CARBON MARKET WATCH

A framework for assessing THE CLIMATE VALUE OF TEMPORARY CARBON STORAGE

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1. INTRODUCTION

This report provides a scientifically grounded framework for assessing the climate value of temporary carbon dioxide (CO_2) storage, with applications for carbon dioxide removal (CDR) and carbon capture, storage, and utilisation (CCS/CCU) policies. It is also relevant for efforts to credit avoided emissions based on temporary carbon storage.

However, this report does not consider nor intend to diminish the non-climate value of temporary carbon storage, such as forest conservation or biodiversity protection. (In the author's opinion, these non-climate considerations are likely as or more important than carbon; carbon storage is probably better thought of as a co-benefit of forest conservation, rather than its guiding principle.) Similarly, this report does not provide a comprehensive view of the environmental and social risks presented by carbon storage approaches. Its singular goal is to describe how duration of temporary carbon storage affects its climate mitigation value.

Carefully defining the climate contribution of temporary, non-permanent carbon storage depends on nuanced concepts in climate science, climate economics, and real-world market practices. In light of this complexity, why is a focus on temporary storage so important?

One answer is that a large share of carbon credits today reflect claims based on temporary carbon storage (So et al., 2023) and nearly all carbon removal achieved by intentional human intervention to date involves carbon storage in non-permanent biological systems, such as forests or soils. Although any form of carbon storage is potentially at risk of loss and re-emission to the atmosphere, carbon stored in biological systems is fundamentally transient in relation to carbon stored in or emitted from fossil fuels (Anderegg et al., 2020; Fankhauser et al., 2022). According to a recent assessment of global carbon dioxide removal outcomes, however, of the approximately 2 $GtCO_2$ per year removed from the atmosphere through anthropogenic activity, nearly all is stored in biological systems in the land sector and less than 0.002 $GtCO_2$ per year comes from novel methods (Smith et al., 2023). Although governments and private companies are increasingly interested in permanent carbon removal, very few long-duration or truly permanent carbon removal credits are available in the voluntary carbon market today (Joppa et al., 2021; So et al., 2023); instead, what supply exists is contracted for future delivery.

Because carbon removal outcomes today are dominated by temporary carbon storage reservoirs, such as forests, it is important to understand the climate consequences associated with crediting carbon that is stored on a non-permanent basis. Accordingly, this report sets out to answer the following questions:

- From a climate science perspective, how similar or different are temporary and permanent carbon storage outcomes?
- Under what conditions is temporary carbon storage consistent with the Paris Agreement's commitment to limiting warming to well below 2°C and ideally no more than 1.5°C?
- How long does temporarily stored carbon need to remain out of the atmosphere in order to contribute to global temperature stabilisation under the Paris Agreement?
- Is all carbon storage that meets a minimum durability requirement equally valuable?
- Is all carbon storage that meets a minimum durability requirement as valuable as permanent carbon storage or permanently avoided emissions?

As the rest of the report explains, a robust framework for valuing temporary carbon storage and answering these questions must contend with three related issues:

- **PHYSICAL CLIMATE SCIENCE.** Unlike most other air pollutants, carbon dioxide has an effectively permanent impact on the global atmosphere and oceans. As a result, the climate value of temporary carbon storage depends in part on the atmospheric dynamics of CO_2 as well as the science behind global temperature stabilisation. In brief, the ability of temporary carbon storage to contribute to "peak shaving" — that is, reducing the maximum level of peak warming that occurs in the future — depends on it lasting for at least as long as it takes for planetary temperatures to stabilise, and likely substantially longer. If carbon storage expires before temperature stabilisation occurs, then it does not contribute to reducing planetary temperatures. Whenever temporary storage expires, it creates climate impacts that require additional mitigation, and thus achieving durability that extends significantly beyond the point of temperature stabilisation is desirable.
- **CLIMATE-EQUIVALENCE CLAIMS.** Many climate policy systems and carbon markets have adopted technical metrics that attempt to simplify the complexity of physical climate science by asserting that temporary carbon storage produces climate benefits that are equivalent to the harms from emitting CO_2 or the benefits

of permanently avoiding CO_2 emissions. The scientific literature and common market practices feature two divergent sets of climate-equivalence claims. One set of claims is based on physical equivalence and requires carbon storage durability that matches the atmospheric lifetime of CO_2. In contrast, another set of claims is based on economic equivalence. Although economic-equivalence claims are often presented in language that purports to demonstrate physical equivalence, they are fundamentally based on normative, non-physical choices like economic discounting or arbitrary time horizons. These claims attempt to balance the economic benefits of temporarily reducing warming against the economic costs of longer-term climate damages.

- **CARBON CREDIT USE CASES.** Temporary carbon storage has different climate consequences, depending on its use case. Compensatory claims, which seek to offset or neutralise CO_2 emissions, are consistent with temperature stabilisation goals only when they are based on physical equivalence. Because they give permission for CO_2 emissions with effectively permanent impacts, compensatory claims cannot be justified on the basis of temporary carbon storage. In contrast, supplemental claims — which are also called "contribution" claims,[1] and are detached from any kind of permission to offset or continue emissions — are consistent with a broader range of valuation paradigms. Nevertheless, the value of temporary carbon storage in a supplemental claim still depends on its duration: if carbon storage doesn't last at least until global temperature stabilisation is achieved, then it will not contribute to temperature stabilisation goals and will produce substantially less value as a result. Achieving significant value likely requires durability that extends well beyond this minimum requirement.

The rest of the report is organised as follows. The introduction continues with a discussion of the durability of carbon storage and an explanation of two fundamental paradigms in climate economics that inform debates over the value of temporary carbon storage. Next, Section 2 reviews relevant climate science, including the atmospheric lifetime of CO_2, cumulative emissions budgets, and pathways to temperature stabilisation. Section 3 then describes how climate-equivalence claims can be made on a physical or economic basis.

Section 4 brings together the previous sections to assess the conditions under which climate-equivalence claims are consistent with the Paris Agreement's commitment to limit global temperature increases. It explains why physical climate-equivalence is necessary for robust compensatory claims, which in turn requires truly permanent carbon storage —

[1] For example, the Voluntary Carbon Market Integrity Initiative's Claims Code of Practice requires a "contribution" credit-use model (VCMI, 2023, Box 1).

such that the carbon can be expected to remain out of the atmosphere over geologic timescales. In contrast, compensatory claims based on economic equivalence increase global temperatures and are inconsistent with the Paris Agreement as a result. That is not to say that temporary storage has no climate value, but that any significant value is contingent on it not being used for offset-related, compensatory claims.[2] Even in the context of supplemental claims, however, the durability of carbon storage needs to extend sufficiently beyond the point of global temperature stabilisation to support the warming limits of the Paris Agreement. Finally, Section 5 concludes.

1.1. Durability of carbon storage

This report's analysis is based on a central concept, the durability of carbon storage. Durability is defined here as the time period over which a quantity of carbon is stored outside of the atmosphere, measured in years. At the end of that time period, all of the carbon is assumed to be emitted to the atmosphere, following Herzog et al. (2003). For simplicity, storage is assumed to be lossless until the end of the durability period.

Because this definition is somewhat abstract, it excludes several important real-world features. The true risk of carbon loss and re-emission to the atmosphere is much more nuanced (Höglund, 2023a). In practice, some carbon removal pathways will feature a steady decay of carbon that is released to the atmosphere over time. For example, carbon stored in biochar will continuously degrade over time, based on the chemical composition of the biochar and conditions in its local environment (Campbell et al., 2018; Joseph et al., 2021). Other carbon storage applications face stochastic risks of reversal and re-emission. Carbon stored in forests doesn't simply expire at the end of a predetermined period; instead, it is subject to a variety of risks — such as drought, disease, wildfire, and human disturbance — that could manifest at any time, with probabilities that vary by location, species, and climate conditions (Anderegg et al., 2020).

[2] When used for compensatory claims, temporary carbon storage leads to higher warming and higher costs at the end of the storage period. For relatively short durations like 10 or 100 years, it is clear that imposing the resulting harms on current and immediately future generations is tangible and highly problematic. For much longer durations, such as 5000 years, the harms are no less real but the consequences may be different. Given that the global climate mitigation agenda is not on track for the Paris Agreement's warming limits, creating additional harms that manifest in the coming decades only exacerbates the disconnect between what society is currently doing and what is required to achieve temperature stabilisation. In contrast, deferring climate mitigation efforts through temporary storage that lasts 500 or 5000 years does not necessarily run into the same constraints, although extreme caution is warranted whenever considering the interests or capacities of future societies on long timeframes. This report argues that a valid compensatory claim requires storage that matches the atmospheric duration of CO_2, but it is important to note that imperfect compensatory claims — such as those made on the basis of carbon credibly stored for hundreds to thousands of years — might impose future costs that are normatively acceptable to some. In practice, these considerations may be most relevant to only a small number of carbon removal pathways, such as biochar, deep-sea CO_2 storage, and biomass burial (Höglund, 2023a).

