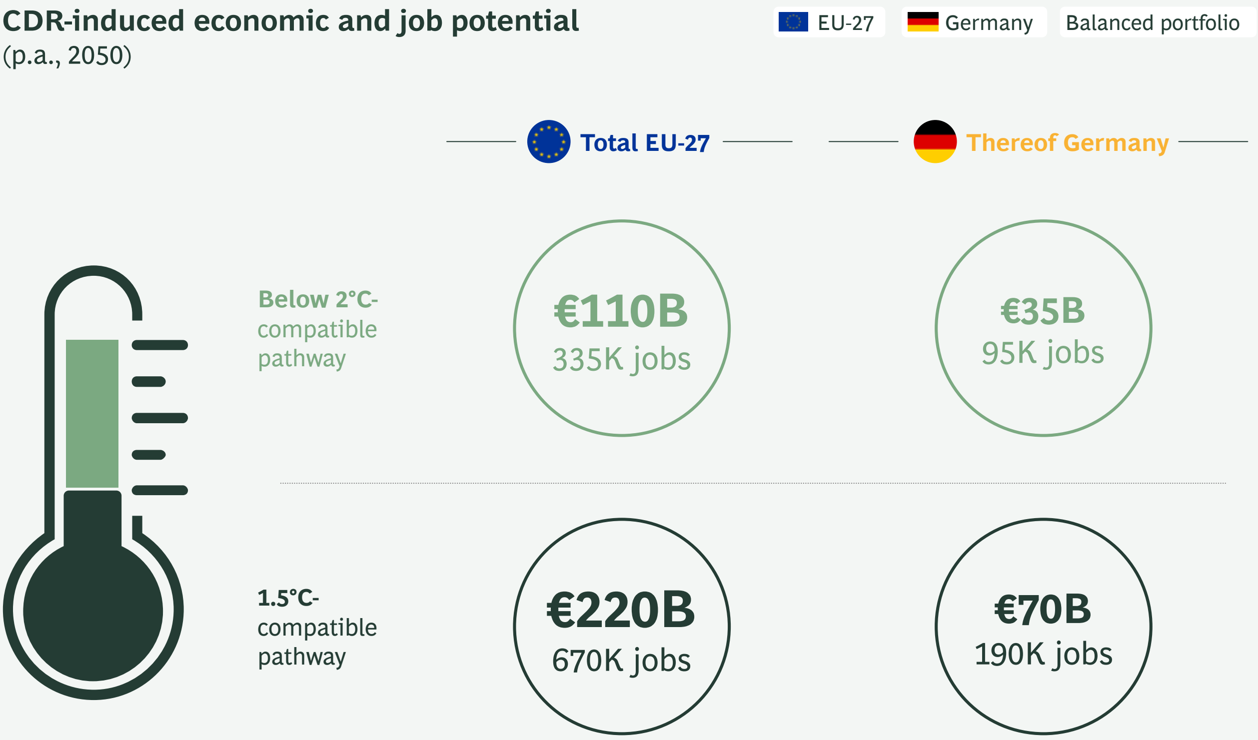
The economic potential for Europe and Germany is estimated in 3 steps

The economic potential for Europe and Germany is estimated using a three-step process:

1. **Competitive advantage:** The leading factor for competitive advantage for each CDR method and value chain step was identified. This leading factor could be either technology leadership or resource availability, such as area or energy.
2. **Comparable industries:** Suitable comparable industries were determined for technology leadership, and appropriate proxies were identified for resource availability.
3. **Market shares:** The shares of the leading country in the comparable industry were analyzed. Additionally, the current shares of the EU-27 and Germany were examined to gauge their realistic economic potential. For BCR, BECCS, and DACCS, an analysis was conducted on component-level to understand the complexity and criticality of each component and whether those components could be supplied by European/German companies at competitive cost, given the existing supplier landscape.

FIGURE 18

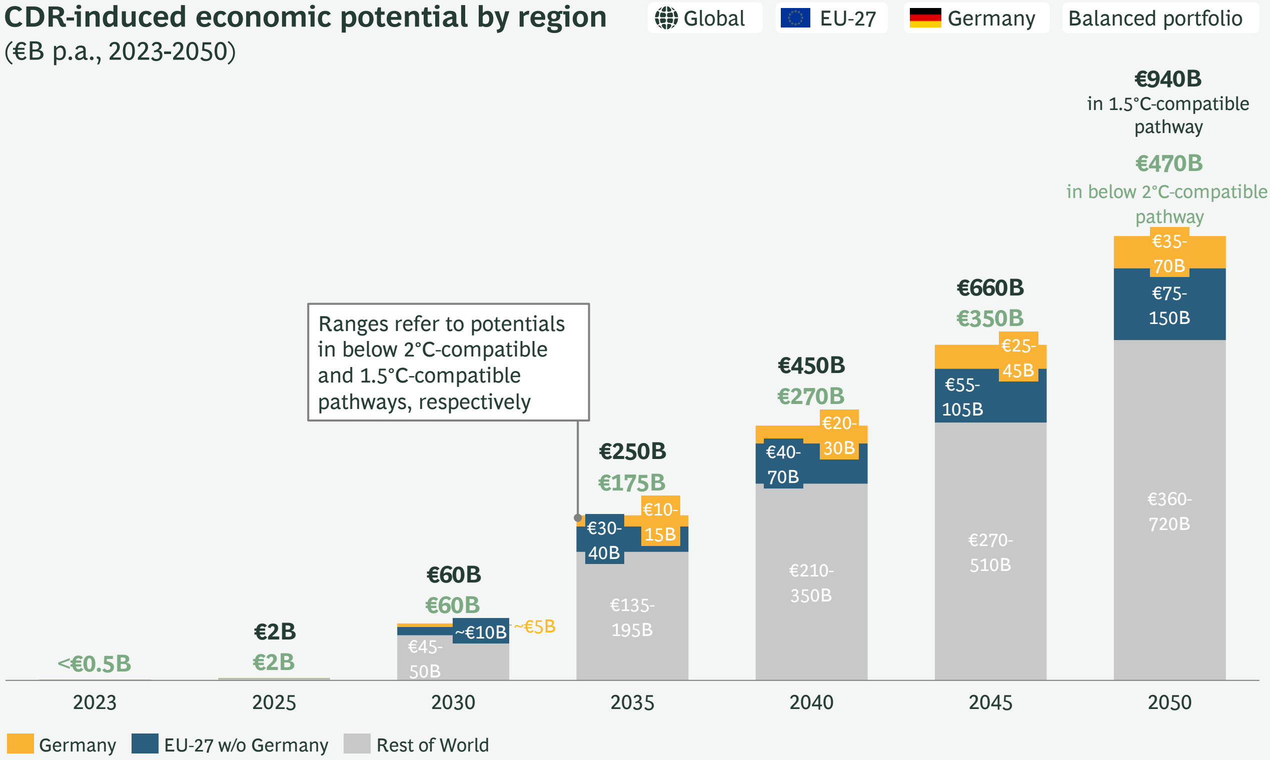
CDR-induced economic and job potential
(p.a., 2050)



