carbon gap

All excess emissions must be removed

Authors: Robert Höglund and Eli Mitchell-Larson

October 2024

Key takeaways

Large historic emitters do not have any remaining carbon budget. Countries with outsized historic emissions have long since exceeded their fair share of the global 1.5°C carbon budget. All of their ongoing emissions add to an ever-accumulating carbon debt.

Emissions in excess of carbon budgets need to be removed. The need for carbon removal includes past, present and future emissions, not only the "residual emissions" remaining at the year of net zero. Policymakers should begin accounting for this growing carbon debt, ultimately adjusting climate ambition to ensure these excess emissions are addressed in time to avoid unsafe temperature overshoot.

Emission reductions still take precedence in most cases, but some emissions are "CDR-optimal". As with other abatement options, neutralising excess emissions with carbon dioxide removal (CDR) may or may not be appropriate or currently cost-effective. For most sources of emissions, the immediate priority remains elimination rather than removal. However, for some limited emissions, carbon removal will be the most appropriate and sustainable mitigation option – what we define as "CDR-optimal". This terminology reflects the fact that all removals will count against some emissions and that all emissions can be either eliminated, sustained, or removed. We must therefore optimise which removals are applied against which emissions.

The terms "excess" and "CDR-optimal" emissions provide more precision than "residual emissions," which is used inconsistently. "Residual emissions" can refer to either all emissions remaining when net zero is achieved, emissions remaining at a specific target year, or emissions from specific hard-to-abate sectors at any point in time. If the term "residual emissions" is used, it's essential to specify whether it refers to a particular time period, a category of emissions, or those emissions best addressed by carbon removal – what we call "CDR-optimal".

Carbon removal is at limited risk of creating stranded assets. There is no shortage of emissions to address. Investing in high-durability carbon removal capacity is essential, regardless of future emission trajectories, due to the growing carbon debt that needs to be paid off to avert or reverse overshoot of 1.5°C. Countries and corporations need to act with much greater urgency and start building the foundation for CDR today while planning for future removals to meet their obligations.

Introduction

Large historic emitters have depleted their share of the global carbon budget. The carbon budget is usually presented as a global budget, which obscures the fact that not all nations have emitted equally since the threat of climate change was well understood. Whether we divide the global carbon budget based on population, GDP, past emissions or ability to pay, equitable 1.5°C-compatible budgets for countries with large historic emissions are already depleted. Every tonne of CO_2 they emit is in excess of their share of the carbon budget and will need to be removed, either now or in the future, to limit and reverse overshoot above 1.5°C. For these countries, the carbon removal needed to pay off this ever-accumulating carbon debt will be in addition to the CDR already needed to counterbalance whichever "residual emissions" they plan to have at the year of net zero. In essence, all emissions in excess of the carbon budget will need to be neutralised with CDR.

In this paper, we argue that countries with large historic emissions will need to use carbon removal not only to counterbalance the emissions that will remain at the year of net zero, but also to pay off their ever-accumulating carbon debt. We then explore how that debt could be paid off, and what doing so might mean in a case study for the EU. We also put this large need for carbon removal in context of residual emissions and offer recommendations for more precision when talking about the role of CDR.

Why large historic emitters do not have any remaining carbon budget

We are now near the depletion of the global carbon budget. The latest 2024 estimates put it at 200 billion tonnes of carbon dioxide (200 $GtCO_2$) to retain a 50% chance of remaining within 1.5°C warming (Forster et al. 2024). The global budget is likely to be depleted by the end of the decade. Looking ahead at how much carbon budget remains to be spent is straightforward, but only looking ahead risks ignoring inequities in how each year's emissions are accounted for. At the end of each year, each country's emissions are effectively locked in as a legitimate carbon "expense" against the global budget. For this reason, many countries that have been "spending" the most carbon can be considered to have exhausted their fair share of the global carbon budget. A growing body of research on equitable national carbon budgets indicates that major emitters have negative carbon budgets when considering their historical emissions.