Although a simplified durability definition does not capture these important dynamics, it has the advantage of reflecting current carbon market practices. When carbon removal projects claim to store carbon to earn carbon credits, they typically make commitments to store carbon for a minimum period of time. In the voluntary carbon markets, these commitments are made by private contracts, whereas in government-run offset programs they are subject to regulatory oversight. In either application, contractual or regulatory rules specify the minimum commitment a carbon storage project must satisfy to earn a credit. Anything beyond that term is aspirational, and therefore is not promised to the purchaser or user of the resulting credits. As a result, the assumption of perfect storage with complete re-emission is both a reasonably conservative approach as well as a good approximation of the kinds of claims made in carbon markets today.[3]

Carbon storage commitments in the voluntary carbon markets tend to be bimodal, with relatively short durability claims involving land-sector projects and substantially longer claims for an emerging category of carbon removal technologies (Joppa et al., 2021). Forest carbon storage commitments range from as short as a single year in an extreme example (Parisa et al., 2022) up to 100 years in duration in the California forest offsets program (Haya et al., 2023). Soil carbon commitments tend to be on the shorter range of that spectrum, with typical commitments of 10 or 20 years (Zelikova et al., 2021). In contrast, projects that seek to store carbon dioxide underground, in mineral form, or by increasing ocean alkalinity often claim durability of 1,000 years or more (Chay et al., 2021; Höglund, 2023a; Joppa et al., 2021). Intermediate durability of 100 to 1,000 years is primarily associated with biochar, biomass burial, and deep-sea CO_2 storage (Chay et al., 2021; Höglund, 2023a).

One important feature of this report's simple definition of durability is that it facilitates a wide range of applications that respond to the contractual and regulatory structure of carbon markets today. Some argue that successful temporary carbon storage projects can be renewed or replaced with longer-duration commitments at the end of the initial durability term in what has been helpfully labelled "horizontal stacking" (Cabiyo and Dolginow, 2022) or "renting carbon" (Marland et al., 2001) to indicate that multiple

[3] Some stakeholders suggest that credited carbon storage might persist beyond the minimum level required for a particular project or program. While this is of course a possibility and its implications can be explored by making more generous durability assumptions than what is legally required in practice, these claims involve substantial risks. Projects generally assert that carbon benefits are additional beyond what would happen in a business-as-usual scenario and made possible only because of the carbon incentive provided by an offset credit. As my colleague Grayson Badgley has pointed out, this additionality assertion is broadly inconsistent with aspirational durability outcomes that extend beyond a contract horizon. In working forests and agricultural lands, for example, a true claim of additionality strongly suggests that reversal of carbon gains is likely if a carbon contract is not renewed, as the market conditions that would have caused worse outcomes in the project's baseline scenario should have similar effects at the end of a contract's term. For the same reasons, if carbon storage would likely exceed the contractual durability commitment, then that could undercut the claim that all of the claimed carbon storage is truly additional. In any case, uncertainty over what market conditions might be expected over time horizons like 50 or 100 years requires highly contingent speculation that contrasts with the well-documented climate impacts caused by more CO_2 emissions.

contracts can be strung together over time to extend the durability of a given carbon storage claim (Cullenward et al., 2020). In turn, some older climate policy systems — such as the 1997 Kyoto Protocol — and more recent policy proposals contemplate assigning liability to credit users to renew or replace short-duration contracts on an ongoing basis, which could provide an enforcement mechanism to encourage horizontal stacking practices (Kalkuhl et al., 2022; Marland et al., 2001; Roston et al., 2023). Many carbon credit programs also include self-insurance programs known as buffer pools that insure individual projects against the risk of carbon loss prior to a program's contractual durability commitment (Badgley et al., 2022; Haya et al., 2023).

This report's simple definition of durability makes it flexible. This flexibility allows for the consideration of one-off durability promises as well as horizontal stacking or carbon rental practices, such that it can be used to evaluate the implications of a single contract or a broader policy environment that requires ongoing liability for emissions or replacement contracts. For example, one can use it to explore the climate consequences of a 10-year carbon storage commitment or a policy regime that requires sequential carbon storage commitments that add up to 100 years.

Nevertheless, caution is warranted whenever one assumes that carbon storage will be more durable than what is promised in an initial carbon contract. Even initial promises can be shaky. Evidence from California's forest carbon offsets program suggests that its self-insurance mechanism substantially underestimated forest carbon loss risks, and failed to account for climate-related risk factors that will get worse over time (Badgley et al., 2022). Voluntary carbon market insurance programs use the same approaches and are frequently less stringent. Meanwhile, efforts to require credit users to renew contractual commitments via horizontal stacking face significant execution risks because making climate benefits today contingent on a regulator's ability to impose costs on polluters in the future is a highly speculative proposition. In many jurisdictions, environmental liabilities can be discharged through bankruptcy, a tactic that large corporations have used to successfully evade environmental debts in industries ranging from fossil fuels to pharmaceuticals (Macey and Salovaara, 2019).

1.2. Climate mitigation policy paradigms

Article 2 of the Paris Agreement establishes a temperature target, with each participating government agreeing to hold the increase in the global average temperature to "well below 2°C" above pre-industrial levels and "pursue efforts to limit the temperature increase to 1.5°C." This choice should be understood in the context of two competing paradigms for how to think about climate mitigation policy (Koomey, 2013), as the global community's alignment in the Paris Agreement has implications for how to value temporary carbon storage.

In a "cost effectiveness" paradigm, a political process, such as the Paris Agreement negotiations, determines a policy target, such as the maximum acceptable level of warming above pre-industrial temperatures. The relevant deliberations can be based on broad considerations, including scientific information as well as normative frameworks such as intergenerational welfare, distributional effects within and across countries, and social and environmental impacts. Critically, however, these issues are treated as political choices, rather than purely scientific constructs — even when they are deliberately informed by scientific evidence, as the Paris Agreement negotiations were.

With a temperature target established under a cost-effectiveness paradigm, climate mitigation policy analysis is primarily concerned with identifying options for achieving that target, as well as their associated costs and benefits (Kaufman et al., 2020; Stern et al., 2022). Many prominent publications from climate scientists also adopt this orientation — for example, by calculating the emissions budgets consistent with a given temperature target (Meinshausen et al., 2009) — even if they only address physical science considerations, without any explicit economic calculations.

In contrast, a "cost-benefit optimization" approach has long been popular among academic economists (Aldy et al., 2021). Research in this paradigm seeks to quantify both the costs and benefits of climate mitigation, and compares these calculations with one another in order to identify an economically "optimal" level of climate mitigation and global warming.

Perhaps the most high-profile application of this concept is in the United States' social cost of carbon calculation, which is based on the use of integrated assessment models (NASEM, 2017; Rennert et al., 2022; Wagner et al., 2021). These models attempt to calculate the cost of climate damages based on temperature-sensitive economic damages and discount rates that treat costs today as more important than costs in the future.

Controversially, cost-benefit optimization analysis identifies “optimal” warming scenarios. Often these scenarios substantially exceed the Paris Agreement’s warming limits. For example, on the basis of his integrated assessment model, DICE, climate economist William Nordhaus has recently argued that optimal warming is about 3°C by 2100 (Nordhaus, 2019, p. 2002) — though he has subsequently reduced that estimate to about 2.73°C (Barrage and Nordhaus, 2023, Table 3). There need not be a conflict between cost-benefit optimization calculations and a given temperature target, however. Some cost-benefit optimization studies select “optimal” warming outcomes that are more ambitious than what the Paris Agreement requires (Hänsel et al., 2020). Similarly, some cost-effectiveness studies produce lower estimates of the social cost of carbon than do contemporary cost-benefit optimization studies (Wagner, 2021).

For the purposes of this report, the key insight is that each approach adopts a different view of temperature limits. One approach (cost effectiveness) adopts the Paris Agreement’s commitment to limiting warming as an input, while the other (cost-benefit optimization) determines the “optimal” temperature levels endogenously. Because many technical assertions about the climate value of temporary carbon storage are based on cost-benefit optimization calculations, it is important to ask whether the assumptions of those analyses are consistent with the Paris Agreement’s commitment to limit global warming. Sometimes they are not.

2. CLIMATE SCIENCE CONCEPTS

With a foundational understanding of durability and competing paradigms in climate economics in mind, three additional concepts from the physical sciences are needed to assess the value of temporary carbon storage. Each concept is reviewed here in turn.

The first concept is the atmospheric lifetime of CO_2, which affects the duration over which its radiative forcing properties trap heat and contribute to global warming. Unlike most other air pollutants, which tend to have relatively short and well-defined atmospheric lifetimes, the atmospheric lifetime of CO_2 is affected by multiple earth systems processes that unfold over distinct and very long timeframes. When a pulse of CO_2 enters the atmosphere, most is absorbed by the biosphere and oceans over a period of a few hundred years to a few thousand; however, even after 10,000 years, about 20% of the original emissions remain in the atmosphere. As a result, the climate impacts of CO_2 emissions are effectively permanent.

The second concept is that temperature outcomes primarily depend on cumulative CO_2 emissions, rather than the rate of CO_2 emissions. In part because CO_2 emissions permanently alter the atmosphere and oceans, the timing of a particular CO_2 emission has minimal effects on the long-term level of warming. As a result, temperature outcomes depend primarily on cumulative emissions, rather than the specific timing of when those emissions occur.

The third concept is that the ability of temporary carbon storage to contribute to temperature targets depends on the expected timing of temperature stabilisation. Although cumulative CO_2 emissions budgets determine expected temperature outcomes, the scientific literature has identified a potential role for temporary carbon removal and storage as a potential supplement to deep decarbonization scenarios. However, not all temporary carbon storage can contribute in this manner. For example, carbon that is stored for only a short duration that expires before global temperature stabilisation is achieved will not contribute to temperature stabilisation outcomes. In contrast, carbon that is stored for a duration that exceeds the date at which temperature stabilisation occurs can help reduce peak global temperatures — but its eventual re-emission still leads to future climate damages. Only truly permanent storage avoids any future climate harms.