Source: DVNE working group; BCG analysis

FIGURE 19

CDR-induced economic potential by region
(€B p.a., 2023-2050)



Note: Figures are rounded
Source: IDC, Gardner, FAO, Statista Market Insights; DVNE; BCG analysis

The European and German economic potential refers to the potential share of global CDR value creation that European and German companies could capture. These potentials include the supply of technology, equipment, and services, regardless of where CDR projects are launched. The term "Europe" in this report refers to the EU-27 member states, not geographical Europe, and is used interchangeably in the following. Figures explicitly mention EU-27.

Europe and Germany have the potential to build a €110-220 billion industry by 2050

Under below 2°C- and 1.5°C-compatible scenarios, the CDR-induced economic potential in Germany could reach €35-70 billion, respectively, while the economic potential for the EU-27 (including Germany) could reach €110-220 billion by 2050. This growth would make a significant contribution to their respective GDPs. For Germany, this represents roughly 2% of its current GDP under the 1.5°C-compatible scenario (for comparison, the automotive sector currently accounts for 4.5% of Germany's GDP). It is important to note that the calculated economic potentials reflect a cost-based view, including average margins for intermediaries. However, they do not reflect potential future supply and demand dynamics that could lead to different market prices, e.g., due to undersupply of credits at a given time. Also, supplier margins are not eliminated between the various value chain steps.

The development of this industry could transform the German and European economies, driving innovation, job creation, and sustainable growth. Figure 18 references the immense potential for job creation, which is detailed in the next section.

The economic potential for Europe and Germany over time is shown in detail in Figure 19. As CDR growth is expected to take off beyond 2030 and early investments by German players start to pay off, the economic potential could reach €20-30 billion in 2040, under below 2°C- and 1.5°C-compatible scenarios. By 2050, German players could capture €35-70 billion under the respective scenarios. The potential for the broader EU, excluding Germany, is also considerable. By 2040, the CDR-induced economic potential could reach €40-70 billion in below 2°C- and 1.5°C-compatible scenarios. By 2050, European players outside Germany could capture

€75-150 billion. These shares of the global potential would reflect Europe's strong technological base and its strategic investments in research and development. The gradual increase in market share from 2025 onwards indicates a solid growth trajectory for the CDR sector, driven by supportive policies and continuous advancements in CDR technologies.

Largest potential for European and German players expected for DACCS, BECCS, and BCR

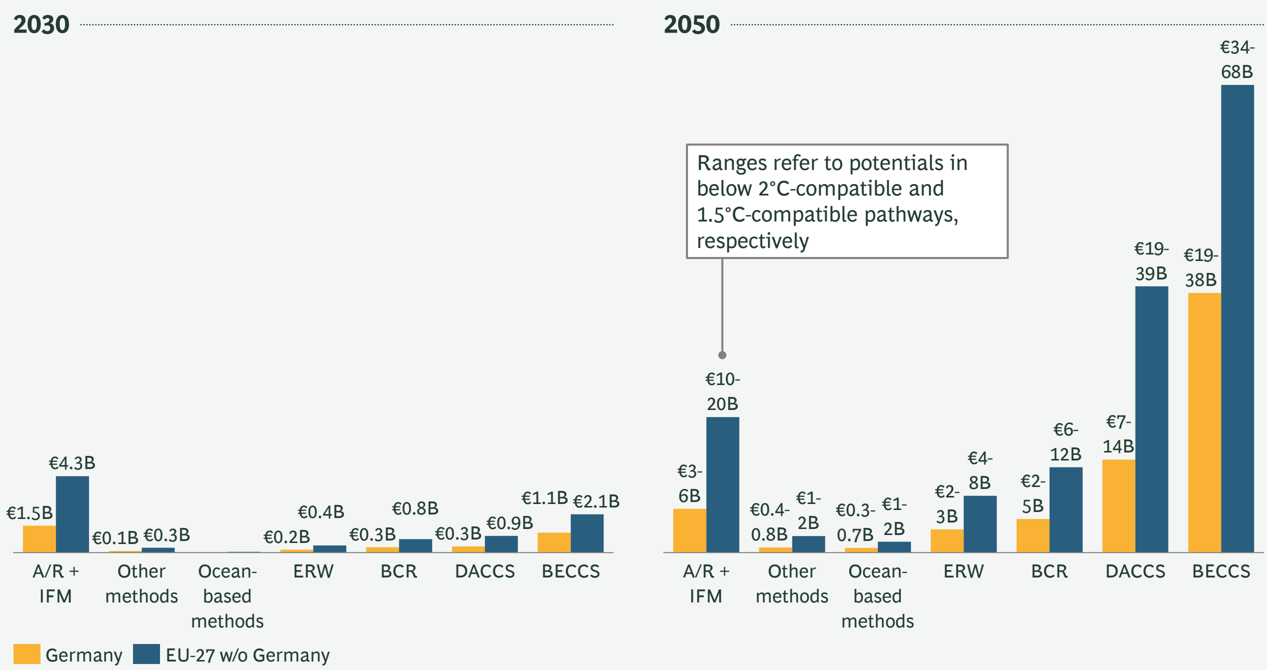
The technological leadership of Europe and Germany positions them especially well to capitalize on the growing markets for DACCS, BECCS, and BCR. By 2050, these methods are expected to offer substantial economic potential in plant and technology equipment supply. Furthermore, Europe and Germany could capture significant shares of the rapidly expanding MRV and intermediary markets, leveraging early investments.

