

# The Carbon Removal Obligation: Beyond Emissions Trading to a Negative Carbon Economy

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# Abstract

The introduction of Carbon Dioxide Removal (CDR) into detailed process-based integrated assessment models enabled increasingly ambitious scenarios in successive assessment cycles of the Intergovernmental Panel on Climate Change, despite continued growth in global emissions between reports. These more stringent end-of-century temperature outcomes became feasible through the gradual incorporation of climate overshoot into scenarios – the notion that temperature targets could be temporarily exceeded and later restored by removing more carbon from the atmosphere than is emitted at that time. Given growing evidence of escalating and potentially uncontrollable climate risks at warming levels above 1.5-2°C, this logic was implicitly codified in the 2015 Paris Agreement temperature goals. More recent scientific literature often interprets the Paris Agreement as a long-term objective of achieving warming of 1.5°C by 2100 while keeping temperatures below 2°C at all times. Framed in these terms, the Agreement thus relies on large-scale CDR deployment, eventually requiring levels where removals exceed residual emissions globally, yet the necessary technologies, policies, markets, and institutions remain profoundly underdeveloped.

Integrating CDR into today's carbon-pricing designs, where removals would merely offset emissions within the same period, is ill-suited to CDR in general and to net-negative operation in particular. Once removals exceed residual emissions and net emissions turn negative, conventional carbon pricing shifts from a source of public revenue to a sustained public expenditure, undermining fiscal sustainability and, in turn, the political feasibility of maintaining net-negative emissions and achieving overshoot reversal.

To address this challenge, the thesis develops the Carbon Removal Obligation (CRO), an intertemporal policy framework that assigns emitters enforceable forward liabilities to remove CO<sub>2</sub> initially emitted and levies a stock charge on carbon temporarily stored in the atmosphere. CROs decentralize and make forward-looking the decision between “abate now” or “emit now” (and, thus, remove later), translating current emissions into predictable, time-bound demand for future removals and thereby reducing investment risk in CDR scale-up. The thesis also advances a case for a stand-alone removals market with dedicated targets and a distinct price path, separate from emissions trading, to better manage technological learning and distributional effects of private-sector CDR, prevent mitigation deterrence and environmental spillovers.

Methodologically, the thesis combines conceptual analysis, an analytical social-planner model, quantitative scenario exploration using an emulator of IAMs, and a legal-institutional blueprint for implementation. It proposes enforcing intertemporal obligations through financialized carbon debt, which, unlike other intertemporal carbon policy designs that depend

on upfront cash collateral, reduces capital immobilization and helps direct financial resources toward CDR project investments. This approach is expected to enhance the political feasibility of implementation while increasing exit costs and resilience against policy reversal.

Finally, the thesis situates CROs within the prospect of centuries-long net-negative governance, which may become unavoidable due to both delayed decarbonization and the growing need to counteract time-lagged climate impacts, including continued sea-level rise, permafrost thaw, and associated risks that persist even under stabilization of warming at 1.5°C. It outlines a sequencing of CDR policy from public-led scale-up to intertemporal obligation based on regulated financialization and, ultimately, utility-like provisioning of removals once CDR-delivering obligations have been exhausted.

