What are residual emissions?

A science-based understanding to underpin corporate carbon accounting guidance

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Summary and key Drax take-aways undertaken by:
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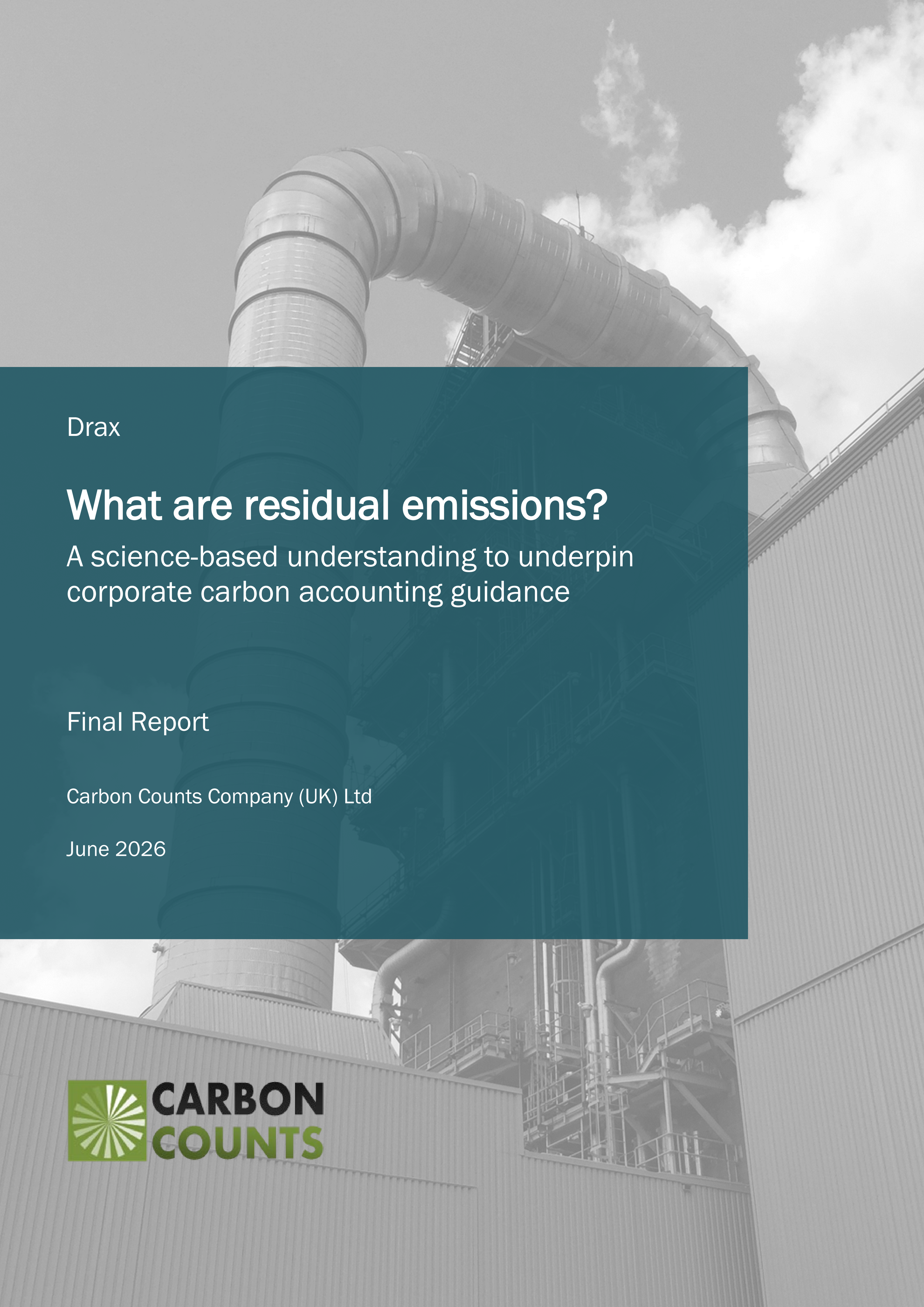
Summary

This report provides a science-based examination of the concept of residual emissions, highlighting that no single authoritative definition exists across academic literature, national strategies or corporate standards. Residual emissions are best understood not as a fixed category but as the emissions that remain at the net-zero balance point after all technically, economically and socially feasible abatement has occurred. However, what is "feasible" is inherently subjective and evolves over time. Because residual emissions are shaped by assumptions in integrated assessment models, sector-specific constraints, and broader social and political choices, corporates require a dynamic, time-bound and technology-conditional approach. The report proposes a practical framework for companies to classify emissions by abatement timeframe, plan and disclose their pathways, and develop robust carbon removal strategies to neutralise remaining emissions, ensuring transparent, credible and adaptable net-zero planning.

Key Drax take-aways

1. **Residual emissions are difficult to define, but they are real and must be addressed.** There is no single, authoritative definition of residual emissions across scientific literature or corporate standards as they depend on normative assumptions, sectoral context, and evolving feasibility constraints. Nevertheless, all credible net zero pathways recognise that some emissions remain after maximal abatement and must be explicitly identified, managed, and neutralised. For corporates, this means moving beyond definitional uncertainty to transparently assess which emissions persist over time and how they will be addressed through abatement, innovation, and high integrity carbon removals.
2. **Residual emissions are not fixed and should be treated as dynamic and revisable.** The designation of residual emissions is shaped by evolving technology, shifting carbon prices and social/political constraints, meaning what counts as residual today may become abatable in the future. Corporates should therefore adopt a time-bound and technology-conditional approach, revising residual emissions assessments regularly.
3. **A three-tier classification of residual emissions offers corporates a potential methodology to guide action.** Instead of identifying a single bucket of "residuals," the report recommends categorising all emissions according to timeframe and abatement difficulty into near-term abatable, medium-term abatable, and long-term removal dependent. This categorisation should be dynamic – emissions can move between categories over time. This approach aligns with emerging science, avoids premature lock-in, and provides a more transparent basis for strategy development and disclosure.
4. **A robust CDR procurement strategy is essential, not optional, at net zero.** All standards require residual emissions to be counterbalanced with high-integrity carbon removals, with an emphasis on durable storage. The report recommends that corporates begin developing CDR supply strategies, internal carbon removal budgets, and offtake arrangements early to avoid future scarcity and cost escalation.
5. **Failure to address residual emissions carries material strategic and reputational risk.** Ignoring or delaying action on residual emissions could make future mitigation more expensive, undermine alignment with best practice standards, and diminish stakeholder confidence, while also increasing national level reliance on CDR. Proactive identification and management of residuals is therefore a core component of a credible transition plan.



Drax

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Cover photo: Boundary Dam CO_2 capture facility (Paul Zakkour)

Summary

The concept of residual emissions is a recent entry to the lexicon of climate policy and governance. The term is closely linked to scientific understanding (i.e. Allen et al. 2009) that reaching net zero GHG emissions by mid-century is crucial to limiting global warming to well below 2°C as enshrined in the 2015 Paris Agreement. Reaching 'net zero emissions' implies that any emissions that have not been mitigated at the net zero target date will be neutralised or counterbalanced (i.e. netted off). Residual emissions are most commonly understood as the greenhouse gas (GHG) emissions that remain at the net zero target date and must therefore be neutralised through carbon dioxide removal (CDR) to achieve a balance between sources and sinks.

Usage of the term 'residual emissions' first appeared in the IPCC's fifth Assessment Report (2014), since when the term has become ubiquitous in IPCC reporting. Various definitions exist within the literature, which describe residual emissions as those that are more expensive to abate than to neutralise, emissions that are technically or socially hard to eliminate, and emissions that simply remain at the net-zero balance point. Such definitions are conceptually similar to related terms such as 'recalcitrant emissions' or 'hard-to-abate emissions'. However, despite the prominence of residual emissions in policy, science and corporate standards, there is no single, agreed definition.

Residual emissions are generally understood to be clustered in agriculture, aviation and heavy industry. In climate models, residual emissions are the outputs of cost-optimised mitigation pathways. The amount of residual emissions in a given pathway is highly sensitive to assumptions made about future carbon prices, discounting, marginal abatement costs, costs of CDR and technological developments and uptake. As such, residual emissions are model artefacts and not prescriptions of what will remain at the net zero date.

For corporates seeking to pursue science aligned mitigation pathways, the predominant corporate standards: the Science Based Targets Initiative (SBTi) and ISO International Workshop Agreement under ISO 42:2022 (ISO IWA 2022) coalesce around a 90-95% reduction target before residuals are neutralised alongside clear guidance that purchase of removals cannot substitute for abatement that is technically and economically feasible. The differing interpretations of residual emissions discussed within this report and the variations in corporate standards makes it difficult to alight upon an agreed definition. Interpretation of guidance within corporate standards on identifying and addressing residual emissions requires careful judgement at the level of an individual corporation. While this can afford latitude in how residual emissions are mapped, the steps to neutralise them in order to reach a net-zero target are generalised which entails risks relating to the actions corporates ultimately take.

In lieu of a definition of residual emissions, any corporate emissions management framework must be explicitly time-bound and technology-conditional. What counts as a residual emission is not immutable it is a normative judgment that depends on the current state of abatement technology, prevailing carbon prices, and the timeframe under consideration. Translating this into clear, actionable, next steps for corporate climate action is challenging, but nevertheless possible as long as regular reviews are carried out. We propose the following five step strategy, each with a series of recommendations (see section 4). The framework is not designed to be prescriptive and, in some cases, recommendations can fit under a number of steps.

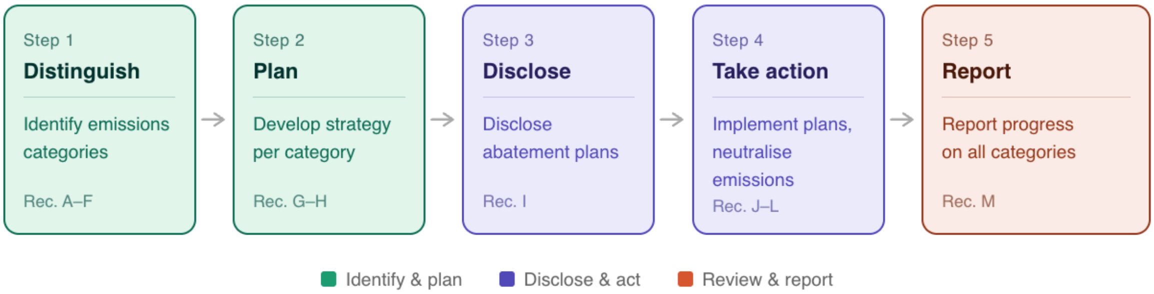

Figure S1: Corporate emissions management framework. Source: Authors

The most important part of the framework is to distinguish between emissions categories rather than using a single term. Instead of asking corporates to identify a single category of "residual emissions," corporates should classify their emissions along two dimensions — abatement difficulty and timeframe — producing the following three-step framework:

- **Near-term abatable** — reductions achievable within the current decade with available technology at reasonable cost
- **Medium-term abatable** — reductions achievable by 2040 with plausible technology development or cost reduction
- **Long-term removal-dependent** — emissions for which no credible abatement pathway currently exists even at the 2050 horizon.