Figure 20 illustrates the economic potentials by CDR method in 2030 and 2050 for European and German players, respectively. The economic potential for German players in BECCS could reach €1.1 billion in 2030, growing to €19-38 billion by 2050 under below 2°C- and 1.5°C-compatible scenarios, respectively. For Europe (excluding Germany), BECCS could reach €2.1 billion in 2030 and expand to €34-68 billion by 2050 under the respective scenarios. Similarly, under the below 2°C- and 1.5°C-compatible scenarios, DACCS is projected to have an economic potential of €7-14 billion for Germany and €19-39 billion for Europe (excluding Germany) by 2050. The economic potential for BCR could reach €2-5 billion and €6-12 billion in 2050 in Germany and Europe without Germany, respectively. Already today, German and European players are frontrunners in BCR production technology and their continuous improvement. These potentials demonstrate the immense opportunity and critical role that BECCS, DACCS, and BCR could play in the German & European CDR landscape.

FIGURE 20

CDR-induced economic potential by method and region (€B p.a., 2030 and 2050)

EU-27 | Germany | Balanced portfolio



Source: IDC; Gardner; FAO; Statista Market Insights; Markets and Markets; DVNE; BCG analysis

Opportunities in further CDR methods are also expected to grow

Additionally, there is a considerable commercial opportunity in afforestation, reforestation, and improved forest management, especially if demands for high-quality monitoring grow and even premium projects can be priced substantially below €100 per ton of CO_2. The growing demand for MRV and intermediary services could also open new avenues for growth, particularly for early movers who can capitalize on these emerging opportunities. There is significant potential for European and German players in ERW, primarily due to the need for innovative and cost-efficient MRV solutions. The expected increase in the deployment of enhanced natural processes and technology-based removal, along with the expansion of the MRV market, could boost Europe and Germany's positions as catalysts and frontrunners of the global CDR industry.

The potential of other methods, especially ocean-based CDR, is still unclear. They are still in early-stage development, but the economic potential for European players is expected to be comparably small.

Industry & manufacturing sector could benefit most from CDR growth

Germany's industry and manufacturing sector is poised to benefit significantly from the expansion of CDR. Significant market shares are expected in plant and mechanical engineering and in manufactured components. Additionally, the services sector holds substantial potential, particularly if European players can leverage early investments in MRV and the intermediary space. The opportunities for European and German service providers mainly lie in software development, such as data aggregation and analytics, carbon tracking and reporting systems, MRV simulation and modeling software, carbon credit marketplaces, and API integration of carbon removal projects.

Energy, construction, and transport sectors could also see substantial opportunities as they integrate CDR technologies and services into their operations. The energy sector can benefit from a project region's focus on sustainable energy solutions. The transport sector is expected to see further innovations in CO_2 transport and storage technologies, e.g., improved cryogenic rail tank cars or dedicated CO_2 carriers, contributing to the overall growth and sustainability of the industry.

In summary, CDR presents a transformative opportunity for Europe and Germany. By focusing on high-potential areas such as DACCS, BECCS, BCR, and MRV services across CDR methods and leveraging their strengths in industry and manufacturing, Germany and Europe can lead the global CDR industry, driving economic growth and sustainability.

4.2 Potential for 95-190K CDR-induced jobs in Germany

The development of the CDR industry could not only bring substantial economic growth but also significant job creation. The potential for CDR-induced jobs in Germany and Europe without Germany is illustrated in Figure 21. The potentials refer to gross employment in each respective year, not to additionally created jobs in that year. By 2050, the CDR sector in Europe could support up to 670,000 jobs, with up to 190,000 of these jobs in Germany. This growth trajectory indicates substantial employment opportunities across various sectors involved in CDR, including engineering & manufacturing, energy, and (digital) services.

If CDR develops as modelled in the 1.5°C- and 2°C-compatible scenarios, the job potential in the CDR industry is expected to increase gradually. Over the next few years, it is expected to remain relatively modest, with a gradual scale-up. By 2035, however, the sector could already support 45,000-70,000 jobs in Germany and 125,000-180,000 jobs in broader Europe under below 2°C- and 1.5°C-compatible scenarios, driven by the increasing deployment of CDR technologies and the scaling of related services and infrastructure. By 2050, the job market could expand further to support 95,000-190,000 jobs in Germany and 240,000-480,000 in other European countries in the respective scenarios.