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# 1. Introduction

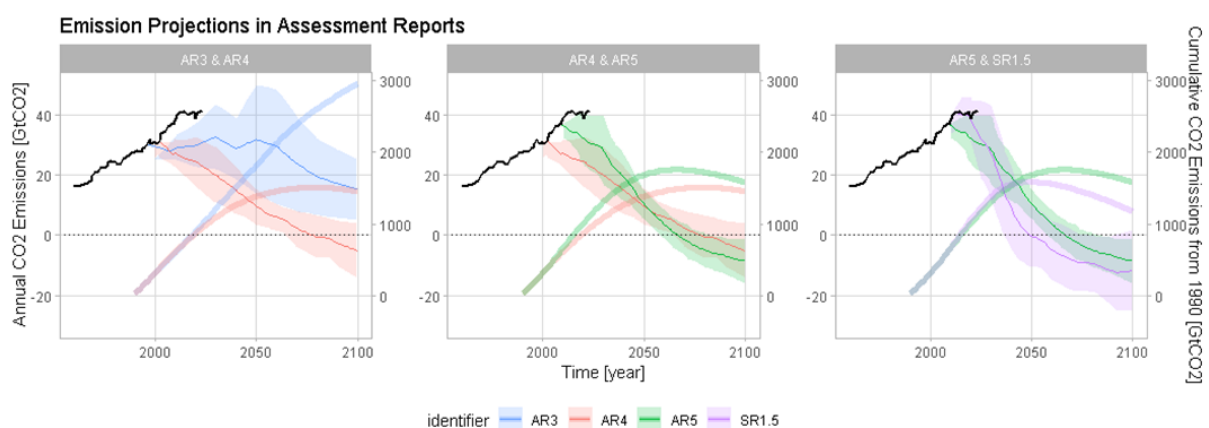
The field of Carbon Dioxide Removal (CDR) is broad, rapidly evolving, and spans multiple disciplines. Since the start of this research, several major reports have been released that provide excellent overviews of CDR in different contexts, including the State of CDR report led by the University of Oxford (1), a report by the European Scientific Advisory Board on Climate Change about scaling of CDR in the EU context (2), a report about the role of CDR for achieving Paris Agreement targets by the Swedish Energy Agency (3) as well as the broad Working Group III contribution to the 6th Assessment Report by the Intergovernmental Panel on Climate Change (4). The introductory chapter of this thesis provides an overview of CDR across disciplines, drawing primarily on the major assessment reports cited above. These reports are used to frame the field in general terms. Only where specific figures, national policies, or other concrete details are discussed, the relevant sources are cited explicitly.

## 1.1. CDR and climate goals

Over the past decades, climate mitigation scenarios generated with detailed process-based Integrated Assessment Models (IAMs) have played a central role in shaping international climate policy, providing quantitative projections of possible global emissions pathways and their climate outcomes. Successive Assessment Reports (ARs) of the Intergovernmental Panel on Climate Change (IPCC) have synthesized these scenarios, which in turn have shaped debates about what levels of atmospheric CO<sub>2</sub> concentrations and global temperature limits can be considered technologically and economically feasible.

The inclusion of CDR in IAMs beginning in the 2000s made it possible to model more ambitious climate outcomes for 2100 than would have been feasible through emission reductions alone. This is because, conceptually, CDR differs fundamentally from emission reductions (5). Emission reductions relative to a baseline imply that a particular activity produces fewer emissions because it has been replaced or modified through less carbon-intensive alternatives. Reductions are thus inseparable from the time and place of the original emitting activity. CDR, in contrast, introduces both spatial and temporal flexibility. CO<sub>2</sub> released at one time and location can, in principle, be recaptured later and elsewhere. This temporal flexibility has been especially influential in establishing CDR as a core mitigation option within IAM scenarios. Instead of avoiding emissions upfront by deploying potentially immature and expensive mitigation technologies, IAMs assume that CO<sub>2</sub> already emitted can be recaptured in the future, contingent on the availability of scalable CDR technologies.

On a global level, this temporal flexibility has given rise to the concept of climate overshoot. Most ambitious mitigation scenarios assessed by the IPCC now follow a two-phase structure (sometimes also described as 3 phases, with the third phase around net-zero). In the first phase, global net CO<sub>2</sub> emissions decline due to a combination of emission reductions and CDR, hence the growth rate of cumulative emissions, and therefore warming, is gradually reduced. After net-zero emissions are reached, marking the peak of cumulative emissions and CO<sub>2</sub> concentration, the second phase begins. Here CDR exceeds residual emissions from sectors that remain hard to decarbonize and drives net CO<sub>2</sub> emissions into negative territory. Assuming concurrent reductions in other greenhouse gases, global temperatures begin to fall, which is referred to as overshoot reversal.