The benefit of this approach is that it gives corporates a practical and dynamic framework without requiring them to commit to a definitive definition of what is permanently residual. Abatement options can move between each category as new evidence emerges.

Thus, rather than asking corporates to identify their residual emissions — which requires resolving the definitional problem upfront — corporates should instead develop a CDR strategy that is commensurate with their abatement ambition and timeline. This is potentially more practical and avoids the definitional hurdle.

Contents

1 Introduction

This report was commissioned by Drax to provide an evidence-based understanding of residual emissions, including the tension between the technocratic/technological responses available to policymakers and the broader social and political issues that will influence decisions and definitions. From a review of existing guidance, it substantiates the range of practical definitions that exist with respect to corporate strategies and provides actionable guidance for how definitions of residual emissions influence corporate net zero targets.

Residual emissions typically represent the “hard-to-abate” or “recalcitrant” portion of greenhouse gas (GHG) emissions that are anticipated to remain even after implementing deep decarbonisation efforts. These emissions determine the scale of carbon dioxide removal (CDR) required to achieve net zero. However, definitions and methods for assessing residual emissions vary widely.

Indeed, not all residual emissions can be considered “hard-to-abate”. Some future sources of residual emissions will likely be avoidable but face political rather than technical abatement barriers. Scale and boundary conditions may also matter in terms of what is considered “hard-to-abate” or “residual” at varying organisational levels. Drax seeks a science-based framework and practical corporate guidance on defining, accounting for, and managing residual emissions and the implications for procuring CDR in the context of net zero targets.

The report is structured as follows. Section 2 provides insights into how the concept of residual emissions emerged within the literature, including how it was defined and investigated by integrated assessment models (IAMs). Section 3 then reviews practical guidance related to residual emissions that has been rendered by climate-related disclosure requirements and standards. Section 4 then draws together these two strands in order to provide some tangible steps for corporates expecting to manage their residual emissions in future.

2 What are residual emissions?

2.1 Backdrop

In order to achieve the Paris Agreement targets to limit warming to well below 2°C, global CO_2 emissions must reach net zero by 2050. In scenarios with high overshoot[1] all GHGs must reach net zero by 2070-2075. In scenarios with no or limited overshoot net zero GHGs must be reached by 2095-2100 (IPCC, 2022).

Absent of completely eliminating all sources of anthropogenic GHG emissions (*absolute* zero; Allwood et al. 2019), the idea underpinning *net* zero emissions is that sources of emissions at a given target date are to be counterbalanced by activities that sequester commensurate amounts of GHGs (Smith et al. 2024). This concept of net zero is enshrined in the balancing language contained in Article 4.1 of the Paris Agreement. Given both this scientific reality and the political direction, the design of national and corporate climate mitigation goals, especially ones framed as 'net zero', should be informed by an accurate understanding of the quantity of emissions that will remain globally and by economic sector in a net zero target year.

This importance is driven by a need for decision makers to understand how decarbonisation trajectories are progressing and, relatedly, the quantity of CO_2 emissions that need to be neutralised by CDR by the second half of the century. The flexibility of the Paris Agreement's "pledge-and-review" system that allows countries to essentially self-define what constitutes residual emissions poses the risk that countries can determine politically inconvenient or expensive – but abatable – sources of emissions at the net zero target date as 'residual emissions'. Such decisions have cross-sectoral fairness and equity dimensions while also substituting investment from emissions abatement towards greater investment in the CDR industry (Smith et al. 2024). These concerns are not just a matter of emissions tracking or carbon accounting; the amount of CDR required at 2050 connects directly to the healthy functioning of terrestrial, riverine and marine ecosystems, the amount of land that can remain in food production, and patterns of land use change regarding biomass demand and energy demand (ibid).

Residual emissions are often discussed alongside terms such as 'hard to abate' or 'difficult to decarbonise'. Although frequently conflated, 'residual emissions' and 'hard-to-abate' emissions are similar, but analytically distinct concepts (Smith et al. 2024). Hard-to-abate emissions refer to emissions for which abatement is constrained by biological (as with enteric fermentation in animal agriculture), technical (as with substituting clinker in cement production), economic (as with producing and deploying biomass derived sustainable aviation

[1] A forecast temporal evolutionary pathway of human activity that leads to the exceeding of a specified level of atmospheric GHG concentration, radiative forcing or global warming, and then returns to or below that level again before a specified period of time.

fuels), or social factors (cultural preferences to eat ruminant derived proteins), which interweave with the aforementioned factors (Lund et al. 2023; Smith et al. 2024). Emissions from agriculture, aviation and cement production, amongst others, will likely persist based on current knowledge and expected rates of technological development and uptake and thus become residual at the net zero date.

By contrast, residual emissions are defined purely by their presence at the net-zero balance point, regardless of whether they are intrinsically difficult to abate or remain due to other strategic, economic, or policy choices. However, what emissions are considered residual at the net zero date makes implicit claims on the need to engage in certain social and cultural practices where options to substitute exist (replacing animal protein with plant-based protein) or scope to scale down demand for high emitting practices such as long-haul aviation. As Lund et al. (2023) contend:

> "Residual emissions are thus discursively constructed, i.e. continuously brought into being through the claims made by various actors navigating mitigation demands". (p.2)

Buck et al (2023) found that, across a sample of 50 long-term low emission development strategies (LT-LEDS), there is no consistent definition of what constitutes national level residual emissions, despite 36 of the countries having explicit net-zero target dates. Half of the sampled countries also did not include a definition of residual emissions, although most emissions are described as arising from agriculture, transport and certain industrial processes. A few countries also include international aviation within their total residual emissions figures (indicating a likely undercount).

2.2 Terminology

2.2.1 Current Definitions

Definitions concerning residual emissions and associated terms varies significantly across science, policy and standards, creating ambiguity and scope for interpretation at the corporate level. To untangle corporate emissions profiles requires distinguishing between:

Ongoing emissions: Emissions that persist during the transition period prior to reaching net zero which may reflect:

- Locked-in capital stock
- Decarbonisation technologies that remain too immature
- Transitional economic or social constraint, and:

Residual Emissions: Emissions that persist after maximum feasible abatement. These are otherwise known as:

- "Hard-to-abate"
- "Technically unavoidable"

- "Economically or socially infeasible to eliminate"
- "Recalcitrant Emissions"

Countries also distinguish between residual emissions differently; Iceland describes residual emissions as ones "*that are unlikely to be eliminated*". By contrast, the US recognises that some emissions are "*challenging to eliminate*" in respect of "*cost and applicability*" due to the variability of mitigation options (Buck et al., 2023).

Residual emissions can also vary temporally, distinguishing between:

- **Anticipated/transitional residual emissions**: Emissions that are expected to remain at net zero despite maximum feasible abatement.
- **Actual/end-state residual emissions**: Emissions that remain at net zero despite maximum feasible abatement.

The following section highlights contemporary use of the term in IPCC reporting and other institutions including the UK Climate Change Committee and connects this with academic literature. Annex 1 presents the evolution of the concept over time.

2.2.2 Residual emissions in institutional literature

Because the concept of residual emissions is connected to the idea of net zero emissions targets, the focus of climate mitigation policy has not historically considered the scale, sectoral composition, and durability of residual emissions. This lies in large part due to the changing scientific understanding of what drives lasting climate change. From around 2010, perspectives shifted away from controlling rates at which emissions are added to the atmosphere towards limiting the overall stock of long lived climate forcing gases in the atmosphere (e.g. Allen et al. 2009). This progressed towards the idea of net zero as a means to stabilise global atmospheric GHG stocks, with the remaining atmospheric carbon budget aligned to 1.5°C or 2°C temperature stabilisation suggesting the need to achieve a state of 'net zero' emissions around mid-century. As global emissions have continued to grow, the net component implicitly calls for greater use of CDR. Thus, the increasing incidence of net zero emissions targets is directly linked to the development of the residual emissions concept.

The Intergovernmental Panel on Climate Change (IPCC) releases an assessment report on the state of science on climate change every 8-9 years. In line with changing emphasis described above, the fifth assessment report (**AR5**) (2013) is the first IPCC Assessment Report where the term residual emissions is mentioned. Although the term is mentioned five times, no definition is provided. The use of CDR is justified on cost grounds with a linkage to compensation of "*residual emissions from technologies and sectors with more expensive abatement*" (p.433). AR5 is also the first IPCC assessment where negative emissions are described as structurally necessary and not optional with large scale negative emission deployment in mitigation pathways modelled; beyond sole reliance on LULUCF which "*facilitate higher near-term emissions, effectively expanding the potential scope for overshoot*" (p.433).

The subsequent IPCC Special Report on 1.5 C (**SR1.5**) (2018) continues to emphasise the importance of CDR in climate governance and models a greater role for CDR aligned to efforts to limit warming to 1.5 C above pre-industrial levels. SR1.5 represents a clear pivot from previous IPCC reports from 'net emissions' framing to a residual emissions and CDR conceptual lens tied to 'climate neutrality'. No assessments are made of what constitutes a fair share of residual emissions; only that residual emissions will exist at the target date, and that CDR can 'compensate for' or 'neutralise' these sources. Residual emissions are not explicitly defined in the glossary but are referenced under the 'climate neutrality' entry. The concept is implied but not explicitly mentioned under various other glossary entries from 'net negative emissions' 'carbon dioxide removal' and 'net zero CO2 emissions'.

