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Commentary

Responsibility for emissions and mitigation capability should guide use of carbon removal offsets

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Stabilizing and then drawing down global temperature requires achieving net-negative CO_2 emissions globally. Carbon removal is needed to offset "hard-to-abate" sectors that remain sources of emissions at net zero and beyond. We argue that the use of scarce carbon removal resources should be guided by the principles enshrined in the Paris Agreement.

In 2015, countries around the world came to a consensus agreement to limit global warming to well below 2°C and strive to limit it to 1.5°C. In some cases, substantial mitigation progress has already been observed. For example, solar and wind surpassed coal as the primary electricity-generation source globally in the first half of 2025. This expansion is happening most rapidly in developing economies that don't have significant incumbent fossil fuel infrastructure, like Pakistan, which imported 34 GW of solar panels in the last 2 years and is on pace to deliver 20% of its total electricity supply in 2026 using solar power, up from <1% in 2023.

Yet greenhouse gas (GHG) emissions on the whole continue to rise. In 2026, we have already experienced the first years where global mean temperature surpassed 1.5°C, and we are hurtling toward a world that exceeds that level not just in single years but in the long-term average.[1] At the signing of the Paris Agreement, calls for action centered on achieving net-zero CO_2 emissions by around mid-century, a precondition for halting the rise in global temperatures. Countries further pledged to achieve this goal equitably, with developed countries "taking the lead."[2] Pathways limiting warming to 1.5°C with minimal overshoot required rapid, deep reductions; those allowing overshoot—i.e., exceeding and then returning to 1.5°C or lower temperature levels—assumed that net-negative emissions beyond mid-century would eventually draw temperatures back down.[3] Limited global action has now locked the world into the latter, where both deep reductions and sizable carbon removal are needed. Now, net-zero CO_2 is insufficient to achieve the Paris long-term temperature goal; instead, a net-negative emissions future is needed.

Carbon removal needed to offset residual emissions

Many sectors of the economy that are currently carbon polluters, such as power generation and road transportation, can be electrified directly or can have fuels and other material inputs generated through electrified processes. However, there are several important areas of human livelihood and socioeconomic development that don't have such solutions—agriculture, iron and steel production, long-haul transportation, and certain industrial processes all have limited electrification opportunities at present.[4] Taken together, these sectors that have been colloquially called "hard-to-abate" contribute to around 22% of current global total GHG emissions[5,6] and, without further technological or behavioral change, will remain net sources of emissions.

To reach net-zero (or, in some cases, net-negative) emissions targets, residual emissions—i.e., remaining sources of emissions at and after the time of net zero—will need to be compensated for. There are three compensation options available to both countries and firms: (1) deploy carbon removal domestically or within domestic value chains, (2) pay for additional emissions reductions elsewhere, or (3) pay for carbon removal elsewhere. Past climate policy and corporate action have largely focused on the second option using "carbon offsets." Carbon offsets can be purchased on either the voluntary carbon market (VCM) or through international markets like the Clean Development Mechanism or the new Paris Agreement carbon market. The most recent examples of market-based carbon offsets resulted in a "race to the bottom" for low-cost, low-credibility carbon offsets[7] used to prop up claims of achieving country[8] or corporate[9] climate targets.

Technological advances have increasingly made carbon removal offsets a possible option for corporations and countries to compensate for their remaining emissions. Here, we use the term "carbon removal offset" to mean a credit, certificate, or other tradeable quantity (whether between firms or between countries) for a unit of carbon durably removed from the atmosphere that is used to compensate for continued emissions

and that is additional to what would have happened anyway. Carbon removal with novel approaches, such as through mineralization or physical trapping in geologic formations, offers more durable, longer-lasting carbon storage than with conventional approaches, like reforestation, which instead have lasting environmental co-benefits if pursued sustainably.[10]

Carbon removal offsets that are combined with domestic mitigation and domestic carbon removal to compensate for any remaining residual emissions will likely be most effective if they are seen as highly credible with well-regulated monitoring, reporting, and verification. High-confidence, high-durability offsets will likely be limited,[11,12] especially in the near and medium terms, and need to be utilized judiciously to compensate for genuinely unavoidable emissions, rather than those that could have been reduced otherwise. Learning from past failures—including failures in offset markets—is key to avoiding a credibility crisis in the removal offset market that could severely limit an important tool in our toolbox to address climate harms in a 1.5°C overshoot world.

