The Landscape of Carbon Dioxide Removal

US Policies to Scale Solutions

Energy & Climate

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About Rhodium Group

Rhodium Group is an independent research provider with deep expertise in policy and economic analysis. We help decision-makers in both the public and private sectors navigate global challenges through objective, original, and data-driven research and insights. Our key areas of expertise are China's economy and policy dynamics, and global climate change and energy systems.

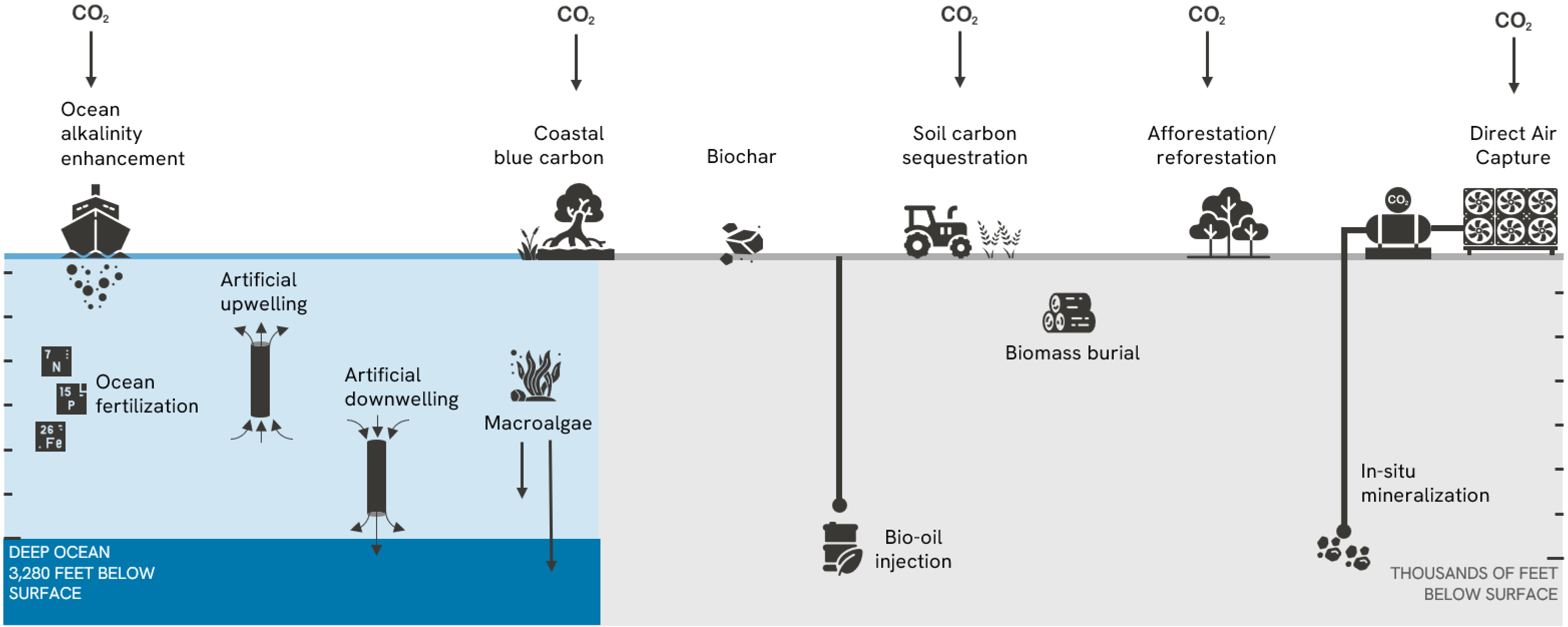
Rhodium Group's Energy & Climate practice analyzes the effects of policy and market developments on greenhouse gas emissions and energy systems, and provides actionable information about the impacts of climate change.

More information is available at www.rhg.com.

What is Carbon Dioxide Removal (CDR)?

CDR is a broad set of processes and technologies that result in the net removal of CO_2 from the atmosphere.

Illustration of select CDR approaches



Source: Rhodium Group

The need for CDR

Based on global climate models, various decarbonization studies, and Rhodium internal modeling estimates, **at least one gigaton of annual CDR capacity** will need to be available in order for the US to decarbonize by mid-century.