For instance, recent work by Hahn et al. (2023) shows that high historic emitters have large negative carbon budgets if an equal per capita approach is taken for past emissions starting in 1990. They also demonstrate that even if large historic emitters were to eliminate their emissions immediately, the global carbon budget for staying within 1.5°C of warming would still be surpassed due to the large planned emissions from other countries. This discrepancy points to the need for these actors to finance carbon removal and emissions reductions in other countries going beyond the targets they have already set, including addressing their historical carbon debt. Gantti et al. (2024) also support this conclusion, highlighting that regions such as North America, Europe, and some parts of Asia-Pacific have already

exhausted their carbon budget allocations well before 2020. Their work shows that even under optimistic scenarios, the global carbon budget for limiting peak warming to below 1.5°C is likely to be significantly exceeded.

These analyses suggest that any new "excess emissions" coming from these historic emitters above and beyond their share of the remaining carbon budget would need to be counterbalanced either with carbon removal, or by financing further emissions reductions in countries with remaining carbon budgets (using Article 6 and corresponding adjustments). The latter approach is made challenging by the fact that even the global 1.5°C carbon budget will most likely be depleted in less than a decade. The looming depletion of the global 1.5°C carbon budget only strengthens the case for sustained emergency climate action, both in the form of rapid emissions cuts and carbon removal. Global coordination will be facilitated by clearer pronouncements from countries as to their relative planned reliance on reduction and removals.

Governments could clarify their efforts by:

1. Specifying which means they are using to calculate their and other's shares of the 1.5°C global carbon budget;
2. Indicating the year in which their share of the 1.5°C carbon budget was or will likely will be exhausted;
3. Publishing an ongoing account of the carbon debt they have accumulated since their budget was exhausted, if applicable;
4. Clearly accounting for which removals they are using to counterbalance which emissions, based on whether they are current or past emissions;
5. Demonstrating consideration in their future planning for what it would take to scale removals to levels necessary not just to deliver net zero, but also tackle their carbon debt in time to limit the most dangerous effects of overshoot.

It is important to note that all subdivisions of the global carbon budget are inherently based on value judgments about what is fair or equitable. The default method, often referred to as "grandfathering", allocates the carbon budget based on the need for reductions from today's emissions levels. Yet such calculations massively reward past polluters, meaning that countries with high historical emissions are allowed to emit more relative to others in the future simply because they have emitted more in the past. Another method, the equal per capita model used in the papers described above, divides the global carbon budget based on countries' current population. This method results in large historic emitters having already depleted their equitable share of the carbon budget and in some cases, accumulating significant carbon debt. An alternative carbon budget allocation method is based on the "ability-to-pay", which considers a country's economic capacity to reduce and remove emissions. This method produces results similar to the equal per capita model.

Understanding carbon budgets

> The global carbon budget is the amount of carbon that could be emitted with a reasonable chance of keeping temperatures below a given threshold, such as 1.5°C or 2°C. As of the start of 2024, the remaining global carbon budget for a 50% chance of staying within 1.5°C of warming is estimated to be around 200 gigatonnes of CO_2 (Forster et al 2024).
>
> At current global emission rates—about 41 $GtCO_2$/year—this budget could be exhausted in less than six years, meaning that if we continue emitting at the same pace, we will surpass the threshold that gives us a coin-flip chance of keeping global temperatures in check. For a more cautious approach, where we aim for an 83% chance of staying below 1.5°C, the budget shrinks to just 100 gigatonnes, highlighting the urgent need for immediate and dramatic emissions cuts.
>
> Note that the global carbon budget only pertains to CO_2 emissions. Non-CO_2 gases behave differently than CO_2 and do not have budgets in the same way, but are included in the global carbon budget based on projections of emissions for those non-CO_2 gases. For example, the latest estimates of the global carbon budget (Forster et al. 2024) assume that today's methane emissions will be halved by the time net zero is achieved and then persist at that same level in perpetuity. If methane emissions decrease by less than this amount, the carbon budget becomes even smaller.

How can countries take action on their carbon debt?

In practice, countries with exhausted budgets would need to either remove carbon to cover their debt and ongoing emissions, or finance emissions reductions in those countries with a remaining share of the carbon budget. Agreeing on the size of historical debt for different countries is particularly challenging. Politically, it may be more feasible to agree on a "start date" from which emissions from large historical emitters are to be classified as "excess", in other words, the point at which a country began accumulating a carbon debt. This date could be the actual moment the carbon budget was exhausted, a symbolic year, such as when a global consensus on climate action was reached (e.g., 1992 Rio Earth Summit or 2015 Paris agreement signing), or a future year, such as 2025 or 2030.