2.1. The atmospheric lifetime of CO_2 emissions

In a foundational review paper, David Archer and colleagues describe the carbon cycle dynamics that govern the impact of fossil fuel CO_2 emissions. They point out the widespread public confusion about the atmospheric lifetime of CO_2 emissions, the timeframe of which many non-scientists misunderstand (Archer et al., 2009, p. 118):

> " *The gulf between the widespread preconception of a relatively short (hundred-year) lifetime of CO_2 on the one hand and the evidence of a much longer climate impact of CO_2 on the other arguably has its origins in semantics. There are rival definitions of a lifetime for anthropogenic CO_2. One is the average amount of time that individual carbon atoms spend in the atmosphere before they are removed, by uptake into the ocean or the terrestrial biosphere. Another is the amount of time it takes until the CO_2 concentration in the air recovers substantially toward its original concentration. The difference between the two definitions is that exchange of carbon between the atmosphere and other reservoirs [such as the biosphere and the oceans] affects the first definition, by removing specific CO_2 molecules, but not the second because exchange does not result in net CO_2 drawdown. The misinterpretation that has plagued the question of the atmospheric lifetime of CO_2 seems to arise from confusion of these two very different definitions*."

These misunderstandings likely continue to distort perceptions about the value of temporary carbon storage. While the first definition of the atmospheric lifetime of CO_2 may be most intuitive — how long it takes, on average, for a carbon atom emitted to the atmosphere to get absorbed into the biosphere or the oceans — this is the wrong way to think about the timeframe over which CO_2 emissions have climate impacts.

Fossil CO_2 emissions change the equilibrium atmospheric CO_2 concentration and contribute to global warming over a much longer period of time as a result. After rising in response to emissions, atmospheric CO_2 concentrations diminish over time via a set of feedback mechanisms that operate over widely distinct timeframes. These feedbacks can be summarised in four categories (Table 1).

Table 1: Carbon cycle feedbacks on CO_2 emissions

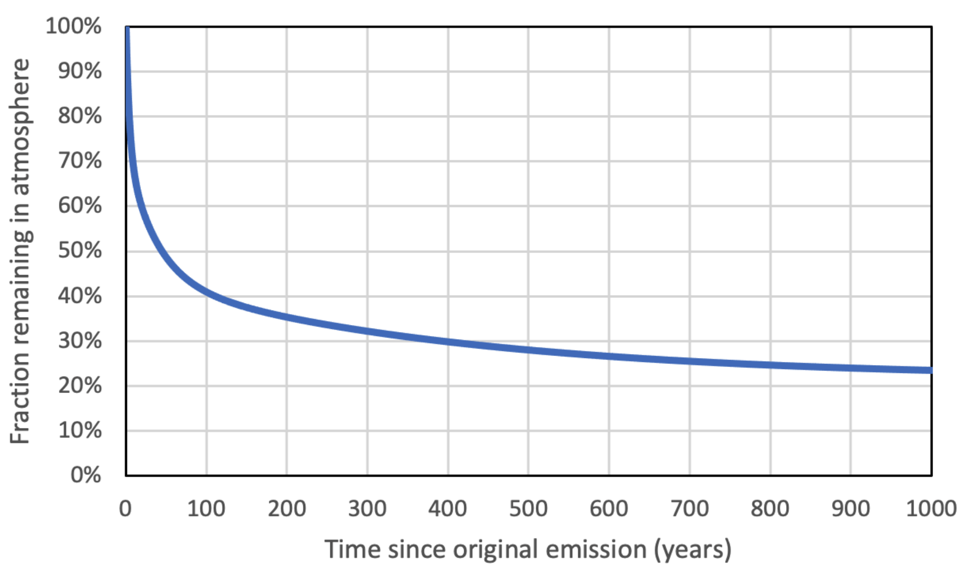
Based and National Research Council (2011) and Pierrehumbert (2014)

Timeframe	Primary feedback mechanisms
0-100 years	Land biosphere uptake Upper-ocean uptake, acidification
100-1,000 years	Deep-ocean uptake, acidification
1,000-10,000 years	Neutralisation by sediment dissolution and carbonate weathering
More than 10,000 years	Silicate weathering

The modelled effect of these dynamics on the atmospheric concentration of CO_2 is shown in Figure 1, which is based on Joos et al. (2013). As the IPCC notes, "[n]o single lifetime can be given" to CO_2 because of its complex atmospheric dynamics (Myhre et al., 2013a, p. 737). However, the fraction of the original emissions remaining in the atmosphere can be characterised using an impulse response function, like the one shown in Figure 1.[4]

Figure 1: Fraction of atmospheric CO_2 remaining over time

Based on Joos et al. (2013)



[4] The IPCC's Sixth Assessment Report observed that although the scientific community has improved its understanding of carbon cycle responses to CO_2 emissions since the Joos et al. (2013) results were reviewed in the Fifth Assessment Report, "there has been no new quantification of the response of the carbon cycle" since that time (Forster et al., 2021, p. 1012). Thus, the results reported by Joos et al. (2013) and Myhre et al. (2013a, 2013b) represent the best assessed information as of the IPCC's Sixth Assessment Report in 2021.

The impulse response function defined by Joos et al. (2013) is specifically restricted to a time horizon of no more than 1,000 years, so it is not appropriate for estimating the fraction of atmospheric CO_2 remaining on longer timescales. However, Archer et al. (2009) report results out to 10,000 years, at which point about 20% of the increase in atmospheric CO_2 concentrations remain.[5] The full set of results is reported in Table 2.

Table 2: Fraction of atmospheric CO_2 remaining over time

Based on Joos et al. (2013) and Archer et al. (2009)

	20 years	100 years	500 years	1,000 years	10,000 years
Fraction remaining	60% (±14%)	41% (±13%)	28% (±10%)	25% (±9%)	About 20%

As this discussion illustrates, the atmospheric lifetime of CO_2 emissions is a complex concept that cannot reasonably be described with a simple number — unlike most other air pollutants. Once CO_2 is emitted, it constantly cycles between Earth systems reservoirs. A large share of the initial concentration gets uptaken by the biosphere and oceans over the course of decades to centuries. The initial reduction is rapid, with significant uptake in the first few years and decades following the original emissions; it then plateaus over a few centuries to a few thousand years as the ocean and atmosphere equilibrate.

Once equilibration between the atmosphere and oceans is achieved, a substantial fraction of the original emissions — about 20% — remains in the atmosphere, where it is subject to reductions by natural geologic processes that operate on timeframes that are longer than all of written human history. Meanwhile, a substantial share of the original CO_2 emissions have also been absorbed in the oceans, where they are already contributing to problems like ocean acidification that will persist on comparably long-term timescales. Simply put, CO_2 emissions have global environmental impacts that are permanent by any measure relevant to our species.

[5] Archer et al. (2009) report results for two different scenarios, an initial pulse of 1,000 PgC and an initial pulse of 5,000 PgC over a background concentration of 280 ppm CO_2, i.e. pre-industrial atmospheric levels. The results from the 1,000 PgC scenario are reported here. For the 1,000 PgC scenario, about 20% of emissions remain in the atmosphere at 10,000 years, whereas that fraction rises to about 35% for the 5,000 PgC scenario. The 1,000 PgC scenario is reasonably comparable to the scenario used by Joos et al. (2013) and Myhre et al. (2013a, 2013b), which employed a pulse of 100 PgC over a background concentration of 389 ppm CO_2, which is approximately the level observed in 2010. A petagram of carbon (PgC) is equivalent to 1 billion metric tons of carbon, or 3.67 billion metric tons of carbon dioxide.

2.2. Temperature impacts depend on cumulative CO_2 emissions

A second foundational concept from the physical climate sciences is that temperature outcomes primarily depend on cumulative CO_2 emissions. The IPCC provides a helpful summary of the issue and its implications for thinking about climate mitigation:

> "*There is a near-linear relationship between cumulative CO_2 emissions and the increase in global mean surface air temperature (GSAT) caused by CO_2 over the course of this century for global warming levels up to at least 2°C relative to pre-industrial* (high confidence)." (Canadell et al., 2021, p. 678)[6]

> "*Mitigation requirements over this century for limiting maximum warming to specific levels can be quantified using a carbon budget that relates cumulative CO_2 emissions to global mean temperature increase* (high confidence)." (Canadell et al., 2021, p. 678)

Although this understanding now informs today's climate science and climate policy analysis, its contemporary origins are relatively recent (Lahn, 2021, 2020). As climate scientist Myles Allen and colleagues discuss in a recent review paper, the contemporary understanding of the approximately linear relationship between cumulative CO_2 emissions and temperature outcomes — as well as the need to achieve near-net-zero emissions in order to stabilise temperature levels — only emerged in the mid-to-late 2000s (Allen et al., 2022, pp. 850–853). Scientists have been aware of the effectively permanent nature of CO_2 emissions for some time (Archer, 2005; Siegenthaler and Oeschger, 1978), but it wasn't until a series of high-profile papers that two additional insights became clear: first, that temperature stabilisation requires near-zero CO_2 emissions (Matthews and Caldeira, 2008) and second, that projected temperature outcomes largely depend on cumulative emissions (Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009; Zickfeld et al., 2009).[7]

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[6] Other studies indicate that this relationship is robust for higher-warming scenarios as well, including up to 3°C above pre-industrial temperatures (Allen et al., 2022, p. 859). However, the linear relationship between cumulative emissions and temperature outcomes assumes carbon cycle feedbacks from "natural" carbon sinks on land, which many national greenhouse gas inventories inconsistently attribute to "managed" land sinks (Grassi et al., 2023, 2021). Because managed land sinks are generally reported as carbon removal in national inventories, they reduce countries' reported net emissions relative to the carbon cycle feedbacks assumed in most physical climate models. Thus, it may be necessary to adjust calculated carbon emissions budgets downward to account for the inconsistency between climate models and national inventories. Thanks to Pierre Friedlingstein, Giacomo Grassi, and Ken Rice for helpful guidance on these important nuances.