AR6 (2022) explicitly defines residual emissions by operationalising CDR in all scenarios "… that limit warming to 2°C or lower by 2100" and publishes various metrics such as, 'Per-Capita Residual Emissions from Energy/Industry'. AR6 discusses residual emissions extensively and qualitatively develops the concept within a net zero emissions context. A framework through which to quantify a countries' share of residual emissions is, however, not provided, but the vexed nature of identifying this slice of emissions is alluded to in stating that:

> "Not all emissions can be avoided. Achieving net zero CO2 emissions globally therefore requires deep emissions cuts across all sectors and regions, along with active removal of CO2 from the atmosphere to balance remaining emissions that may be too difficult, too costly, or impossible to abate at that time" (p.385).

Decisions about the level of 'acceptable' residual emissions are seen as normative judgements:

> "the choice of CDR methods and the scale and timing of their deployment will depend on the respective ambitions for gross emissions reductions, how sustainability and feasibility constraints are managed, and how political preferences and social acceptability evolve" (p.1277).

The State of CDR 1st and 2nd Editions (2023 and 2025) define residual emissions as:

> "Remaining gross emissions when net-zero, and subsequently, net negative, emissions are reached. Can apply to both net zero CO2 and net zero GHG emissions, from local to global scales and at company or sector level. To reach net-zero emissions, the amount of CDR must equal the amount of residual emissions over a given period. To reach net-negative emissions, the amount of CDR must exceed residual emissions."

The UK CCC's Seventh Carbon Budget (2025), by contrast, does not set out a standalone definition of residual emissions. Instead, the term is used consistently but implicitly throughout the report, with its meaning inferred from the context of national and sectoral pathways. Residual emissions are treated as the emissions that remain after all technically and economically feasible abatement options have been applied; where the efficiency of CO2 capture from point sources is not 100% and where process emissions are not completely abated in cement, chemicals, glass, and ceramics or where emissions remain in hard-to-abate sectors such as agriculture and aviation.

2.2.3 Connections with academic literature

Governance-oriented definitions tend to present residual emissions as carbon accounting realities - gross emissions that must be counterbalanced to achieve a net-zero balance - rather than normative classifications based on techno-economic constraints. Smith et al. (2024) define residual emissions as "*emissions at the point of net zero irrespective of their difficulty of abatement*." Likewise, Brad et al. (2024) describe them as "*a specific quantity of emissions in reference to a net zero year which will necessitate negative emissions*". Schenuit et al. (2023) refer to "*a quantity that simply describes which emissions actually enter the atmosphere in and after the net-zero year*". In contrast, Lund et al. (2023) explicitly align residual emissions as "*deriving from activities that are deemed socially necessary, yet hard-to-abate*".

Residual emissions are described in recent IPCC literature according to economic considerations. In cost-optimised mitigation pathways, residual emissions are those that remain because further abatement is more expensive than using CDR to balance. The IPCC AR5 WGIII (2014) justifies CDR usage across pathways in order to "*…compensate for residual emissions from sectors where mitigation is more expensive*" (p.12). The IPCC SR1.5 (2018) continues this logic, projecting 100–1000 GtCO2 of CDR over the century in 1.5°C-consistent pathways and substantially scaling CDR to address "*…residual emissions from technologies and sectors with more expensive abatement*" (p.433).

Another categorisation of definitions relates residual emissions to technical constraints. The IPCC AR6 WGIII (2022) contends that deployment of CDR "*to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO2 or GHG emissions are to be achieved*" (p.36). The report further states that "*not all emissions can be avoided,*" and mitigating remaining emissions at the net zero date may be "*too difficult, too costly, or impossible to abate at that time*" (p.385). Davis et al. (2019) highlight a related term, "*difficult-to-decarbonize*" energy services within aviation, shipping, electricity supply or in the manufacture of steel and cement and contend that net zero emissions "*will also entail active management of carbon.*" Another similar term, 'recalcitrant emissions' is used by Tavoni and Socolow (2012) to justify CDR expansion to "*substitute for the elimination of the most recalcitrant emissions*" in the aviation sector.

2.3 How Integrated Assessment Models determine residual emissions

Integrated Assessment Models (IAMs) are quantitative frameworks that link economic systems, energy systems, land use, and climate systems to explore mitigation pathways consistent with temperature goals (e.g., 1.5°C and 2°C) (Riahi et al., 2017). IAMs are not explicitly developed by the IPCC; rather, they are developed by academic and research institutions. The IPCC assembles large ensembles of IAM scenarios to synthesize possible futures but does not itself devise scenarios or operate the models.

In IPCC reports, residual emissions appear as an outcome of IAM scenario ensembles rather than a normative policy rule. Scenarios consistent with 1.5°C and 2°C typically show residual emissions, arising because IAMs represent the balance between abatement potential and cost optimisation given assumptions about technical feasibility, socio-economic trends, and policies within specific models or scenarios (Buck et al., 2023).

Importantly, no numeric threshold is endorsed, no sector is declared inherently residual and shares (e.g. 5%, 10%) are rarely canonized (except in a small number of scenarios where exogenous constraints on CDR are set). These are normative and governance questions that sit outside the scope of IAMs and the IPCC.

2.3.1 Residual emissions are an outcome, not an input

IAMs calculate mitigation pathways as an optimization (or simulation) of emissions reductions over time, driven by assumptions about the following:

A) Marginal abatement costs (MAC)

MACs define the cost of reducing each additional tonne of GHG emissions, which can be arranged graphically in a cost-ordered fashion to show a MAC curve (MACC). IAMs represent abatement options with increasing marginal costs. Lower-cost mitigation measures lie at the left of the MACC (e.g., power sector decarbonisation, energy efficiency), which are cheaper and, in theory, abated early. Harder-to-abate emissions (e.g., from agriculture or certain industrial processes) lie towards the right of the MACC, requiring higher cost abatement options to eliminate fully.

It is important to note that the numbers illustrated in MACCs present a static representation of homogenized cost in isolation and must be revised over time (and, usually, space), allowing for behaviour change and technological and process innovation (and taking account of geographical circumstances). This is evident when examining the well-covered global MACC developed by McKinsey in 2007 (figure 1 below). Although many of the core technologies considered therein have remained important, some decarbonisation levers have advanced rapidly (e.g. renewables, EV's and heat pumps) whilst others have fallen short of expectations (e.g nuclear, CCS, and hydrogen).

A MACC is also therefore unable to show the dynamic costs of abatement and what happens after you invest: learning rates, spillovers, and network effects that cascade through an economy. Some actions taken today with seemingly high static costs can have low dynamic costs as was the case with Solar PV. The implication is that one should not only pick what looks cheapest today but rather ask "what actions, taken today will minimise the future cost of mitigation, both today and into the future" (Gillingam and Stock, 2018). The view that seemingly expensive investments today result in lower costs in the future, is broadly akin to the theoretical work of Vogt-Schilb, Meunier, and Hallegatte (2018). Although it might seem counterintuitive, they find that in certain circumstances – such as achieving a carbon budget -

it makes sense to implement some expensive options before exhausting the abating potential of the cheapest options if their potential is higher and their inertia is great.

For an organisation developing a decarbonisation roadmap, this generally implies two things. First, start with the low hanging fruit that already pays for itself. Second, identify which high static cost items have the strongest dynamic potential and invest in them. Viewing a MACC in this way may drive corporate decarbonisation strategies to move in a non-linear way, bringing CDR into their portfolio at a much earlier juncture even when cheaper abatement options exist. This is no longer theoretical. Microsoft and Google are already procuring CDR at scale to address emissions across their value chains.

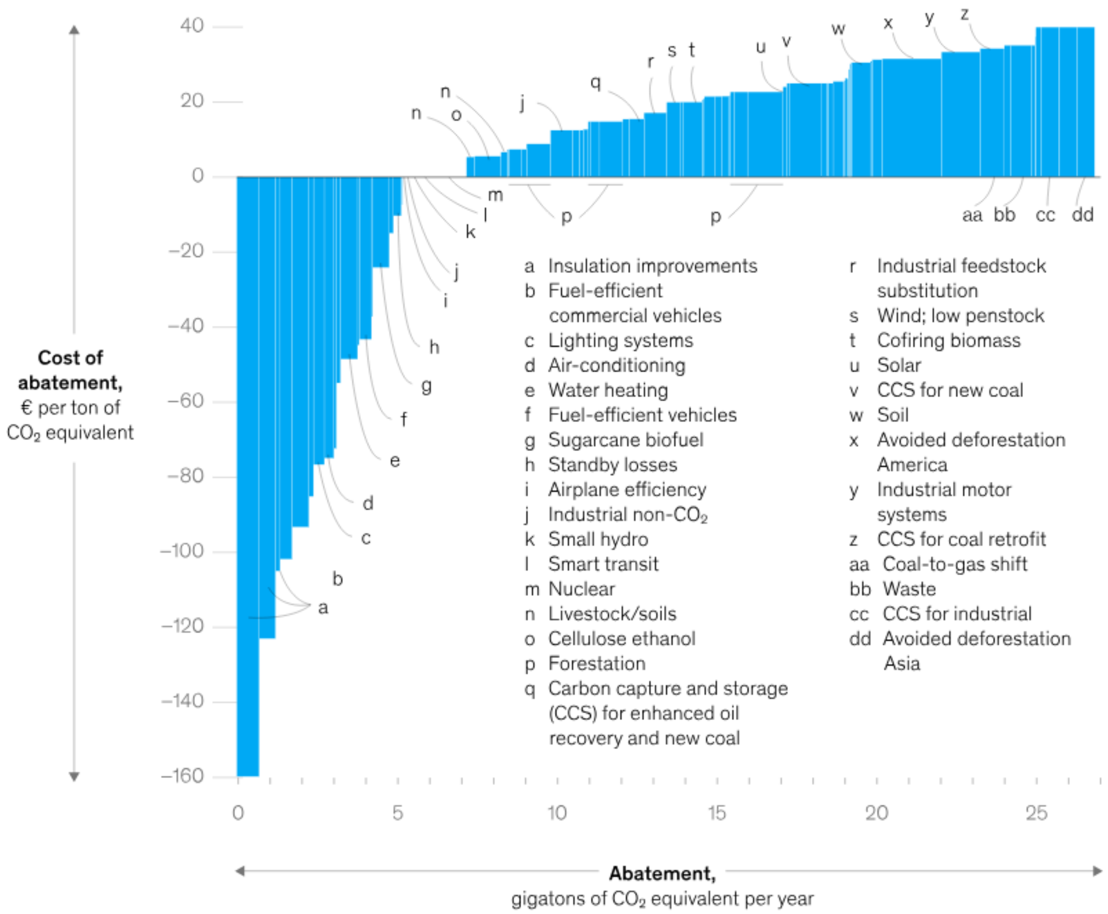

Figure 1: Example of the first Marginal Abatement Cost Curve (MACC) produced by McKinsey in 2007. Source: McKinsey, 2025

B) Carbon prices

Many IAMs assume an internal economy-wide carbon price within the model as a proxy for wider climate policy: as carbon prices rise over time, cheaper mitigation options are used first. Once expensive abatement options are exhausted, residual emissions remain because the economic cost of eliminating them outweighs benefits relative to the target. This dynamic is central to the way in which residual emissions materialise in IAM outputs (Akimoto, 2024) and illustrates how they are model outputs rather than scenario inputs.