Estimates of CDR required by mid-century from US decarbonization studies

Gigatons of CO_2

Source: Rhodium Group; Princeton University Net-Zero America: Potential Pathways, Infrastructure, and Impacts; The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050; Evolved Energy Annual Decarbonization Perspective 2023: Carbon-Neutral Pathways for the United States; The Fifth National Climate Assessment

A diverse array of approaches

Natural solutions

Natural CDR solutions are processes that naturally capture CO_2 without requiring significant human or technological intervention.

Many of these processes have been occurring for hundreds of millions of years; the difference here is we are now expanding or maintaining the locations where these natural processes are taking place.

Includes: Reforestation and afforestation, soil carbon sequestration, and coastal blue carbon

Hybrid solutions

Hybrid CDR solutions are processes that enhance the speed of natural CO_2 capture and/or transfer the captured CO_2 to more permanent storage.

Many of these processes naturally occur today but at a slower pace than is desired for meaningful decarbonization.

Includes: Ocean biomass with carbon removal and storage, biochar, ocean alkalinity enhancement, bio-oil, and enhanced weathering

Engineered solutions

Engineered CDR solutions are processes that use human-made technologies to capture CO_2 from ambient air or oceans.

These processes can lead to significantly faster CO_2 removal than would otherwise occur using natural methods of removal.

Includes: Direct ocean capture and direct air capture

Note: The CDR space is evolving rapidly. Not all CDR approaches neatly fit within these three categories thought most do.

A diverse array of approaches

Current CDR solutions vary across a range of key factors

Stage of deployment

Lab: theory has been proven; still being studied in a lab setting

Pilot: being tested in a real-world environment at a small scale

Demonstration: prototype at or approaching commercial size

Commercial: full-scale facility operating at intended size

Cost of CDR solutions

CDR approaches span a wide range of costs—from less than $100 per ton of CO_2 removed to more than $1,000 per ton of CO_2.

Monitoring, reporting, and verification (MRV)

MRV is a process in which CO_2 removal from a CDR approach is actually measured and validated.

Developing a uniform MRV framework can be challenging since the process for capturing and storing CO_2 varies greatly across CDR approaches.

Permanence of CO_2 storage

Permanence describes how long a CDR approach keeps CO_2 out of the atmosphere.

Some methods may only store carbon for a handful of years, whereas others operate on geologic time scales (millions of years).

Summary of CDR approaches

Natural solutions

Natural

CDR APPROACH	STAGE OF DEPLOYMENT	COST	MONITORING, REPORTING, AND VERIFI...	PERMANENCE				
	Lab Pilot Demo Commerical	Less than $150/ton $150 - $600/ton Over $600/ton		DECADES	100-200 YEARS	200-1,000 YEARS	MILLENNIA	MILLIONS OF YEARS
Improved forest management			Hard					
Afforestation/ reforestation			Medium					
Coastal blue carbon			Hard			*more research needed*		
Soil carbon sequestration			Hard			*up to 1,000 years if soil cover is turned back into forest*		
Peatland/wetland restoration			Hard			*Wetlands*	*Peatlands*	

Rhodium estimates based on a range of sources (see Table 1 section in References of full report). Note: Cost ranges reflect current cost estimates concurrent with the stage of development; they are not future cost projections. MRV for improved forest management varies depending on the practice used.

Summary of CDR approaches

Hybrid solutions

Hybrid

CDR APPROACH	STAGE OF DEPLOYMENT	COST	MONITORING, REPORTING, AND VERIFI...	PERMANENCE				
	Lab, Pilot, Demo, Commerical	$ Less than $150/ton $$ $150 - $600/ton $$$ Over $600/ton		DECADES	100-200 YEARS	200-1,000 YEARS	MILLENNIA	MILLIONS OF YEARS
Ocean fertilization (Ocean BiCRS)	Lab	$ - $$	Hard	*shallow ocean*		*deep ocean*		
Macroalgae (Ocean BiCRS)	Pilot	$ - $$	Hard	*shallow ocean*		*deep ocean*		
Artificial upwelling and downwelling (Ocean BiCRS)	Lab	$	Hard	*shallow ocean*		*deep ocean*		
Biomass burial (Terrestrial BiCRS)	Demo	$	Medium					
Biochar (Terrestrial BiCRS)	Demo	$ - $$	Medium					
Ocean alkalinity enhancement	Lab, Pilot	$ - $$	Hard				*100s of Millennia*	
Bio-oil injection (Terrestrial BiCRS)	Pilot	$$	Easy					
BECCS* (Terrestrial BiCRS)	Pilot, Demo	$ - $$	Easy					
Surficial mineralization/ enhanced weathering	Pilot	$ - $$	Medium					
Ex situ mineralization (CO2 storage)	Lab, Demo	$ - $$	Easy					
In situ mineralization (CO2 storage)	Demo	$ - $$	Easy					