Ill-defined hard-to-abate muddies carbon removal needs

So how can one weigh which sources of emissions should be compensated for by carbon removal offsets and which emissions should be reduced and avoided? Cost-effective mitigation modeling studies, widely used to assess progress toward global climate targets (e.g., in IPCC reports and by the UNFCCC) converge on a set of common sectoral transformations that underpin an attainable net-negative emissions future (Figure 1A). These pathways identify the sectors and geographical regions where it is cheapest to reduce emissions and scale up carbon removal. When net-zero and net-negative CO_2 emissions are reached, a certain amount of "residual emissions" remain (those above the "net-zero line" in Figure 1A). The level of residual emissions defines the amount of carbon removal offsets that is needed to at least achieve net-zero CO_2 emissions at a given point in time.

While global benchmarks, such as achieving net-zero emissions, are useful, not all sectors achieve the same outcomes (Figure 1B). For example, sectors like agriculture have to contend with competing priorities of emission reductions, food security, and food sovereignty as well as deeply embedded cultural preferences. Others, such as cement and lime production, have costly options to abate emissions but are also critical for society and infrastructure development in developing economies. Collectively using the umbrella terminology hard-to-abate for these diverse sectors globally hides complex trade-offs between development, cultural considerations, and sectoral lobbying with technological availability and responsibility for mitigation action (Table 1). Blindly assuming that all emissions globally from certain sectors are hard-to-abate can cause available mitigation action to be underestimated while the needed carbon removal offsets could be greatly overestimated.

Indeed, the estimated level of residual emissions—and thus the level of carbon removal offsets needed—has reduced over time (Figure 1C), from around 11 Gt in IPCC's AR5 in 2014[15] to about 9 Gt in the SR1.5 (in 2018)[16] and further reduced to around 7 Gt in the latest AR6 (2022).[3] This reduction is a result of revised assumptions on the costs of renewable electricity generation, as well as the inclusion of additional mitigation approaches, such as synthetic e-fuels, hydrogen, and ammonia production. Future assessments may continue this trend as additional mitigation technologies are included and limits to carbon removal approaches are better understood.

Identifying which residual emissions should be offset with carbon removal is critical for enabling successful market mechanisms. As an example, the median estimate of carbon prices in AR6 scenarios is around \$60/tCO_2 in 2030 and \$300/tCO_2 in 2050, offering a reasonable proxy for the modeled costs of mitigating "hard-to-abate" sectors over time. On today's VCM, carbon removal offsets range from \$12/tCO_2 to \$16/tCO_2 for conventional carbon dioxide removal (CDR), like reforestation, and \$111/tCO_2 to \$1,608/tCO_2 for novel CDR, such as direct air carbon capture and storage (DACCS).[17] Misaligning easier-to-abate emissions from affluent countries and corporates with cheaper carbon removal offsets risks potentially causing market failures and undermining the effectiveness of carbon removal offsets in the long term.

From "model land" to equitable action in the real world

Modeled mitigation pathways are used to guide countries and corporations, yet they don't incorporate important real-world considerations of mitigation responsibility and capability that form the foundation of international environmental agreements. For example, parties to the Paris Agreement are required to set climate targets that are both ambitious and fair. As a result, not all countries are expected to achieve net-zero emissions at the same time, and indeed, some may not have the capability to achieve net zero at all. While "hard-to-abate" economic sectors for most countries map clearly to modeled scenarios, the principles of environmental treaties do not. Indeed, in many cases, the Paris Agreement's tenet that "developed countries take the lead" implies that "hard-to-abate" sectors in countries with advanced economies should depend less on carbon removal offsets and mitigate emissions from these sectors further than those in low and lower-middle income countries.

Similar considerations are applicable to private-sector climate action. Corporate climate target-setting organizations, like the Science Based Targets Initiative (SBTi), develop benchmarks for carbon removal offsets that firms can use while claiming to be aligned with the Paris Agreement. The latest standards from the SBTi provide an avenue for including considerations of fairness in corporate climate targets by recommending that high-income-country companies set earlier net-zero dates and support developing-country value chain partners, but these remain recommendations rather than binding criteria. Furthermore, the sectoral benchmarks for gross emission reductions (i.e., residual "hard-to-abate" emissions) that determine whether a company passes or fails validation are ultimately identical regardless of national context. As such, this type of offset architecture not only brings in the biases of the modeling frameworks described above but also inherits the equity blind spots of those pathways. Preliminary analysis of multinational companies across "hard-to-abate" sectors using asset-level