A critical element of this process is the method by which internal carbon prices are modelled/ calculated. IAMs typically generate carbon prices endogenously as *shadow prices* associated with emissions constraints (e.g. carbon budgets or temperature targets, see Rogelj et al., 2015).[2] These prices are not policy recommendations per se, but in an idealised world represent the marginal cost of achieving a climate objective within the model's assumptions and structure (Clarke et al., 2014; Kriegler et al., 2014). The carbon price in IAMs and the policy instrument of carbon pricing can sometimes incorrectly be conflated. Carbon prices are simply used to induce mitigation,[3] but models do not seek to prescribe this as the only or right instrument to induce mitigation or innovation for deep emission reductions (Roelfsema et al., 2017).

In these respects, two distinct but related concepts are relevant:

Social Cost of Carbon (SCC). The SCC is defined as the net present value of marginal climate damages caused by emitting one additional tonne of CO_2 (Tol, 2009; Nordhaus, 2017). In IAMs such as DICE, FUND, and PAGE, the SCC is calculated by simulating the incremental damages from an additional unit of emissions relative to a baseline pathway (Hope, 2011; Nordhaus and Sztorc, 2013). SCC values are highly sensitive to normative assumptions such as discount rate and damage functions (Anthoff and Tol, 2013). As a result, SCC estimates vary widely across models and studies and are primarily used to inform cost–benefit analysis (for example, the United States published SCC to guide decision making, see EPA guidance) rather than for setting net-zero pathways (Ackerman et al., 2009), although there are some more recent examples of where this is possible (Dietz et al., 2018)

Endogenous carbon prices in mitigation pathways (also known as target consistent prices). In contrast, most IPCC-assessed mitigation scenarios derive carbon prices endogenously from cost optimization models such as REMIND, MESSAGE-GLOBIOM and GCAM. The carbon price reflects the MAC of meeting the constraint at a given time and prices typically rise over time as cheaper mitigation options are exhausted.

Although conceptually related, SCC and endogenous carbon prices are not equivalent as SCC arises from assumptions on welfare maximisation and damages, whereas mitigation pathway prices arise from cost minimisation subject to climate constraints. In both cases, the generated carbon prices bare no direct influence over prices in voluntary or compliance carbon markets which operate independently.

Endogenous carbon prices strongly influence residual emissions: when the MAC exceeds the modelled cost of CDR, emissions persist and are offset rather than eliminated. Residual

[2] In other words, the carbon price is determined by the interaction of the MACC and the assumed level of action.

[3] What is called the carbon price in a model is in essence the marginal abatement cost. Models impose that all abatement opportunities that are cheaper than the marginal abatement cost are realized. Models do not specify if this is obtained by a tax, ETS or command and control.

emissions therefore emerge economically as a function of relative prices and technological assumptions, rather than normatively, through explicit decisions about which emissions should remain (Anderson and Peters, 2016). Thus, changing assumptions about mitigation and carbon removal costs can significantly redefine the type and scale of what is to be considered as residual emissions and the corresponding level of removals.

Whilst a full critique of IAM's is out of scope for this report, it is important to note that real world transitions are rarely price led. Rather, they are driven by a confluence of factors including technology cost curves, societal behaviour, infrastructure constraints and geopolitics. Despite this, IAMs include an implicit (or explicit) assumption that carbon pricing can act as an economic enabler to create markets for new CDR methods, to drive their diffusion and commercialisation. There are several reasons to question this assumption, not least the innovation and commercialisation story from analogue industries such as CCS and the success of solar PV which scaled when carbon prices were either absent or an order of magnitude too low to level the playing field for it to compete (Burke and Gambhir, 2022). Other factors such as cost reduction rates, innovation policy, deployment incentives, inertia and public acceptance matter more, and these interactions are rarely caught in IAMs.

C) Temporal optimization

Optimal pathways that balance costs over time often favour delaying some more costly near-term emissions reductions in favour of CDR over the longer-term. The latter can be considered relatively cheaper in present value terms when discounting assumptions are applied in models. If future CDR deployment is assumed to be cheaper relative to expensive near-term abatement, IAMs may leave certain emissions until late or treat them as residual near net-zero. Temporal economic optimization can thus shape how residuals are quantified (see section 2.4.1).

D) Availability and cost, of CDR technologies.

The extent and cost of CDR crucially determine residual emissions in scenarios. Lowering the estimated cost of CDR and/or forward-looking estimates of technology learning and cost reduction, has two key effects. First, it can increase emissions in other sectors by reducing the pressure to abate. Indeed, as Afrane (2025) finds, although endogenously deployed CDR offers a cost-effective solution, this can also lower the speed of emissions reductions in specific sectors and increase sectoral residual emissions, particularly in the power sector if the operational lifetimes of emissions-intensive assets are extended (Afrane, 2025). But secondly, this never increases total emissions, since total emissions are fixed by the target in cost-effectiveness analysis.

Some models treat DACCS as a backstop technology, delivering abatement at a constant marginal cost in any quantity demanded. In such cases, model outcomes become highly sensitive to the assumed cost of DACCS, especially regarding over-optimistic forward-looking estimates of technology learning and cost reduction, potentially resulting in very large volumes of DACCS abatement, particularly towards the end of the modelling period.

E) Sectoral and regional aggregation within the model structure.

Aggregated representations (e.g., aviation bundled with transport) can obscure the granularity of mitigation choices, making some emissions appear as residual simply because the model lacks detailed mitigation technologies or sector-specific cost data (Liu et al, 2025). Regional aggregation may also hide large variation between countries with distributional constraints invisible within models (see section 2.4.2).

F) Technical constraints

IAMs incorporate technical constraints in several ways. They impose upper bounds on deployment rates (e.g., maximum annual capacity additions for a technology), resource potentials (e.g., geological storage capacity for CO_2, sustainable biomass supply), ramp-up constraints that prevent technologies from scaling instantaneously, and availability dates before which a technology simply cannot be deployed. The technical constraints are very much dependant on the IAM, and therefore all these constraints might not be present in one IAM.

Where technical constraints and cost constraints meet, IAMs need to navigate both dimensions simultaneously. A technology might be cheaper but technically constrained, or the inverse. In practice the two are deeply intertwined since technical constraints become cost constraints. When hard technical constraints bind — for example, a maximum deployment rate is reached for CCS — the model is forced to deploy more expensive options and so the overall cost of meeting a given target goes up. Conversely, cost constraints can mimic technical constraints. A steeply rising supply curve effectively creates a soft ceiling: deployment beyond a certain point is technically possible but so expensive that the model never chooses it. As such, technical and cost constraints in IAMs are not easily separable; technical limits shape what's available, and that availability directly determines how expensive the pathway ends up being.

2.3.2 Why agriculture, aviation, and industry dominate residuals

Some literature (e.g IPCC 2022), treats residual emissions as sector-specific by convention, particularly in policy and corporate net-zero discourse. Aviation, agriculture, and heavy industry are often labelled “hard-to-abate” and assumed to persist as residual emissions because abating them is technically infeasible or there is a lack of commercially mature mitigation options within a given time horizon (e.g. by 2050; Box 1). This framing is common in sectoral decarbonization studies and implicitly reflected in IAMs.

Box 1. Technical abatement constraints in hard to abate sectors

Aviation: Energy-dense fuels are hard to replace with low-carbon alternatives at scale with current technology. Electrification faces physical limits, and sustainable aviation fuels or hydrogen remain expensive and limited, which results in aviation emissions being residual (Smith et al., 2024)

Agriculture: Non-CO_2 emissions from livestock and fertiliser are technically challenging to fully abate (e.g., CH_4 and N_2O), with limited mitigation technologies and high costs — making them a large share of residual emissions in many IAM scenarios (Edenhofer et al, 2025, Springer, 2025).

Industry: Heavy industry (steel, cement, chemicals) often lacks fully mature low-carbon processes or substitute products at scale. Some process emissions inherently involve chemical reactions that generate CO_2 (e.g., cement calcination), which cannot be eliminated easily with present technologies (Davis et al., 2018; Buck et al., 2023).

For these sectors, residual emissions are tied to technical constraints such as technology readiness levels (TRLs). This approach aligns more closely with bottom-up engineering assessments and industrial roadmaps but risks underestimating the role of demand reduction or structural change.

The challenge of this approach is that it risks locking in current technological limits and embedding implicit value judgments about which activities society chooses to preserve. IAMs partially reinforce this through sectoral aggregation, which can mask mitigation options and lock in quasi-definitional perspectives of what activities cause residual emissions.

Thus, even in ambitious IAM pathways compatible with well-below 2 °C, these sectors remain significant sources of residual emissions due to limited abatement pathways, cost or socio-political constraints. Political and socio-economical acceptability or a lack of, should not be underestimated.

A growing body of work emphasizes political feasibility and social acceptability as determinants of residual emissions (Creutzig et al. ,2018; Grubler et al., 2018). In this view, some emissions persist not because they are strictly infeasible, but because they are deemed socially necessary based on values and norms (Lund et al., 2023).

Both aviation and meat consumption are frequently cited. Residuals thus reflect societal preferences and political constraints, not purely technical or economic limits.

The balance of residual emissions across these sectors will ultimately vary depending on the structure of a given economy. In the UK for example, the Climate Change Committee (2025) estimates that the majority of residual emissions in 2050 are attributable to aviation (35%) and agriculture (41%) and not Industry (6%; see Box 1).

