Scaling CDR: Demand Drivers for Durable Carbon Removal

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Executive Summary

There is broad consensus that durable carbon dioxide removal (CDR) will play a crucial role in global decarbonization. According to the Intergovernmental Panel on Climate Change (IPCC), the use of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 is to be achieved. This report focuses specifically on durable CDR, which plays a role in all IPCC 1.5 and 2.0 degree-aligned scenarios.[1] The role of durable CDR in limiting temperature rise could be greater than anticipated, given that globally, the world is not on track to meet decarbonization commitments.

This report, an independent study by the Boston Consulting Group (BCG), is intended to assess the demand potential for CDR in the light of both voluntary and regulatory drivers, through 2050. The report leverages insights from extensive interviews with policy and regulatory experts, as well as primary and secondary research and modeling. The results represent an optimistic yet realistic view of how future markets may evolve based on today's information. Below is a summary of our key findings:

1 Multi-gigaton-scale durable CDR will be needed to achieve net zero given current emissions trends; however, it is unlikely to materialize without new policy demand drivers.

- **Between 6 and 10 gigatons per annum (Gtpa) of residual CO_2 emissions are likely to remain unabated globally in 2050,[2] suggesting that substantial durable CDR is needed to achieve net zero CO_2.** Given that many carbon reduction technologies are still nascent, and there is uncertainty around how they will develop and scale, there is no consensus on the expected volume of residual emissions in net zero scenarios. Estimates from the IPCC and the International Energy Agency (IEA) for residual CO_2 emissions at the time of net zero range from ~2 to ~8 Gtpa, excluding CO_2 emissions from land-use activities.[3] We estimate that in 2050, between ~6 and ~10 Gtpa in CO_2 emissions will likely remain unabated because they are either impossible or overly expensive to reduce.[4]
- **Voluntary CDR demand is growing rapidly but will fall short of delivering the ultimate scale needed.** Last year, BCG estimated that the voluntary market would grow significantly, driving ~60 to ~750 megatons per annum (Mtpa) in durable CDR demand by 2040, depending on how much CDR costs decline.[5] Unlike other climate technologies, CDR could primarily be considered a public good. As a result, there are barriers to scaling CDR demand that are unlikely to be overcome without governmental policy demand drivers.

2 The expansion of existing and proposed policies to incorporate durable CDR could lead to ~0.5 to 2.5 Gtpa of CO_2 in durable CDR demand in 2050, covering up to ~30% of global residual emissions.

- **Governments could use a range of existing and proposed policy drivers to directly or indirectly drive durable CDR demand.** Direct demand drivers include integrating durable CDR pathways into carbon pricing mechanisms, regulatory requirements to decarbonize, and direct government procurement of CDR. Indirect drivers include enabling policies such as financial incentives to reduce prices and CO_2 accounting enablers such as requirements that must be met for a company to claim it is "net zero."
- **Integrating durable CDR pathways into carbon pricing mechanisms could drive the largest share of potential demand (up to ~1.25 Gtpa).** Existing and proposed carbon pricing mechanisms are a significant potential demand driver because of the scale of existing and proposed schemes. Emissions trading schemes cover industries generating ~26 Gt in emissions globally by 2050.[6] If all regions with existing and proposed ETSs implemented border carbon adjustments (BCAs), they would cover an additional ~4 Gtpa[7].

1. Select examples of high-durability carbon removal technologies include direct air capture, bioenergy with carbon capture and storage (BECCS), and enhanced weathering / CO2 mineralization. Source: IPCC AR6 Report - WG III: Mitigation of Climate Change.
2. BCG Residual Emissions Model, assumes all abatement action costing less than \$450 / t-CO_2 is achieved.
3. IPCC AR6 Report: Mitigation of Climate Change, IEA 2023 World Energy Outlook; land use emissions excluded when estimating durable CDR need given that they are likely to be covered by land-use changes that sequester carbon.
4. Excludes residual CO_2 emissions from land-use, which are likely to be covered by land-use changes that sequester carbon. Does not include non-CO_2 greenhouse gases. Estimate based on projected economic growth and abatement costs.
5. "The Time for Carbon Removal Has Come," BCG, 2023.
6. Assumes business-as-usual growth in emissions before considering reductions.
7. Note that BCAs can be applied even in the absence of domestic carbon prices (as pure pollution fees for importers), but when used in conjunction with domestic schemes like ETSs, it effectively multiplies their scope internationally.

- **Carbon pricing mechanisms will be most effective in promoting reductions and CDR demand when durable CDR is prioritized and its price is not artificially lowered through subsidies.** ETSs and BCAs can incorporate CDR by allowing durable CDR to generate allowances or reductions in levies directly or by creating parallel removal trading schemes. These approaches will drive the greatest demand for durable CDR and the most CO_2 reductions when: (1) inclusion is restricted to high-quality durable CDR; (2) a larger number of industries or baskets of goods are covered; and (3) the price of durable CDR decreases to an average of ~$100 to ~$200 per ton of CO_2 (t/CO_2). Additionally, while adopting subsidies to lower durable CDR prices in the near-term would encourage CDR purchases, keeping prices artificially low in the long term could incentivize emitters to remove emissions rather than reducing them.

- **Other significant durable CDR demand drivers include regulatory requirements in industries including aviation (up to ~400 Mtpa in durable CDR demand by 2050), marine (up to ~200 Mtpa) and power (up to ~200 Mtpa).** Decarbonization requirements in transportation could increase durable CDR demand through the use of CO_2 as a feedstock for e-fuels and direct purchases to counterbalance fossil fuel emissions. Net zero portfolio standards for the power industry could drive demand through bioenergy with carbon capture and storage (BECCS), and additional CDR credit purchases to account for residual emissions from peaker plants and remaining fossil power generation, even when mostly mitigated with carbon capture and storage (CCS).

3 The scale of durable CDR demand will vary regionally, driven by the maturity of existing climate policies, the ambition of proposed policies, and the ability to finance decarbonization, with the largest gaps likely to remain in Asia Pacific.

- **Europe and North America are the most advanced regions in the implementation of climate policies and therefore also present the greatest opportunity to drive demand for durable CDR.** Durable CDR demand from a comprehensive ETS and decarbonization requirement for aviation could drive ~65% coverage of residual emissions in Europe. North America could also see ~60% coverage from smaller, more targeted domestic carbon pricing mechanisms, BCAs imposed by the EU and others, and regulatory requirements in power and transportation. Asia Pacific will face challenges in covering residual emissions with durable CDR due to the scale of projected residuals, a lack of regional consistency in the advancement of climate policy, and the high cost of decarbonization and durable CDR.

- **Methods for increasing CDR demand in Asia Pacific and globally could include expanding the scope of existing and proposed demand drivers and creating new durable CDR demand drivers.** ETSs and BCAs could expand to cover additional industries or goods. Similarly, durable CDR demand could grow significantly if more governments were to implement sustainable fuel blending or decarbonization requirements in transport. Among new demand drivers, government procurement of enhanced rock weathering (ERW) or biochar on agricultural lands has significant potential: allocating just 2% of total existing agricultural subsidies in the regions with the highest capacity for ERW could generate ~1 Gtpa or more in durable CO_2 removals.

4 Near-term actions could support multi-gigaton-scale demand for durable CDR by 2050.

- **Governments could set clear durable CDR goals and encourage near-term supply and demand.** Actions in the near term could include pursuing durable CDR targets, government procurement, research and development funding, and policies to incentivize voluntary demand, such as financial incentives. Governments can also define frameworks for durable CDR to be integrated into compliance and voluntary markets.

- **Standard-setters could encourage near-term adoption of durable CDR and provide clarity on how to set targets for durable CDR procurement.** Standard-setters could encourage procurement of high-quality durable CDR in tandem with meaningful emissions reduction measures. Standard-setters could also provide market clarity by defining guidelines for when durable CDR is needed (such as encouraging the use of durable CDR in accounting for fossil emissions).

- **Drive innovation in CDR supply.** While this report defines pathways to increase demand for durable CDR, it will be crucial for supply to continue to grow and for costs to decrease. This will require public-private collaboration and increased investment in technology and infrastructure, including expanded R&D, pilot projects and demonstration plants, to prove the viability and efficiency of new technologies. Suppliers, investors, and other relevant stakeholders should focus on building a supportive ecosystem that includes financial incentives, partnerships, and streamlined regulatory processes to accelerate innovation.[8]

8. This topic is further discussed in BCG's 2023 publications, "Shifting the Paradigm: Solving the Direct Air Carbon Capture Challenge," and "Scaling Carbon Capture Technology Won't Break the Bank."

Objectives and Scope

This report aims to demonstrate a credible pathway for durable CDR to reach multi-gigaton scale. This is an immense scale-up from 125 kt of durable CDR delivered in 2023[9] to ~6 to 10 Gt of durable CDR needed in a 2050 net zero CO_2 world—a 50,000 to 80,000 times increase. Specifically, this report has the following goals:

1. Identify durable CDR demand drivers with the largest potential for scale.

2. Summarize policy implementation choices and implications that could shape CDR demand.

CDR methods range across lower durability methods (such as afforestation, reforestation) that have existed for decades, and medium and high durability methods that are under development (such as direct air capture). This report specifically explores the market opportunity associated with CDR methods with medium and high durability, which we refer to throughout as "durable CDR." Select examples include:[10]

- **Direct Air Carbon Capture and Sequestration (DACCS)** uses chemical or physical processes to separate CO_2 from ambient air and stores the captured CO_2 underground or permanently in a product such as cement.[11]

- **Biomass with Carbon Removal and Storage (BiCRS)** refers to land-based biological methods that involve processing biomass for CO_2 removal and can have variations depending on storage methodology.[12] These include, among others, biochar—the storage of CO_2 in a stable solid state made from biomass that is combusted in the presence of limited oxygen.

- **Bioenergy Carbon Capture and Storage (BECCS)** refers to the use of biomass to produce energy coupled with the capture and storage of emitted CO_2, either underground or permanently in a product.