[7] As discussed below in Section 3.2, many methods for valuing temporary carbon storage were developed before the contemporary scientific consensus on the linear relationship between temperature outcomes and cumulative emissions emerged at the end of the 2000s. For example, global warming potentials were developed around 1990 (Lashof and Ahuja, 1990) and related tonne-year accounting

2.3. Temperature stabilisation scenarios

A third physical climate concept that should inform a framework for valuing temporary carbon storage is the expected timeframe for temperature stabilisation. Its importance is straightforward, if often underemphasized. Carbon that is only temporarily stored outside the atmosphere can reduce peak temperature outcomes if the duration of its storage extends beyond the time at which peak warming occurs (Matthews et al., 2022). If the carbon is re-emitted before peak warming occurs, however, then it can increase peak warming without supporting the temperature stabilisation goal of the Paris Agreement (Kirschbaum, 2006).

Contemporary climate policy targets link the Paris Agreement's temperature target — limiting warming to well under 2°C above pre-industrial temperatures, with a goal of 1.5°C — to reaching and sustaining net-zero greenhouse gas emissions (Allen et al., 2022; Fankhauser et al., 2022). Depending on the evolution of short-lived greenhouse gas emissions, aerosol emissions, and net-negative CO_2 emissions in a given future scenario, however, temperature stabilisation might be more closely related to the timing of net-zero CO_2 emissions or net-zero emissions across all greenhouse gases.

As the IPCC summarised the issue:

> "*Achieving global net zero CO_2 emissions, with anthropogenic CO_2 emissions balanced by anthropogenic removals of CO_2, is a requirement for stabilizing CO_2-induced global surface temperature increase. This is different from achieving net zero [greenhouse gas] emissions, where metric-weighted anthropogenic [greenhouse gas] emissions equal metric-weighted anthropogenic [greenhouse gas] removals. For a given [greenhouse gas] emissions pathway, the pathways of individual [greenhouse gas] determine the resulting climate response, whereas the choice of emissions metric used to calculate aggregated emissions and removals of different [greenhouse gases] affects what point in time the aggregated [greenhouse gases] are calculated to be net zero. Emissions pathways that reach and sustain net zero [greenhouse gas] emissions defined by the 100-year global warming potential are projected to result in a decline in surface temperature after an earlier peak* (high confidence)." (IPCC, 2021, § D.1.8)

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methods were developed about a decade later (Fearnside et al., 2000; Moura Costa and Wilson, 1999; Noble et al., 2000). The fact that these frameworks were developed so much earlier suggests that they should be re-interpreted in light of the contemporary understanding that temporary delays in emissions do not reduce expected long-term warming effects.

Although the precise timing of temperature stabilisation depends on scenario-specific information, it is related to the timing of when each scenario achieves net-zero CO_2 emissions and net-zero greenhouse gas emissions. Working Group III of the IPCC summarised this information across each of the scenarios in its database (see Table 3).

In every scenario where both outcomes are achieved, the timing of net-zero CO_2 emissions occurs before that of net-zero greenhouse gas emissions; and in most cases where both are achieved, the point of net-zero greenhouse gas emissions follows approximately 10 to 40 years after net-zero CO_2 emissions (IPCC, 2022, § C.2.4). Note, however, that some extremely low-emissions scenarios do not achieve net-zero emissions by 2100, and that only those scenarios that achieve these outcomes by 2100 are reported in Table 3. Because the IPCC's working definition of temperature increases looks to the maximum temperature increase experienced by 2100 rather than maximum temperatures over their entire future, some scenarios with non-net-zero emissions continue to project increasing warming past 2100. As a result, the timing of net-zero CO_2 and net-zero greenhouse gas emissions reported in Table 3 concerns only a subset of relevant scenarios.

Table 3: Net-zero milestones by scenario family

Based on Riahi et al. (2022, Table 3.2)

Category[8]	Description[9]	Net zero, CO_2 only[10]	Net zero, all greenhouse gases
C1	Limit warming to 1.5°C (>50% likelihood) with limited or no overshoot	2050 – 2055 [2035 – 2070]	2095 – 2100 [2050 – after 2100]
C1a	Same as C1, with net-zero greenhouse gases	2050 – 2055 [2035 – 2070]	2070 – 2075 [2050 – 2090]
C2	Return warming to 1.5°C (>50% likelihood) after a high overshoot	2055 – 2060 [2045 – 2070]	2070 – 2075 [2055 – after 2100]
C3	Limit warming to 2°C (>67% likelihood)	2070 – 2075 [2055 – after 2100]	After 2100 [2075 – after 2100]

8 See IPCC (2022, Box SPM.1) for additional details for each scenario category. For brevity, some higher-warming categories have been omitted.

9 Temperature limits are defined as the maximum warming above pre-industrial temperatures experienced by 2100. Many scenarios do not achieve net-zero CO_2 emissions or net-zero greenhouse gas emissions by 2100, even if they limit warming by 2100 to a certain amount.

10 Brackets show the 5-95% confidence interval. Because the IPCC only reports outcomes through 2100, the term "after 2100" is reported here without greater specificity.

C3a	Same as C3, with action starting in 2020	2070 – 2075 [2055 – after 2100]	After 2100 [2080 – after 2100]
C3b	Same as C3, with current nationally determined contributions through 2030	2065 – 2070 [2055 – 2090]	After 2100 [2075 – after 2100]
C4	Limit warming to 2°C (>50% likelihood)	2080 – 2085 [2065 – after 2100]	After 2100 [2075 – after 2100]
C5	Limit warming to 2.5°C (>50% likelihood)	After 2100 [2080 – after 2100]	After 2100 [2090 – after 2100]
C6	Limit warming to 3°C (>50% likelihood)	Net-zero emissions not reached by 2100	Net-zero emissions not reached by 2100

The data reported in Table 3 illustrate an important inverse relationship between the ambition of global emission reductions and the duration of carbon storage needed to contribute to temperature stabilisation. The more successful the world is at rapidly reducing emissions, the sooner temperature stabilisation will be achieved. In contrast, higher-emission scenarios take longer to reach temperature stabilisation. While these patterns are intuitive, their implications for temporary carbon storage may not be. Longer duration storage is required to contribute to temperature stabilisation in moderate- to low-ambition futures, whereas shorter-duration storage could contribute to high-ambition futures.

The inverse relationship between climate policy ambition and carbon storage duration requirements should be interpreted in light of two significant challenges. The first is that global climate policy action is not in line with the Paris Agreement target, even though on paper current pledges could be enough to limit warming to just under 2°C (Meinshausen et al., 2022). Although the Paris Agreement aims to keep temperature increases to no more than 1.5°C and well below 2°C— and thus is most consistent with categories C1 through as high as C4 — the vast majority of countries are not on track to achieve their emission reduction pledges (Rogelj et al., 2023; Victor et al., 2017), with the global emissions outlook more consistent with categories C5 and C6 as a result (Sognnaes et al., 2021). The second challenge is that while policymakers in a given polity might set a relatively ambitious net-zero climate target for their own jurisdiction, they do not have direct control over global emissions, which are ultimately what determine the extent of total warming and the timing of peak temperatures.

From Table 3, a few broad patterns emerge. For the most ambitious scenarios, such as categories C1 and C2, the median timing of net-zero CO_2 emissions is expected between 2050 and 2060, indicating that the most optimistic outcome would require carbon durability to extend at least to this point. Even in these scenarios, the median timing of net-zero greenhouse gas emissions spans 2070 through 2100, indicating that longer durability might be required even for the most ambitious emissions scenarios.

For high-ambition scenarios that limit warming to 2°C, such as categories C3 and C4, the median timing of net-zero CO_2 emissions is expected to arrive about 10 to 20 years later, between 2065 and 2085. The median timing to net-zero greenhouse gas emissions is expected after 2100, indicating that substantially longer-duration carbon storage could be required to support temperature outcomes in these scenarios.

Finally, for medium-ambition scenarios that limit warming to 2.5°C, such as category C5, the median timing of net-zero CO_2 emissions is not expected before 2100. Scenarios that limit warming to 3°C or higher do not achieve net-zero CO_2 emissions before 2100.