**Figure 1: Evolution of scenario envelopes along successive IPCC Assessment Reports (ARs).** The three panels show a comparison between the different ARs and their associated projections for annual (large colored plumes with central estimate shown in thin colored lines) as well as cumulative CO<sub>2</sub> emissions (thick colored lines) until year 2100. In each of the three panels, observed annual historical emissions are presented by the thin black line. In AR3 (2001) the theoretically feasible end-of-century temperature was around 3°C above preindustrial levels. By AR4 (2007), this frontier had shifted to 2–2.4°C, with the consideration of early BECCS scenarios. Across all scenarios, AR5 (2013) approximately retained the end-of-century temperature range from AR4 but projected the reversal of a higher quantity of historical emissions, and therefore, a higher reliance on CDR. Moreover, the feasibility frontier in AR5 had shifted to 1.5–1.7°C, with BECCS becoming a standard component even in less ambitious scenarios due to its cost-effectiveness. SR1.5 (2018) provided the first comprehensive assessment of scenarios limiting warming to below 1.5°C by 2100. Limitations: The first data limitation concerns sectoral emissions data inconsistency. Historical data (black line) includes fossil fuel and land use change CO<sub>2</sub> emissions. Data used in the projections of the more recent Reports also includes both, however, this is less standardized in earlier ARs. Secondly, due to the nature of AR data, the center line in each panel does not reflect the mean or median but is instead approximated as a midpoint of min and max of the scenario envelope. Third, the transitions between the individual AR projections and historical data are linearly interpolated. In the absence of interpolation, a gap would exist between the historical emissions and the projections. This gap likely occurs due to the ARs basing the projections on data issued prior to the AR publication date. Due to the interpolation, each thin colored AR line may be slightly out of the AR’s intended range at its beginning.

Indeed, subsequent IPCC reports have featured increasingly ambitious mitigation pathways, despite continued global emissions growth, largely due to the introduction of CDR as a compensating mechanism, and the ability to overshoot and reverse (Figure 1). This went hand in hand with mounting evidence that warming beyond 2°C could lead to catastrophic

outcomes, including irreversible shifts in Earth-system dynamics. After the release of the IPCC's Fifth Assessment Report (AR5) in 2014, which demonstrated the feasibility of limiting warming to 2°C by the end of the century, the Paris Agreement codified a global temperature goal of “well below 2°C” and to “pursue efforts” towards 1.5°C. The subsequent IPCC Special Report on 1.5 °C (SR1.5) extended this proof-of-concept exercise, assessing scenarios consistent with 1.5°C pathways.

Today's global temperature goals rest on a foundation of large-scale CDR deployment, even though the technologies, legal and governance structures, as well as policy instruments required to deliver such deployment remain underdeveloped.

## 1.2. Definition and classification of CDR

CDR refers to a set of human interventions that capture CO<sub>2</sub> directly from the atmosphere and store it in a durable form, whether in geological reservoirs, terrestrial or marine ecosystems, or long-lived products. This definition encompasses both the deliberate enhancement of natural removal processes and the development of technological approaches for extracting and storing atmospheric carbon (1).

CDR is not a single technology but a heterogeneous family of approaches. They differ in terms of the mechanisms of capture (biological versus geochemical), the storage pools involved (e.g., vegetation, soils, geological formations, marine sediments, the built environment), and the durability of storage, which ranges from decades to millennia. These approaches also vary widely in their mitigation potential, technological readiness, costs and side-effects, which can be beneficial or detrimental. Among several classification schemes, two leading ones have emerged in recent literature. The first is between conventional and novel methods (1). Conventional approaches, such as afforestation, reforestation, or the use of harvested biomass in durable wood products, are already deployed at scale. Novel approaches, by contrast, remain largely at the pilot or demonstration stage, with leading examples including Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS), but also including novel options that enhance natural sinks. A second distinction is between temporary and permanent removals (2), which relates primarily to the durability of storage and associated reversal risks. Temporary removals are susceptible to reversal through human or natural disturbances; conventional CDR methods hence generally generate temporary removals. Permanent removals, in contrast, involve long-lived storage pools such as geological reservoirs and are primarily associated with novel, technologically intensive options.