Rhodium estimates based on a range of sources (see Table 1 section in References of full report). Note: Cost ranges reflect current cost estimates concurrent with the stage of development; they are not future cost projections. For ocean BiCRS, shallow water refers to depths above 1,000 meters (3,280 feet) and deep ocean refers to depths below 1,000 meters. These CDR approaches are means of capturing CO_2 and involve being paired with a method of CO_2 storage (e.g. saline storage or enhanced mineralization) to achieve the levels of permanence outlined.

Summary of CDR approaches

Engineered solutions

Engineered								
CDR APPROACH	STAGE OF DEPLOYMENT	COST	MONITORING, REPORTING, AND VERIFI...	PERMANENCE				
	Lab Pilot Demo Commerical	$ Less than $150/ton $$ $150 - $600/ton $$$ Over $600/ton		DECADES	100-200 YEARS	200-1,000 YEARS	MILLENNIA	MILLIONS OF YEARS
Direct ocean capture*	Pilot	$$	Medium					
Electrochemical* (DAC)	Lab	$$$	Easy					
Solid solvent/ mineralization* (DAC)	Pilot	$$$	Easy					
Solid sorbent* (DAC)	Demo	$$ - $$$	Easy					
Liquid solvent* (DAC)	Pilot Demo	$$ - $$$	Easy					

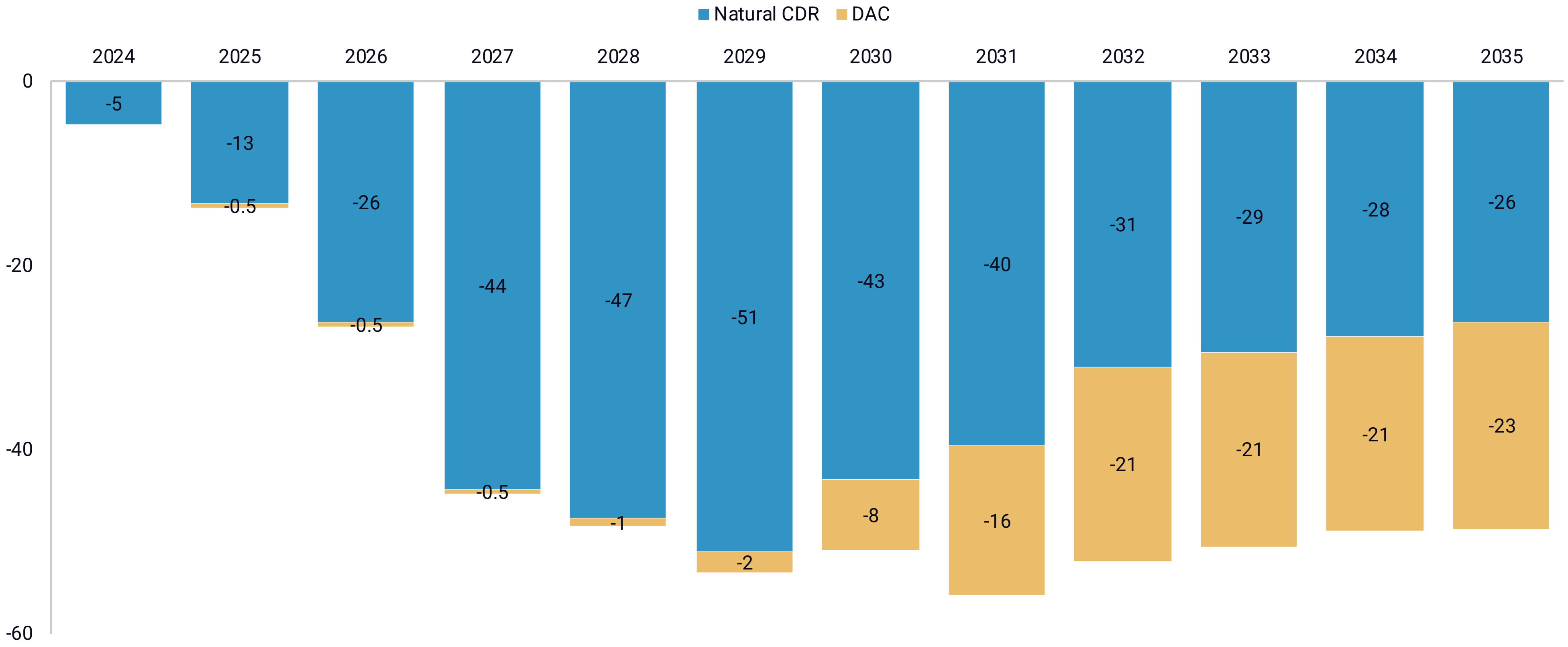
Rhodium estimates based on a range of sources (see Table 1 section in References of full report). Note: Cost ranges reflect current cost estimates concurrent with the stage of development; they are not future cost projections. These CDR approaches are means of capturing CO_2 and involve being paired with a method of CO_2 storage (e.g. saline storage or enhanced mineralization) to achieve the levels of permanence outlined.