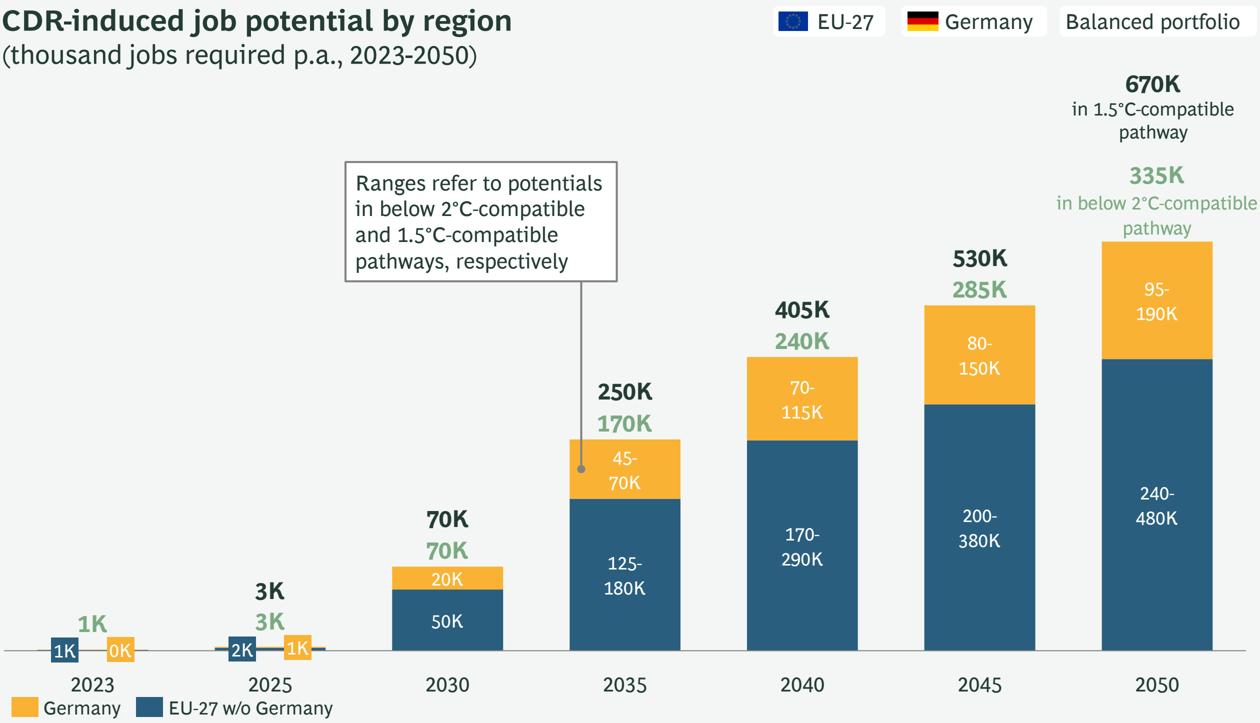
This potential is indicative of the major opportunity for the German and European economies if climate commitments are upheld and equivalent investments are made in the market for carbon dioxide removal.

The job potential is estimated based on current sector ratios of jobs per €1 million value added.[24] Automation and digitalization, especially in services and engineering, could drive a significant reduction in the number of jobs required per €1 million value added. This reduction has been accounted for. However, the rapid growth of the CDR-induced economic potential could still lead to significant job creation, counterbalancing the reduction effect.

[24] Based on data from Eurostat and Oxford Economics.

FIGURE 21

CDR-induced job potential by region
(thousand jobs required p.a., 2023-2050)



Central assumption: Reduction in jobs per €1M of -2% p.a. assumed, driven by automation and digitalization of the economy

Source: Eurostat; Oxford Economics; DVNE; BCG analysis

4.3 Germany as catalyst and orchestrator for CDR

Germany is uniquely positioned to lead and orchestrate CDR initiatives across Europe and beyond, leveraging its strong foundation in several key areas:

Progressive climate policies

Germany's commitment to ambitious climate goals, such as achieving net zero by 2045, sets the stage for substantial advancements and implementations in CDR. The government's progressive climate policies create a conducive environment for CDR development and deployment, ensuring regulatory support and channeling public investment into sustainable technologies.

Influence in European decisions

As a policy leader in Europe, Germany significantly shapes European climate strategies. This capacity to shape European and global CDR efforts positions Germany as a key player in driving the continent's climate agenda forward.

Strong innovation hub

Germany is the 8th most innovative country worldwide, reflecting its strong innovation culture.[25] With numerous patents and top tech companies, Germany leads in developing cutting-edge CDR technologies and solutions. The country's robust research and development infrastructure supports continuous innovation in CDR, making it a critical hub for technological advancements in the sector.

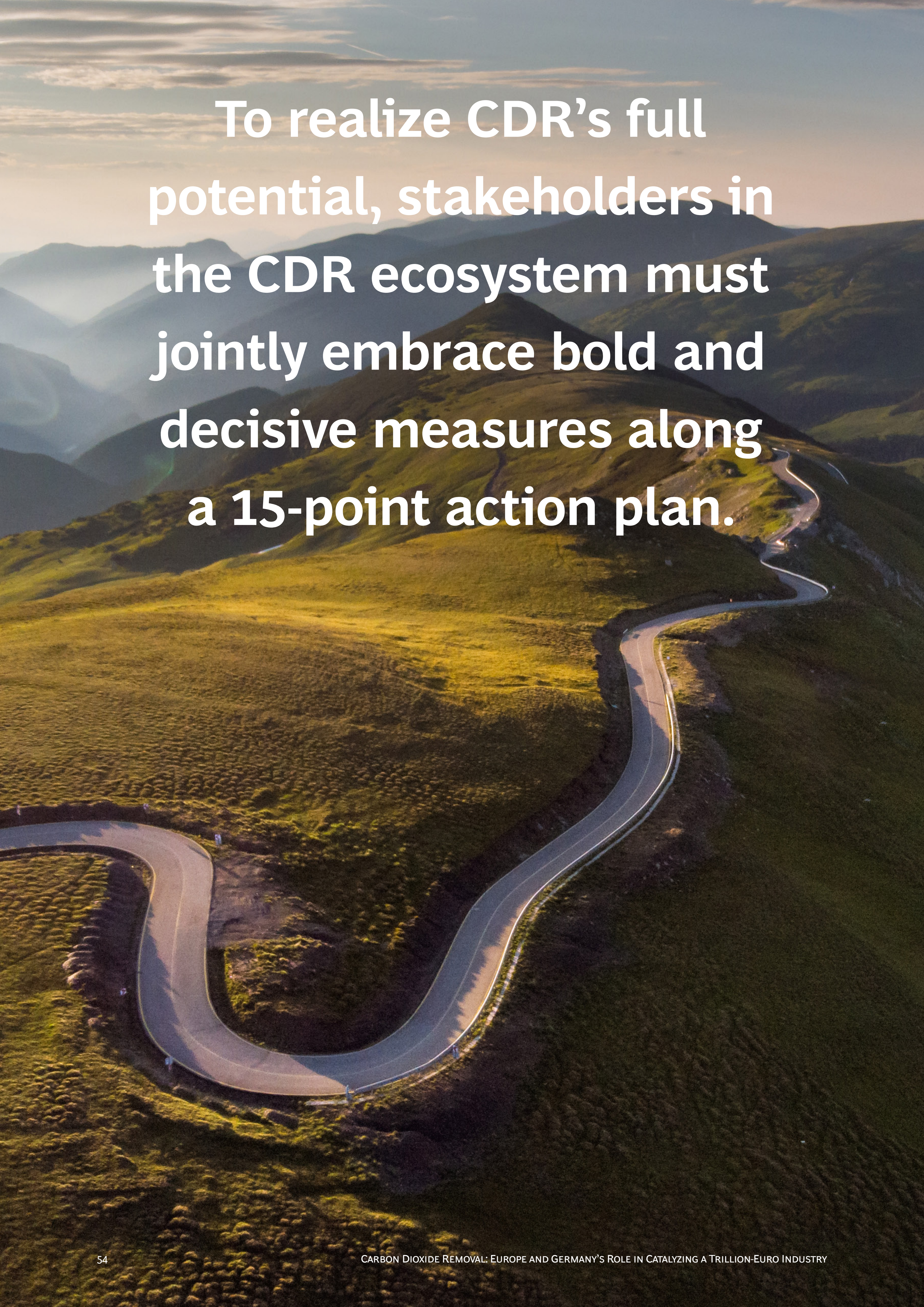
[25] WIPO Global Innovation Index, 2024.