Today, roughly 2 GtCO<sub>2</sub> per year are already removed from the atmosphere. However, the vast majority of this stems from conventional approaches in the Land Use, Land-Use Change and Forestry (LULUCF) sector, and even here, gross removals are smaller than the gross emissions generated within the same sector. By contrast, novel CDR methods remain at a nascent stage. They currently account for less than 0.1% of total removals, despite growing research and investment (1). While climate scenarios consistent with the Paris Agreement rely heavily on large-scale deployment of novel CDR, present-day deployment is negligible, highlighting the magnitude of the gap that must be closed.

### 1.3. Trends and challenges in CDR governance and policymaking

At the international level, CDR has entered climate negotiations but remains weakly defined: Under the Paris Agreement, progress is reviewed through the Global Stocktake (6), a periodic assessment of collective progress toward long-term goals. Within this process, government commitments to CDR remain vague. Nationally Determined Contributions (NDCs) and long-term strategies sometimes reference removals, but conventional pledges are often criticized for overreliance on land, while novel CDR commitments are rare and lack concrete national policy pathways that would generate sufficient demand (1).

Methodologies for accounting and certifying removals are under development for Article 6 of the Paris Agreement, which, with respect to CDR, establishes high-level guidance for voluntary international cooperation through tradable carbon credits. Yet the question of who should finance or deliver how much of the global removal effort has received little attention in negotiations so far. This debate will likely hinge on the United Nations Framework Convention on Climate Change's (UNFCCC's) principle of Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC), raising politically sensitive questions of equity, responsibility, and capacity among Parties.

#### 1.3.1. CDR policy objectives

The realization of CDR will ultimately depend on national or regional policy and governance. At the domestic or regional level, governance, among other functions, serves to enable research and innovation, creating standards for Measurement, Verification and Reporting (MRV) of removals, integration of removals into climate policy frameworks, and safeguarding against harmful deployment. Because CDR is highly heterogeneous, governance cuts across diverse policy domains, including, for instance, forestry, agriculture, energy, industry and

oceans. For example, conventional methods such as afforestation are linked to agricultural, land-use and biodiversity policies. DACCS, on the other hand, requires complex coordination along the infrastructure-heavy value chain, which includes CO<sub>2</sub> capture, transport and injection into geological storage. It thus may depend on energy, infrastructure, and industrial regulation. As a result, emerging CDR policy is shaped by existing sectoral frameworks and their path dependencies rather than by a dedicated governance architecture alone.

Moreover, to contribute credibly to national and international climate goals, CDR policy must navigate multiple, often competing, objectives. Foremost are avoiding mitigation deterrence, i.e., ensuring removals supplement rather than substitute for emissions reductions, and managing reversal risk of temporary removals. Additional objectives include achieving static and dynamic cost-effectiveness; ensuring fiscal sustainability; distributing costs and benefits fairly across society; safeguarding competitiveness across jurisdictions and addressing carbon leakage; internalizing environmental spillovers; and fostering technological learning. Given the heterogeneity of CDR options, the literature and early policy experiments converge on a sequenced, CDR-type-specific policy mix. In this approach, robust MRV and integrity safeguards, together with targeted research and technology support, are often prioritized first, before demand is scaled up through fiscally sustainable integration into competitive markets, complemented by measures to manage carbon leakage and maintain competitiveness, like the EU's Carbon Border Adjustment Mechanism (CBAM).

To date, most tangible progress has been made in supporting innovation. Particularly the United States have funded pilot projects and demonstration programs for novel CDR through the Inflation Reduction Act (IRA) and Bipartisan Infrastructure Law during the Biden Administration. However, many jurisdictions make MRV the first step toward integrating (especially novel) CDR into policies and markets. MRV means quantifying and tracking removals over a project's life, reporting results, and independent third-party verification. Because CDR methods differ, their evidence systems do too. For some approaches (e.g., ocean alkalization, peatland and wetland restoration, soil carbon sequestration) measurement is inaccurate and/or potentially very costly (with transaction costs of up to 80-90% of the value of issued credits (2)), forcing accuracy-cost trade-offs that can slow ramp-up or credibility. In the absence of harmonized supranational rules, today's MRV landscape is fragmented. Protocols overlap for some methods and are absent for others, and accounting diverges on how to treat measurement uncertainty, storage durability, and life-cycle emissions. MRV must also be coupled with governance for reversal risk, liability ownership and transfer of stored CO<sub>2</sub>, and legal accountability, so monetized benefits are not privatized while perpetual carbon liabilities and local impacts from CDR deployment are socialized.