Some additional caveats are in order. First, the precise requirements for temperature stabilisation are slightly more nuanced than simply reaching and sustaining net-zero CO_2 or net-zero greenhouse gas emissions (MacDougall et al., 2020). Jenkins et al. (2022) argue that temperature stabilisation is best characterised as requiring "approximately net zero" CO_2 emissions due to uncertainty in the effects of residual CO_2 emissions. For a scenario that limits warming to 1.5°C, they find that temperature stabilisation is consistent with emissions that range from between -7.3 billion to 6.2 billion tCO_2 per year, with a median estimate of 2.2 billion tCO_2 per year. Thus, reaching net-zero CO_2 emissions is not a perfect proxy for stabilising the temperature effects of CO_2 emissions; substantial uncertainty remains.

Second, the timing of temperature stabilisation depends on more than just CO_2 emissions. While achieving approximately net-zero CO_2 emissions is a prerequisite for temperature stabilisation (Jenkins et al., 2022), temperature levels could stabilise quickly or relatively slowly thereafter depending on emissions of non-CO_2 greenhouse gases (Abernethy and Jackson, 2022) and aerosols (IPCC, 2021, Section D.1). The effect of non-CO_2 greenhouse gas emissions is difficult to characterise across scenarios because of the challenge in comparing the warming effect of CO_2 and non-CO_2 gases. As discussed above, CO_2 emissions are effectively permanent and primarily affect temperature outcomes on the basis of *cumulative emissions*; in contrast, most other greenhouse gases are relatively short-lived and primarily affect temperature outcomes on the basis of *emission rates* (Duan and Caldeira, 2023; Pierrehumbert, 2014). Meanwhile, short-lived aerosol pollution has contributed up to 0.8°C of cooling that partially counteracts emissions-induced warming, but aerosol pollution is expected to drop substantially in the near future due to reduction in heavy-polluting combustion that drives aerosol production (IPCC, 2021, Sections A.1.3 and D.1.7).

Despite these caveats, the inverse relationship between climate ambition and the minimum durability of carbon storage required to support temperature stabilisation is clear. The more ambitious the emissions scenario, the shorter the necessary durability of carbon storage; the less ambitious the emissions scenario, the longer carbon must be stored outside the atmosphere to contribute to temperature stabilisation.

Policymakers looking to set minimum durability requirements face a difficult challenge. They may control what durability they deem acceptable, as well as the net-zero CO_2 or net-zero greenhouse gas emission targets they require for their jurisdiction. But the ability of a given carbon storage duration to contribute to temperature stabilisation depends not just on what one country achieves, but on how global emissions evolve in the decades and centuries ahead.

Because real-world climate mitigation policy ambition lags substantially behind countries' pledges (Rogelj et al., 2023), policymakers should explicitly consider the possibility that temperature stabilisation will not be achieved according to the timeframe of countries' climate pledges or even achieved prior to 2100. Policymakers should set minimum durability requirements with these risks in mind, and ideally with a precautionary mindset that recognizes the lack of control anyone has over global emissions futures. A minimum durability requirement that is premised on rapid global climate action that does not actually materialise in time would fail to contribute to limiting warming under the precise conditions when failure matters most.

3. CLIMATE-EQUIVALENCE CLAIMS

Having addressed fundamental scientific constructs above, this report now turns to a discussion of how carbon markets and climate policy systems apply these concepts in practice. This section concerns how these systems determine climate-equivalence between carbon storage and CO_2 emissions.

There are two general categories of climate-equivalence assertions. The first is physical equivalence, which requires that the durability of carbon storage is reasonably comparable to the effectively permanent consequences of CO_2 emissions. As explained further in Section 4, properly substantiated physical-equivalence claims provide for the most robust carbon credit use cases. However, very few carbon storage applications are physically equivalent to fossil CO_2 emissions.

An alternative approach, economic-equivalence, uses economic discounting to favour near-term climate benefits at the expense of long-term climate damages. This can be done either by ignoring climate damages past a certain point in time, or through the application of compounding discount rates to climate damages over time. In practice, most climate-equivalence claims are based on economic equivalence methods. As explained further in Section 4, these methods are usually inconsistent with temperature stabilisation targets when they are used to offset or otherwise compensate for fossil CO_2 emissions — although they can be adequately functional when used for non-compensatory purposes, depending on the details of how they are implemented.

It is worth noting that the very idea of climate-equivalence has been thoughtfully criticised. A growing social science literature highlights a number of reasons why, in practice, human systems fail to live up to theoretical standards for equivalence (Carton et al., 2021; Gifford, 2020). In particular, many studies raise concerns about the potential for carbon removal and carbon storage claims to operate as a form of “moral hazard” or “mitigation deterrence” (Carton et al., 2023, 2020). These concerns deserve to be taken seriously. They may already be manifesting in practice, as evidenced by many governments’ net-zero plans projecting significant, unabated residual greenhouse gas emissions (Buck et al., 2023). The types of equivalence presented below are not intended to dismiss or ignore these lines of criticism, but rather to categorise the claims being made to bring precision to their use cases as well as the distinct risks they present.

3.1 Physical equivalence

Because CO_2 emissions have effectively permanent consequences on the atmosphere and oceans, carbon storage can be said to be physically equivalent when its durability offers a reasonably comparable timeframe.

The key word here is permanent. Very few forms of carbon storage — such as CO_2 mineralization (NASEM, 2019, p. 247) or supercritical geologic CO_2 storage that avoid all permeable faults, fractures, and leaky wellbores (NASEM, 2019, p. 319) — feature physical characteristics that justify the permanent label. For inherently less durable storage, liability regimes and other policy arrangements could seek to impose the requirement to renew or replace temporary carbon storage far into the future. Although potentially valid, these approaches face questions about their fundamental political and institutional feasibility, as very few human institutions have persisted for more than a few hundred years.

Several other approaches could plausibly deliver long-duration carbon storage, but there is an important difference between long-duration and permanent storage. For example, the long-duration carbon removal procurement fund, Frontier, generally uses a 1,000-year durability threshold for its purchasing activities.[11] This threshold provides for very long-duration claims, but even carbon storage for 1,000 years isn't permanent. Delaying emissions by several hundred years or even a thousand doesn't permanently avoid the warming impacts of those delayed emissions, and thus isn't strictly physically equivalent to avoiding emissions in the first place — although very long delays in emissions defer climate damages beyond peak warming and therefore could contribute to temperature stabilisation outcomes.[12]

Furthermore, while physical equivalence invokes the notion of a 1:1 relationship between permanent carbon storage and CO_2 emissions, there is some initial evidence that suggests carbon removal claims do not exhibit perfect symmetry. Zickfeld et al. (2021) present modelling analysis that shows that CO_2 emissions are modestly more effective at raising atmospheric concentrations than carbon removal is at reducing concentrations. Specifically, they use a climate model to compare the fraction of CO_2 that remains airborne (for emissions) to the fraction of CO_2 that remains outside the atmosphere for removals (for removal) after 100 years. For a 100 $GtCO_2$ pulse, those fractions are 0.53 and 0.51, respectively, indicating that removals are modestly less effective than emissions. For a

[11] Disclosure: I have provided occasional unpaid advice to Frontier, and have also consulted for Isometric, a carbon removal verification and registry company that works with long-duration carbon removal supplies and buyers.

[12] See footnote 2 for additional discussion on this point.

much larger 500 $GtCO_2$ pulse, those fractions are 0.57 and 0.47, respectively, indicating that removals are notably less effective. At the same time, however, Zickfeld et al. also find the opposite effect with respect to temperature outcomes: specifically, they find that carbon removal is modestly more effective at reducing temperatures than additional emissions are at increasing temperatures.

These findings suggest that permanent carbon removal and storage is not physically equivalent to CO_2 emissions on a 1:1 basis. Nevertheless, the policy implications are not entirely clear. Zickfeld et al. (2021) find that while atmospheric carbon removal is (1) *less effective* at reducing atmospheric CO_2 concentrations than emissions are at increasing them (which suggests a greater than 1:1 ratio is needed for physical equivalence with respect to CO_2 concentrations), it is also (2) modestly *more effective* at reducing temperatures (which suggests a less than 1:1 ratio is needed for physical equivalence with respect to temperature outcomes).

A complete analysis of physical equivalence is outside the scope of this report and remains an active area of research. Because of the scale of human interference in the climate system — both current and prospective — our ability to project expected climate outcomes requires the use of complex earth systems models. Studies like Zickfeld et al. (2021) and Jenkins et al. (2022) help illustrate how climate modelling tools can be applied to study the implications of deep decarbonization and efforts to stabilise temperatures, including atmospheric carbon removal. It is plausible and perhaps likely that additional research will change the scientific understanding of physical climate-equivalence, uncertainty about which is relevant to grounding climate policy in the best available research.

3.2 Economic equivalence

In contrast to physical-equivalence claims, which equates carbon durability requirements to the physical properties of the climate system, economic-equivalence claims are based on the expected costs and benefits of carbon storage. Within the economic-equivalence paradigm, benefits are calculated as the climate impacts that are avoided or deferred as a result of carbon storage, whether permanent or temporary, while costs are based on the climate impacts caused by emissions at the end of the carbon storage period.[13]

[13] Technically, this is a definition for the social cost of temporary carbon storage. Private costs would reflect the actual economic costs of temporarily storing carbon, e.g. the expenditures required to protect and monitor a forest for a 50-year term. Because temporary carbon storage defers climate impacts, the social cost is given by the time-discounted value of deferred climate impacts, which can be compared to the time-discounted value of the avoided climate impacts in the interim.