Current policy is not sufficient to get the US to a gigaton of CDR

A gigaton of CDR means at least $100 billion per year in support for commercial CDR by midcentury. Less than 10% of economy-wide energy costs annually.

CDR in the US, excluding baseline natural CDR

Net million metric tons (MMT) of CO_2e removal



Source: Rhodium Group's Taking Stock 2023, under our mid-emissions scenario. Note: Annual energy costs are based on total expenditures in 2021.

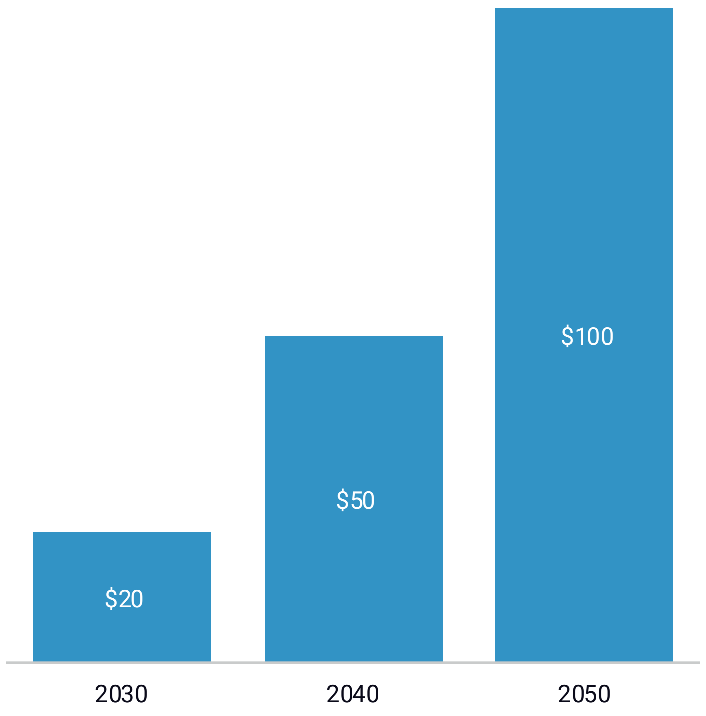
US policies to get to a gigaton of CDR

Establish, expand and scale

Establish a long-term revenue market

Total annual revenue

US billions of dollars



Source: Rhodium Group

Expand the CDR portfolio

Further research and development (R&D) can help discover novel technological designs and expand the research around CO_2 permanence and MRV.

R&D programs should include support for pilot projects and test centers to transition technologies out of the lab into real-world operating conditions.

We recommend a minimum of **$6 billion in total R&D policy support** over the next 10 years, including funding for pilot projects and test centers.

Scale CDR approaches

Demonstration and deployment policies can help CDR scale by supporting companies to transition out of the pilot phase, increase the facility size, overcome operational hurdles, and drive cost learning.