Both the EU and the UK appear to be following a sequence that develops MRV frameworks first, before scaling removals. The EU's Carbon Removals and Carbon Farming (CRCF) Certification Regulation establishes a voluntary framework to certify carbon removals, with integration into the EU's Emission Trading System (ETS) under consideration. The UK is developing a framework for Greenhouse Gas Removal (GGR) MRV, and is considering carbon Contracts for Difference (CfDs) and the inclusion of CDR in the UK ETS. Compliance markets, that is, government driven markets based on regulatory requirements, like the EU or UK ETS as well as carbon taxes, are operating in multiple jurisdictions worldwide. However, at present the integration of CDR into compliance markets remains limited. As a result, commercialization has so far relied more heavily on voluntary than on compliance-based mechanisms.

### 1.3.2. Voluntary Carbon Market

The Voluntary Carbon Market (VCM) currently accounts for only around 2% of global carbon trading, compared with 98% in compliance markets, where trading is primarily in emissions allowances (1). The VCM is best understood as a decentralized system of registries through which actors voluntarily finance projects that reduce or avoid emissions, or remove CO<sub>2</sub> from the atmosphere. Each verified ton of CO<sub>2</sub> corresponds to one carbon credit, which can be retired for voluntary or compliance purposes.

CDR credits within the VCM exhibit a price disparity between conventional and novel approaches. Afforestation and reforestation projects typically generate credits priced below USD 20/tCO<sub>2</sub>, while credits for novel approaches such as DACCS can reach around USD 1,000/tCO<sub>2</sub> (1). Although overall volumes remain small, the VCM has emerged as an important early-stage platform for financing novel CDRs, providing early demand signals and a “laboratory” for the development and testing of MRV protocols. In fact, most practical MRV-related innovation is occurring in VCM at the project level, templates that will likely shape future compliance regimes.

Yet, the VCM also faces significant challenges. Oversight is complex, with a proliferation of crediting programs and standards for MRV, many of which are only beginning to adapt their frameworks to CDR. Integrity concerns have been widespread. Forestry projects, in particular, have been criticized for issuing credits of questionable value due to problems with baselines and additionality, while similar concerns have been raised for energy-related projects. Questions also remain about the role of major buyers. Analyses indicate that some of the largest purchasers of voluntary credits are fossil fuel companies, raising doubts as to whether VCM participation genuinely contributes to decarbonization or simply enables continued high-emission practices under the guise of offsetting.

In sum, the VCM is unlikely to mobilize sufficient finance to scale CDR to the levels implied in Paris Agreement-consistent scenarios. While it may serve as a critical incubator for novel approaches and MRV methodologies, significant long-term demand for CDR will ultimately require its integration into existing compliance markets, or the development of new compliance instruments.

## 1.4. CDR policy instruments

This section discusses approaches to create demand for CDR during the transition to net zero. Instruments for net-negative emissions raise additional design issues and are treated in Chapter 2.

### 1.4.1. Carbon pricing and CDR market integration

The main rationale behind carbon pricing is the attainment of cost-effective mitigation pathways. Static cost-effectiveness requires equalizing marginal costs of emission reductions and removals across sectors at a point in time. Dynamic cost-effectiveness extends this intertemporally to achieve a long-run goal at minimum discounted cost (7). Price-based instruments, like carbon taxes, and quantity-based instruments (carbon trading) are equivalent under idealized textbook assumptions, however, differences prevail in real-world implementations due to imperfect information, transaction costs, external shocks and political economy considerations (7). While comparatively little attention has been given to incorporating removals into carbon tax schemes, most proposals focus on integrating CDR into ETSs, especially in the EU context (2).