An economic-equivalence methodology compares the time-discounted costs and benefits of temporary carbon storage against the costs and benefits of permanently avoiding CO_2 emissions. Because temporary storage offers strictly fewer net economic benefits than does permanent storage, more than 1 tonne of CO_2 temporarily kept out of the atmosphere is needed to match the net economic consequences of 1 tonne of CO_2 emitted or permanently stored — a number that has been called an "equivalence ratio" (Chay et al., 2022; Marshall and Kelly, 2010).

Some argue that one should be able to "vertically stack" temporary carbon credits to make an economic-equivalency claim (Cabiyo and Dolginow, 2022; Groom and Venmans, 2023). Vertical stacking creates near-term climate benefits by temporarily deferring the emission of more than 1 tonne of CO_2 — with the appropriate number given by the equivalence ratio — but comes at the cost of emitting those same tons later. The general idea is to create sufficiently more benefits today to justify greater costs in the future.[14] For example, Groom and Venmans (2023) argue that between 2 and 3 tonnes of CO_2 stored for 50 years is equivalent to the effectively permanent impact of 1 tonne emitted to the atmosphere. When this approach is used to make a compensatory offsetting claim (see Section 4 below), however, it necessarily results in higher long-term warming (Badgley et al., 2023; Kirschbaum, 2006).

To date, two broad categories of economic equivalence have emerged in the academic literature and in practice. The first is based on the concept of balancing cumulative radiative forcing over specified time horizons, which stops short of projecting temperature outcomes and temperature-based damages. The second is based on a more comprehensive economic optimization informed by a fuller consideration of temperature-based damages.

3.2.1 Cumulative radiative forcing

One family of economic-equivalence claims is rooted in the concept of radiative forcing, which is expressed in terms of watts per metre squared (W/m^2). It represents a flux of energy per unit area, and can be used to describe the overall warming effect of greenhouse gases on the Earth's energy balance. By adding up fluxes over time, one can compare the

[14] In economic terms, this condition requires that the growth rate of climate damages is less than the social discount rate. As Richards (1997) and Herzog et al. (2003) note, however, this isn't the only possibility. Alternatively, it might be true that the growth rate of climate damages exceeds the social discount rate, in which case there is greater net-present value to avoiding future climate impacts than avoiding present climate impacts. Under those conditions, no case can be made that temporary carbon storage efficiently defers climate impacts under a cost-benefit optimization framework.

cumulative radiative forcing of one action (e.g., temporarily storing carbon) against another (e.g., emitting CO_2 to the atmosphere).[15]

Cumulative radiative forcing metrics are sometimes used to develop an economic-equivalence methodology known as tonne-year accounting. Tonne-year accounting, in turn, is based on a more familiar method for asserting the equivalence between CO_2 and non-CO_2 gases, the global warming potential. To explain how tonne-year accounting works, we begin with global warming potentials.

Global warming potentials

The idea of determining equivalency between greenhouse gas emissions on the basis of cumulative radiative forcing was first applied to develop global warming potentials (GWPs) (Lashof and Ahuja, 1990). Because CO_2 is the most important anthropogenic greenhouse gas from a warming perspective — yet it also has a distinctly complex and long atmospheric lifetime — it is difficult to quantify the relative warming impacts of non-CO_2 greenhouse gases. The GWP metric is designed to fill that gap. It is a unitless ratio that compares the cumulative heat-trapping properties of two greenhouse gases, based on a thought experiment of releasing the same mass of each gas at the same time.

A GWP metric describes how much heat a greenhouse gas traps relative to CO_2 over a specified time horizon. It is calculated by taking the integral of the radiative forcing of each gas over a fixed time period [*t*] as follows:

$$GWP_{GHG,t} = [\int_0^t RF(t)_{GHG} \cdot dt] / [\int_0^t RF(t)_{CO2} \cdot dt]$$

Where the radiative forcing over time [$RF(t)_i$] depends on the instantaneous radiative forcing due to an increase in the concentration of a greenhouse gas [a_i] and the concentration of that gas remaining in the atmosphere at time *t* [$c(t)_i$]:

$$RF(t)_i = a_i \cdot c(t)_i$$

[15] Some might reasonably characterise equivalence claims based on radiative forcing as primarily physical in nature. This report classifies them as primarily economic in nature because all equivalence claims based on radiative forcing also include a time horizon cut-off or other temporal discounting practice that leads to fundamentally normative rather than physical consequences. One's preferred categorization makes no difference to this report's analysis or conclusions.

Where *c(t)*$_{CO2}$ is given by an impulse response function for CO_2, such as Joos et al. (2013), and *c(t)*$_{GHG}$ is given by an impulse response function for the non-CO_2 greenhouse gas.

Using this simple construct, the first IPCC report reported GWP calculations for a range of greenhouse gases across three representative but ultimately arbitrary time horizons: 20 years, 100 years, and 500 years (Shine et al., 1990, Table 2.8). For example, GWP values for fossil methane were reported as 63, 21, and 9 in the IPCC's first assessment; in the IPCC's most recent sixth assessment report, those values were estimated as 82.5 (±25.8), 29.8 (±11), and 10 (±3.8) (Forster et al., 2021, Table 7.15).

GWP calculations lie behind common popular assertions that a greenhouse gas like methane is 30 or 82 times more potent than CO_2. The reality is much more complicated. For many years, climate scientists have raised substantial and appropriate concerns with GWPs (Fuglestvedt et al., 2000; Pierrehumbert, 2014; Shine, 2009; Shine et al., 2005; Smith and Wigley, 2000a, 2000b). Because CO_2 has effectively permanent effects on the global climate, while most other greenhouse gases have fixed and relatively short atmospheric lifetimes, GWP metrics do not reflect physical equivalency between two greenhouse gases.

Instead, GWP metrics measure the relative warming effects of two greenhouse gases over a fixed period of time, while ignoring everything that follows afterwards.[16] Looking at the cumulative radiative forcing of a relatively short-lived gas might not present any problems, but because the GWP compares this against the cumulative radiative forcing of CO_2 — which has permanent effects that stretch over geologic time, but are discounted by any fixed time horizon *t* — the GWP metric inherently departs from physical reality.

Climate scientists have developed alternative summary metrics that attempt to correct for the distinct time-dynamics of atmospheric CO_2 emissions (Lynch et al., 2020; Meinshausen and Nicholls, 2022). Although these alternatives can produce more physically meaningful insights, they are not simple for non-experts to generate or use. Likely for that reason, none has yet caught on in public-facing applications outside of the scientific community.

[16] The choice to count all radiative forcing through a certain point in time while ignoring everything that follows can be normalised to an effective discount rate. Sarofim and Giordano (2018) calculate that the implicit discount rates for standard GWP-100 and GWP-20 metrics for methane are about 3.3% and 12.7%, respectively — far above the kinds of long-run social discount rates preferred by economists, which tend to be closer to 2% (Drupp et al., 2018).

Tonne-year accounting

A few years after the construct of global warming potentials was developed to summarise the relative warming effects of CO_2 and non-CO_2 greenhouse gases, it was extended to address the value of temporary carbon storage (Fearnside et al., 2000; Moura Costa and Wilson, 1999; Noble et al., 2000, Section 2.3.6.3).

The resulting family of approaches, known as tonne-year accounting, uses the same basic concepts underlying the GWP metric (Brandão et al., 2013; Chay et al., 2022; Parisa et al., 2022). Instead of comparing a non-CO_2 greenhouse gas against CO_2, tonne-year accounting methods compare the value of temporary and permanent carbon storage over a fixed time period.[17] Nearly everything about the conceptual basis of tonne-year accounting is directly analogous to GWPs (Chay et al., 2022):

- Tonne-year accounting methods calculate cumulative radiative forcing across temporary and permanent emissions scenarios to calculate an equivalence ratio.
- Tonne-year equivalence ratios can be used to assert that a certain number of tonnes of temporarily-stored CO_2 are equivalent to the impact of a ton of CO_2 emitted or avoided.
- Tonne-year accounting methods look only at cumulative radiative forcing up through a specified time horizon (such as 100 years) and ignore all consequences thereafter. This makes the approach fundamentally subjective and physically unrepresentative of the effects of CO_2 emissions.

Although tonne-year accounting might seem like a physical construct because it is rooted in the impulse response function of CO_2 (Joos et al., 2013) and based on the concept of radiative forcing, it departs from physical reality in several material respects. Like a GWP, it ignores all damages past a fixed time horizon and therefore is incapable of making a physical-equivalence claim. Even within the artificial construct of the metric's time horizon, however, the approach does not account for all of the relevant physical considerations (Kirschbaum, 2006).

One significant shortcoming of tonne-year accounting is that the approach ignores substantial radiative forcing effects. Although tonne-year accounting was developed for use in forest carbon applications (Noble et al., 2000) and has most recently been applied to this

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[17] Technically there are multiple distinct sub-methods, with the Lashof and Moura-Costa methods most commonly used in practice. This discussion is limited to the Lashof method, which is by far the less problematic of the two. See Chay et al. (2022) for details and open source code that implements several different approaches.

sector of carbon storage (Parisa et al., 2022), forest carbon storage has important effects on albedo and radiative forcing that aren't incorporated into tonne-year calculations. In addition to storing carbon, trees and forest cover can change the reflectivity of the earth's surface, increasing its albedo and therefore increasing radiative forcing from the surface — an effect that counteracts the radiative forcing benefits of carbon storage (Bright et al., 2015; Novick et al., 2022).