Operationalising these responsibilities to pay off carbon debts would involve a combination of domestic policies, international agreements and market mechanisms. Countries might set national targets for CDR, create regulatory frameworks for accruing future removal debt to be paid later, and participate in international carbon markets. The latter could help finance emissions reductions in countries with a remaining share of the carbon budget, through mechanisms like Article 6 of the Paris Agreement with corresponding adjustments.

To ensure that the responsibility to remove is not forever pushed into the future, policymakers could apply mechanisms to penalise delay akin to interest rates on financial

debt. Bednar et al. (2021) propose "carbon removal obligations" (CROs) as one such potential policy instrument. CROs function analogously to financial debt, where emitters accrue obligations to remove carbon and pay interest on these obligations. Lyngfelt et al. (2024) introduce a similar mechanism called Atmospheric CO_2 Removal Deposits (ACORDs), a financial mechanism to enforce emitter liability and fund future negative emissions. Under ACORDs, emitters must finance the removal of at least as much CO_2 as they emit, with deposits redeemed upon proof of removal.

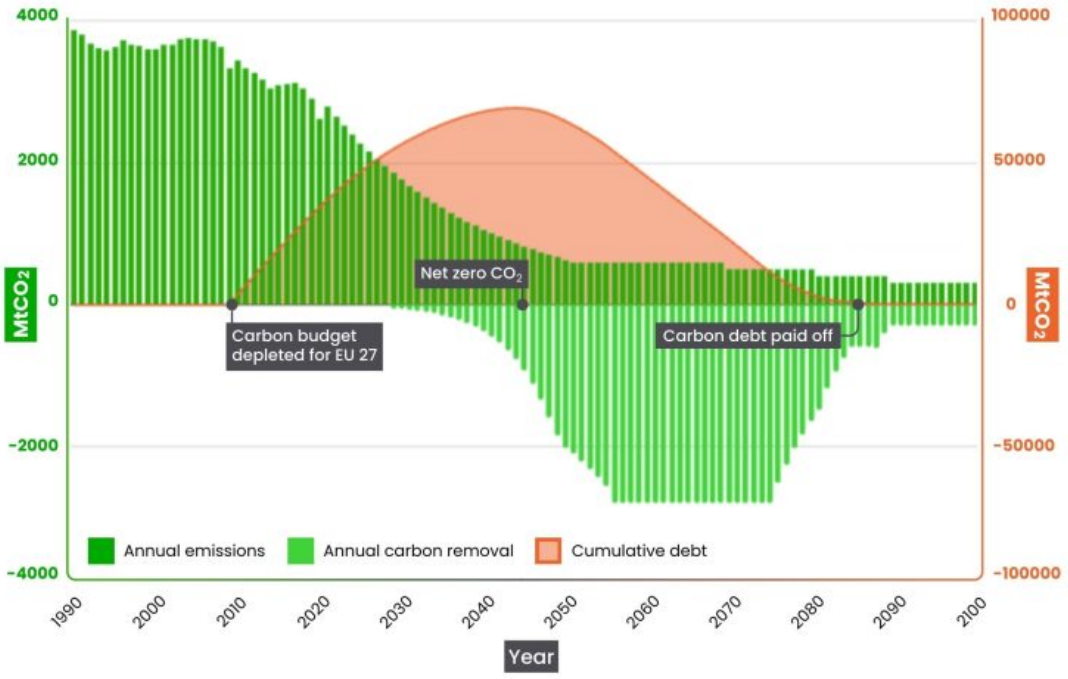
These suggestions apply to countries, but companies could be encouraged to adopt a similar approach and, for example, commit to removing all their historical emissions as Microsoft has opted to do.

The EU as an example

The figure below shows the past emissions of the 27 EU member states and hypothetical future emissions and removals in a scenario where the EU's fair share of the carbon budget was assumed to have been depleted in 2009 (based on Hahn et al 2023). We further assume that net zero CO_2 emissions is achieved in 2045, and that the carbon debt that began accumulating in 2009 peaks in 2045 and is fully paid off before 2100.

Under these assumptions, the EU's carbon debt already exceeds 40 Gt CO_2 and may peak around 70 Gt CO_2 in 2045. Paying off such a debt before 2100 would require 1-2 $GtCO_2$ of annual removals, in addition to the removals needed to neutralise any ongoing emissions to sustain net zero.