Economic powerhouse

As both the world's third-largest economy[26] and exporter[27], Germany's strong industrial base provides crucial support for CDR initiatives. This economic strength ensures the availability of necessary resources to scale up CDR projects and offers an attractive pool of potentially large industrial CDR off-takers, such as multinational corporations.

In conclusion, Germany's progressive climate policies, influential role in European decisions, strong innovation ecosystem, and robust economy collectively position it as a leading catalyst and orchestrator for CDR in Europe and beyond. By leveraging these strengths, Germany can drive the adoption of CDR technologies and support the successful implementation of CDR projects at scale.

[26] Politico, 2024.
[27] World Trade Organization, 2024.



To realize CDR's full potential, stakeholders in the CDR ecosystem must jointly embrace bold and decisive measures along a 15-point action plan.

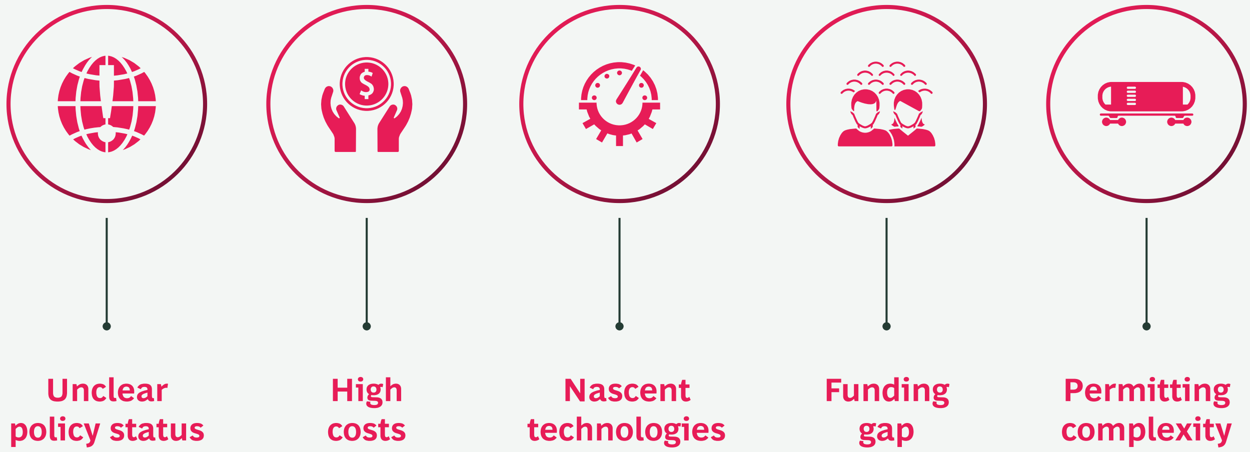
5 Bold action needed now by policymakers, industry, buyers, investors

5.1 A 15-point action plan to overcome CDR roadblocks

Current roadblocks make CDR market development, value creation, and job potential highly uncertain

Despite the tremendous climate change mitigation and economic potential CDR could offer, as explained in this report, it is highly uncertain whether CDR will develop and grow as projected in a 2°C- or 1.5°C-compatible scenario. Several roadblocks currently inhibit a rapid scale-up of the CDR industry (Figure 22). Holistically addressing these obstacles is crucial to unlocking the full potential of CDR technologies and recognizing their vital role in mitigating climate change.

FIGURE 22



Unclear climate policies make integrating CDR challenging

Despite recent progress in CDR policy development in Europe and Germany, significant gaps still exist, and many countries need to incorporate CDR into their climate strategies explicitly. The unclear role of CDR in overarching climate policy hinders its integration with existing regulations and market mechanisms. Similar to the state of renewable energy sources ~30 years ago, CDR research & development is only evolving, and effective policy instruments need to catch up. While European policies like the Emissions Trading Scheme and LULUCF regulations have already been adopted, others, such as Germany's "Langfriststrategie Negativemissionen" (LNe), are still in development, with drafts expected in 2025. The EU also recently agreed to establish a certification framework for permanent carbon removals, carbon farming and carbon storage in products (CRCF), with certification under CRCF planned from 2026 – however, this timeline is very preliminary. The impact of mechanisms like the Green Claims Directive (GCD), which provides guardrails for claims companies can make related to their removal credit purchases, must be examined. The lack of dedicated removal targets in German and European legislation further prevents companies from developing actionable roadmaps.[28] While 11 European countries have no CDR targets, another 11 only have targets for land use, land use change, and forestry (LULUCF).[29] Additionally, there is no clear link with the EU Emissions Trading System (ETS), making CDR purchases entirely voluntary. Clear accounting rules still need to be developed.[30] This ambiguity creates uncertainty, especially for investors and CDR buyers, and hinders the widespread adoption of CDR.