- **Enhanced Weathering/CO_2 Mineralization** uses the natural chemical mineralization of carbon to capture CO_2 from the atmosphere. This process can be accelerated by treating material on-site at active industrial mines (such as ultramafic mine waste) or through the distribution of silicate rocks (such as basalt) over forests or cropland. Rainwater dissolves the minerals, and the aqueous solution reacts with CO_2 from the atmosphere, mineralizing the CO_2 and storing it permanently as solid carbonate minerals. Ocean removals such as ocean alkalinity enhancement accelerate the natural process of sequestering carbon in the ocean by increasing the alkalinity of seawater to enhance its capacity to absorb and store atmospheric CO_2.[13]

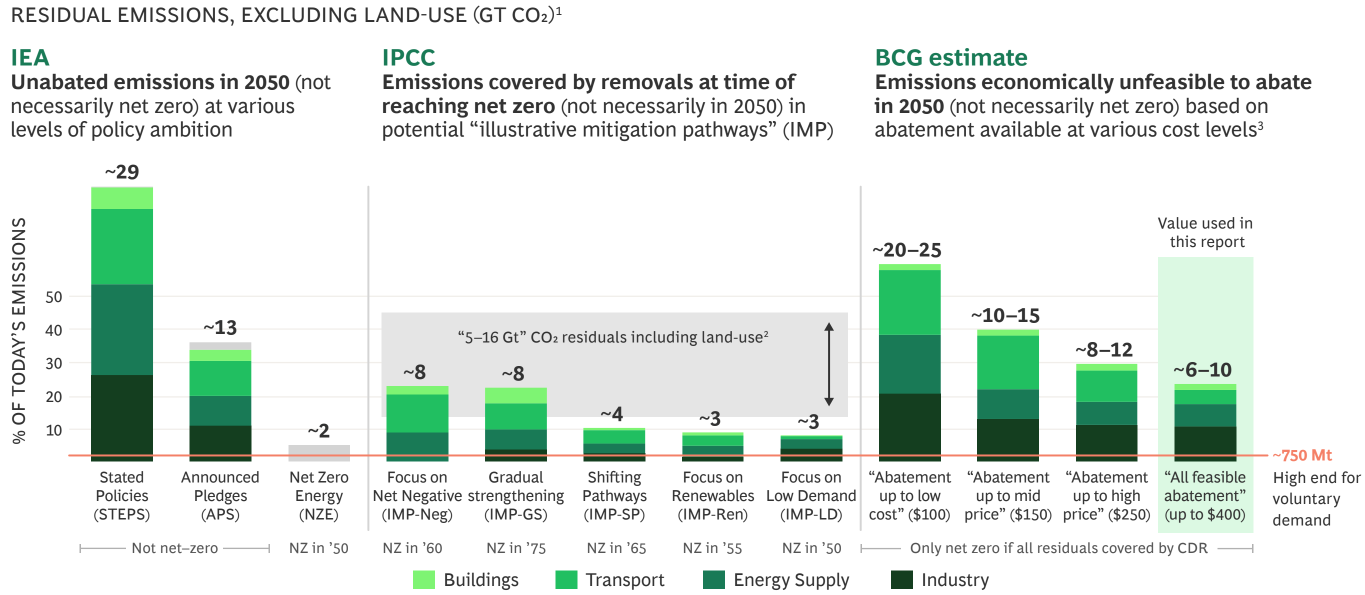
9. CDR.fyi 2023 Year in Review.
10. Other forms of durable CDR may also emerge as promising pathways in the future, whether variants of the above examples (such as bio-oil storage, a process similar to biochar; or biomass sinking, a novel form of ocean removal), or other new technologies.
11. IPCC Special Report: Global Warming of 1.5°C.
12. Biomass Carbon Removal and Storage (BiCRS) Roadmap; Lawrence Livermore National Lab 2021.
13. IPCC AR6 – WG III: Mitigation of Climate Change.

Current Trajectory of CDR Demand is Far Below What is Needed

While there is consensus that CDR is needed, there is a lack of consensus on how much durable CDR will be required. This is due to significant variation in estimates for residual, or unabatable, CO_2 emissions, which range from ~2 to ~8 Gtpa (see Exhibit 1).[14] The range reflects varying decarbonization scenarios with differences in how effectively various sectors decarbonize, depending on the implementation of existing abatement solutions and the development and scaling of new and emerging technologies.

14. IPCC AR6 – WG III: Mitigation of Climate Change; IEA 2023 World Energy Outlook; BCG Residual Emissions Model, based on global marginal abatement cost estimates and excluding residual CO_2 emissions from land use.

Exhibit 1 - Estimates for Unabated Residual Emissions Vary Considerably, Depending on Scenario



Sources: IPCC AR6 report, IEA 2023 World Energy Outlook; BCG analysis.

Note: Grey boxes are residuals not allocated to sectors.

[1]Land-use CO_2 excluded given likely to be offset by practice changes making land-use a net CO_2 sink (though not necessarily a net GHG sink).

[2]5-16 Gt is range referenced in AR6 Summary for Policy Makers paragraph C.3.3.

[3]Cost levels estimated in 2050. Abatement is calculated vs. emissions in business-as-usual trajectory. Note that any policies that force non-economical abatement would shrink residuals.

The process to account for neutralizing residual emissions could incorporate a variety of CDR methods ranging in durability. Policy options for how to determine what share should be neutralized using durable CDR include:

- **Taking a "like-for-like" removal approach,**[15] which is defined by the United Nations Framework Convention on Climate Change (UNFCCC) as "when a source of emissions and an emissions sink correspond in terms of their warming impact, and in terms of the timescale and durability of carbon storage." As an example, CO_2 emitted from permanent geological storage (fossil fuel) must be neutralized by CO_2 in permanent geological storage (such as DACCS), as opposed to CO_2 in non-permanent biosphere storage (such as afforestation).

- **Taking a discounting approach,**[16] in which targets are set on the basis of the total CO_2 sequestered weighted against the durability or permanence of CO_2 removal. Removals that geologically sequester CO_2 for a millennium to millions of years are weighted proportionally more than removals with a shorter average sequestration, such as forestry-based removals that sequester CO_2 for tens to hundreds of years. All removal methods could be used, but significantly more removals of a shorter time scale would be needed to cover the same portion of the target as longer-duration removals. This incentivizes the use of longer-duration removals, but also allows for a range of durabilities to minimize overall CDR costs.

15. UNFCCC Race to Zero.

16. NOAA 2023.

1 Insufficiency of current demand drivers and the voluntary market

Voluntary purchases and policy drivers are scaling CDR significantly (from 600 kt purchased in 2022 to 4.5 Mt in 2023), but these existing drivers are insufficient to achieve the scale of removals required to achieve global net zero. In 2023, ~4.5 Mt of durable CDR was purchased (up from ~600 kt in 2022), and just 125 kt were delivered.[17] Last year, BCG demonstrated a potential pathway to achieve between 80 and 870 megatons of demand for durable CDR by 2040, driven primarily by purchases in the voluntary carbon market.[18] However, this is still significantly below all current estimates of the CDR needed to reach net zero, highlighting the necessity for additional drivers to bridge the gap. It is crucial to note that unlike solar, wind and many other climate technologies that provide an end good or service, such as energy, the primary value of CDR could be considered a public good. Thus policy demand drivers are likely to be required even in the longer term.

2 Defining residual emissions

Governments and policymakers have outlined a variety of ways to estimate residual emissions. Most countries do not explicitly mention or define residual emissions in their Nationally Determined Contributions (NDCs), and those that do provide little detail on the definition or calculation methodology.[19] Some of the ways countries have defined residuals include emissions that cannot be addressed by current or developing technologies,[20] emissions that are unlikely to be addressed by future technological developments,[21] and emissions that are overly expensive or impossible to reduce.[22]

For the purposes of this report, we propose one potential view of residual CO_2 emissions, based on an economic perspective, by industry and geography, which defines residual emissions as emissions that are either impossible or overly expensive to reduce.[23] We estimate residual emissions by calculating emissions in a business-as-usual scenario and estimating the percentage of emissions that are abatable at a variety of cost points and those that are unfeasible to abate at any cost. While there are a variety of approaches to determining overall residuals, our estimates are broadly in line with estimates from a range of organizations.

Across sectors, residual CO_2 emissions are expected to be concentrated in the industrial (~40%), energy supply (~30%) and transport (~20%) sectors (see Exhibit 2). These residuals come from CO_2-emitting activities in industrials (such as high-temperature heat requirements for steelmaking) and transport (such as long-haul flights) that cannot be feasibly or economically abated in full, based on technologies expected to be available in 2050. In the energy sector, as power generation increases its share of renewables, the costs and complexity of operating the power generation system increase significantly, making it likely that some level of residual emissions will remain from continued fossil generation in peaker plants. Additionally, across industrials and power, plants with CCS could abate 90% to 95% of emissions, but still release residual emissions of 10% or less.

Residual emissions will be particularly concentrated (~55%) in the Asia Pacific region. This is due to a combination of large populations, rapid economic growth, and a high concentration of industry and manufacturing. While more residual emissions will be in Asia Pacific, the products associated with those emissions are consumed globally. Therefore, achieving net zero in Asia Pacific through reductions and removals would make a significant contribution to global climate goals.