Figure 1: Comparing annual emissions and carbon removal with cumulative carbon debt among EU member states

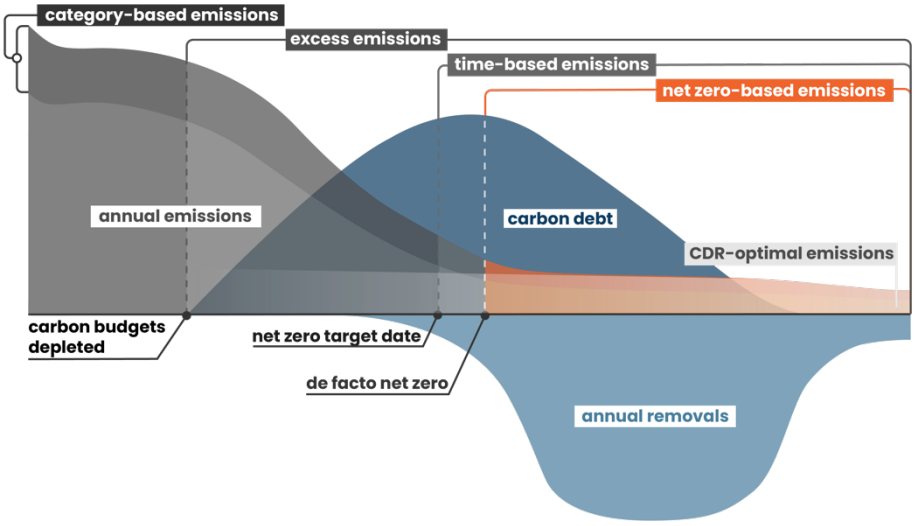


Illustrating an EU carbon emissions and removals trajectory, assuming the EU-27 depleted its fair share of the global carbon budget in 2009. It depicts the projected peak of carbon debt in 2045, when net zero CO_2 emissions are assumed to be reached. Carbon removal continues until the debt is fully paid off by 2100.

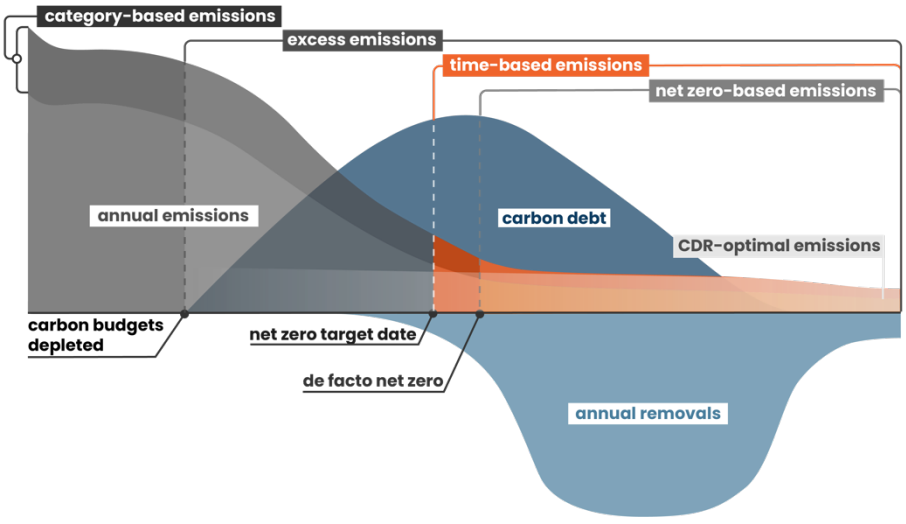
Linking carbon removal and residual emissions requires precision

The exercise above recontextualises the need for carbon removal. Carbon removal is not just needed to counterbalance "residual emissions", but also to remove large amounts of past, present, and planned emissions that are in excess of carbon budgets. The term residual, however, points to something important. There is a difference between excess emissions in need of removal, and the subset of emissions that are most optimally dealt with using removals. The term "residual" is ambiguous and lacks a consensus definition. There are currently several ways that "residual emissions" is being used. To provide better precision we will disentangle them here.