Many CDR methods are yet prohibitively costly

Many CDR methods remain more expensive than avoidance offsets, often due to high CAPEX requirements.[31] For instance, technology-based CDR methods like DACCS can cost over €700 per ton, making them unattractive for many buyers when cheaper CDR credits are available. The high cost of these methods prevents a timely increase in demand, as only a few buyers are willing to pay premium prices in 2023. Only 0.5% of companies with science-based targets have purchased durable carbon removal, underpinning the limited willingness to pay. The vast majority of purchased removal credits can be attributed to only a handful of companies.[32]

Nascent CDR technologies yet need to improve on key parameters

Given that multiple CDR methods are only emerging and have a relatively low (technological) readiness level, they yet need to improve key parameters, for example, capture efficiency, energy intensity, or subsequent storage permanence. Complex MRV approaches, and credibility challenges regarding the verifiability of sequestered CO_2 may further impede progress.[33] These issues are partly due to the industry's relative newness and fragmented nature.

[28] The State of Carbon Dioxide Removal, 2014.
[29] Manhart, S., 2023.

[30] European Zero Emission Technology and Innovation Platform, 2021.
[31] Prado et al., 2023.
[32] Cdr.fyi, 2023.

A considerable funding gap impedes the growth of CDR projects

The current investment gap limits many CDR projects' financing and commercial operations.[34] This is intensified because most permanent technology-based removals require high upfront CAPEX investments, have long payback periods, and entail uncertainties around future carbon markets. Specifically, CDR projects struggle to obtain final investment decisions (FID) as they are often not bankable because only a few prospective buyers are willing to commit to long-term removal credit off-take agreements, trying to avoid lock-in at high prices. However, long-term off-take agreements are a critical pre-condition for banks to finance projects. At the same time, CDR start-ups & scale-ups struggle to attract (equity) investors as the overall prospect of the CDR industry remains uncertain. Despite signs of growing momentum for private investments in the CDR space, these investments are largely focused on the USA and Canada, and on pre-growth stages.[35] Without suitable and highly tailored project financing and growth-stage support, CDR initiatives will continue to struggle to move towards FID.

Complex permitting processes may delay infrastructure development or plant commercial operation

Infrastructure, especially renewable energy supply and CO_2 transport networks, is crucial for implementing multiple CDR methods at scale. However, these essential components face significant permitting challenges. For instance, pipelines for CO_2 transport and secure geological storage sites require extensive regulatory approval.[36] Additionally, complex approval procedures for plant operation can lead to delays and increased costs, hindering CDR projects' timely deployment and scalability. On the German national level, the Carbon Management Strategy (CMS) has triggered a revision of the current Carbon Storage Act (KSpG) to streamline permitting procedures for transport and storage infrastructure and legally enable large-scale carbon storage. However, the process is still ongoing.

[33] Jones et al., 2024; World Resources Institute, 2023.
[34] The Time for Carbon Removal Has Come, 2023.
[35] CDR.fyi, 2024.
[36] Blanchard et al., 2024, Edenhofer et al., 2021.

CDR uptake necessitates cohesive action from four key stakeholder groups

Policymakers should commit strategically to CDR by funding technology research and project deployment and setting dedicated removal targets.

CDR industry should improve sequestration potential and capacity while decreasing unit costs and activating early movers.

CDR buyers should commit to long-term offtakes of high-quality removal in their corporate offset portfolios and gradually shift away from avoidance credits.

Investors can act as orchestrators between policymakers, insurers, and CDR project developers.

The proposed 15-point action plan shall catalyze and coordinate the required measures (Figure 23).

FIGURE 23

Stakeholders should embrace a 15-point action plan to drive CDR uptake

POLICYMAKERS

1. Embrace CDR as integral part of climate policy and set deployment targets
2. Include CDR in compliance market (e.g., link with EU ETS, Corsia)
3. Fund research programs and early-stage CDR projects
4. Provide securities and subsidies for deployment of specific CDR projects
5. Remove regulatory hurdles & frictions that prevent CDR adoption
6. Foster (cross-border) infrastructure and storage build-out
7. Boost CDR demand through public procurement

CDR INDUSTRY

8. Increase TRL and industrialize production for economies of scale
9. Support research to improve CDR parameters and transparency
10. Activate “early movers” among customer base

CDR BUYERS

11. Shift voluntary carbon market portfolio from avoidance to removal
12. Engage in long-term offtakes and make financial commitments
13. Push for full eligibility of CDR credits towards climate targets
14. Develop strong communication strategies and engage the public

INVESTORS

15. Develop project financing solutions to address CDR funding gap

5.2 Policymakers

1: Embrace CDR as integral part of climate policy and set deployment targets

Policymakers should integrate CDR into climate policies by explicitly endorsing CDR as an integral part of reaching climate ambitions and establishing specific removal targets at both European and national levels to address hard-to-abate residual emissions. For example, they could mandate that a particular share of remaining total emissions needs to be neutralized through CDR as part of their decarbonization plans. Setting incremental annual CDR targets to track progress and adapt policies as needed could effectively grow the CDR market in the long run. Additionally, differentiating between permanent and temporary removal in these policies can ensure a more tailored approach to scaling CDR.

2: Include CDR in compliance market (e.g., link with EU ETS, Corsia)

The EU should assess in detail the possibility of linking CDR with the existing EU Emissions Trading System (ETS) schemes. In doing so, it is crucial to recognize and address the distinctions between carbon removals and emission reductions, e.g., in the temporal element of carbon removals, and prevent double counting.[37] Nevertheless, allowing the substitution of 10% of required EU ETS emission allowances with CDR credits or aligning CDR governance with existing emission reduction mechanisms could help drive and coordinate CDR demand. Alternatively, a 'carbon central bank' that subsidizes removals by translating them into emission allowances could be established at the EU level and integrated with the ECB, as the Kiel Institute and Potsdam Institute proposed.[38]

3: Fund research programs and early-stage CDR projects

Funding tailored R&D programs for fundamental CDR research and reducing administrative hurdles for subsidy schemes can accelerate CDR innovation. For example, direct CAPEX grants, such as those from EIB capital, can provide essential early-stage financial support, while innovation hubs or incubators could foster collaboration and rapid CDR development. Furthermore, research funds could support universities and research institutes in driving the speed of CDR innovation. Creating public-private partnerships would facilitate the testing and advancement of novel CDR methods, helping to identify and address regulatory barriers and knowledge gaps that require further time and investment.