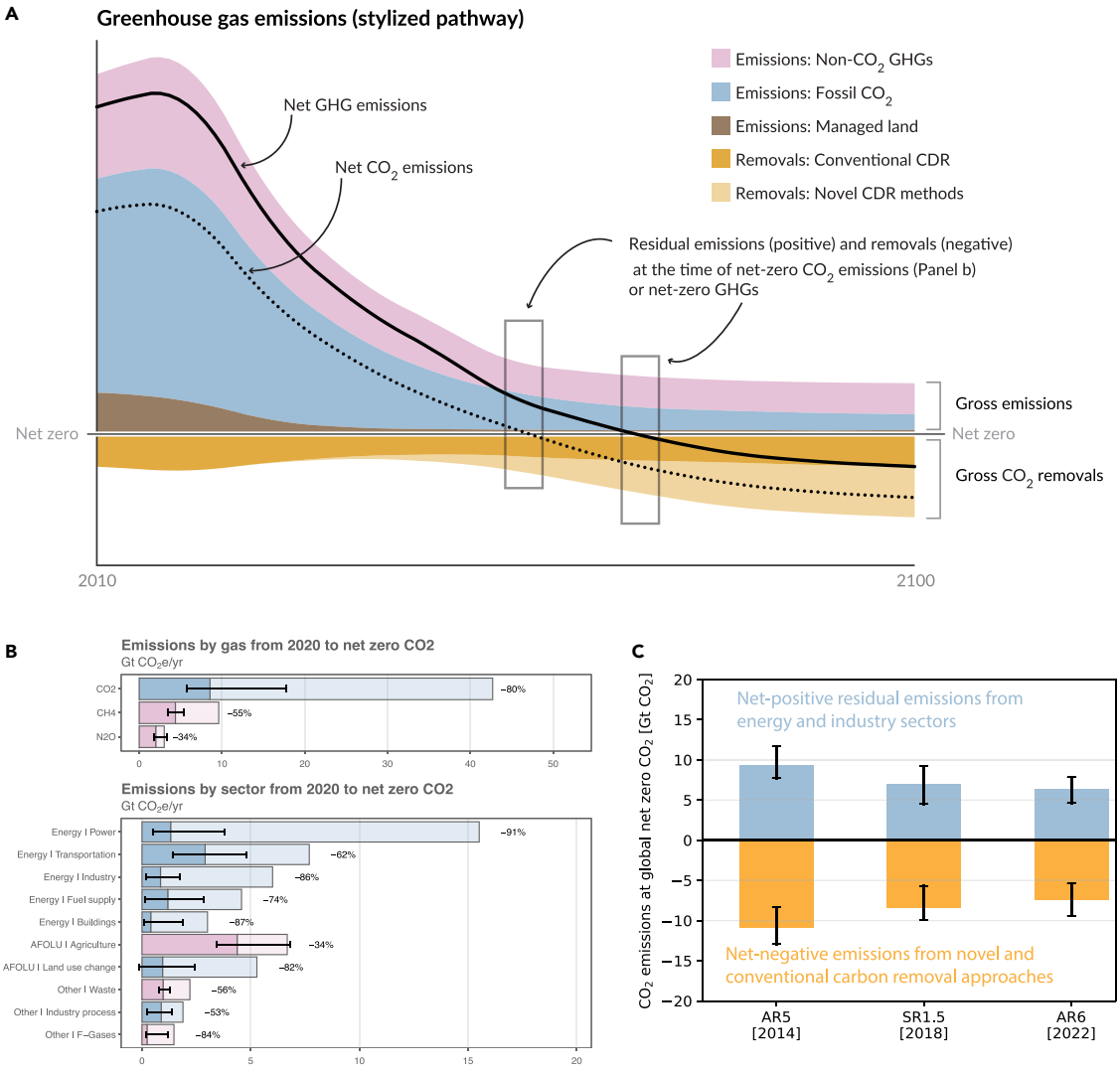

Figure 1. Characteristics of mitigation pathways including residual emissions and carbon removal

(A) A stylized mitigation pathway consistent with the Paris Agreement where net-zero CO_2 is achieved around mid-century and net-zero GHGs is achieved in the second half of the century. These pathways generally follow similar mitigation strategies. First, sectors are electrified to the extent possible, renewable electricity generation is dramatically scaled up, and any remaining electricity generated from fossil sources is assumed to be abated by high-quality (e.g., >95% efficient) carbon capture and storage (CCS) processes.[13] Second, land-use practices, with varying degrees of sustainability, are adopted to reduce deforestation and enhance carbon removal in vegetation and soils. Third, methane and other GHGs from the fossil extraction, agriculture, and waste sectors are abated through production and technical improvements, as well as demand-side shifts. Fourth, novel forms of CDR, such as direct air carbon capture and storage (DACCS), are scaled up to compensate for any remaining emissions.