In theory, an integrated market with a uniform price for removals and emission reductions can deliver cost-effectiveness. In practice, unconstrained CDR integration risks environmental spillovers, integrity failures (especially with temporary CDR) and the substitution of emission reductions with removals, i.e., mitigation deterrence. Some design elements have thus gained prominence in recent debates as potential safeguards against the main challenges of integrating CDR into markets, i.e., mitigation deterrence and integrity risks from reversal.

#### 1.4.1.1. CDR integration with safeguards

CDR market integration has been proposed with supply and demand controls to exclude or strictly limit low-durability removals. Other safeguards include setting quantitative caps on the contribution of CDR overall, and/or to apply sustainability screens to prevent negative spillovers. Alternatively, integration via an intermediary institution, such as a proposed Carbon Central Bank (8), relies on a dedicated body to source and pool removals, manage supply and

demand (including durability screens), and operate counter-cyclically by placing removal units into the ETS when prices are high. This approach can substitute for or complement market-stability reserves and enables a diversified early-stage CDR portfolio before full market fungibility.

#### 1.4.1.2. Separating removals from emissions trading

Because some objectives of CDR policy pull in different directions (e.g., dynamic cost-effectiveness versus deterrence), policy proposals often combine target-led elements, such as quantitative goals for emission reductions and removals, with price-led elements that allow well-designed price signals to discover the efficient emission reduction-removal split, into hybrid instruments. One widely discussed approach to limiting mitigation deterrence is to establish separate targets for gross emissions and for removals, and, in some proposals, to isolate CDR markets from emissions trading altogether. Implementing such a distinction, however, is politically and administratively complex, as it requires alignment across target-setting, MRV, incentive schemes, and market design within the broader policy landscape (1). Another structural safeguard frequently recommended is to differentiate temporary and permanent removals through separate markets or a two-tier system, thereby limiting fungibility while allowing tailored rules for integrity and liability. Related concepts include the like-for-like principle, which holds that fossil emissions should be balanced only by permanent (geological) storage, an idea that underpins the notion of geological net-zero (9).

#### 1.4.2. Carbon storage obligations

Beyond demand-side carbon pricing, recent proposals have increasingly focused on supply-side obligations placed on fossil fuel extractors, producers, or importers. Under these approaches, firms placing fossil carbon into the economy would be required to demonstrate that an increasing share of an equivalent carbon quantity is permanently returned to geological storage. Examples include Carbon Storage Obligations (CSOs) or Carbon Takeback Obligations (CTBOs), which have recently been discussed in the UK, the Netherlands and Norway (10–12), with early implementations in the context of the EU's Net-Zero Industry Act (NZIA).

These instruments are generally framed as a complement to existing climate policy rather than a stand-alone substitute, acting as a backstop or safety net where carbon pricing alone does not deliver sufficient deployment of CCS or durable removals. By linking continued fossil supply to an increasing storage requirement, they can help ensure progress toward geological net zero (9), i.e., balancing carbon extracted from the geosphere with carbon permanently returned to it. Because fossil carbon is measured at the point of extraction or import, monitoring

may also be simpler than tracing emissions once carbon is diffused throughout the wider economy.

Well-designed obligations can also be structured in a cost-effective manner through tradable Carbon Storage Units (CSUs) or related certificate markets, allowing compliance to occur where storage can be delivered most efficiently. They may be especially valuable during ramp-up phases, when predictable demand signals are needed to accelerate early investment, learning, and infrastructure build-out. In addition, ratcheting obligations can create clearer long-term incentives for transport and storage networks, helping to coordinate the capture-to-storage value chain where conventional ETS incentives have often proven insufficient. Such frameworks may also harness engineering, geological, and project-management capabilities already present in the oil and gas sector.