4: Provide securities and subsidies for deployment of specific CDR projects

Offering government-backed securities, feed-in tariffs, contracts for difference, or buyer discounts can stabilize the market and encourage investments. Government or sovereign guarantees have been used to attract investments in renewable energy in emerging countries and could be a suitable instrument to reduce investors' residual risks.[39] Feed-in tariffs and contracts for difference can protect both suppliers and investors from fluctuations of removal credit prices. Measures like this can mitigate upfront expenditure challenges and encourage the deployment of CDR in Germany and Europe through domestic and international removal companies.

5: Remove regulatory hurdles & frictions that prevent CDR adoption

To attract investors, policymakers on the European level should harmonize its CDR-related terminology with that of the IPCC and explicitly include all CDR methods as "green investments" under the EU Taxonomy and Sustainable Finance Disclosure Regulation (SFDR). Clear accounting standards (e.g., for MRV) and adapting insurance regulations to facilitate "insurability" of delivery risks can also lower the barriers to CDR investment and adoption.

On German national level, for example, amendments to the Carbon Storage Act (KSpG), as recently drafted by the Federal Ministry for Economic Affairs and Climate Action (BMWK), are welcomed, but could go further to permit onshore CO_2 storage in Germany in federal legislation. Closely interlinking related policies and mechanisms like the LNe and the KSpG on German level will be crucial to avoid redundancies, gaps and controversial stipulations.

[37] TechEthos, 2023.
[38] Kiel Institute for the World Economy, 2024; Edenhofer et al., 2023.
[39] IRENA, 2020.

6: Foster (cross-border) infrastructure and storage build-out

Building infrastructure to support CDR technologies and fostering bilateral cross-border agreements on transporting and storing carbon or CO_2 can enhance CDR's timely uptake. A key challenge is the lack of a unified international solution for cross-border CO_2 transport—a challenge that would be alleviated by the ratification of the Article 6 amendment to the London Protocol, allowing for the export of CO_2 for permanent offshore storage.[41] Additionally, enabling technologies like renewable energy sources and district heating networks should be closely considered when planning local and cross-border infrastructure for CDR projects. The need for transport and storage infrastructure, including CO_2 pipelines, should be mapped at both national and cross-border levels to understand how transport modalities can be optimized.

7: Boost CDR demand through public procurement

Governments are at different stages of integrating CDR into their climate strategies. While only few countries have implemented dedicated programs or made extensive CDR purchases, others are slowly following with related regulatory advancements. Yet others have not made any explicit commitments, let alone purchases. Responsible ministries can promote confidence and investments in CDR methods by fostering such government procurement. Leading by example, the U.S. Department of Energy recently launched a funding program to allow companies to compete to deliver CDR credits to the U.S. government.[42] Denmark constitutes a prime example in the EU with the largest government-led removal purchase in history of 1.1 Mt durable CDR credits.[43] Further European countries and the German government could follow suit, thus providing additional funding to CDR companies and strong positive demand signals.

5.3 CDR industry

8: Increase TRL and industrialize production for economies of scale

The CDR industry should enhance energy efficiency to reduce infrastructure dependency, such as DACCS, and improve long-term storage concepts to ensure stability over geologically relevant time frames. Specific examples include insulation improvements, the capture efficiency of sorbents and solvents, and other measures. Developing standardized manufacturing processes and plant configurations can also enable economies of scale, decreasing costs, especially for technology-based CDR solutions. This can be achieved by collaborating with universities and research institutes, such as the Fraunhofer Institute, and partnering with large German industrial players to accelerate innovation in this space.

9: Support research to improve CDR parameters and transparency

Fostering research consortia to improve permanence, reduce the risk of leakage, and enhance the accuracy of CO_2 removal measurements can enable more accurate reporting and build trust in CDR solutions. Digital solutions like artificial intelligence and digital twins could further boost monitoring performance. Improving technical interfaces for integrating CDR data into corporate sustainability reports and sharing supply chain data can enhance transparency, ensuring credibility and broader public acceptance. Investing in data-sharing platforms for carbon removals and associated data - such as on geological storage or mineral sources – can support CDR companies in their search for optimal project locationsand broader public acceptance.

[40] BMWK, 2024.
[41] Global CCS Institute, 2022.
[42] U.S. Department of Energy, 2024.
[43] Carboncredits.com, 2024.

10: Activate “early movers” among customer base

The CDR industry should identify niche customers with strict quality criteria and a high willingness to pay for early, high-cost CDR projects. Engaging these early adopters can increase awareness and certainty for second movers, driving broader market uptake. Further, technology firms like Microsoft or other professional services firms could serve as promising early adopters to start building and diversifying their corporate removal portfolios. At the same time, heavy emitters such as the steel or automotive industries continue to focus on reduction measures first. Approaching industry associations like the German Association of the Automotive Industry (VDA) can help effectively target specific customer groups early on. By promoting tailored CDR methods to buyers based on location, industry overlaps, and willingness to pay, among other factors, early movers can be further encouraged to invest in CDR methods. Confidence in evolving methods like ERW could be further strengthened through strategic cooperations between CDR companies and carbon credit certification bodies (e.g., Verra) to ensure acceptance of methods by these standards.

5.4 CDR buyers

11: Shift voluntary carbon market portfolio from avoidance to removal

CDR buyers should gradually reduce the share of avoidance credits in their corporate offset portfolios to signal the demand for high-quality removal certificates. Buyers and associations can promote this by setting goals to reduce avoidance credits by a specific percentage annually and replace them with CDR credits. For example, the World Economic Forum’s First Movers Coalition has set a CDR target for its members by 2030, which other associations could follow.[44] This strategy could include highlighting supply chain synergies, such as buyers using carbon removal products in supply chains (e.g., biochar in construction materials like concrete). Additionally, internal carbon pricing in line with CDR prices can be an effective measure to incentivize and finance the purchase of CDR. By purchasing a diverse set of CDR certificates, including those from new technologies, buyers can drive the market demand for higher-quality carbon removal.

12: Engage in long-term offtakes and make financial commitments

Committing to long-term offtake contracts can provide a strong demand signal and mitigate supplier risk. For example, companies can agree to purchase a fixed amount of CDR credits annually for the next decade, ensuring predictable revenue streams for suppliers. Making advance commitments or direct investments in CDR projects can further support the industry’s growth and stability by reducing suppliers’ risks.