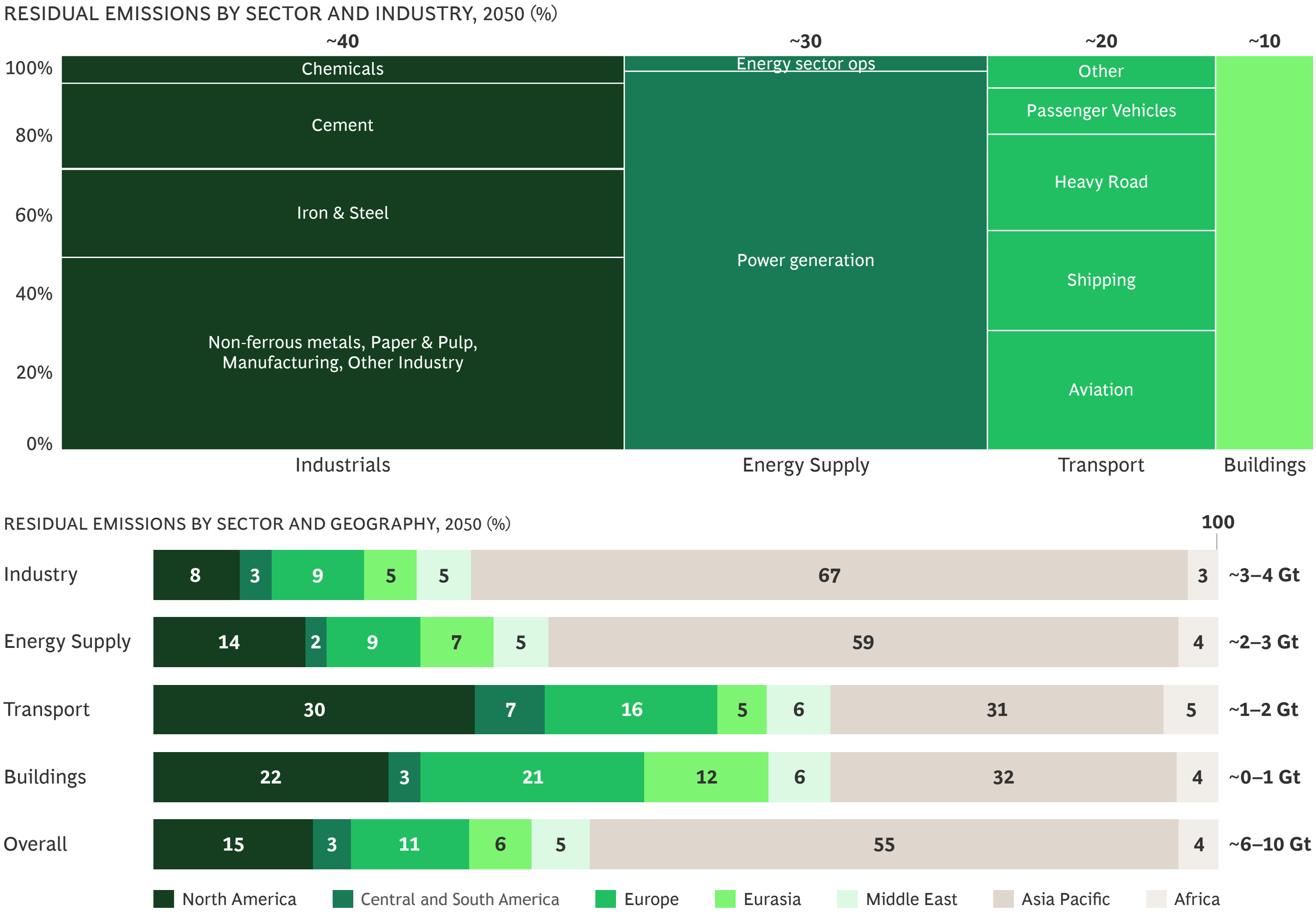
3 Modeling approach and methodology

In this report, we have sized the largest potential policy demand drivers for durable CDR. We have taken efforts to avoid double-counting the combined impact of two interrelated demand drivers, such as demand arising from both a net zero power portfolio standard and an ETS in the same jurisdiction. Furthermore, all estimates in this study are based on a set of core assumptions:

- **Reductions come first.** We assumed that demand drivers would largely incentivize economical reductions before the use of any form of CDR. We also assumed that companies will act rationally, choosing to reduce their emissions up until those reductions become more expensive than CDR or relevant penalties. We did not account for any potential further upside, if, for example, companies chose to purchase CDR even if it were more expensive than the levelized cost of reductions requiring a significant capital investment, such as a CCS retrofit.

17. ICDR.fyi 2023 Year in Review.
18. "The Time for Carbon Removal Has Come," BCG, 2023.
19. Buck, Holly, et al. "Why Residual Emissions Matter Right Now." 2023.
20. For example, France defines residual emissions as "emissions which are unavoidable according to the current state of knowledge."
21. Switzerland assesses existing emissions and available abatement levers by industry. This leads to a target of 2 Mtpa of negative emissions technologies, defined as technologies facilitating the permanent storage of removed CO_2 for several decades or, ideally, centuries.
22. Both the US and Australia mention the varying costs of abatement in their definitions of residual emissions.
23. Note: For the purposes of this report, we have focused on residual CO_2 emissions only, given the target of 2050 net zero CO_2 (but not necessarily net zero GHGs), as discussed by the IPCC and others. Furthermore, the case for using carbon dioxide removals to cover non-carbon dioxide emissions is less clear and does not yet have consensus.

Exhibit 2 - Asia Pacific Dominates Estimated Residual Emissions by Sector and Geography



Sources: IEA World Energy Outlook 2021 and 2023; BCG analysis.

- **Sizing is based on the "art of the possible."** When sizing demand drivers, we focused on evaluating an optimistic, yet realistic view on the potential impact of each driver.

- **Policies will likely prioritize durable CDR when economically feasible, using a "like-for-like" principal.** We assumed that policies will aim to incentivize emitting sectors to use high-durability CO_2 storage to neutralize their emissions from permanent sources. For many demand drivers, we estimate a range of scenarios that incorporate both durable and non-durable CDR to consider the full economic impact of policies.

- **CDR supply innovation will continue.** While this paper focuses on ways to increase demand, innovation in the supply of CDR that supports both the global scale-up and the significant reduction in costs of numerous CDR technologies will be required to enable the demand for removals. This topic has been discussed in several prior articles.[24]

24. This topic is discussed further in BCG's 2023 publications, "Shifting the Paradigm: Solving the Direct Air Carbon Capture Challenge," and "Scaling Carbon Capture Technology Won't Break the Bank."

Potential Impact of CDR Demand Drivers

In general, there are five categories of policy drivers that could generate durable CDR demand to address residual emissions. Some of these policies create new demand for CDR directly; these include carbon pricing, regulatory requirements and government procurement of CDR. Others create demand indirectly; these include finanical incentives, accounting adjustments and product standards (see Exhibit 3).

1 Demand driver estimates

We estimate between ~0.5 and 2.5 Gtpa in 2050 durable CDR demand (up to ~30% of residual emissions) from the largest drivers, depending on which of three scenarios play out (see Exhibit 4). The largest drivers include ETSs (up to ~725 Mtpa); BCAs (up to ~550 Mtpa); and regulatory requirements in aviation (up to ~400 Mtpa), shipping (up to ~200 Mtpa), and power (up to ~200 Mtpa). Beyond regulatory measures, we sized remaining voluntary purchases after accounting for voluntary market cannibalization from broader regulatory demand (up to ~325 Mtpa). Importantly, while these levers are significant drivers of CDR demand, they also drive significant CO_2 reductions.

Exhibit 3 - A Range of Policy Drivers Is Available to Increase Demand for CDR

	MECHANISMS	TYPES OF DRIVERS AND SPECIFIC EXAMPLES	
Direct drivers (directly create new demand)	**Carbon pricing mechanisms**	Emissions trading schemes	· Some form of cap-and-trade system that incorporates CDR as a way to generate emissions allowances
		Direct carbon prices/carbon tax	· Simple tax per ton of CO_2, with scheme allowing CDR use to reduce emissions liability
		Carbon takeback obligations	· Requirement to pay for CDR to cover any emissions not abated from use of fossil fuels or other products
		Border carbon adjustments	· Carbon intensity-based tariffs on imports, with CDR considered in carbon intensity calculations
		Other trading-based schemes	· Tradable credits associated with low-carbon fuel production that allow for using removed CO_2 as an input
	Standards and regulatory requirements	Product/performance standards	· Requirement to meet some threshold metric, on average (e.g., CO_2 intensity, use of particular tech) for fuel, electricity, or other products produced or used (e.g., aviation fuels), with CDR counting towards metrics
		Eligibility standards	· Eligibility for permitting, leasing government land, federal funding, etc., tied to net project emissions
		Procurement standards	· Carbon intensity standards for government purchases of specific products (e.g., industrial goods like steel and cement) or carbon intensity considered in bid selection (with CDR considered in
		CDR purchase requirements	· Requirement to purchase some fixed amount of CDR
	Government procurement of CDR	Direct procurement of CDR	· Direct government purchases of CDR credits from third parties (potentially funded by ETS or carbon tax revenue) or payment for activities to remove atmospheric CO_2 (e.g., paying farmers to spread silicates)
		Direct build and operation of CDR	· Direct government investment in CO_2 removal operations
Indirect drivers (can indirectly impact demand by lowering prices and boosting voluntary volume, or by enabling new compliance levers)	**Financial incentives**	Tax credits, feed-in tariffs, and other subsidies	· Providing subsidies for purchases or generation of CDR, similar to 45Q or ITC/PTC credits in US, or green feed-in tariffs in EU; or tailoring other existing subsidies to include activities that also remove CO_2 (e.g., adding silicate spreading to subsidized farming activities)
		Contracts for difference	· Direct government actions to guarantee floor price for CDR credits to reduce risk and price volatility
		Grants and loans	· Government investment in increased production to lower costs and prices
	CO_2 accounting enablers	Use of CDR to meet company or national targets	· Clarification by governments, standards setters, or in international agreements that CDR can or will be used to hit targets (potentially up to certain thresholds)
		Green product certifications	· Certification (by government or third parties) of specific products (e.g., fuels or industrial products) as low-carbon, based on removed carbon or use of CDR as offsets, enabling green premium

Sources: Interviews with CDR and policy experts; BCG analysis.