Biophysical feedbacks to albedo can be quite substantial in some applications, such as carbon storage in boreal forests. In the context of a recent tonne-year carbon crediting protocol for reforestation in Canada, researchers estimate that these non-carbon biophysical feedback effects could lead to over-crediting of about 16% for deciduous tree species and about 45% for evergreen trees (Badgley et al., 2023). These are purely physical effects that are left out of the tonne-year accounting calculations, illustrating their inconsistency with climate physics.[18]

A second shortcoming is that cumulative radiative forcing is a poor proxy for climate damages in the first place. For one thing, an atmosphere-only approach ignores all of the effects on the oceans, including ocean acidification. But more broadly, contemporary climate economics looks at a fuller chain of causal effects in projecting climate damages, incorporating emissions, their effect on CO_2 concentrations, the warming that results, and then calculating climate damages that follow from a changed climate (NASEM, 2017; Rennert et al., 2022). For this reason, more advanced economic-equivalence claims are rooted in the contemporary social cost of carbon paradigm that uses simple climate modelling to project temperature outcomes from emissions trajectories.

3.2.2. Temperature-based damages

A second family of economic-equivalence claims follows the general logic of integrated assessment models to calculate temperature-based damages, rather than on based simple metrics of radiative forcing over time. These approaches then compare the discounted climate damages of two scenarios to determine their relative values.

[18] Some tonne-year accounting approaches also employ double-discounting methods in inconsistent and problematic ways. For example, the forest offsets company NCX initially proposed to include economic discounting of cumulative radiative forcing in addition to cutting off calculations after a fixed economic period (Parisa et al., 2022). Thus, the company's radiative forcing calculations are discounted twice: once with a standard time-dependent discount rate, and a second time with an arbitrary cut-off point that ignores all effects past a fixed point in time (Chay et al., 2022).

Calculating temperature-based damages requires the use of a climate model. In this framework, a given emissions scenario is modelled to determine its effect on atmospheric greenhouse gas concentrations and the warming impacts that follow. Next, this model-derived information is used to project time-discounted economic damages expected in response to warming. Discounted economic damages in one scenario can be compared to another to give an equivalence ratio, just as is done for cumulative radiative forcing outcomes for global warming potentials or tonne-year accounting. Thus, temperature-based damages can be used to make equivalence claims between different greenhouse gases (Sarofim and Giordano, 2018) or the value of temporary relative to permanent storage (Groom and Venmans, 2023).

Temperature-based damage calculations offer a superior way of asserting climate-equivalence than simple metrics based on radiative forcing because they explicitly project the climate outcomes of a given emissions scenario, rather than use simple and physically imprecise heuristics as proxies for climate damages. When it comes to valuing temporary carbon storage, they represent an important improvement over tonne-year approaches.

Nevertheless, temperature-based damages also feature important limits. Arguably the most important is that damage estimates are typically based on a subset of relevant impact pathways, based on incomplete empirical records that are extrapolated into the future. Even if damage estimates were perfectly accurate, they produce equivalence ratios that can be inconsistent with policy goals that seek to limit temperature increases, such as the Paris Agreement, because they compare discounted economic damages across scenarios. Like any other economic-equivalence claim, temperature-based damages use economic discounting and therefore can favour scenarios that reduce near-term damages at the expense of higher-long-term damages. In contrast, temperature stabilisation requires limiting long-term damages, which requires limiting cumulative CO_2 emissions and does not justify offsetting or otherwise substituting temporary carbon storage in place of permanent emission reductions.

Because economic-equivalence claims can justify ongoing CO_2 emissions on the basis of mitigating short-lived greenhouse gases or temporarily storing carbon, these claims are often inconsistent with temperature stabilisation goals. Instead, they should be thought of as a robust framework in the cost-benefit optimization paradigm, rather than the cost-effectiveness paradigm associated with achieving temperature stabilisation goals.

As discussed in Section 1.2, above, the cost-benefit optimization paradigm is often inconsistent with the Paris Agreement's temperature stabilisation requirement. For this reason, climate-equivalence claims based on cost-benefit optimization techniques may not be consistent with the Paris Agreement's temperature stabilisation goals. In turn, any claim of consistency should be justified with appropriate analytical reasoning, rather than presumed.

4. CARBON CREDIT USE CASES

The value of temporary carbon storage depends not just on critical scientific concepts in climate science and the category of climate-equivalence claims, but also for what purpose or use these claims are made.

For the sake of simplicity, it is easiest to think about any carbon storage claims — whether temporary or permanent — as being embodied in individual carbon credits. The question is, how might such carbon credits be used? Broadly speaking, there are two types of claims that a credit user might make, compensatory and supplemental.

A compensatory claim is one in which a carbon credit is used to assert that an individual, company, or government has neutralised or offset its own emissions, such as for the purposes of satisfying a net-zero target or reporting net emissions outcomes inclusive of carbon removal. In effect, a compensatory claim seeks to cancel out the harms of CO_2 emissions via the unique retirement of carbon credits.

Alternatively, one could also use the same credits to make a non-compensatory, supplemental claim. Here, the benefit of carbon storage is asserted as an addition to, rather than replacement for, ambitious climate mitigation efforts; those making these claims are sometimes said to be following a "contribution" model (e.g., by the Voluntary Carbon Markets Integrity Initiative) or pursuing "beyond value chain mitigation" (e.g., by the Science-Based Targets initiative) (SBTi, 2023; VCMI, 2023). Most academic modelling of the potential climate benefits of temporary storage contemplate supplemental claims that do not substitute for mitigation (Matthews et al., 2022). A supplemental claim does not attempt to justify the statement that CO_2 emissions have been neutralised or otherwise offset, but could potentially be used to contribute to an effort to slow the rate of overall global warming or reduce the incidence of peak global warming by temporarily reducing atmospheric CO_2 concentrations.

The difference between the two use cases for carbon credits has significant policy implications. Because carbon pollution has effectively permanent impacts on the atmosphere and oceans, temporary carbon storage shifts the timing of climate impacts, rather than reducing their long-term magnitude (Herzog et al., 2003). Mitigating the consequences of fossil CO_2 pollution requires carbon storage on geologic time frames (Fankhauser et al., 2022). As a result, compensatory claims contribute to the Paris Agreement's global temperature stabilisation goal only when they are based on physical equivalence (Höglund, 2023b).

Table 4 provides a summary of the interaction between the type of credit use claim being made (compensatory vs. supplemental) and the basis for asserting equivalence (physical vs. economic). Notably, physical equivalence provides a valid basis for compensatory and supplemental claims, but is likely limited because of its strict requirement that the durability of carbon storage match the geologic time frames over which CO_2 pollution impacts the atmosphere. In contrast, compensatory claims based on economic-equivalence do not support temperature stabilisation, but supplemental claims based on economic equivalence can be consistent with temperature stabilisation — so long as carbon storage durability extends sufficiently beyond the time of peak warming (see Section 2.3).

Table 4: Does temporary carbon storage support temperature stabilisation?

Basis	Compensatory claim	Supplemental claim
Physical equivalence	Yes	Yes
Economic equivalence	No	Yes, if durability sufficiently exceeds the point of temperature stabilisation

It is worth emphasising that temporary carbon storage that expires before temperature stabilisation does not contribute toward that end. At the same time, temporarily avoiding emissions is better than doing nothing, so this conclusion would seem to present a paradox: how can something that is better than nothing have nothing to offer a policy target?

The answer is that all temporary carbon storage has a non-zero climate benefit under a cost-benefit-optimization paradigm, whereas carbon storage with a durability below a minimum threshold does not help to achieve a temperature target and therefore has no value under a cost-effectiveness paradigm (see Section 1.2). The difference in value reflects the different objective of each valuation exercise, which is concerned with optimal economic benefits in the first instance and achieving a temperature stabilisation outcome in the second. The fact that short-duration carbon storage has different values under the two paradigms reflects the fact that cost-benefit optimization is not necessarily consistent with temperature stabilisation.

As discussed in Section 2.3, the minimum durability required to contribute to temperature stabilisation is based on the timing of temperature stabilisation outcomes in global emissions scenarios. This concept involves three vulnerabilities that justify a precautionary approach to risk management. First, the minimum durability concept cannot be observed in advance because it is based on what will happen in the future. Second, it depends on what will happen globally, rather than what any one country can achieve on its own. And third, the minimum durability requirement is inversely related to global climate policy ambition: the more successful the world is at decarbonizing, the shorter the minimum durability needed to contribute to temperature stabilisation, and the less successful the world is at decarbonizing, the longer the minimum durability needed to contribute to temperature stabilisation.

Because of the substantial uncertainty involved in setting minimum durability requirements, policymakers may wish to set durability requirements that significantly exceed their anticipated minimum durability needs. Not only are there major risks in setting a minimum durability threshold that turns out to be too short in practice, but there are also climate impacts associated with the emissions that follow the end of temporary carbon storage. The longer those impacts can be deferred, the better off future societies will be. This report does not quantify the extent to which durability requirements should exceed policymakers' expected minimum needs, but it identifies reasons that policymakers should go beyond the bare minimum, both from a practical perspective and on a normative basis. Additional research is needed to help quantify a more robust answer.