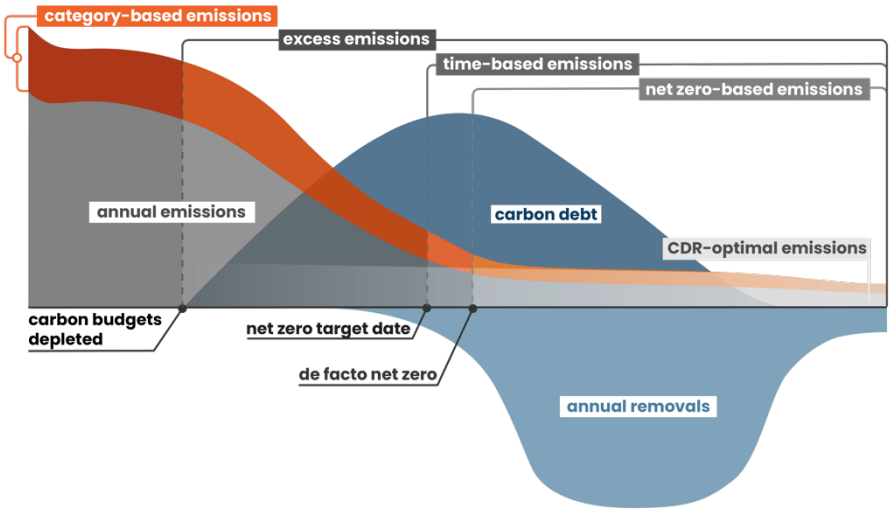
Net zero-based – "Residual emissions" are often defined as whichever ongoing emissions remain from the moment of net zero and onward (Lamb 2024). By this definition, no emissions are "residual" today, since net additions of CO_2 to the atmosphere are still occurring. Whichever emissions remain at the moment we reach global net zero will be classified as "residual" by default, regardless of which and whose emissions they are and the difficulty or cost of eliminating them.



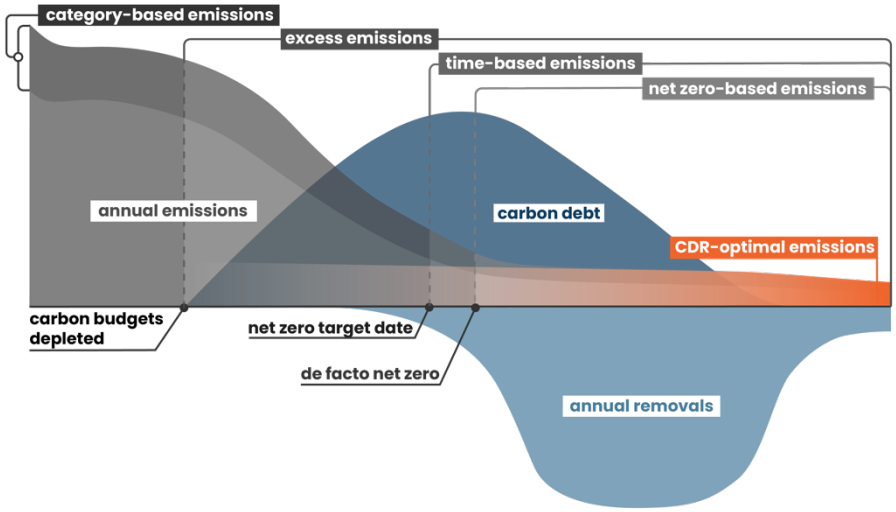
Time-based – "Residual emissions" sometimes refers to whichever emissions remain at a specific net zero target date, such as 2050, even when the date is reached without net zero having been achieved.