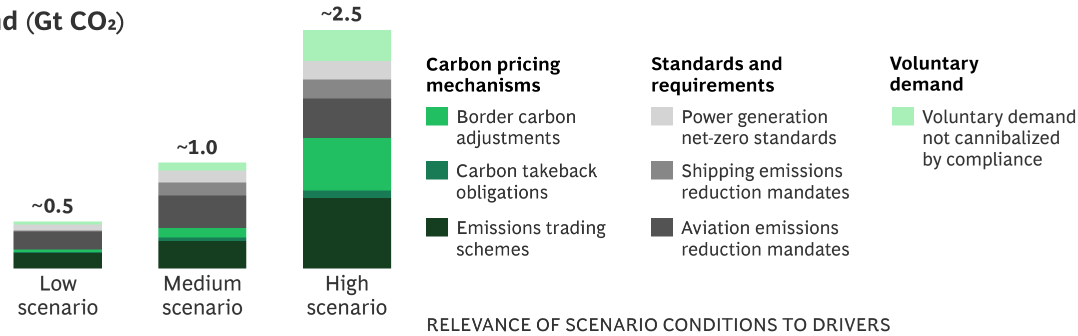
In the following sections, we provide an overview of the various types of direct and indirect drivers, and analyze in depth the potential demand creation from five prioritized direct demand drivers:

- Carbon pricing mechanisms:
  - Emissions trading schemes and carbon takeback obligations
  - Border carbon adjustments
- Standards and regulatory requirements:
  - Aviation fuel decarbonization requirements
  - Shipping fuel requirements and carbon intensity standards
  - Net zero power portfolio standards

We did not specifically size the impact of government procurement, financial incentives, or CO_2 accounting enablers. Because demand derived from direct government procurement would be driven by policy decisions on funding allocated to CDR procurement, it would therefore be impossible to estimate demand without making assumptions about specific future funding decisions. In addition, indirect drivers such as financial incentives and CO_2 accounting enablers are likely to predominately further incentivize voluntary demand, which was sized in our previous study.

Exhibit 4 - CDR Demand Will Ultimately Depend on Variations in Policy and Price

2050 durable CDR demand (Gt CO_2)



RELEVANCE OF SCENARIO CONDITIONS TO DRIVERS

	Low scenario	Medium scenario	High scenario	Carbon pricing mechanisms	Standards and requirements	Voluntary demand
Strength of policy pressure to address emissions	Weak	Moderate	Aggressive	✓	✓	Some effect from increased compliance demand cannibalizing voluntary demand
Prioritization of durable CDR vs. non-durable, by governments	Low	Medium	High	✓	✗ "Like-for-like" approach requires durable only	
Average CDR portfolio price (including low durability CDR)	Moderate	Moderate	High	✓	✗	✓
Average durable CDR price per ton CO_2	~$200–$300	~$150–$250	~$100–$200	✓	✓	✓
Degree of demand reductions due to behavior change	Significant	Moderate	Minimal	✓	✓	✗

Source: BCG analysis.

This demand will not fully cover residual emissions. The remaining gap will be uneven across geographies, largely based on the maturity of climate policies in existence or in discussion today, with the highest coverage in Europe (~65%) and North America (~60%), and with the largest gap in absolute emissions remaining in Asia Pacific (~20% coverage). Europe could see high penetration of durable CDR demand in covering residual emissions, driven largely by a comprehensive ETS and decarbonization requirements for aviation. North America will also see relatively high penetration through BCAs, decarbonization requirements in power and aviation, and agricultural subsidies. Asia Pacific will see some penetration from ETSs and BCAs but will require additional demand drivers to close the gap. (See Exhibit 5.)

Exhibit 5 - Significant Gaps in Coverage of Residual Emissions will Remain, Even Under the Most Optimistic Scenario

Maximum coverage—high scenario (% of total/Mtpa)

	North America	Central and South America	Europe	Eurasia	Middle East	Asia Pacific	Africa	
Industrials	~65% / ~290	~35% / ~110	~70% / ~320	~2% / ~180	~7% / ~190	~20% / ~2430	~15% / ~110	~30% ~3–4 Gt
Energy Supply	~70% / ~340	~25% / ~50	~90% / ~210	~5% / ~170	~10% / ~120	~10% / ~1420	~15% / ~90	~30% ~2–3 Gt
Transport	~65% / ~460	~0% / ~100	~60% / ~250	~0% / ~70	~60% / ~90	~50% / ~480	~0% / ~80	~50% ~1–2 Gt
Buildings	~40% / ~140	~40% / ~20	~0% / ~140	~0% / ~70	~0% / ~40	~25% / ~210	~0% / ~30	~20% ~0–1 Gt
Regional totals (Separate scale)	~60% / ~1240	~20% / ~280	~65% / ~910	~5% / ~490	~20% / ~440	~20% / ~4540	~10% / ~300	~30% ~6–10 Gt

Source: BCG analysis.

Unlike other climate technologies, CDR could primarily be considered a public good. As a result, there are barriers to scaling CDR demand that are unlikely to be overcome without governmental policy demand drivers.

Carbon pricing mechanisms

There are multiple pathways to put a price on CO_2 emissions:

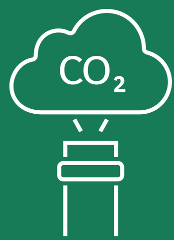
- **Direct carbon price or carbon tax.** Set a direct price on carbon by defining a tax rate on emissions or the carbon content of fossil fuels.[25] Carbon taxes or carbon prices could incentivize CDR demand if the purchase of durable CDR instead of a tax were allowed and priced lower than the carbon tax or price. South Africa, for example, established a carbon tax in their Carbon Tax Act No. 15 in 2019. Beyond regulatory carbon prices, some companies with more advanced climate goals have begun adopting internal carbon pricing (such as Microsoft, H&M Group and Unilever).[26]

- **Emissions trading schemes.** ETSs cap the total level of emissions and allow emitters with low emissions to sell their extra allowances to larger emitters. Already, ETSs are common in developed economies like the European Union, the UK, Japan, and Canada, and some middle-income economies like China and Mexico are also developing or have proposed ETSs. Some early-stage ETSs currently allow 5% to 10% of emissions to be covered by offsets, including "avoidance" credits earned by developing renewable energy projects, credits earned through energy efficiency initiatives, and credits earned through nature-based CDR. No existing ETS exclusively allows durable CDR, and only a few systems, including the UK[27] and Japan,[28] are considering limiting offsets exclusively to removals.

- **Carbon takeback obligations (CTOs).** CTOs require all fossil fuel extracted or imported into a region to be neutralized by storing back underground an amount of CO_2 equivalent to the amount that will be generated by that fuel.[29] CTOs would require the direct purchase of CDR to offset the lifecycle emissions of the fossil fuel. (See sidebar, "How Carbon Takeback Obligations Work.")

- **Border carbon adjustments.** BCAs drive emissions reductions beyond national borders by making importers pay for the carbon content of goods at a level equivalent to that paid by domestic producers of the same product. The goal is to prevent carbon leakage, or a producer moving to a jurisdiction without a carbon tax to avoid fees. BCAs encourage importers to reduce emissions or, potentially, to purchase removals. However, BCAs can lead to trade diversion, with companies shifting exports based on emissions intensity. Typically, BCAs would be imposed on goods imported into a jurisdiction that has domestic carbon pricing, although they could also be implemented in jurisdictions without a domestic car-

How Carbon Takeback Obligations Work



A carbon takeback obligation (CTO) is a proposed regulation that requires oil and gas producers to purchase CDR credits worth at least a portion of the lifetime emissions of the fuels they produce or import. At present, CTOs are theoretical, and the subject of academic[30] and legislative proposals[31] in some developed economies. However, CTOs could be considered as alternative policy designs to ETSs that shift the cost burden of carbon management to fossil fuel producers.

Because CTOs would target similar sectors as ETSs, we estimate that the impact on durable CDR demand would be of a similar scale in geographies where implemented. However, if these policies were to go beyond the emissions generated from the use of fossil fuels to also cover the emissions created in producing fossil fuels, it would create ~10 to 80 Mtpa in new CDR demand. It is also important to note that while these policies would target fuel producers, it is likely that the costs would be passed on and shared across the entire value chain of fossil fuel usage.

25. World Bank, What is Carbon Pricing?
26. Company press releases.
27. UK Department for Energy Security and Net Zero.
28. S&P Global.
29. University of Oxford.
30. Jenkins, Mitchel-Larson, Ives, Haszeldine & Allen (2021).
31. California SB 308.

bon price. The EU is preparing to implement its Carbon Border Adjustment Mechanism (CBAM), which will be phased in starting in 2034.

EMISSIONS TRADING SCHEMES

ETSs could incorporate CDR by allowing durable CDR to generate allowances directly or by creating requirements for companies to purchase CDR through a parallel removal trading scheme (RTS). With either option, regulators could choose to accept a wide range of carbon credits, control the mix of durable and non-durable technologies, or limit allowable CDR credits to high-durability CDR. In either model, incentive-based schemes such as Carbon Contracts for Difference (CfDs) could be introduced to reduce the risk from low and volatile market prices.

Impact of ETS on durable CDR demand

Integrating CDR into ETSs could generate ~150 to 725 Mtpa in durable CDR demand. We estimate demand for durable CDR by estimating the total emissions covered under ETSs, removing available allowances, and comparing the cost to abate remaining emissions with the cost to remove them. We project that ETSs will cover a total of 26 Gtpa of emissions by 2050, and projected allowances would cover ~30% to 40% of these emissions.[32] In our high-demand scenario, up to ~95% of the remaining ~17.5 Gtpa post-allowance emissions could be reduced at costs lower than the price of CDR. This leaves a balance of ~900 Mtpa in CDR demand (see Exhibit 6). Of that ~900 Mtpa, we estimate up to ~725 Mtpa is likely to be durable CDR in the high-demand scenario, in which most countries prioritize durable CDR over allowing CDR with lower levels of durability.

Implementation Choices

How CDR is integrated in ETSs will have implications for the incentives created for regulated companies. The following design elements will drive the greatest durable CDR demand as well as the highest level of emission reductions:

- **Regularly tighten available allowances to reach net zero by 2050 or decouple CDR purchase requirements by creating a parallel removal trading scheme.** If companies can turn to abundant allowances and regulatory exceptions, the price of allowances will remain low, providing a cheap alternative to emission reductions and removals. Companies will only purchase durable CDR if ETSs enforce strict limits on allowances or require CDR purchases at a certain level through an RTS.