Analyses of national net-zero plans shows that residual emissions often remain sizeable in developed countries. For example, according to Buck et al. (2023) projected residual emissions are a substantial percentage of current emissions, averaging around 18% for

Annex I countries in the most ambitious scenarios. This is broadly similar to research by Smith et al. (2024) which suggests that developed (Annex I) countries may anticipate residual emissions of ~21% of initial emissions in some national plans, dominated by emissions from the sectors noted above (Section 2.2.5).

The increasing reliance on CDR to offset residual emissions raises questions about ambition. Where targets have changed from, for example, an 80% emission reduction against a given base or initial year, to a net zero target but without commensurate increases in emissions abatement, the gap is simply filled by assumed uptake of CDR. Therefore, even though a country may be considered to have 'increased' its target to net zero, there can be no appreciable increase in the underlying *mitigation* ambition, but rather an augmented perception of possible future CDR evolutions. This underscores an observation from Anderson and Peters (2016) shortly after the Paris Agreement that many national targets based on net zero will implicitly rely on significant scale up of CDR.

2.4 Addressing what is residual

The translation of IAM-derived residual emissions into policy prescriptions is not straightforward. IAM outputs represent internally consistent pathways based on specific technological, socio-economic, and political assumptions, and play mediating roles between science and policy (Van Beek et al., 2020). But they do not constitute policy recommendations. Indeed, some observers assert that the misuse of scenarios in support of policy can lead to myopic or misleading perspectives on future climate change (Pielke and Ritchie, 2021).

Nevertheless, scenario results increasingly shape policy discourse, particularly through IPCC assessments that synthesize IAM ensembles to inform climate targets and national net-zero strategies (Livingston and Rummukainen, 2020).

This translation process involves several critical steps where model artefacts are reinterpreted as policy guidance. First, residual emission levels identified in cost-optimal scenarios are often interpreted as politically feasible or acceptable targets, despite being contingent on model structure and assumptions and not on the political will to intervene on a portfolio of measures (Jewell and Cherp, 2019). Second, sectoral patterns of residuals in IAM ensembles become embedded in policy frameworks, with aviation, agriculture, and industry frequently designated as "hard-to-abate" sectors eligible for offsetting rather than deep decarbonisation. Third, the assumed availability and cost of CDR technologies in models inform expectations about future removal capacity, despite significant uncertainties about scalability, governance, and social acceptance (Bellamy et al., 2021).

This gap between model assumptions (e.g. assumptions on learning curves, behaviour change and broader demand side policies) and political reality creates risks of policy lock-in, where current decisions based on optimistic CDR projections may prove difficult to reverse if removals underperform. McLaren (2020) terms this the "mitigation deterrence" problem, whereby anticipated future removals reduce the urgency of near-term mitigation, potentially increasing cumulative emissions and peak warming.

2.4.1 Temporal dimensions

The temporal aspects of residual emissions and their neutralisation through CDR raise important questions about climate effectiveness and intergenerational equity. Because cumulative CO_2 emissions determine long-term warming (Matthews et al., 2009), the timing of emissions reductions versus removals is not neutral. Scenarios that delay mitigation in favour of future CDR deployment risk higher peak temperatures, even if net-zero is eventually achieved. This is due to asymmetries in the climate-carbon cycle where a CO_2 emission into the atmosphere is more effective at raising atmospheric CO_2 than an equivalent CO_2 removal is at lowering it (Zickfeld et al., 2021).

This temporal asymmetry has several implications. First, delaying emission reductions can lock in high-carbon infrastructure with long lifetimes, increasing stranded asset risks and future abatement costs (Tong et al., 2019). Second, peak warming matters for irreversible tipping points and impacts, meaning that pathways with high overshoot followed by net-negative emissions may cause more damage than pathways with earlier mitigation (Lenton et al., 2019). Third, front-loading CDR deployment assumes rapid scaling of technologies that currently exist only at small scale, creating significant feasibility and governance challenges (Nemet et al., 2018).

The permanence and reversibility of removals used to offset residuals presents additional temporal concerns. Biogenic CO_2 removal by afforestation is prone to the risk of reversal through fire, disease, or land-use change (Houghton and Nassikas, 2017), while geological storage durability depends on site selection, monitoring and institutional continuity over centuries (Haszeldine et al., 2018).

This mismatch/non-fungibility between permanent fossil emissions and potentially temporary removals raises fundamental questions about the validity of using transient CDR to meet climate goals, as research suggests sequestration ought to be permanent on climate-relevant timescales which geoscience has determined to be in excess of 10,000 years (Arcusa and Lackner, 2025; see also box 4.3 in IEAGHG, 2024 for a longer discussion). This could be exacerbated in IAMs as the risk of reversal may be underappreciated. This is because IAMs are fundamentally indifferent between emissions and removal or abatement of emissions and only look at cost.

Temporal and distributional dimensions are therefore intertwined since the choice of how long is ‘long enough’ will affect future generations and the ability to sustain net-zero conditions. That said, temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario (Matthews, 2022).

The politics of residual emissions and CDR reliance amplify these temporal concerns. McLaren and Markusson (2020) argue that the prospect of future negative emissions may reduce political pressure for near-term action, creating a form of "moral hazard" in climate policy. This temporal shifting of responsibility raises ethical questions about intergenerational equity which is discussed further below.

2.4.2 Distributional aspects

The distributional aspects of residual emissions operate across multiple geographic and temporal scales, each raising distinct equity concerns. At the global scale, the allocation of residual emission allowances between major emitters remains deeply contested (Fyson et al., 2020). Scenarios typically do not prescribe burden-sharing frameworks, yet the implicit allocation embedded in regional disaggregation carries significant equity implications. For example, analysis suggests that Paris Agreement climate action pledges (“NDCs”) from the EU, US, and China leave little room for other countries to emit CO_2 under a 2°C temperature limitation objective, essentially requiring all other countries to move towards per capita emissions 7 to 14 times lower than the EU, USA, or China by 2030. (Peters et al., 2015). In accordance with historical responsibility for cumulative emissions this implies that a fair share of CDR for these countries is 2–3 times larger this century compared with a global least-cost approach (Fyson et al., 2020).

However, this raises questions of climate justice and differentiated responsibilities to act on climate change mitigation. The principle of "common but differentiated responsibilities and respective capabilities" (CBDR-RC) enshrined the UNFCCC and its daughter agreements (i.e. Kyoto; Paris) as well as the polluter pays principle imply that residual emission allowances should reflect capacity and historical contribution. Yet, as noted previously by Robiou du Pont et al. (2017), the current Paris Agreement allocation process of unilateral pledge-and-[subsequent]-peer review is not well-suited to operationalizing these principles (2017).

Cross-country inequality extends to CDR capacity and governance. Deploying engineered CDR technologies such as DACCS and BECCS requires substantial capital investments, technical expertise, and geological storage capacity all of which are unevenly distributed around the world (Fuss et al., 2018). If developed countries rely on CDR to offset residuals while developing countries lack equivalent access, this creates a new form of carbon inequality (McLaren, 2020). Furthermore, land-based CDR approaches such as afforestation may compete with food security and development priorities in the Global South, potentially exacerbating existing vulnerabilities (Heck et al., 2018).

Within countries, the distribution of costs and benefits from residual emission policies raises questions of procedural and distributive justice. The choice of policy instruments matters significantly: carbon pricing mechanisms may be regressive if not accompanied by revenue recycling or complementary social policies (Klenert et al., 2018). Moreover, the question of "who pays" for both mitigation in hard-to-abate sectors and for CDR deployment to offset residuals remains politically contentious and under-theorized in IAM frameworks (Owen et al., 2022).

Intergenerational distribution represents another critical equity dimension. Current decisions about residual emissions impose costs and risks on future generations, who inherit both the burden of deploying CDR at scale and the consequences of any mitigation shortfalls (Shue, 2017). The discount rates embedded in IAM optimization effectively devalue future costs, potentially leading to ethically problematic pathways that prioritize present consumption over long-term climate stability (Stern, 2007).

Normative vs descriptive approaches

IAM-derived residual emissions are descriptive — statistical properties of scenario ensembles. In contrast, policy and corporate net-zero frameworks increasingly use normative definitions, explicitly stating which emissions should be allowed to remain and under what conditions they may be neutralised.

This distinction is critical and is discussed further in section 3. Translating IAM residuals into corporate or national policy without adjustment risks misinterpreting model outputs as prescriptions, particularly when CDR availability, prices, or governance differ from model assumptions.

3 What do residual emissions mean for corporate climate action?

In the same way as global and national assessments, understanding an organisation's current and projected capacity to abate GHG emissions and projected residual emissions, is an essential step in any corporate decarbonisation and net zero journey. However, there is very little guidance currently available for how businesses should identify residual emissions and address them. As highlighted above, a variety of definitions of residual emissions have emerged, and a variety of climate target setting and GHG accounting standard-setters have sought to operationalize these for corporate practice. Such standards interface with corporate plans in overlapping and varied ways. Standards themselves may be sector based or focused on achieving a given mitigation pathway such as 'science-aligned'. Equally their application to a given corporate context could differ depending on geography, business size or economic constraints and/or opportunities.

The choice as to which standard a corporate chooses to follow, and how the standard is then applied, is not without controversy, especially with regard to residual emissions. Choices related to what constitutes residual emissions can, for instance, lead to claims of mitigation deterrence or inversely allude to climate leadership. Discussion of residual emissions invariably raises questions relating to scaling demand side management especially in some sectors deemed hard-to-abate, such as aviation. Equity concerns can also permeate these considerations in terms of, for example, which sectors should do what, and in which locations and whether historical emissions should factor into these obligations?

These observations notwithstanding, obtaining insights into levels of corporate residual emissions and abatement or neutralization options can help improve investor confidence and regulatory scrutiny in a world of net zero commitments. In this sense mapping residual emissions is a pre-requisite for action on mitigation. This includes identifying potential sectoral breakthroughs as well as committing to acquire the volume and type of carbon credit for required neutralisation at net zero. In all, the lens of residual emissions can help broker more honest conversations about dependencies associated with reaching net zero (Höglund, 2026).