(B) Gross reductions and residual emissions by gas and sector in IPCC AR6 scenarios. Faded bars indicate the median scenario gross emissions level in 2020, while corresponding solid bars indicate the residual emission level at the point of net-zero CO_2. Error bars indicate the 5th–95th percentiles of the scenario range at the point of net-zero CO_2. AFOLU refers to agriculture, forestry, and other land use.

(C) Net-positive and net-negative CO_2 emissions at the time of net-zero CO_2 in pathways assessed by the IPCC over the course of different IPCC assessments. In general, models that find lower levels of residual emissions are needed as understanding of mitigation technologies progresses. Emissions are summed across sectors and therefore likely underestimate total residual emissions—e.g., from cement production coupled with CCS—due to analysis limitations from the underlying dataset.

Figures 1A and 1B are reproduced from Smith et al.[14]

data[11] shows that the vast majority of companies exceed equity-based allocations even under their stated transition plans, with the scale of exceedance varying by orders of magnitude depending on facility location. This highlights how what currently passes for "science-aligned" at the corporate level systematically favors companies in high-income countries at the expense of those in economies that have contributed least to the problem.

And while many corporate entities, including oil and gas firms and other historically high-emitting companies, do not even attempt to align with science-based targets nor develop credible emission reduction plans, those that do are not delineated based on their historic responsibility or capacity to mitigate, only based on the particular sector of which they are a constituent. Because not all economic

Table 1. Different definitions and considerations of the term hard-to-abate

Category	Technical definition	Examples
Technically hard-to-abate	process emissions or thermodynamic constraints preclude full decarbonization with known technologies	cement calcination, steel reduction, long-haul aviation, ruminant livestock in otherwise efficient production systems
Economically hard-to-abate	technologies or options for product replacement or systems change exist but carry high costs relative to ability to pay, to the cost of abatement in other sectors, or to the cost of CDR	green hydrogen in developing regions, CCS retrofit of young assets in emerging economies, cheap afforestation displacing emission reductions, recently built thermal power plants whose premature closure would result in high costs through stranded assets
Infrastructurally hard-to-abate	technologies exist but enabling infrastructure absent (grids, storage, and supply chains)	electrification in regions without grid access, alternative fuels without refueling networks
Politically hard-to-abate	abatement could occur via making changes in production systems or requiring sectors to bear the cost of their emissions, but the political costs of doing so are, or are perceived to be, too high	climate policies that would tackle vested interests, mis- and disinformation campaigns that make ambitious climate action politically poisonous
Culturally hard-to-abate	abatement could occur via demand-side changes, but cultural attachment leaves such changes with insufficient popular support to achieve a rapid and sustained change	meat production and consumption in countries where meat and meat farming forms an important part of cultural identity and status
Socially hard-to-abate	abatement could occur via demand-side changes, but there are insufficient options to provide for a just transition for those on the production side who would be phased out	livestock production in countries where livestock provides a key lever for poverty alleviation and insurance

actors engage in such target setting, there is a clear path to carbon "leakage"—i.e., if a company is responsible only for its direct emissions (so-called scope 1 and 2 emissions), it can engage economically with actors that continue to pursue emissions-enabling activity (accounted through so-called scope 3 emissions).

Principled approaches for carbon removal offsets

Credibly and effectively matching carbon removal offsets with "hard-to-abate" emissions will require new policies, approaches, and safeguards to ensure that failed market mechanisms of the past do not doom the new efforts of the Paris Agreement's Article 6.4 and the VCM. Robust market engagement begins with clearly communicating intentions. In the first instance, this will require that national and corporate climate targets explicitly state which sectors or parts of their value chains are anticipated to remain sources of emissions, why that constitutes their highest possible ambition, and what their corresponding use of CDR will be.