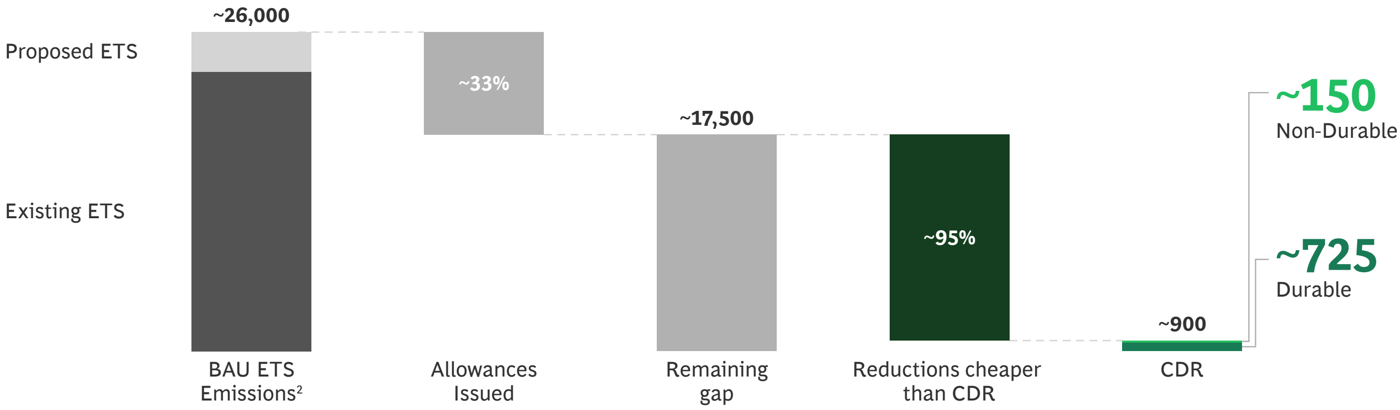
- **Incorporate cap-and-trade models rather than intensity-based models into ETS design.** CDR, particularly high-cost durable CDR, can be a logical economic choice for companies addressing the last 5% to 15% of their emissions. Intensity-based ETS targets will struggle to incentivize companies to reduce those last residual emissions.

- **Limit accepted removals to higher-priced durable CDR.** Durable CDR demand will be highest in systems that minimize the amount of lower-durability removal or reduction credits that can be used for compliance or that discount the value of a removal based on its durability. Emitters under systems without these controls will prioritize low-cost, low-durability removals at the expense of economical reductions and higher durability removals (see Exhibit 7).

Exhibit 6 - By 2050, ETSs could Drive 725 Megatons of Durable CDR Demand

High scenario

EMISSIONS, REDUCTIONS AND REMOVALS, 2050[1] (MT CO_2)



Sources: Emission data from IPCC, OECD, and EPA; Allowance data from IPCC and local regulators; BCG analysis.

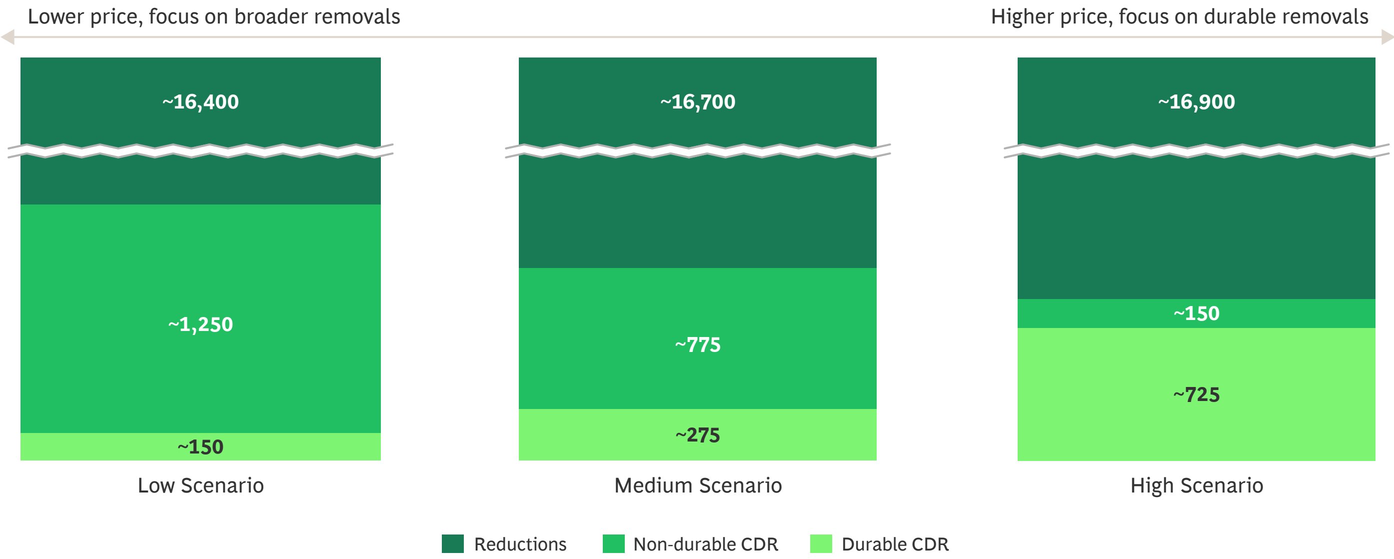
[1]Covers all countries with existing and proposed ETS systems as selected for the model.

[2]Business as Usual, assumes emissions grow in line with economic growth and no abatement measures are taken.

32. Assumes business-as-usual growth in emissions before considering reductions.

Exhibit 7 - Higher Carbon Prices and Prioritizing Durable Removals Could Incentivize More CO_2 Reductions and Higher Demand

2050 REDUCTIONS AND REMOVALS BY SCENARIO (MT CO_2)



Sources: Emission data from IPCC, OECD, and EPA; Allowance data from IPCC and local regulators; BCG analysis.

ETS implementation will also determine who bears the cost for purchasing CDR. ETS systems generally place cost burdens on the end emitters, but the following levers can stabilize and redistribute costs:

- **Contracts for difference can split costs and risk between emitters and governments in the short term.** Government-backed contracts for difference could also guarantee a single price for CDR buyers to support demand in the near term. The backing government would pay or receive the difference between the contract price and the ETS market price for CDR. Adopting contracts for difference in the near-term would encourage CDR purchases. However, keeping prices artificially low in the longer-term creates incentives for emitters to remove emissions rather than reducing them.

- **Replacing ETSs with CTOs could shift some of the cost of covering unabated emissions with CDR from emitters to fuel producers.** CTOs would require upstream fuel extraction and production companies to purchase removals to cover a portion of the lifetime emissions from the fuels they produce, creating further demand for CDR.

- **A carbon removal reserve can prevent major CDR prices fluctuations or spikes in the long term.[33] An ETS administrator operator may stock CDR credits for future use to prevent CDR price spikes in case of CDR shortages as allowances near zero.** This would mirror the EU ETS's Market Stability Reserve. Maintaining a CDR reserve is fundamental to keeping the system stable: the economic burden from unexpectedly high prices could drive regulatory changes that reduce or eliminate CDR demand. A reserve could also provide the stability needed to allow suppliers to proceed with projects to serve CDR demand from ETSs.

33. Model proposed by the Kiel Institute

BORDER CARBON ADJUSTMENTS

BCAs could generate CDR demand by allowing companies to use CDR to reduce the CO_2 intensity and associated BCA liability of their imported products. Countries could choose to do this by providing a process through which importers could certify the carbon intensity of their product and use CDR to reduce that amount (with or without a cap on the percentage of their emissions that could be neutralized with CDR). CDR demand from BCAs can be estimated using an approach similar to ETSs. We estimated total emissions covered under BCAs (from all imported goods under covered import categories) and subtracted emissions that could be reduced at a cost below the cost of CDR.

However, we adjusted our approach to account for the impact of trade diversions and a limitless cap on paying to emit that are unique to BCAs.

- **Trade diversion:** Some companies and countries will likely respond to BCAs by shifting their exports to new end markets. The degree of diversion will vary depending primarily on the emissions intensity of the company's or country's products and the extent to which BCAs are rolled out globally. Producers with low intensity may be incentivized to increase exports to markets with BCAs given increased competitiveness, while those with high intensities may want to divert exports elsewhere, or decarbonize.
- **Paying to emit:** Unlike cap-and-trade systems, BCAs do not typically cap the ability to pay to emit. However, they will still have a significant impact on emissions, by incentivizing companies to pursue reductions and removals that are cheaper than the levy, which will itself increase over time in line with domestic carbon prices.

Impact of BCAs on durable CDR demand

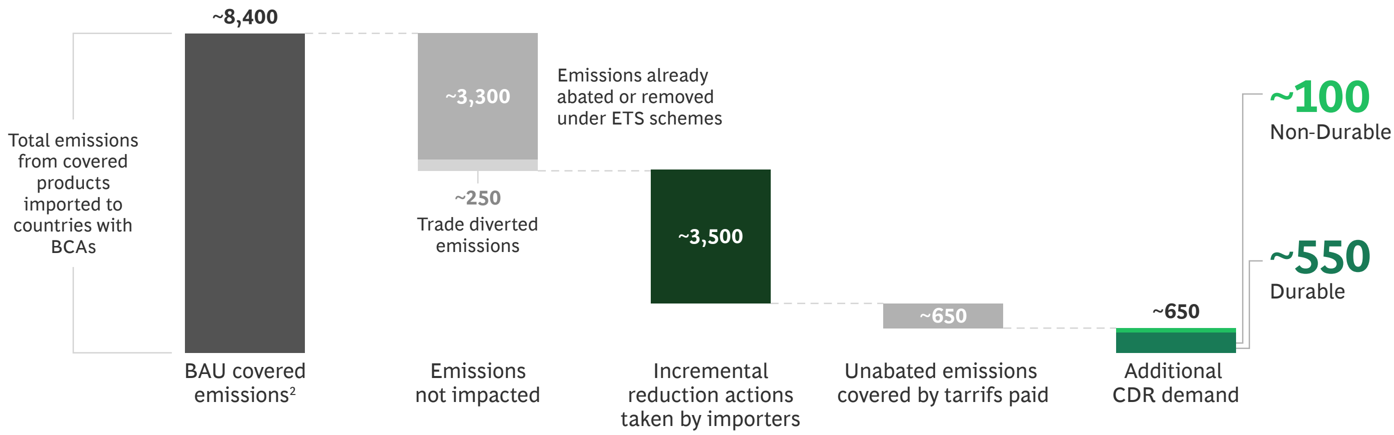
Overall, BCAs could drive ~50 to 550 Mtpa in incremental durable CDR demand by 2050, beyond what is driven by domestic carbon prices (see Exhibit 8). The actual amount of durable CDR demand will be depend on the rate of global adoption of BCAs and how they incorporate durable CDR.