Table 1. Key differences in leading standards with respect to different dimensions of residual emissions and how they apply to the level of a corporation

	SBTi Corporate Net-Zero Standard*	ISO	UN HLEG	GHG Protocol	Race to Zero	Oxford Offsetting Principles	Transition Pathways Initiative
Definition	Those GHG emissions that are expected to remain at the net-zero year after all feasible abatement has been achieved[1]	A residual GHG emission is one remaining after implementing all technically and economically feasible *GHG emission reductions*[2] (International Organization for Standardization [ISO] 2023 ISO 14068-1)	Residual emissions or annual unabated emissions beyond their net zero pathways[3]	Does not define directly.	Not feasible to eliminate (and justified as such).	GHG emissions that remain after taking all possible actions to implement emissions reductions given current resources and technology.	No direct definition. Infers residuals only from sectoral misalignment
Epistemic Anchor	1.5°C aligned pathways and global carbon budgets.	Mitigation hierarchy (ISO 2023,14068-1)	Principles of science, equity, and integrity	Emissions Accounting	Science-based transition pathways	Durable net zero	Sectoral decarbonisation pathways
Deciding What is Residual	Defined as ≤5–10% of baseline GHG emissions (although sector-dependent)	0% (power sector) to 28% (forestry and agriculture) (ISO IWA 2022)	Evidence that emissions cannot be eliminated	No Applicable Guidance	An economy-wide emissions reduction of at least 90% by 2050 should inform the level of residual emissions for most companies.	The volume of residual emissions will be specific to the organisation, based on available technologies, equity and inclusivity.	Sector-level feasibility benchmarks

	SBTi Corporate Net-Zero Standard*	ISO	UN HLEG	GHG Protocol	Race to Zero	Oxford Offsetting Principles	Transition Pathways Initiative
Treatment of Residual Emissions	To be neutralised with permanent removals	Offsetting using either reduction or removal credits (s.11.2) (notes action must be taken to reduce emissions and that offsetting could be restricted to removals only – s.0.3) (ISO 2023, 14068-1).	Obtaining high-integrity removals	No Applicable Guidance	Requires neutralisation	Compensate with removals with durable storage (low risk of reversal)	No Applicable Guidance
Monitoring Residual Emissions Over Time	Residuals may shrink over time but reassessment expected	Carbon neutrality plan to include base period and target year by which only residual GHG emissions will remain, including rational for timing (ISO 2023, 14068-1).	Emphasises dynamic reassessment	No Applicable Guidance	Ongoing alignment checks	Regularly revise offsetting practice	TPI Pathways updated over time
Distributional aspects	Implicit sector differentiation but no corporate level allocation	Limited to organisational rather than sectoral action (ISO 2023, 14068-1).	Recognition of equity and burden-sharing	No Applicable Guidance	Implicitly sector dependent via different initiative rules	Some sectors will be able to reduce to absolute zero while others not.	Sector benchmarks by pathway

3.1 Backdrop to corporate climate action

Corporate climate action has emerged in the last two decades and evolved from a focus on intensity-based or absolute reduction pledges to net-zero commitments which require attention to the volume of the 'net' needed to address recalcitrant emissions.

Corporates increasingly face a number of pressures (social, economic, governmental) to:

- Map a science-based pathway to net zero;
- Avoid over-reliance on conventional carbon credit based "'offsets'" and demonstrate good-faith efforts to minimise emissions first;
- Ramp up their investments into CDR to be able to 'neutralise' all residual emissions and reach net zero.

Against this backdrop, the concept of residual emissions has emerged as a necessary but contested concept at the intersection of technical feasibility, economic constraints and social and political acceptability (Schenuit et al., 2023; Lund et al., 2023). Interpreting what this means for an individual corporate GHG footprint[4] at net-zero can involve a variety of both top-down and bottom-up approaches. It is possible to, for instance, downscale IPCC and IEA modelling to provide insights as to what sectors' emissions profiles will look like at global net zero. (Section 2). Academic research has also emerged to help interpret such modelling and render it applicable to the decarbonisation options faced by state and non-state actors alike (Section 2). To complement these a range of strategies to identify residual emissions, from analysis on the level of an individual corporate to the development of sectoral transition plans have emerged, with standards such as SBTI's Corporate Net Zero Standard V1.0 and the ISO Net Zero Framework have also attempted to mediate between both worlds

3.2 Deciding what emissions are residual for corporates

As per Section 2, the world of corporate standards also lacks any definitive definitions of the types of emissions to be treated as residual, either at a sectoral or individual level of a corporate. The central question remains: which emissions are genuinely unavoidable versus insufficiently addressed within one's own value chain? Scientific pathways define residual emissions at system or sector level (See section 2.). By contrast, corporate level decisions require reference to company-specific considerations and value-chain emissions. Such considerations could be affected by factors such as the sector, geography and composition (small medium enterprise vs large multinational corporate).

Standards are a first point of departure for considering definitions of net zero. What is clear from section 2 is that despite small semantic differences, the definitions of residual emission

[4] Footprint here refers to any of own inventory (Scope 1 emissions) or the inclusion of broader value chain effects (Scopes 2 and 3 emissions)

converge around it being the amount of emissions remaining after all feasible abatement has been implemented. They also all recognise that the question of what residual emissions remains dynamic, requiring reassessment. Moreover, that the levels of residual emissions are sector dependent. As Table 2 further outlines, quantitative perceptions of the avoidable or unavoidable (residual) fractions of current GHG footprints range from SBTi's 5–10%, Race to Zero 90% reduction economy-wide and ISO with its sectoral ranges up to 28%. However, inferred connectivity between economy-wide or sectoral benchmarks and corporate action requires care and should be used only as a reference point upon which to compare the results of an internal assessment process.

To decide what is residual an operator must first appreciate its full GHG emissions inventory using a recognised standard such as the GHG Protocol or ISO 14064-1. The GHG Protocol is the most widely used standard and distinguishes between:

- **Scope 1:** Emissions from sources that are owned or controlled by the organisation, such as fuel combustion, company vehicles, on-site industrial processes or fugitive emissions.
- **Scope 2:** Emissions from the generation of purchased electricity, steam, heating or cooling that the organisation consumes
- **Scope 3:** All other indirect emissions not covered in Scope 1 and 2 including: purchased goods and services, capital goods, fuel- and energy-related activities, upstream transportation and distribution, waste generated in operations, business travel, employee commuting, upstream leased assets**,** emissions from assets you lease out, downstream transportation and distribution, processing of sold products, use of sold products, end-of-life treatment of sold products, downstream leased assets, franchises, and investments (financed emissions).

It can be helpful at this stage, as per recommendations from standards such as the SBTi, to initially focus actions on the largest types/sources of emissions and decarbonisation efforts on areas of greatest materiality to the business. Corporate level MACCs can then help focus efforts by identifying relative costs of decarbonisation for each emission type (e.g. by GHG or scope). Emission sources with lowest abatement cost will typically be focused on first by organisations to maximise impact, followed by examining which abatement options have high static cost but high dynamic potentials (see section 2.3.1). Those that emerge at the highest end of the MACC, after both of these steps, can help identify emissions that may in turn be defined as residual emissions.

As a complement to MACCs, a corporate may apply its judgement across multiple dimensions to further assist in identifying potential residual emissions:

1. **Availability of alternatives:** Does a sufficient alternative exist?
2. **Accessibility of alternatives:** Is there supply chain connectivity?
3. **Effectiveness of alternatives:** Is the technological readiness levels of the alternative robust?

4. **Economic feasibility:** What is the cost of the alternative?
5. **Social and political constraints:** Is there risk of demand suppression and/or potential for regressive effects? Is the alternative legal in the operating jurisdiction?

Carbon pricing options can also be employed at this juncture, adding a complementary lens to the above considerations. A net zero aligned carbon price should be climate-compatible (set in reference to a Paris-aligned temperature target), contextual (by benchmarking against sectoral peers), clear (in order to be effectively integrated into an organisation), and lead to commitment of funds towards climate action in a catalytic manner (Oxford Net Zero, Patch and BCG, 2025).

Yet, such judgements pose the risk of differential interpretation including (noting some parallels with national level decision-making described above):

- Between different corporates within the same sector, based on their differing assessment of the various dimensions outlined above
- Between bottom-up corporate led assessments and top-down IAMs, with the latter assuming a given category of emissions had been eliminated (which may be existential to some corporates).
- Geographic heterogeneity of alternatives (and associated risk of leakage)

As such, when undertaken in isolation there is a significant chance of corporations overestimating what they wish to define as 'residual emissions'. This type of bias has prompted some observers to recommend that residual emission levels should not be determined by corporates alone but rather also involve governments and civil society actors to inform a fair share of what's possible (Arendt, 2024).

The difficulty of establishing accurate projections of residual emissions across companies has led to attempts to make residual emissions measurable and comparable. For example, some efforts have explored definitions of sector-specific decarbonisation benchmarks such as those published by the Transition Pathways Initiative (TPI), which attempt to account for sector technological readiness and MACCs to identify residual emissions. However, several challenges persist. Data availability can be poor for some asset classes and inconsistent throughout a given supply chain especially for large corporates. It can also be especially difficult to forecast anticipated residual emissions as innovative practices evolve over time based on technological readiness and costs. Given these risks, once the work to identify residual emissions has been done, it is essential to cross reference back to standards and guidance especially to ensure that the expected residual emissions fit within the target range for a sector or standard (see Table 1).

Alternatively, given that reaching net zero targets requires all residual emissions to be neutralised with carbon removal (Buck et.al, 2022), some observers have proposed that an alternative approach to decarbonization planning could be to focus on what is achievable through CDR rather than what is too difficult or hard to abate. In this way it may even be possible to define residual emissions by the availability of carbon removal available to neutralise those emissions (Smith et al., 2024, p150). Some early thinking to quantify feasible volumes of such carbon removal via the advent of a carbon removal budget has been put forward (Caldecott and Johnstone, 2024).

Despite the lack of consensus in the way that corporates should identify their residual emissions, there remains good reason why it is necessary to engage early with their current and projected emissions inventory to be able to map out what will remain on the way to, at and beyond net-zero and accordingly take measures to address it.

3.3 Addressing what is residual

Standards also offer guidance as to how to address residual emissions. All standards referenced require residual emissions to be addressed in order to meet their given target such as net zero. SBTI requires strict neutralisation with permanent removals, while ISO imparts potentially more flexible targets on how residual emissions are addressed. Irrespective of the framework, there is a common requirement for users to maximise mitigation before neutralisation and to value carbon removals as a scarce and valuable resource (Caldecott and Johnstone, 2024). Addressing residual emissions is necessarily a continued obligation to maintain the state of net zero. Determining categories of an emissions' profile as persistently "residual" without regular renewal, despite prospects for technological evolution, risks lock-in and mitigation deterrence. However, once one is reasonably certain that residual emissions will persist in future there are several response options (Axelsson et al., 2024, Johnstone, 2024). These include:

Within your value chain:

Supporting sectoral innovations and collaborations: Such investments in individual and collective research and development can help to reduce anticipated residual emissions overtime.