In other words, net-zero targets ought to be disaggregated into gross emissions reductions and removals, rendering the "hard-to-abate" residual emissions visible for observers and regulators, with clear plans for how to achieve emissions reductions up to this point. Ambitious actors could go further and make transparent their considerations for labeling emissions as hard-to-abate (e.g., drawing from Table 1). Multiple categories may apply to a single emission source: for example, a source may be economically hard-to-abate due to technological limitations, which can also make it politically challenging. Each hard-to-abate category poses distinct barriers to mitigation, requiring context-specific interventions to address them effectively. Ultimately, though, credible plans to use carbon removal offsets can come only after credible plans to reduce sources of emissions.

As a next step, long-term climate targets should explicitly consider notions of fairness and equity. Extending adequate and fair contributions in near-term global mitigation efforts, currently enshrined in the Paris Agreement, to long-term targets implies that net zero will not remain the endpoint of climate action but rather become a milestone into net-negative territory for those entities with high historic contributions to global temperature rise or high capacity to go further. But again, equity-informed net-negative targets should be clear about the objectives they aim to achieve and where they anticipate compensating for "hard-to-abate" emissions with carbon removal offsets. For example, the latest corporate standards from the SBTi can advance the offset architecture from addressing the question of *how* companies may use carbon credits to *how much* different companies should be expected to reduce emissions in the first place. A framework that requires steeper reduction pathways for companies in high-responsibility, high-capacity jurisdictions would both align with principles of fairness laid out in the Paris Agreement and reduce aggregate demand for scarce carbon removal, leaving more removal capacity for those in economies where the transition will take longer.

Achieving global net-zero and net-negative CO_2 emissions will require an "all hands on deck" approach, combining ambitious emissions reductions with conventional carbon removal—e.g., through reforestation and ecosystem conservation—as well as removals from more nascent and novel sources like biochar, DACCS, and enhanced weathering, among others. Both kinds of carbon removal have a role to play and should be deployed and incentivized in separate contexts.

Conventional CDR methods, compared with novel ones, typically offer lower

durability—i.e., expected carbon storage lifetime. However, they often align better with broader sustainable development priorities (e.g., improving biodiversity and enhancing ecosystem services). Despite their shorter lifetimes, conventional CDR's carbon storage duration can match that of other GHGs, such as methane, and pairing conventional CDR with methane abatement strategies can negate the powerful climate impacts of short-lived climate forcers.[18] Such a scheme has the added co-benefit of avoiding offsetting permanent fossil CO_2 from developed economies in the atmosphere with less durable conventional carbon removal on land in developing regions. Regular re-assessments of these options is essential for deep decarbonization and minimization of ''hard-to-abate'' emissions, since the potential, costs, and side effects of CDR options are constantly evolving.

Notions of equity can be extended from the *appropriate use* of scarce carbon removal resources to also inform efforts to *increase the portfolio* and level of sustainable carbon removal resources over time.[19] Those who have benefited most from fossil fuel extraction can invest in, build, and support the infrastructure that can halt and potentially reverse the effects of climate change. Capacity to act also matters: carbon majors have not only the revenue streams but also, in many cases, the access to sovereign wealth funds that can lead the research, development, and deployment of novel CDR approaches.[20] As countries and corporates progress to net-zero emissions, carbon credit revenues from remaining ''hard-to-abate'' emissions can be earmarked and recycled to support extensive CDR technology scaling. If one is not able to deploy such removal technologies domestically (e.g., due to a lack of carbon storage locations), then they can invest elsewhere in durable removal offsets to support the technology development and deployment required.

Taken together, equity and fairness should play two roles in facilitating credibility and trust in emerging carbon removal markets. Companies that either are located in countries with high historical responsibility or have the capacity and resources to cut emissions should do so instead of relying predominantly on carbon removal offsets. Anticipating future removal scarcity is an approach grounded in precaution and is the only way to ensure that high-quality removals increase collective ambition by being made available to countries with lower responsibility. At the same time, companies and countries with high responsibility and capacity should simultaneously invest in increasing the total supply of sustainable removals in such markets.

As we enter a period where we will exceed the 1.5°C temperature target, companies and corporations will need to develop clear, credible plans for minimizing emissions and scaling CDR. Returning to 1.5°C after exceeding it means achieving sustained net-negative CO_2 emissions globally, placing even more importance on utilizing the limited high-quality carbon removal offsets efficiently, not wasting them on emissions that could have been avoided in the first place. Transparency in how hard-to-abate is defined and justified is a critical first step. Countries and companies should then develop explicit long-term plans to reduce emission sources and sparingly use carbon removal offsets to arrive at a net-negative carbon future. Principles embedded in the international treaties and environmental law of due diligence, equity, and fairness can help guide them.

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