13: Push for full eligibility of CDR credits toward climate targets

CDR buyers should advocate for including CDR in environmental, social, and governance (ESG) reporting and target-setting standards. By promoting an even more prominent acceptance and role of CDR credits in voluntary frameworks such as the Science-Based Targets initiative (SBTi) or Carbon Disclosure Project (CDP), buyers can drive demand for high-quality removal. For instance, incorporating CDR into company sustainability reports and climate action plans can signal its importance to stakeholders and investors, increasing their credibility and adoption.

14: Develop strong communication strategies and engage the public

Offering educational formats to increase awareness of CDR’s social and regional benefits and launching campaigns highlighting co-benefits like biodiversity and circular economy advantages can foster broader engagement. Strategic PR efforts that send strong demand signals to “second movers” and showcase success stories of specific CDR methods can enhance public understanding and support for CDR initiatives, driving wider adoption and acceptance. For instance, webinars, press releases, community events, and partnerships with industry associations can effectively reach the right audience.

[44] World Economic Forum White Paper, 2024.

5.5 Investors

15: Develop project financing solutions to address CDR funding gap

Investors should create non-dilutive financial instruments and implement debt vehicles for high setup costs, supporting scale-ups with a "non-VC" return profile (e.g., grant and loan programs). Increasing seed financing options by establishing dedicated CDR seed funds and providing credit enhancements for start-ups can make CDR projects more viable. Additionally, collaborating with insurance companies to manage delivery risks and accepting various guarantees beyond upfront payments can facilitate project FIDs. For instance, using blended finance models to share the risk between public and private investors could encourage more investment in CDR. These actions can ensure robust financing options, mitigate risks, and foster investment in early-stage CDR projects.

The analysis in this report demonstrates the urgent need for CDR across various climate scenarios, presenting a diverse range of methods and the significant potential that CDR can unlock globally. A collaborative approach involving policymakers, the entire CDR industry, CDR buyers, and investors is crucial to overcoming existing hurdles and scaling up partially nascent CDR methods.

By leveraging technological expertise and fostering robust policy frameworks, Germany and Europe can catalyze the growth of a vibrant CDR industry, addressing climate change while stimulating economic growth and job creation. Moving forward, bold and decisive measures will be imperative to harness the full potential of CDR, ensuring a sustainable and resilient future for generations to come.

About the lead authors

Patrick Herhold

Managing Director and Senior Partner, Munich
Patrick is the co-founder of BCG's Center for Climate & Sustainability, and he leads the firm's Decarbonization Solutions business. He is an expert in climate change and abatement levers, markets and emission regulation, and related strategies for private and public actors.
Herhold.Patrick@bcg.com

Johanna Pütz

Managing Director and Partner, Berlin
Johanna leads BCG's Climate & Sustainability business in Central Europe. She specializes in decarbonization incl. scope 3, circularity, and ESG for energy and industrial companies, especially automotive and raw materials, and has extensive experience in carbon markets.
Puetz.Johanna@bcg.com

Karan Mistry

Managing Director and Partner, Los Angeles
As a lead member of BCG's Climate & Sustainability team, Karan focuses on decarbonization and climate technologies, particularly within the energy and public sectors. He is an expert in carbon free energy sourcing and carbon dioxide removal.
Mistry.Karan@bcg.com

Robin Bierganz

Project Leader, Munich
Robin is a core member of BCG's Climate & Sustainability team. He has developed decarbonization roadmaps and sourcing strategies in the CDR space. He has further supported large-scale transformation and investment programs in the industrial goods and energy sectors.
Bierganz.Robin@bcg.com

Phillip Spiekermann

Consultant, Munich
Phillip has experience across different climate and sustainability topics, specifically in consumer goods and industrial goods. He has worked on a variety of projects, ranging from building electric vehicle OEMs to sustainable sourcing in fashion.

Louisa Maier

Consultant, Munich
Louisa specializes in strategy and business development, emphasizing ESG-driven organizational change and growth strategies. She has applied her expertise across diverse sectors, including private equity, consumer, and industrial goods.

Glossary

Abbreviation	Term
°C	Degree Celcius
A/R	Afforestation / reforestation
API	Application Programming Interface
BCR	Biochar carbon removal
BECCS	Bioenergy with carbon capture and storage
BMWK	Federal Ministry for Economic Affairs and Climate Action
BPU	Biochar production unit
CAPEX	Capital expenditures
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Corsia	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
DE	Germany
DVNE	Deutscher Verband für Negative Emissionen
EIB	European Investment Bank
ERW	Enhanced (rock) weathering
ESG	Environmental, social, and governance
EU ETS	European Union Emissions Trading System
FID	Final investment decision
GHG	Greenhouse gas emissions
IFM	Improved forest management
IPCC	Intergovernmental Panel on Climate Change
KSpG	Carbon Storage Act
LNe	Langfriststrategie Negativemissionen
LULUCF	Land-use, land-use change, and forestry
MRV	Measurement, reporting & verification
NDC	Nationally determined contribution
OPEX	Operating expenditures
p.a.	Per annum / per year
PR	Public relations
PV	Photovoltaics
R&D	Research and development
TRL	Technical readiness level
VC	Venture capital
WACCS	Waste to energy with carbon capture and storage

Disclaimer

This study has been commissioned by the German Association for Negative Emissions (DVNE) and has been jointly conducted by BCG, DVNE, and a selection of DVNE's affiliated member companies (see authors and acknowledgements). The findings, interpretations and conclusions expressed herein are a result of a collaborative process. While representatives from these companies were interviewed as part of the research & modeling work for this study and provided input on technical, regulatory, and economic aspects of the CDR market and specific CDR methods, the findings from this report represent the views of the authors, backed by both primary and secondary research. They do not necessarily represent the views of the entirety of DVNE's members, partners, or other stakeholders.

Additionally, it is worth noting that while BCG itself is a purchaser of carbon dioxide removal credits, the authors of this report have not been involved in BCG's procurement decisions.


BCG
bcg.com