Divestment: Ultimately, if there are emissions that remain unavoidable, divesting from the source of residual emissions. This strategy has its limitations in isolation. While this can make sense at a corporate level, this does not cause the systemic shifts necessary to decarbonise globally. Financial endowments, including universities, have utilised this as a key strategy (Stephens, Frumhoff and Yona, 2018).

Insetting: Developing projects that neutralise emissions within your own value chain. For instance, afforestation efforts to address persistent agricultural emissions (Klim, 2024). These actions can be funded by proceeds of internal carbon pricing.

Beyond your value chain:

Procuring carbon removal credits: Several specialised platforms have emerged which help broker investments into carbon removal projects beyond one's own value chain, including in a manner that can neutralise emissions in a like-for-like manner, where biogenic emissions are balanced by investment into additional biogenic carbon storage and fossil-fuel based emissions are balanced with durable geologic storage.

Investing in bilateral off-take agreements: Forward contracting of carbon removal capacity for neutralisation. This can be undertaken on the level of an individual corporate via direct bilateral arrangements or reverse auction style tenders.[5]

Joining a buyer consortium: Joining a pooled advanced market commitment such as Frontier or NextGen can help aggregate and scale-up demand and provide access to CDR supply with shared costs, for example, on project and/or supplier due diligence.

Contributing to shared removal infrastructure and procurement expertise: Pooling expertise to develop further architecture to address residual emissions is a further option. Examples of this include the payment processer Stripe hosted a Climate Fellows programme to meet policy needs of the emerging CDR architecture developed and the XPrize which developed a carbon removal prize.

3.4 Risks of not addressing residual emissions

There are numerous risks involved when residual emissions remain unaddressed. One of the first is that a failure to address residual emissions can make options to address them at a later point expensive or inaccessible. In line with Principle Four of the Oxford Principles for Net Zero Aligned Carbon Offsetting (Axelsson et al., 2024), an innovated and integrated approach is required to offset residual emissions as the capacity to address residual emissions depends on concerted and pre-emptive effort to unlock the full value chain. Another consequence of failing to address residual emissions ineligibility for best practice corporate standards, such as those established by the ISO and the SBTi, which can impact upon corporate climate-related action narratives. In addition, failure to address residual emissions can lead to loss in consumer and investor confidence, especially in cases where there was a prior net zero target that was set and action to implement it fully by neutralising residual emissions was not.

Moving beyond a corporate footprint, failure to address a corporate's residual emissions, it also leaves the country or countries where it is hosted responsible for those ongoing emissions. In this sense, failure to address residual emissions contributes to the already growing CDR gap (Lamb et al., 2024). The CDR gap emerges when the "efforts proposed by countries fall short of those in integrated assessment model scenarios that limit warming to 1.5 °C" (Lamb et al., 2024). The consequence of this failure to stabilise cumulative emissions is thus excess emissions, which in turn could inform the carbon debt that has to be additionally drawn down in future.

[5] Arguably these should be "like-for-like".

3.5 Future Considerations

3.5.1 How the definition of what is residual could change

Problematically, evidently what is *residual* today may be *reducible* and thus not residual in future. Such an evolution can be measured based on the pace of technological development within a sector as well as asset lifetimes and turnover of capital/stock. Noting this difference, it is key that residual emissions are regularly revised as a key response measure. However external measures, especially any attempts to apportion a fair share, could shift in future. This is recognised in France's definition of residual emissions as those being sources:

> "which are unavoidable according to the *current* state of knowledge" (emphasis added, Ministry for the Ecological and Solidary Transition, 2020, p162).

The question of whether the reverse could happen, namely, that a currently remaining abatable emission that could be residual in future may be made *more* difficult to neutralise if expected technological developments do not occur or decarbonisation supply chains do not scale or other scenarios inhibiting CDR scale up come to pass needs also to be factored into corporate risk management strategies.

Equally the opportunity and/or burden to address residual emissions also may evolve over time. In sectors such as international aviation and maritime–which lie beyond the responsibility of individual nation states in respect of the United Nations Framework Convention on Climate Change–dedicated international schemes have emerged that require operators to take steps to decarbonise their activities and residuals. As countries become under pressure to decarbonise and revisit their own NDCs, this too could change. In particular, demand side management could also be looked at, in tandem with coordinated efforts to make industrial decarbonisation breakthroughs and address the growing CDR gap (Smith et al., 2024).

Several countries, such as Germany, Sweden and the EU are developing strategies to address residual emissions which could provide the foundation for this (Federal Ministry for Economic Affairs and Climate Action, 2024; Klimatlag, 2017; European Commission, 2024).

3.5.2 How the burden may be distributed between corporates

There are currently limited formal mechanisms to distribute residuals at corporate level. Only partial approaches currently exist, including:

- Sectoral benchmarks and pathways such as the TPI and IEA scenarios;
- Expectations embedded in net-zero standards such as SBTi and ISO;
- Mechanisms such as CORSIA for the international aviation industry and the Net Zero Scheme of the IMO for international shipping;
- National schemes such as Switzerland's offsetting obligation on fuel importers, managed by the surcharge of up to CHF 8 cents per litre on petrol and diesel managed

by the Klik Foundation which uses the funds to support domestic and international projects (Klik, 2023).

There are also a number of ongoing challenges:

- Encouraging incentives to map and address residual emissions early, including investing in shared removal capacity
- Addressing free-rider incentives
- Aligning corporate claims with global carbon and global carbon removal budgets

There are a range of ways one could distribute residual emissions in future:

Sectoral: System-level pathways implicitly allocate residual emissions unevenly across different sectors with higher residual emissions in sectors such as aviation, cement, agriculture and near-zero or zero residual emissions in power generation. While recognition of sector pathways has thus far been limited within the context of the Paris Agreement, the opportunity to develop sectoral residual emission allowances is one emerging idea (Caldecott and Johnstone, 2024).

Geographic: Geographic distribution in line with the principle of CBDR-RC would also result in different residual emissions profiles. Literature that explores such allocations typically does so from a fair share perspective, including historical emissions (Pelz et al., 2025). Given the presence of multinational supply chains operationalising such a distribution could prove complex without consideration to other distributional factors.

Ability to Pay: Residual emissions have a cost to the atmosphere, as well as their proponent in a net zero scenario. One way of distributing allocations of residual emissions is considering who is able to pay for the costs to neutralise them. In effect this would likely have the counter effect to a fair share geographic distribution when considering emerging economies with rising emissions but constrained fiscal space and thus who might not have ability to pay as a result. Höglund and Mitchell Larson (2022) suggest, for instance, that this should be based on profits per ton emitted, and the internal investment needs a company has to reduce their own emissions. While most sectors with hard to abate emissions have a lower working capital and thus ability to pay, this would mean companies with higher profit per tons, such as the finance, insurance, and technology sectors would carry a greater share of the cost.

Demand Management Prospects: Some sectors and sub-sectors with residual emissions have higher prospect of demand management. With air freight, for instance, being deemed more unavoidable than air travel, making the former more likely to be deemed residual than the latter under a demand management scenario.

Size of the Entity: Some obligations in climate mitigation, such as the EU CSRD only apply to corporates based on employee headcount and turnover. Questions related to distributing residual emissions could also similarly apply a de-minimis threshold of business size.

While these obligations largely remain voluntary considerations for corporates to engage with, they should be borne in mind when designing a responsible and resilient strategy for addressing residual emissions.

4 Conclusions and recommendations

The term ‘residual emissions’ is a recent entry into the lexicon of climate strategy and policymaking. In the first instance, usage of the term can be linked to the development and spread of net zero emissions or other temperature-based target. The term has antecedent definitions, with ‘recalcitrant emissions’, ‘hard-to-abate emissions’ and others describing a similar phenomenon.

The IPCC first used the term in its 5th Assessment Report (2014), since when the term has increased in prominence – despite not receiving a formal definition in the glossary. The UK CCC has used the term from 2010 onwards, but as with the IPCC, the normative assumptions underpinning usage of the term is not explored deeply.

Across IPCC reports, national strategies, and academic literature, residual emissions are variously described as emissions that are more expensive to abate than to neutralise, emissions that are technically or socially hard to eliminate, and emissions that simply remain at the net-zero balance point globally. These usages overlap but are not equivalent. While governance-oriented definitions frame residual emissions as an accounting remainder at the target date, techno-economic definitions implicitly define them by reference to feasibility constraints. Consequentially, alighting on a clear definition across the literature surveyed has not been possible due to different understandings of what emissions can/cannot be abated given expectations of technological developments, and what emissions are designated as residual for economic, cultural or political reasons.

This diversity of definitions complicates efforts to operationalise the concept in policy and corporate climate action. Without a consistent analytical boundary between ‘hard-to-abate’ and ‘residual’, countries and firms classify emissions as residual on economic or political grounds. As the IPCC has acknowledged in recent assessment reports, decisions on the quantity of residual emissions are driven by national circumstances and decisions on the ambition, feasibility, and social acceptability of cross-sectoral mitigation by 2050 and the resultant levels of removals needed to counterbalance remaining emissions by that date. Thus, the absence of an agreed upon definition precludes prescribing a standardised ‘residual emissions’ share for countries.

Consensus concerning exactly what constitutes residual emissions may continue to be elusive. There are important differences between top-down assessments of IAMs and the more bottom-up assessments of nations or corporations themselves–as well as the standards that mediate between them.

Solving the distributional challenges associated with residual emissions underscore that these are fundamentally normative questions requiring political negotiation rather than technical optimization. While IAMs provide valuable insights into cost-effective pathways, translating their outputs into equitable and legitimate policy frameworks requires explicit attention to allocation principles, historical responsibilities, and differential capabilities across and within jurisdictions.. In lieu of a definition of residual emissions, any corporate emissions management framework must be explicitly time-bound and technology-conditional. What counts as a residual emission is not a fixed property of a sector or process — it is a normative judgment that depends on the current state of abatement technology, prevailing carbon prices, and the timeframe under consideration. Translating this into clear, actionable, next steps for corporate climate action is challenging, but nevertheless possible. We propose the following five step strategy, each with a series of recommendations. The framework is not meant to be completely prescriptive and in some cases, recommendations can fit under a number of steps.