Europe's Carbon Border Adjustment Mechanism (CBAM), the only BCA framework in existence today, is likely to be the most significant driver. The CBAM will be phased in in its initial form by 2034, imposing carbon levies on imports of select high-emissions raw materials like iron; over time, the scheme may be expanded to cover additional imports.[34] Depending on the basket of goods included in the long term, we expect integration of durable CDR into the EU's CBAM alone to drive a minimum of ~10 to 20 Mtpa of durable CDR demand in 2050, and potentially up to ~110 Mtpa. In either case, the EU CBAM is likely to be the single biggest BCA driver of demand for durable CDR.

Exhibit 8 - Border Carbon Adjustment Mechanisms could Add up to 550 Megatons of Durable CDR Demand by 2050

High scenario

BCA-DRIVEN EMISSIONS, REDUCTIONS AND REMOVALS, 2050 (MT CO_2)



Sources: UN Comtrade; OECD; World Bank; BCG analysis.

BCAs in other large end markets for trade could also drive considerable CDR demand. If the US imposed a BCA with a structure similar to the EU's, it could drive up to an additional ~150 Mtpa, and if all other countries with domestic carbon prices were to implement BCAs by 2050, it could add up to a further ~200 Mtpa or more. In total, across all regions, BCAs could account for ~50 to 550 Mtpa of CDR demand in addition to domestic carbon prices. Based on global trade flows, we expect that the biggest impact will be felt by large exporters of raw and mid-supply chain materials, like India and China. Thus, BCAs alone could generate up to ~250 Mtpa of durable CDR demand in Asia Pacific.

Implementation choices

Choices available to policymakers with the largest impact on CDR demand include the range of imports subject to levies and the structure and basis for levies.

The most impactful decision is the range of imports subject to levies. A broader range of goods would increase demand for durable removals and result in more net reductions (see Exhibit 9). However, a larger basket also poses larger geopolitical and legal risks to trade. To maintain a level playing field, one option is to impose levies on goods directly corresponding to those produced by domestic industries subject to carbon pricing or regulation. This approach is also most compatible with the World Trade Organization's rules that underpin global trade.

The strength and structure of BCA levies will impact the scale of emission reductions and removals and the distribution of the costs. Options for structuring levies include:

- **Levies based on domestic carbon price.** Assessed on the total carbon content of imported goods, requiring measurement of carbon intensities.
- **Tiered levies.** Based on the degree of other countries' climate legislation or national industry-average emission intensities.
- **Discounts and exemptions.** For countries with strong climate policies including their own carbon pricing schemes.

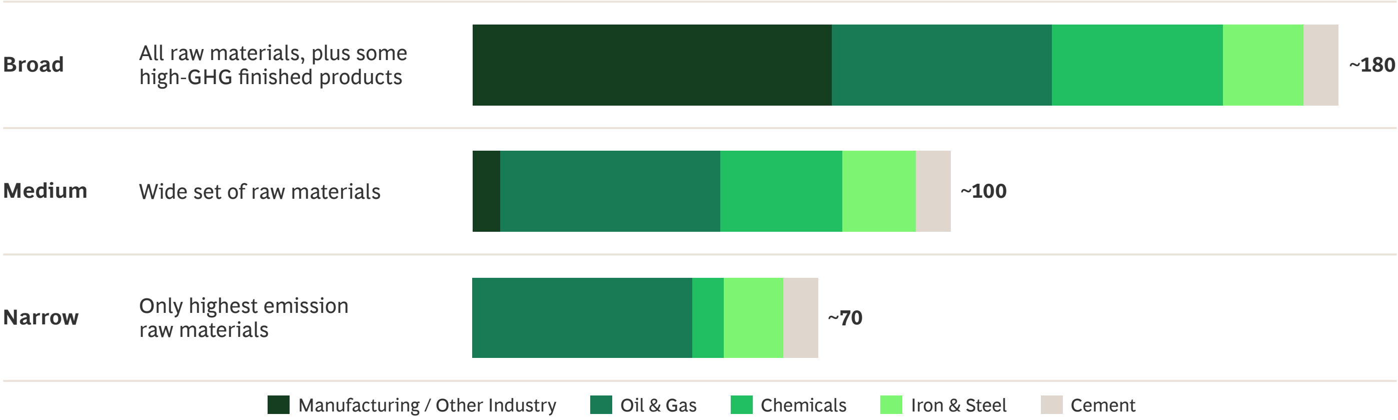
Across these options, lower effective levies—a smaller basket of goods, lower fees, more discounts—would lead to less emissions reduction and smaller price increases for consumers. Higher levies would impose greater costs on consumers but will drive stronger emission reductions as producers and consumers adapt to higher prices on emission-intensive products.

Finally, allowing only durable CDR to avoid levies would maximize emissions reductions and durable CDR demand. Given the relatively high cost of durable CDR, limiting inclusion only to durable CDR options would incentivize more reductions than if less durable options were allowed. One option for how to set these restrictions is to closely mirror requirements for removals under domestic schemes, creating a level playing field for both importers and domestic producers.

Exhibit 9 - The Amount of Durable CDR Demand Generated by Border Carbon Adjustment Mechanisms Depends on the Range of Imports Affected

2050 DURABLE CDR DEMAND FROM BCAS BY INDUSTRY, 2050 (MT CO_2)

Potential covered import options[1]



Sources: UN Comtrade: OECD; World Bank; BCG analysis.

[1]All coverage scenarios shown are under "mid" price scenario.

34. European Union.

Regulatory requirements and Industry Standards

Standards and regulatory requirements take a variety of forms, from requiring companies to reduce the carbon intensity of their products to directly mandating the purchase of CDR. Such standards could allow companies to use CDR as one option to decrease emissions, incentivizing demand when CDR is more economically attractive than alternatives. For example, performance standards typically set targets for emissions reductions or carbon intensity that parties must meet, on average, and CDR could be one option to meet these targets. Government procurement or eligibility standards can have a similar effect, imposing emissions intensity thresholds on companies that sell products to the government or receive government funding, for example. For the purposes of this report, we focused our sizing for regulatory requirements on the aviation, shipping, and power industries, since such regulations would likely have the largest meaningful impact on durable CDR demand.

AVIATION

Aviation is among the most difficult sectors to decarbonize, and therefore has a disproportionately great need for durable CDR to cover residual emissions. According to IEA projections, demand for aviation services could increase twofold by 2050, dramatically increasing the emissions it generates.[35] The primary decarbonization levers available in aviation include reducing flights taken (through voluntary or policy-driven behavior change), new technologies (electrification and the use of hydrogen as fuel), sustainable aviation fuel (SAF), and using CDR to counterbalance the residual emissions from the ongoing use of jet fuel. In addition to technological challenges, governing aviation decarbonization is challenging, since most of the industry's emissions come from international flights, which are difficult for individual governments to regulate.

Bio-SAF is the most feasible and economical decarbonization lever in the near term. While SAF can be used as a drop-in fuel, alternatives such as electrification and hydrogen are unlikely to offer the energy density needed for long-haul flights. SAF can be produced using biomass feedstock (bio-SAF) or made from chemical reactions between hydrogen and CO_2 (e-SAF). There are concerns about bio-SAF's sustainability in the long term, however: bio-SAF's emissions intensity is 20% that of jet fuel,[36] significantly higher than e-SAF, which has emissions as low as 1% of jet fuel's.[37] Moreover, large-scale bio-SAF production has a sizable impact on the environment, making it difficult to accurately measure the full lifecycle impact of bio-SAF on the many biomass feedstocks needed.

However, bio-SAF is likely to be the more economically feasible alternatives in the near term, as e-SAF is expected to be between two and six times more expensive than bio-SAF in the near term.[38] As a result, near-term demand for low-carbon aviation fuel is focused on bio-SAF. The availability of bio-SAF will be limited in the long term because multiple sectors of the economy, including energy production, road, and marine transportation fuels, and even animal feed, compete for a limited supply of biomass.

In the long term, it's unclear to what degree e-SAF vs. continued jet fuel use with durable CDR will meet the need to abate CO_2 not abated by bio-SAF and other alternatives. The relative proportion of e-SAF vs. continued jet fuel use will depend on cost, environmental impact (including CO_2 and non-CO_2 effects), and feasibility.

- **Cost.** While e-SAF is likely to be more expensive and less energy efficient than jet fuel with durable CDR in the near term, e-SAF's long-term cost competitiveness will depend on declining costs of green hydrogen and sustainable CO_2 as well as the projected cost of fossil jet fuel.

- **Non-CO_2 impacts.** More research is required to fully understand the impact of the non-CO_2 emissions associated with the combustion of fossil jet fuel. e-SAF eliminates non-CO_2 emissions that cause public health issues such as sulfur oxide (SOx) and could reduce the contrails resulting from soot particles associated with aromatic jet fuels.

- **Feasibility.** Fossil jet fuel paired with durable CDR will require less renewable energy and has a more efficient technological pathway that only requires the development of one new technology (cheap durable CDR), rather than the development of the hydrogen and CO_2 technologies associated with e-SAF.