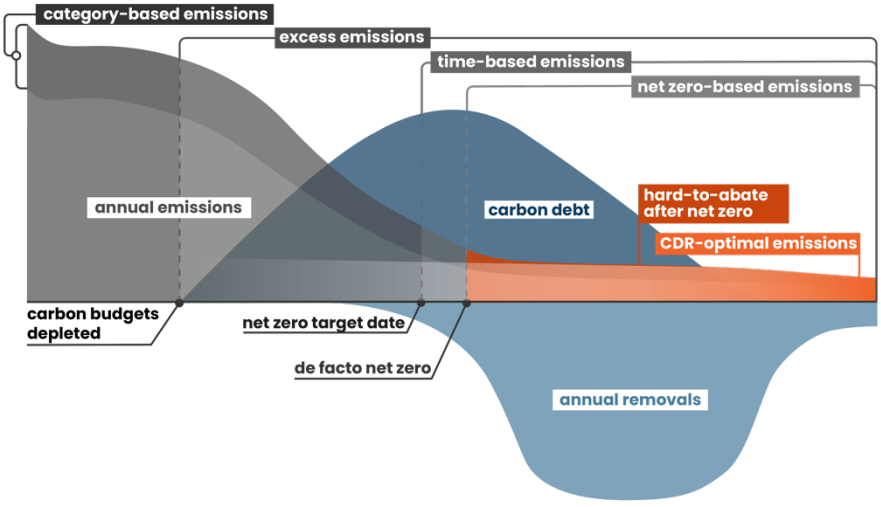
Category-based (hard-to-abate) – Often "residual" describes ongoing emissions, regardless of date, which come from sectors considered to be very expensive or difficult to eliminate, such as long-distance air travel or some forms of agriculture. These sector-specific emissions are often referred to as "hard-to-abate". By this definition, emissions from some industries are always "residual", **regardless of when** they are emitted.



CDR-optimal emissions – CDR is not always the best solution[1] for neutralising hard-to-abate emissions. Residual emissions is sometimes used to refer to the subset of hard-to-abate emissions that are optimally dealt with by carbon removal.

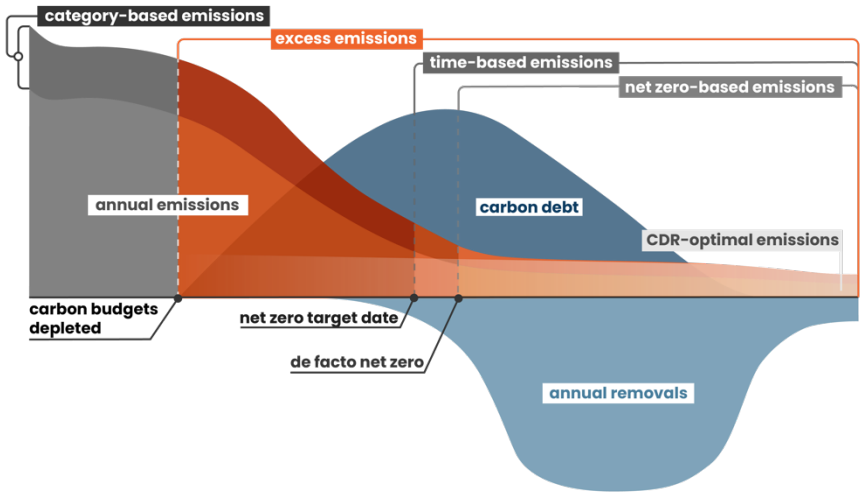


Category-based or CDR-optimal only at and after net zero – Yet another interpretation of residual emissions is that of hard-to-abate, or CDR-optimal emissions but **only at and after** net zero. Following this definition, the subset of residual emissions still occurring at net zero are only from specific sectors deemed very difficult to



decarbonise. The IPCC defines one of three roles for removals, described as "counterbalancing 'hard-to-abate' residual emissions (e.g., emissions from agriculture, aviation, shipping, industrial processes) in order to help reach net zero CO_2 or net zero GHG emissions in the mid-term". However, as noted above not all hard-to-abate emissions are optimally neutralised with CDR.