### 1.4.3. Subsidies and public procurement

Government led grant funding, reverse auctions, CfDs, feed-in premia, and tax credits reduce cost and investment risk for early projects, helping promising but non-viable options the difficult step from demonstration to commercialization. Concrete examples include Sweden's reverse auction for BECCS; CfD-style programs in Denmark (CCUS Fund), the UK (Industrial Carbon Capture contracts), and the Netherlands (SDE++); and the US 45Q tax credit (2). These instruments are powerful for supporting learning and deployment but raise fiscal-sustainability questions if used as the sole demand channel for CDR. Earmarking carbon-pricing revenue helps overcome these fiscal constraints but is considered politically fragile when funds pass through general budgets.

Notably, many designs straddle this taxonomy (i.e., pricing vs. mandates vs. subsidies). CTBOs generate a shadow emissions price via removal/CCS costs embedded in fossil products; an ETS operating in a net-negative regime resembles a subsidy to removals; and public procurement often relies on price-competitive mechanisms like CfDs or reverse auctions similar to emissions trading.

### 1.4.4. Pricing architectures for temporary CDR

Temporary removals face substantial MRV and integrity challenges, as discussed in Section 1.3. These include measurement procedures that are often either inaccurate or costly and thus inaccessible for smaller actors; blurred boundaries between removals and emission reductions, depending on baseline and additionality assumptions; and a generally strong dependence on baseline design, which can create perverse incentives, for example, deforestation prior to project integration to establish a more favorable baseline as seen in New

Zealand's ETS (2). In addition, some temporary removals are vulnerable to climate-related disturbances such as fire, drought, and pest outbreaks, events largely outside the control of project developers and akin to force majeure. Cross-sectoral overlaps, for example with agricultural, forestry, or biodiversity policies may further introduce conflicts and complicate governance.

Despite these challenges, temporary removals will need to become a cornerstone of climate mitigation according to scenarios assessed by the IPCC. Incentive schemes thus need to consider reversal risks with rewards remaining strictly lower than for permanent removals or emission reductions. Three broad architectures for pricing temporary removals have been discussed (2):

The simplest option is funding via subsidy programs, which in turn might rely on carbon-pricing revenue recycling. Such programs may pay discounted rewards reflecting storage duration and reversal risk; however, commitment issues remain. Once discounted rewards are paid, project operators may face limited incentives to minimize reversal risks.

Alternatively, temporary removal credits can be integrated into emission trading at the prevailing price while charging the then current price if reversal occurs. This reduces commitment problems, as operators incur penalties upon reversal, but demands guardrails against integrity failures, notably limited liability or enforceability of liability upon reversal. Several mechanisms have been proposed to improve the equivalence in carbon trading of emission reductions and permanent as well as temporary removals, including expiry-dated credits with renewal options; automatic credit cancellation and compensation through the buyer of removal credits upon reversal; contractual liabilities for project owners; buffer pools; insurance against reversal (2); or bundling of different durability profiles into removal units (RUs) (13). Clarifying liability for stored CO<sub>2</sub> and synchronizing financial flows at issuance with physical reversals decades later mirrors intertemporal policy challenges for overshoot management, discussed in Chapter 2. Designs where the CDR project owner bears reversal risk are generally better suited to internalize these risks.

A third variant is stock-storage-based subsidies, or carbon rental, where governments or markets pay rewards conditional on additional carbon stock (e.g., in biomass), with payments stopping if reversal occurs. This mitigates commitment problems but imposes heavy MRV demands. In practice, approaches that pay discounted rewards without managing reversal may be most feasible initially, with later integration into economy-wide pricing only after robust equivalence metrics and long-term reversal management are established.

### 1.4.5. Integrating high-durability, high-cost removals

Many proposals prioritize integrating permanent removals into emission trading first, given lower reversal risks and the fact that low-cost temporary credits might crowd out investment in durable options and higher-cost emission reductions. Yet early-stage ETS carbon prices may be too low to induce deployment, strengthening the case for targeted transitional support (for example, subsidies and public procurement) and for partitioning markets or setting minimum shares for durable CDR through mandates.