Decarbonization requirements for the aviation industry could require either specific solutions, like bio-SAF and e-SAF, or general net CO_2 reductions on an absolute or intensity basis. Requiring the blending of SAF at a certain percentage of overall fuel use could drive demand for forms of CDR that generate CO_2 usable as a feedstock for e-SAF, such as CO_2 capture from biogenic sources and DACCS. Requirements for net CO_2 reductions on an absolute or intensity basis could also drive CDR demand directly to account for ongoing residual emissions from the combustion of jet fuel and SAF.

Today, most aviation decarbonization efforts require producers to blend sustainable aviation fuel and for airlines to purchase it. Starting in 2025, blending requirements through ReFuelEU Aviation Initiative will be put in place in Europe. Similar requirements are in discussion across other regions globally. Across regions with high aviation demand and decarbonization ambitions, blending requirements could drive 45 billion to 70 billion gallons of SAF demand per year. The estimated feedstock available

35. Based on IEA World Energy Outlook 2023, STEPS scenario.
36. Calculated based on average bio-SAF emission intensity for HEFA, AtJ, and FT alternatives.
37. Very low carbon intensities are achievable if e-SAF's supply chain is decarbonized.
38. International Civil Aviation Organization.

for bio-SAF is sufficient to meet this demand[39] (see Exhibit 10), even though fulfilling demand for SAF will require a high percentage of available feedstock, which is also in demand for other applications. Hence, it is expected that other regions will take an approach similar to the ReFuelEU Aviation Initiative and impose an e-SAF sub-requirement. If aviation regulations elsewhere follow a trajectory similar to the EU's, e-SAF demand alone could reach 20 billion to 30 billion gallons per year.

Impact of aviation decarbonization on CDR demand

Demand for CDR as a feedstock for e-SAF could reach ~190 to 400 Mtpa by 2050. The majority of CDR demand is expected to come from aviation fuel standards in North America (up to ~200 Mtpa) and blending mandates in Europe (up to ~125 Mtpa).[40]

CDR demand in aviation will primarily come from e-SAF sub-requirements or direct procurement of durable CDR. Blending requirements could drive 45 to 70 billion gallons of SAF demand per year. Without significant cost declines, however, CDR demand for e-SAF is likely to materialize only when required by e-SAF sub-requirements. e-SAF demand of 20 to 30 billion gallons per year will require 190 to 340 Mtpa of CDR capacity by 2050. Additional requirements to remove the residual emissions associated with the production of bio-SAF would create an additional ~60 Mtpa in CDR demand.

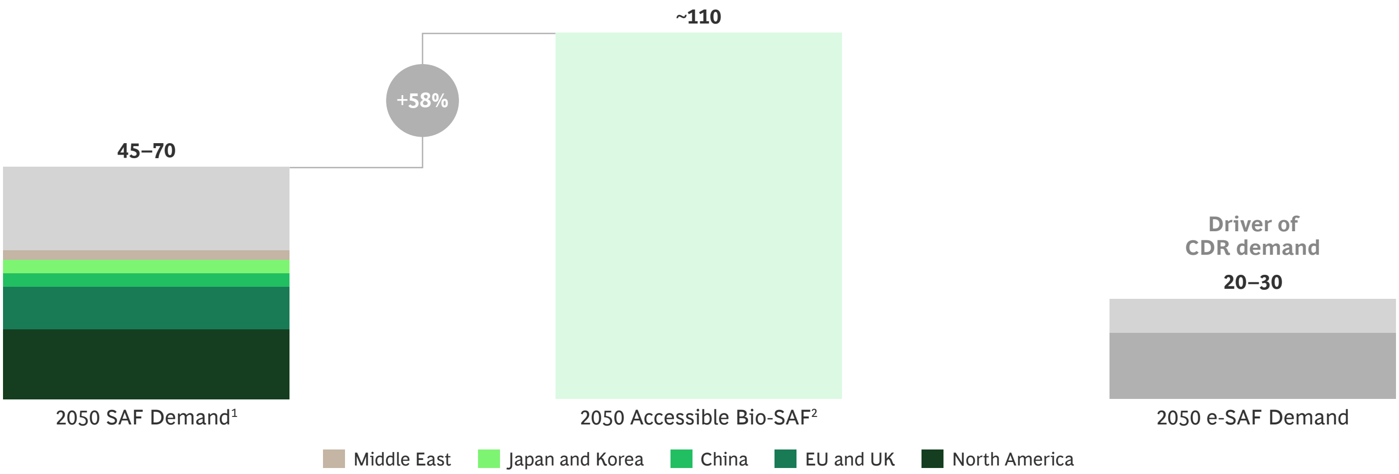
Implementation considerations

Direct e-SAF sub-requirements in blending policies would generate a significant net increase in CDR demand. Although e-SAF is expected to be cost-competitive by 2050, bio-SAF's lower cost and availability will likely reduce the demand for e-SAF in the near term. A direct sub-requirement for e-SAF in SAF blending policies and stringent requirements for lifecycle carbon intensity of bio-SAF would increase the demand for CDR.

Policy emphasis on using durable CDR to counterbalance aviation residual emissions would increase CDR demand. Allowing for the direct use of CDR credits to address fossil jet fuel emissions and requiring it to neutralize residual emissions from bio-SAF would significantly increase demand. In parallel, it is crucial either to require high-quality durable CDR or to establish measures addressing the disparity in the amount of emissions reduced when low-cost, less durable carbon offsets are used.

Exhibit 10 - e-SAF Demand is Likely to Arise Primarily When Specifically Required by Legislation

Estimated annual SAF volumes, 2050 (billions of gallons)



Sources: : IEA WEO 2023; WEF; BCG analysis

¹Estimated SAF demand modeled based on demand potential from aviation decarbonization policies

²Based on WEF report: "Clean Skies for Tomorrow."

39. Estimated biomass capacity excludes first gen crop-based feedstocks.

40. CDR demand ranges include use of biogenic CO_2 as feedstock for e-SAF production. Although limited by supply, biogenic CO_2 is cheaper than CO_2 feedstock from DAC.

SHIPPING

Shipping is responsible for 2% to 3% of total global GHG emissions. Considering the increasing demand and limited decarbonization options facing the industry, CDR could play a role in decarbonizing it and covering its residual emissions. According to the IEA, shipping demand will continue to rise to 2050, albeit more slowly than aviation. Similar to aviation, regulating GHG emissions from shipping faces governance challenges, and technological solutions for existing ships are limited. The primary decarbonization levers in shipping include improving operational and technological efficiency and adopting alternative fuels. Ammonia, biofuel, and liquid natural gas (LNG) as a transitional solution will likely be the primary alternative fuels, leaving a small share for e-methanol in decarbonizing the industry.[41] CDR's primary role will be providing CO_2 feedstock for e-methanol and in addressing residual emissions from biofuel production.

While not yet certain, ammonia is likely to be the most cost-effective alternative in the long term. LNG and biofuels are the most cost-effective short-term solutions, although they are limited by sustainability concerns and feedstock availability. At $16 to $23 per gigajoule (GJ) by 2050, e-Ammonia is expected to dominate shipping decarbonization; however, regulatory and safety concerns over toxicity may limit its role.[42] Failing to address ammonia's safety risk will increase the share of e-methanol and raise CDR demand.

How shipping decarbonization could work

Decarbonization in shipping is typically driven by efficiency improvements and requirements for alternative fuels. The International Marine Organization (IMO), which serves as the global regulatory body for shipping, has set indicative targets in its 2023 strategy to achieve net zero GHG emissions in international shipping by or around 2050. This strategy emphasizes enhancing efficiency standards and aims to ensure that alternative fuels and energy sources constitute 5% to 10% of the energy consumption in shipping by 2030. This strategy could be used as a proxy, alongside what countries are currently pursuing, for how shipping decarbonization regulations could develop.

As one example, the EU is pursuing even more aggressive decarbonization goals for shipping through net emission reductions on a GHG-intensity basis. In 2023, the EU adopted the FuelEU Maritime Initiative, which establishes annual average requirements for the GHG intensity of energy (measured in gCO_2e per megajoule) used by ships operating within the EU or the European Economic Area (EEA). These regulations will be implemented starting in January 2025.

Impact of shipping decarbonization on CDR demand

Durable CDR demand due to regulatory requirements to decarbonize shipping could reach 10 to 200 Mtpa by 2050. Most of the demand is expected to come from Asia Pacific (up to ~100 Mtpa) and North America (up to ~30 Mtpa). CDR demand from the EU will be relatively lower (~5-25 Mtpa) due mainly to stringent FuelEU requirements, which cannot be met without strong reliance on e-ammonia.[43]

CDR demand in the shipping industry will come primarily from the consumption of e-methanol as an alternative fuel and through addressing residual emissions from biofuel. CDR demand will range substantially depending on how broadly ammonia is adopted as an alternative fuel.

Implementation considerations

The role of CDR in shipping depends directly on policy considerations regarding ammonia. CDR will only be adopted if regulatory and safety concerns over ammonia's toxicity prevent its widespread use and increase reliance on e-methanol as the primary alternative shipping fuel.

Additionally, requiring CDR to address the residual lifecycle emissions from biofuels and ongoing use of fossil fuels will further increase CDR demand used in the decarbonization of shipping.

POWER GENERATION

Most developed economies are planning to use ETS systems as the main tool to decarbonize their power grids, but some jurisdictions may never adopt an ETS. In those cases, an alternative decarbonization lever and source of CDR demand could be net zero power generation policies that allow the use of CDR for compliance. North American jurisdictions without an ETS, for example, could still generate ~60 to 200 Mtpa in CDR demand through net zero power generation policies.