5. CONCLUSION

This report develops a science-based framework for assessing the climate value of temporary carbon storage. It begins with the premise that the goal of global climate policy is to limit warming in line with the Paris Agreement. This policy objective effectively prioritises a cost-effectiveness framework (which seeks to achieve the stated goal with minimum costs) above the alternative economic paradigm of cost-benefit optimization (which tends to prioritise near-term climate benefits at the expense of higher long-term warming outcomes).

The value of temporary carbon storage depends on a set of concepts from physical climate science, the basis of a climate-equivalence claim, and the use case for any associated carbon credits. Each of these insights is summarised here.

Climate science concepts:

- **CO_2 EMISSIONS ARE FOREVER.** CO_2 emissions have effectively permanent impacts on the atmosphere and oceans. About 20% of carbon pollution remains in the atmosphere 10,000 years after it is emitted, with the remainder drawn down slowly over geologic timescales that exceed the scope of written human history.
- **WARMING DEPENDS ON CUMULATIVE CO_2 EMISSIONS.** The extent of global warming primarily depends on cumulative CO_2 emissions, not their rate or timing. Because temporary carbon storage only delays CO_2 emissions, it does not reduce long-term temperatures.
- **TEMPERATURE STABILISATION DEPENDS ON THE TIMING OF NEAR-NET-ZERO EMISSIONS.** Temperature stabilisation requires near-net-zero CO_2 emissions and also depends on the rate of short-lived climate-forcing emissions, such as methane (which increases warming) and aerosols (which decrease warming). The timeframe over which temperature stabilisation is expected to occur can be approximated by looking at future emissions scenarios that reach net-zero greenhouse gas emissions. The more ambitious the climate mitigation scenario, the shorter the time to temperature stabilisation; the less ambitious the climate mitigation scenario, the longer the time to temperature stabilisation. Because ambition depends on global emissions, policymakers in a single jurisdiction

do not control this outcome. Net-zero greenhouse gas emissions are generally reached in the second half of this century for 1.5°C-aligned scenarios, closer to the end of the century for 2°C-aligned scenarios, and likely beyond 2100 for higher-warming scenarios. Because the world is not on track to constrain emissions consistent with a 2°C warming limit, it would be pragmatic as well as consistent with the precautionary principle to anticipate that the timeframe for global temperature stabilisation is closer to 100 years than to 50 years.

Climate-equivalence claims:

- **PHYSICAL EQUIVALENCE.** Only truly permanent carbon storage applications can be deemed physically equivalent to CO_2 emissions, and even then an adjustment may be required to account for asymmetry in the effect of carbon removal relative to CO_2 emissions. Physical-equivalence claims provide a valid basis for all use cases considered below, but are likely limited in scope due to their extreme durability requirements.

- **ECONOMIC EQUIVALENCE.** Most real-world climate claims rely on economic-equivalence claims, which compare discounted costs and benefits across emission scenarios to generate equivalence ratios. An equivalence ratio allows one to assert that a certain number of tons of CO_2 temporarily stored is normatively equivalent to CO_2 emissions. One family of economic-equivalence claims is based on the cumulative radiative forcing of an emissions scenario (W/m^2 integrated over time), which is used to calculate the well-known global warming potential of non-CO_2 greenhouse gases as well as to calculate the value of temporary carbon storage using a family of methods known as tonne-year accounting. Another, relatively more robust family of economic-equivalence methods uses climate models to calculate the warming impact of emissions scenarios and then uses temperature-based damage functions to project economic consequences. All economic-equivalence methods use economic discounting and favour short-term climate benefits (such as deferred warming from temporary carbon storage) at the expense of long-term climate damages (such as higher warming from temporary carbon storage that is re-emitted at the end of its storage period).

Carbon removal use cases:

- **COMPENSATORY CLAIMS.** Compensatory claims seek to offset or neutralise the effects of CO_2 emissions. The only valid, Paris-aligned compensatory claims are based on physical equivalence. Compensatory claims based on temporary carbon storage are physically inconsistent and increase warming at the end of the carbon storage period.

- **SUPPLEMENTAL CLAIMS.** Supplemental claims do not seek to offset or neutralise the effects of CO_2 emissions, and instead are made in addition to, rather than in place of, CO_2 mitigation strategies. Because supplemental claims do not replace CO_2 mitigation, valid claims can be made on the basis of either physical equivalence or economic equivalence. However, in order for a supplemental claim based on economic-equivalence to support a temperature stabilisation outcome, the durability of carbon storage must extend sufficiently beyond the timing of peak warming — with a safety margin based on policymakers' risk tolerance and view of how manageable a climate liability will be left to the future when temporary carbon storage expires.

Using this framework, one can answer policy-relevant questions.

- **From a climate science perspective, how similar or different are temporary and permanent carbon storage outcomes?**

  Temporary and permanent carbon storage outcomes are fundamentally different. Because CO_2 emissions have effectively permanent impacts on the atmosphere and oceans, temporary storage isn't physically equivalent to CO_2 emissions. Offsetting or neutralising CO_2 emissions using temporary carbon storage leads to higher warming outcomes at the end of the carbon storage period, and thus is generally inconsistent with limiting warming under the Paris Agreement.

- **Under what conditions is temporary carbon storage consistent with the Paris Agreement's commitment to limiting warming to well under 2°C?**

  Although temporary carbon storage cannot offset the permanent effect of CO_2 emissions, it can contribute to the Paris Agreement's goals if it is used to supplement greenhouse gas emission reductions, rather than to replace CO_2 emission reductions.

This condition requires that temporary carbon storage not be equated with CO_2 emissions and that temporary carbon storage does not give social, economic, or legal licence to emit CO_2. In turn, temporary carbon storage claims should not be used to offset CO_2 emissions nor be made eligible for use in government compliance programs that seek to limit CO_2 pollution. Temporary carbon storage should be encouraged as a complement to CO_2 mitigation, rather than a substitute for CO_2 mitigation, subject to minimum durability requirements that are aligned with the Paris Agreement's warming limits.

- **How long does temporarily stored carbon need to remain out of the atmosphere in order to contribute to global temperature stabilisation under the Paris Agreement?**

  Even though encouraging temporary carbon storage as a supplement to CO_2 mitigation can help reduce peak warming outcomes, its effectiveness depends on the durability of carbon storage. Carbon must be stored beyond the point of global temperature stabilisation — a minimum storage durability — if it is to contribute to the Paris Agreement's goals. Policymakers do not control when temperature stabilisation will occur, as that depends on global emissions rather than emissions under the control of any single jurisdiction. Based on the IPCC's analysis of future emissions scenarios, temperature stabilisation might not occur until the second half of this century for 1.5°C-aligned scenarios; close to the end of the century for 2°C-aligned scenarios; and not until after 2100 for higher-warming scenarios. The world is not yet on track for 2°C, suggesting that minimum durability should be set closer to 100 years than to 50 years.

- **Is all carbon storage that meets a minimum durability requirement equally valuable?**

  No. The minimum durability concept describes the point at which temporary storage begins to contribute to temperature stabilisation. Storage that is less durable does not contribute to stabilising temperatures, and therefore has no value toward that objective at all. This does not mean that all storage that meets the minimum durability requirement is equally valuable. For example, suppose that temperature stabilisation will occur in 100 years and there is a temporary storage option that stores carbon for 105 years. If enough carbon is temporarily stored for 105 years and then released, it could cause temperatures to exceed the business-as-usual peak or lead the world to experience near-peak temperatures for longer, compared to a scenario without temporary storage. In contrast, carbon storage with a durability of 200 or 500 years would be more valuable than storage with a durability of 105 years, both because these longer durations provide greater physical benefits (via a longer time period in which climate impacts are avoided) but also because longer storage periods increase the plausibility of identifying new carbon storage options to replace expiring temporary storage. This pattern holds in general: temporary carbon storage is more valuable the longer its duration, although calculating the analytical value of sufficiently durable but still impermanent carbon storage is outside the scope of this report.

- **Is all carbon storage that meets a minimum durability requirement as valuable as permanent carbon storage or permanently avoided emissions?**

  No. From a temperature stabilisation perspective, the climate mitigation contribution of temporary carbon storage is always less than permanent carbon storage and always less than permanently avoided emissions. Even when temporary carbon storage is durable enough to contribute to supporting temperature stabilisation goals, there is always an opportunity cost associated with pursuing temporary storage whenever permanent alternatives are available. There are good reasons to support the development of early-stage climate strategies when more effort is needed to support mature decarbonization efforts, such as supporting innovation and learning in order to be able to deploy newer solutions at scale in the future. However, these arguments must be carefully distinguished from simple equivalence claims that give permission to pollute or equate temporary carbon removal with emissions in carbon accounting frameworks. Quantifying the break-even conditions under which support for temporary carbon storage makes sense is outside the scope of this analysis.

It is important to acknowledge that temporary carbon storage has value. However, its value in contributing to the goal of planetary temperature stabilisation is contingent on the duration of its carbon storage. Temporary carbon storage must last at least as long as it takes the world to reach peak temperatures. Anything less will fail to reduce peak temperatures, and could even increase peak temperatures if used as a carbon offset.

Policymakers should also consider establishing minimum durability requirements that exceed their best estimate of the time before peak temperatures are expected. Not only would this be sound as a precautionary practice in the face of substantial uncertainty, but also in recognition of the fact that release of temporarily stored carbon will impose harms on the future.

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