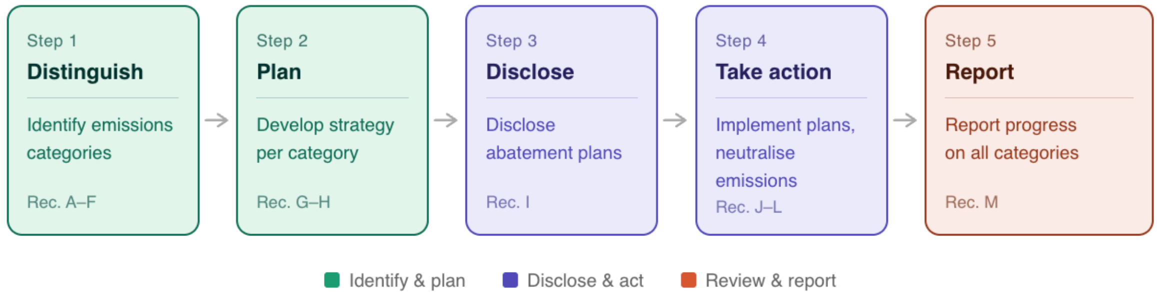

Figure 2: Corporate emissions management framework. Source: Authors

Distinguish

A) Distinguish between emissions categories rather than using a single term. Instead of asking corporates to identify a single category of "residual emissions," the corporate should classify their emissions along two dimensions — abatement difficulty and timeframe — producing the following framework with three-time steps:

- **Near-term abatable** — reductions achievable within the current decade with available technology at reasonable cost
- **Medium-term abatable** — reductions achievable by 2040 with plausible technology development or cost reduction
- **Long-term removal-dependent** — emissions for which no credible abatement pathway currently exists even at the 2050 horizon.

The benefit of this approach is that it gives corporates a practical and dynamic framework without requiring them to commit to a definitive definition of what is permanently residual. Abatement options can move between each category as new evidence emerges.

B) Identifying appropriate standards and guidance frameworks, including any that may be particularly relevant for a given sector. This can provide more granular data on a corporates' emissions profile, including the volume of emissions attributable to each time step above as well as providing a starting point for how to address them.

C) Investigate how your sector's emissions are treated in IAMs: review and understand the application of Paris-aligned temperature limitation goals in modelling pathways to the category of emissions. Does your sector belong to one that is anticipated at a state of net zero to be one that has near to or no emissions, or persistent levels. What technological assumptions is that based on and are those reasonable? A practical starting point for organisations could be to engage, and feedback to, the IAM community through the resources such as the Integrated Assessment Modelling Consortium, who host a repository of resources including an IAM scenario database, hosted by IIASA and makes them available to the scientific community, policy analysts, decision makers and the public at large for easy reuse.

D) Ensure Paris consistency: Review the LT-LEDS and NDCs of jurisdictions in which corporate operations are active in order to take into account host country plans and actions that contribute toward achievement of the Paris Agreement. The next step would include mapping one's own emissions to sectoral emissions within the jurisdiction's NDC and where gaps exist between sectoral benchmarks and a corporate pathway; engaging constructively with the jurisdiction to limit this gap.

E) Integrate carbon pricing and investment decisions. Establish an internal carbon price and use marginal abatement cost curves to identify the economic threshold where CDR becomes more cost-effective than further abatement, taking into account dynamic not just static costs.

F) Differentiate technical from political/ economic barriers. Categorise barriers to abatement and be explicit about value judgements.

Plan

G) Create an emissions baseline and establish transparent boundary conditions: Distinguish between the organisation's current levels of ongoing emissions, including measured scopes of emissions under the current GHG inventory, and anticipated volumes of emissions at each time step by emission source and geography. The process should identify and consider the availability, accessibility and effectiveness of means to address those emissions (e.g. lower carbon processes or product alternatives as well as economic, social, cultural and/or political constraints to their use). Review conditions periodically, as technologies, regulations and social norms evolve to ensure the residual emissions baseline remains accurate.

H) Study potential levers that could turn anticipated emissions at each time step into abatable emissions over time: Understand what factors currently justify the emission sources being classified as long term removal dependant at present. For example, are they uneconomic, at low TRL, or simply do not yet exist. Continue to monitor TRLs for emerging solutions in respective sectors, updating classifications as technologies mature.

Disclose

(I) Disclose whether emissions at each time step have been mapped, are material and accordingly are likely to be a material future risk in a corporate transition plan in accordance with the TCFD disclosure rules.

Take action

(J) Take action to address the factors which lead to emissions remaining in the medium to long term: Consider internal and sectoral collaboration and partnerships on research and development to identify potential breakthroughs, and the conditions necessary for them.

(K) Develop a CDR procurement strategy that is commensurate with abatement ambition and timeline, particularly for emissions that are long-term removal dependant: Consider developing an internal carbon removal budget forecast that maps anticipated residual emissions and the corresponding volume of durable CDR needed for neutralization. Begin early engagement with CDR suppliers/market makers to secure offtakes of carbon removal. This assessment also includes understanding the budgetary implications of such procurement strategies, particularly if they prioritise durable methods. This approach avoids asking corporates to identify their residual emissions, resolving the definitional problem identified.

(L) Support the deployment of associated infrastructure for emissions at each time step to be neutralised at scale: An integrated and innovative ecosystem is needed to reach net zero, including lending support for policy interventions (Axelsson et al., 2024).

Report

(M) Companies should report annually on the distribution of their emissions across the three categories, **and — critically — on movement between them.** Progress is not measured solely by the absolute level of emissions in the long-term removal-dependent category, but by the rate at which emissions are migrating from that category into the medium- and near-term abatable categories as technology develops, costs fall, and internal abatement programmes mature. Where emissions remain in the long-term removal-dependent category, companies should disclose the specific technical or economic barriers that currently prevent abatement, the actions being taken to monitor and respond to developments that might change that assessment, and the volume and type of carbon dioxide removal being procured or invested in to address those emissions in the interim. This approach ensures that the removal-dependent category does not function as a permanent exemption from ambition, but as a dynamic and contestable boundary subject to regular reassessment — with the expectation that, over time, the category should shrink rather than remain static.

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Annex A

A-1 Development of the residual emissions concept in the literature

AR1-AR3 (1990-2001) focussed on the physical carbon-cycle and stabilising atmospheric CO_2 concentrations, without explicit reference to residual emissions. At time of writing, the focus of climate action and policy measures was on quantity based GHG abatement targets and target years (e.g. cutting emissions in line with the Kyoto Protocol's approach of defined quantified emissions limitation and reduction obligations (QELROs) within a given compliance period). Discourses around carbon sinks were largely framed biophysically as a constituent of the earth system and not as an economic or policy tool that can be enhanced to deliver climate targets.

In this period, the concept of residual emissions would be hard to define given the absence of 'net zero' and only nascent quantity based GHG abatement targets and target years emerging form Kyoto discussions. In line with its UNFCCC mandate, AR1 primarily focussed on outlining the climate system and the science of climate change. Where prescriptions are made, these include "[targeting] *severe reductions on emissions…* [without reference to strengthening sinks] *to avoid a continued rapid growth of* CO_2 *in the atmosphere… because of the length of time taken for atmospheric* CO_2 *to adjust to changes in sources and sinks of emissions"* [p.1].

No normative hierarchy in AR1 (1990) is made across the difficulties of abating specific GHGs and connecting this challenge to specific industries and economic actors. Discussion of carbon sinks was framed biophysically, as a constituent of the earth system, and not as an economic or policy tool that can be enhanced to deliver climate targets.

Similarly, **the IPCC Special Report on CCS (2005)** discussed the current state of technology of CCS and the contributions this could make to global mitigation efforts, but it did not explicitly link this to a section of emissions that cannot be cost-effectively or technically neutralised. CCS in 2005 is framed as pre-emptive mitigation, not part of global balancing efforts.

AR4 (2007) represents the beginning of a change in how global GHG concentrations are represented, with a shift from biophysical balance framing to a modern residual-emissions concept, when sinks begin to be discussed as mitigation measures and stabilisation is portrayed in terms of emissions end-states rather than atmospheric GHG concentrations alone. AR4 integrates terminology such as '[reducing emissions to] *very low levels*'; with the concept of '*negative net emissions'* introduced in terms of emissions end-states rather than atmospheric GHG concentrations alone. AR4 integrates terminology such as '[reducing emissions to] *very low levels*'; with the concept of '*negative net emissions'* introduced in terms of:

"… any specific concentration or radiative forcing target, from the lowest to the highest, requires emissions to eventually fall to very low levels as the removal processes of the ocean and terrestrial systems saturate… emissions must ultimately be reduced well below current levels. For achievement of the very low stabilization targets… negative net emissions are required towards the end of the century" (AR4, p.172).

Table A. Development of residual emissions concept over IPCC, UK CCC and State of CDR literature.

Report	Treatment of residual emissions	Role of CDR	Key conceptual shift
AR1–AR3 (1990–2001)	Not referenced	Sinks framed biophysically as part of the Earth system, not a policy or economic tool	Focus on physical carbon cycle and emissions reduction, not end-state emissions
IPCC Special Report on CCS (2005)	Not linked to emissions that cannot be abated	CCS framed as pre-emptive mitigation	CCS not part of balancing or net-zero logic
AR4 (2007)	Implicit emergence of residual-emissions logic	Sinks discussed as mitigation measures; introduction of negative net emissions	Transition from concentration stabilisation to emissions-based framing
AR5 (2013)	Term "residual emissions" used but not defined	CDR justified to compensate expensive-to-abate emissions; large-scale negative emissions modelled	Residual emissions implicitly recognised as structurally necessary
SR1.5 (2018)	Residual emissions implied but not defined	Expanded role for CDR to neutralise remaining emissions	Clear pivot to residual-emissions and CDR conceptual lens
AR6 (2022)	Explicitly defined and operationalised	CDR required to balance remaining emissions; residuals quantified in scenarios	Residual emissions framed as unavoidable and normatively determined
State of CDR (2023, 2025)	Explicit definition provided	CDR must equal or exceed residual emissions	Formalisation of residual-emissions definition across scales
UK CCC Seventh Carbon Budget (2025)	No standalone definition; used implicitly	CDR balances emissions remaining after feasible abatement deployed	Residual emissions treated emissions that remain after all technically and economically feasible abatement options have been applied