North America's grids could pursue net zero goals through renewable portfolio standards and emissions performance standards. The Biden administration,[44] for example, has announced a goal for US power grids to reach net zero emissions by 2035. North America has a complex web of federal, provincial, and state jurisdictions with intersecting energy and climate policies. The region's net zero goals will therefore be addressed with a mix of different policy tools across different jurisdictions. Two such tools commonly applied in North America and globally are:

- **Renewable portfolio standards (RPSs):** These require a percentage of grid power to come from renewable sources. Regulators set a schedule for the growth of

41. E-methane is excluded from the analysis due to its low potential as a shipping alternative fuel.
42. Fuel Option Scenarios report by Maersk Mc-Kinney Moller Center.
43. CDR demand ranges include use of biogenic CO_2 as feedstock for e-methanol production. Although limited by supply, biogenic CO_2 is cheaper than CO_2 feedstock from DAC.
44. US White House briefing.

the percentage requirement, and enforce the standard by monitoring the share of power retailers' power portfolio that comes from renewable sources. This policy is used in territories like the state of California,[45] where the goal is to reach net zero grid emissions by 2045.

- **Emissions performance standards (EPSs):** These set the maximum amount of greenhouse gas emissions that power plants can emit per unit of energy produced. The maximum may fall over time, and plants that fail to meet the standard would be required to close. The US Environmental Protection Agency[46] is proposing a set of different performance standards depending on a power plant's energy source, intended dates of operation, and capacity factor.

Durable CDR can be a tool for addressing residual emissions in power systems. As the grid incorporates more renewables, power generation players will need a source of firm, dispatchable energy to complement variable renewable generation and will likely continue to use small amounts of unabated fossil power for peaking capacity. The US National Renewables Laboratory finds that "achieving complete decarbonization requires offsetting the carbon emissions of these remaining fossil assets [. . .] A small amount of negative emissions DAC or BECCS capacity can support a much larger amount of non-CCS fossil capacity used infrequently for peaking capacity."

Impact of power decarbonization on CDR demand

The use of CDR to reach net zero grid emission goals could drive durable CDR demand of ~60 to 200 Mtpa in North America by 2050.[47] The level of potential demand will depend on available resources and costs to provide CDR. Demand for BECCS would be higher if biomass is readily available and the cost to transport and store it is low, and when the cost of CCS is low. Demand for other forms of CDR credits will depend on whether regulators accept them for RPS and EPS compliance. Demand will also depend on the extent to which the grid's generation mix includes fossil fuels. The estimates above correspond to scenarios where 2% to 4% of energy generation comes from fossil fuels. Measures to close or further limit the dispatch of fossil fuel generation would further reduce the need for CDR to reduce grid emissions.

Implementation Options

A focus on EPSs would incentivize a greater use of CDR than a focus on RPSs. EPSs only reward measures that reduce emissions among fossil fuel generators. They therefore create no incentive for the development of renewable generation, utility-scale storage, and other system-level abatement measures. Under EPSs, removals do not have to compete with these potentially lower cost abatement measures. This means that EPS would generally drive higher CDR demand than RPS. In practice, however, RPS and EPS are often deployed together. Such a policy mix would lead to a moderate level of CDR demand.

Government procurement of durable CDR

Government procurement of CDR is another potential direct contributor to CDR demand. Governments can create predictable demand for CDR by allocating a budget for direct procurement. CDR purchases may also support governments in meeting NDCs and goals for reducing historical emissions. Government procurement will likely play a significant role in driving near-term demand for durable CDR. Examples include the U.S. Department of Energy's purchase challenge[48] and Denmark's commitment to purchasing ~160 ktCO_2 annually in CDR from 2026 to 2032.[49] Governments can continue to purchase CDR beyond pilot projects and at a larger scale to cover residual emissions not covered by other policy levers.

3 Indirect Drivers

FINANCIAL INCENTIVES

Financial incentives include any policies which reduce the cost or risk associated with CDR production and purchasing. Primary examples include tax credits or feed-in tariffs such as current tax credits for various green technologies under the US Inflation Reduction Act and similar feed-in tariffs or contracts for differences for green technologies in Europe. While these can be helpful in driving demand, they would not "grow the pie" of potential CDR buyers; rather, they would increase demand from buyers who were already interested in purchasing CDR but deterred by price or lack of supply.

CO_2 ACCOUNTING ENABLERS

Finally, clarifications around CO_2 accounting can make CDR purchasing more attractive, indirectly increasing demand. This could include standards-setting bodies such as the Science Based Targets initiative (SBTi), which could clarify how companies should use CDR to meet net zero targets, or international agreements like the Paris Agreement allowing countries to use carbon removals to meet their NDCs or frameworks that allow for inclusion of CDR in ETSs or voluntary carbon markets such as EU's Carbon Removal Certification Framework (CRCF). Accounting enablers could also include governments and other bodies certifying products that use high-quality removals to offset their emissions as "green," allowing producers to charge a premium that can help fund CDR. Note that any accounting enablers that incentivize the use of CDR, including the above examples, could also incentivize emission reductions.

45. California Public Utilities Commission.
46. US Environmental Protection Agency.
47. National Renewable Energy Laboratory; BCG analysis
48. US Department of Energy.
49. Danish Energy Agency.
50. EU Emissions Database for Global Atmospheric Research; BCG analysis.

Addressing the Remaining Residual Emissions

The demand drivers identified and measured in this report will not be sufficient to address all residual emissions in 2050. Even if regulators around the world adopt every policy driver identified in this report, 70% or more of residual emissions would remain unaccounted for. Asia Pacific is the region with the largest residual gap, followed by developing countries across the rest of the world. The gap could be even higher if CDR demand policies are not fully implemented or if sectors do not reduce all abatable emissions.

The residual emissions gap could be addressed by driving additional CDR demand or through an extended set of economically feasible reductions. The following sections explore available options for each of these two. This set of options is non-exhaustive, focusing primarily on addressing geographies and industries with the greatest remaining gaps. Closing these gaps will require a significant degree of policy ambition.

Measures to extend CDR demand

Additional geographies could introduce CDR demand policies to address residual emissions. One option is for more geographies to adopt ETSs and other forms of carbon pricing. Currently, 40% of the world's emissions come from countries without an existing or proposed carbon pricing scheme, and most of those emissions are concentrated in developing economies, leaving 60% not covered by existing or proposed carbon pricing mechanisms.[50] While most of the Asia Pacific region has already developed some form of carbon pricing, there is significant space to extend these measures in Southeast Asia. Similarly, there is still space to extend carbon pricing across North America, especially in the US at the state level.

Countries expected to adopt CDR demand policies could expand their scope and ambition to address residual emissions. In Asia Pacific, for example, existing ETSs could expand to more sectors and reduce allowances faster. This could be an especially effective measure in the region, as its ETSs have the slowest tightening rates for emission limits and operate some of the largest ETSs currently in place. North America and Europe could tackle residual emissions by expanding the targets for transport fuel standards and blending requirements. They could also encourage removals in the rest of the world by applying BCAs across a wider range of products, with moderate potential for emission reductions.

Policymakers could also address residual emissions through a variety of new regulatory demand drivers. Examples with large potential to drive durable CDR demand include:

- **Revenue from ETS allowance purchases and BCA levies could be used to purchase up to ~200 Mtpa in CDR.**[51] This would be a flexible measure to address residual emissions that cannot be managed by other policies. Spending 10% of revenue from these schemes on CDR could be enough to purchase up to 50 Mtpa from BCA revenue and 150 Mtpa from ETS allowance revenue.

- **Using 2% of conservation and fertilizer subsidies to support CDR activities in agriculture could generate up to 1,000 Mtpa of CDR demand.** Land used for growing crops can capture atmospheric carbon through practices like spreading biochar and enhanced rock weathering. These practices not only sequester CO_2 but can also provide co-benefits such as improved soil health, water conservation, and increased crop yields. CDR practices could be incorporated under existing subsidy schemes for disaster assistance, crop insurance, and fertilizer usage. Depending on the portion of subsidy funds allocated and the cost of materials, CDR demand from agriculture subsidy could range from ~70 to 1,000 Mtpa. Demand would be concentrated in regions with substantial agricultural subsidies and favorable cropland conditions such as China, India, the US, and Southeast Asia.

- **Financial support from developed economies could increase CDR adoption in developed and middle-income economies.** Joint investment programs like South Africa's Just Energy Transition Investment Plan[52] set an example of how developed and middle-income economies can collaborate to fund emission reductions. Once middle-income countries start addressing residual emissions, they may turn to similar joint investment mechanisms specifically for funding removals. Countries could also leverage the Paris Agreement's Article 6 Crediting Mechanism to coordinate removal contributions to their NDCs if it were allowed.

51. Assumes 10% of funds are applied to purchase CDR. ETS allowances assumed to be auctioned at 0.2 times the price of CDR.

52. South Africa Presidential Climate Commission.

Actions to Take Now

While the policies outlined in this report could drive significant demand for durable CDR by 2050, near-term action is needed to lay the groundwork for future scale. As discussed in BCG's report "The Time for Carbon Removal has Come," some of the most impactful actions various stakeholders could take in the near-term include: setting targets for durable CDR; investing in early-stage CDR deployments and financing mechanisms; and developing accounting standards that focus on high-quality and durable CDR. Policy-focused stakeholders in particular, including standards-setting organizations and governments, could play a key role.

Carbon accounting and standard-setting organizations could encourage the procurement of high-quality carbon credits in tandem with meaningful emissions reduction measures, by counting removals toward companies' net zero commitments, for example. Standards bodies should also define more clearly the accounting rules for how removals should be paired with residuals by type of emission (by using "like-for-like" accounting, for example) to achieve the dual objectives of promoting reductions before removals and supporting the scale-up of durable CDR.

Governments can support the advancement of near-term durable CDR supply and demand while outlining longer-term policy mechanisms to achieve scale. In the near term, governments can develop policies to accelerate support for durable CDR to enable further cost reductions and the market's development. These include supply-side mechanisms such as subsidies and innovation funds and demand-side mechanisms such as direct government procurement and compliance regulations. Looking ahead, governments could start to define long-term targets for durable CDR. This could be achieved based on a projected range of estimated residual emissions and requirements for removing them, or through a clear definition of how market mechanisms could align incentives for the private sector to only use durable CDR to account for residual emissions.

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