We recommend a minimum of **$18 billion in total demonstration and deployment policy support** over the next 10 years.

US policies to establish long-term revenue market for CDR

$100 billion in support by 2050

Tax credits

- Establish a separate, more inclusive tax credit where the sole focus is CDR and therefore encompasses a wider range of CDR technologies.
- Make 45Q more inclusive to advance other CDR approaches – keeping policy technology neutral keeps door open to CDR solutions still in the development phase.

Federal procurement

The federal government pays for CDR services in increasing amounts over time.

A procurement program can be structured to pay by the ton for CDR or pay for practices that provide CDR.

Example: USDA programs funded by the IRA that support natural CDR solutions by making per acre payments for forest and soil management practices

Regulatory policies

- Economy-wide or sectoral-level emissions standards can create compliance markets that can permit CDR credits as a means of compliance.

  Example: California Low-Carbon Fuel Standard

- A regulatory requirement could be put on large emitters or energy producers to purchase CDR credits in line with an increasing share of their annual emissions.

  Example: Proposed California legislation SB308

US policies to expand the CDR portfolio

$10 billion in additional R&D policy support over the next 10 years

R&D programs for CDR

Investments in R&D will help spur innovation, bring down costs, mitigate risks, and improve the performance of early-stage CDR methods.

R&D programs are particularly beneficial to CDR projects that are still in the lab stage of development.

Additionally, to bolster CDR methods that use geologic storage, the federal government can continue to invest in R&D for geologic sequestration science and technology under the current programs.

Pilot programs

Pilot programs are designed to spur competition and fuel innovation.

These programs can fund feasibility studies, basic engineering, and pilot-scale demonstrations for CDR approaches.

The goal is to fund the initial stage of development when a technology moves out of the lab into real-world operating conditions.

Current policy supports a DAC prize program as well as support for feasibility studies and front-end engineering and design.

MRV R&D

While start-ups and organizations are starting to pop up to fill this need, government support will serve as a catalyst for this research.

This will require continued investments in the research and development of methods to ensure high levels of scientific certainty on CO_2 removal and reemission expectations.

It's important for the government to invest in MRV now so that there are strong protocols once more CDR technologies scale.

US policies to scale CDR solutions

$18 billion for demonstration and deployment support over the next 10 years

Demonstration programs

Costs can be highest at the point of demonstration, and it is harder to secure financing since there is a greater risk associated with an unproven process at scale.

Demonstration and deployment policies provide support for companies to transition out of the lab, increase the size of their facilities, overcome operational hurdles and drive cost learning.

These policies support approaches in the demonstration and early-commercialization stage of development by providing or securing a large part of the capital investment required to build CDR facilities.

Policy support for each stage ensures the approach will successfully achieve full-scale deployment assuming long-term revenue support is available.

Loan guarantees

The transition out of the lab to the pilot or demonstration phase requires a large amount of capital investment. These projects have a hard time securing financing since they still have engineering, manufacturing, and operational technology risks.

To address this, the federal government can provide loan guarantees at a favorable rate compared to the open market and assume a large part of the financial risk. This funding can come from DOE’s Loan Programs Office or the Office of Clean Energy Demonstrations.

Key takeaways

- A robust CDR industry is necessary to complement US decarbonization.
- The US will need at least a gigaton, one billion metric tons, of CDR per year by mid-century.
- There is a diverse and dynamic set of natural, hybrid, and engineered CDR approaches that can contribute to this goal.
- Supporting a diverse array of CDR approaches is critical to building a robust industry.
- Policy support is needed to establish, expand, and scale the CDR market:
  - **Establish large-scale, long-term revenue**: demand-side policy to support of $20 billion in 2030, $50 billion in 2040 and up to $100 billion in CDR revenue annually in 2050. The majority of this is likely to be public support.
  - **Expand technology options**: research and development policy for $6 billion over the next 10 years to broaden the array of commercial CDR approaches.
  - **Scale the industry**: demonstration and deployment policy with $18 billion in policy support over the next 10 years to support large-scale CDR projects.

Rhodium Group

The Landscape of Carbon Dioxide Removal and US Polices to Scale Solutions

https://rhg.com/research/carbon-dioxide-removal-us-policy/

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