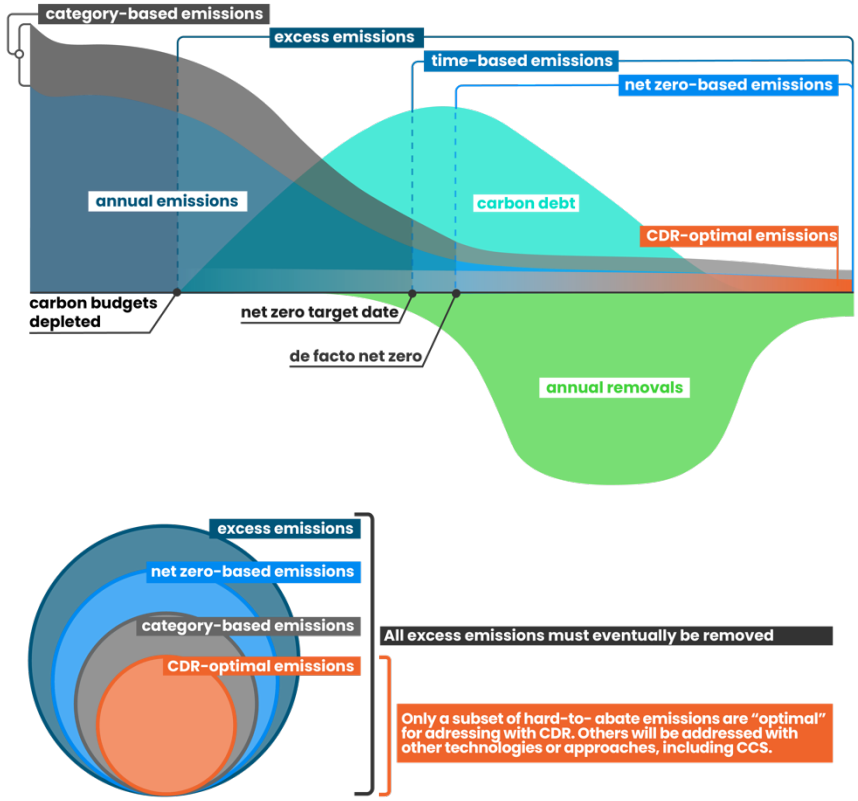
Excess emissions – A final bucket of emissions are those that are neither "residual" by date, by category, or by their relationship with CDR or net zero, but which are nevertheless added to the atmosphere before net zero is achieved. Most emissions today fall into this bucket. While most of these emissions will not be "CDR-optimal" in the near-term, they are still "excess" and will at some point in the future need to be removed in order to stay within the carbon budget.



A persistent and perhaps unproductive debate rages as to which specific subsets of emissions are permissible for neutralisation with removals in the very near term, particularly as it applies to corporate net zero claims. **We address this important question in detail in a companion paper dedicated to classifying "CDR Optimal Emissions".** However, the simple logic of the carbon budget already supports a more expansive view and classification system of which emissions are considered "excess".

Policymakers and corporate leaders need a new, more precise means of specifying different buckets of emissions in their future climate trajectories. When it comes to resource allocation, it makes sense for policymakers to prioritise more cost-effective emissions elimination and limit removals to a narrow set of neutralisation use cases. But in terms of setting the overall level of ambition for climate action, it is more important to focus on the much larger pool of excess emissions and acknowledge the need for a feasible plan to address them.

Figures 2-3: Residual emissions definitions and how they relate



The hierarchy of excess emissions and residual emissions definitions and how the different definitions of "residual emissions" relate. Of all the emissions that are considered "excess" only a portion of those will be considered CDR-optimal.

Carbon removal is at low risk of becoming a stranded asset

As with any burgeoning investment into a new asset class, the scale up of carbon removal infrastructure faces a risk of asset stranding. New fossil fuel infrastructure is not only incompatible with climate goals, but also famously faces the risk of losing its value due to shifts in the market or policy. Carbon removal projects, however, are largely immune to this problem. The size of the carbon debt being built up far exceeds the currently planned levels of CDR, let alone the volume of CDR available today. Unlike fossil fuel infrastructure, which may become obsolete as the world decarbonises, large CDR projects will remain relevant because their climate benefit can be reassigned to other pools of carbon as needed. For instance, if a CDR project is financed by a high-ambition corporation for its first decade of operation, it could later be used to address a country's carbon debt in its second decade. This flexibility de-risks investments in CDR capacity and infrastructure. Even if certain sectors reduce their emissions faster than expected, the CDR capacity can still be used to pay down historic CO_2 debt.

However, stopping the ongoing accumulation of CO_2 in the atmosphere remains where the bulk of climate action must be focused until emissions are in precipitous decline. Although the CDR sector needs to be built up today to be able to fulfil its large role later on, orders of magnitude more resources should be mobilised now to tackle currently cheap emissions reductions. While we have argued that all ongoing emissions from large historic emitters are "excess" and will need to be removed, and that high-ambition countries could begin tackling that challenge soon, redressing carbon debt can of course be further delayed.

Conclusion

Confronting the reality of the inequitably allocated global carbon budget is sobering, as it makes clear that all emissions from large historic emitters are in excess and will need to be removed. This reframing of the long-term requirement for CDR exceeds the most commonly espoused use case of counterbalancing emissions from hard-to-abate sectors at the net zero date. In fact, combining our discussion of "residual emissions" definitions and the EU carbon debt case study suggests that counterbalancing hard-to-abate emissions may be a far smaller role for removals to fill than the eventual elimination of carbon debt. If the global community is serious about first limiting and then reversing overshoot of 1.5°C, the most sizeable role for CDR will eventually be to pay off carbon debts.

There is unlikely to be an orderly, uniform global transition from the more commonly discussed use cases for CDR to the larger scale drawdown of historical emissions. Some companies and countries with high ambition and high ability to pay may move first, allocating some of their removals toward delivering net zero or neutralising emissions from specific sectors and some toward bringing down select pieces of their excess carbon debt. In many more countries, it will be extremely difficult to achieve a near-term admission that their share of the carbon budget is even depleted, let alone that they have accumulated a substantial carbon debt of excess emissions in need of removal. What is unthinkable today will become feasible over time only as high-ambition countries model behavior that is rooted in the logic of carbon budgets. Regardless, countries and corporations need to act with far greater urgency both to scale CDR today as well as building up funds in preparation for discharging future removal obligations. Speed is particularly crucial for profitable sectors that have the financial muscle to pay for CDR, in contrast to less profitable industries.

We have also shown that the terms "excess-" and "CDR-optimal" emissions offer greater clarity than the commonly used "residual emissions," which is often applied ambiguously. When residual emissions are discussed in national climate plans or corporate pledges, greater specificity and clarity is crucial to allow third parties to assess their viability and appropriate levels of ambition, specifically with regards to those emissions that are categorically or temporally residual, or residual in relation to a net zero date or to the appropriate use of CDR. Increasing clarity also means acknowledging that all excess emissions merit eventual removal, which should inspire much greater ambition for near-term emissions abatement and longer-term removals scale up to meet this larger challenge.

While all excess emissions need to be removed, in practice each country or subnational entity needs to account for and document which removals are being applied against which tonne of CO_2, whether it is an ongoing emission from a hard-to-abate activity, or a piece of carbon debt. This exercise requires identifying a limited set of emissions for which neutralisation with CDR is likely to be cheaper, more easily deployed, and/or less resource-intensive than elimination of those emissions or other forms of abatement. We lay out the considerations and criteria needed to determine whether emissions are "CDR optimal" in a forthcoming companion Carbon Gap report **"Which emissions are optimal to remove?"** The report presents an analytical framework to help determine the optimal action for a given type of emissions, including where CDR is or is not the best option. This question is one

that needs to be answered for planning purposes to understand which emissions reductions to prioritise, and which emissions may be better left to be dealt with ongoing carbon removal.

---

[1] Mitigation solutions for various types of emissions should be compared by a variety of factors including cost and capacity. Such an analysis may yield that CCS or even investment in future technologies may be the optimal approach over CDR based on predicted cost and resource use. Determining which ongoing emissions are most optimally dealt with using CDR requires an analysis of direct and indirect costs, viability and scalability and environmental and social side effects. We explore this question deeply in a forthcoming paper, which presents an analytical framework for assessing which emissions are "CDR-optimal".

References

Forster et al, Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence (2024) https://essd.copernicus.org/articles/16/2625/2024/

Bednar, J., Obersteiner, M., Baklanov, A. et al. Operationalizing the net-negative carbon economy. Nature 596, 377–383 (2021). https://doi.org/10.1038/s41586-021-03723-9

Thomas Hahn, Robert Höglund, Johannes Morfeldt, Ingo Fetzer, Mikael Karlsson. (2023). Fair National Carbon Accountability for past and future emissions, Preprint at Research Square https://doi.org/10.21203/rs.3.rs-3655927/v1 New version under publication.

Gantti, G., Gidden, M. J., Smith, C. J., Fyson, C., Nauels, A., Riahi, K., & Schleßner, C.-F. (2024). Using net-zero carbon debt to track climate overshoot responsibility. Preprint at Research Square https://doi.org/10.21203/rs.3.rs-4394688/v1

Lyngfelt, Fridahl & Haszeldine. FinanceForFuture: Enforcing a CO_2 emitter liability using atmospheric CO_2 removal deposits (ACORDs) to finance future negative emissions (2024) Energy Research & Social Science doi.org/10.1016/j.erss.2023.103356