## 1.5. Thematic focus and research questions

My understanding of CDR was initially shaped by two commentaries I (co-) authored before work on this thesis began, which provide a foundation for the analysis developed in this thesis. In ref (14) we examined why IAMs deploy large amounts of CDR late in the century in AR5 scenarios, usually peaking around 2100. We argued that this was an artefact of perfect foresight modeling and mitigation cost discounting, which was later confirmed in a quantitative study (15). Other factors that can lead cost-minimizing IAMs to produce optimal pathways with CDR deployment peaking in 2100 include the treatment of temperature overshoot and later reversal as broadly substitutable for avoiding overshoot in the first place (because transitional damages or tipping risks are often not represented); finite model horizons that leave unresolved whether net-negative emissions should be phased out or continued beyond 2100; limited representation of the feasibility of governing sustained net-negative policies (as discussed in this thesis); and the assumption that future removals can be implemented with high credibility once they become cost-effective (for example, without permanence or delivery risks). We suggested that redistributing CDR over time, through rapid scale-up followed by a sustained plateau or a managed phase-out as temperature goals are approached, can lower climate overshoot and reduce side effects through reduced peak CDR deployment (e.g., land pressure from BECCS). It also resolves the economic oddity of peaking CDR precisely when carbon budget goals are achieved, and CDR thus no longer is needed. Such a rapid ramp-up of CDR would have to be accompanied by policies that suppress deterrence. Standard least-cost IAMs did not typically yield such pathways in AR5, although recent analyses indeed suggest the cost penalty of following similar non-cost-effective CDR paths may be negligible (16).

In ref (17) we highlighted a structural shift needed in economic carbon policy design. A carbon price on positive net emissions generates public revenue; once net emissions turn negative, however, the same hypothetical instrument implies public expenditure. In other words, taxpayers risk underwriting atmospheric clean-up at potentially very large scales. As argued

there: “[...] alternative market and non-market-based mechanisms for incentivizing NET [Negative Emission Technology] deployment at the required scale will have to be developed, focusing on the refinement of tools enabling non-contemporary transfers from present polluters to future negative emissions.” While intertemporal emission trading had been proposed before in the literature to improve dynamic efficiency (7), this observation was, to my knowledge, the first explicit conceptual linkage of net-negative emissions to the need for intertemporal carbon policy instruments. We indicated that operationalization of net-negative emissions cannot be treated as a simple extension of today’s carbon pricing regimes.

### 1.5.1. Research gaps

When this project began, the literature on CDR was expanding rapidly, including various contributions on the integration of CDR into carbon markets, as discussed above. However, research on how to finance and govern net-negative emissions over time and in line with established principles from environmental economics, like the Polluter Pays Principle (PPP) and Extended Producer/Emitter Responsibility (EPR/EER) (2), remained strikingly limited. In particular, there were no formal proposals for instruments that assign present emitters forward obligations to fund future removals<sup>1</sup>.

The economic carbon policy literature had explored intertemporal carbon markets as a means to enhance the dynamic efficiency of emissions trading. However, it had yet to provide worked-through answers to key questions surrounding intertemporal or forward obligations to finance CDR. Chief among these are issues of price and delivery risk: since CDR is not yet available at scale, and existing cost estimates are based at best on small-scale pilot projects, emitters cannot realistically be held to deliver something so inherently uncertain.

Even if the CDR ecosystem were sufficiently developed to allow emitters to form reliable expectations and assign prices to future removals, forward obligations would still carry significant risks. Emitters might default on their obligations, postpone decarbonization in anticipation of future policy relaxation (a time inconsistency problem), or even lobby for the cancellation of their commitments (moral hazard) – as seen, for example, in the debate surrounding the EU’s combustion engine phase-out. Moreover, firms with limited financial or technological capacity to decarbonize may have stronger short-term incentives to emit, yet be the least capable of fulfilling future removal obligations (adverse selection).

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<sup>1</sup> My first thesis paper (18), published in 2021, was developed in parallel with Derek Lemoine’s working paper introducing carbon shares based on the Social Cost of Carbon (19, 20). Since then, a small number of related proposals have emerged, notably by Kai Lessmann and colleagues (21) and by Anders Lyngfelt and colleagues (22) (both in 2024). This left a major conceptual and policy gap between the modelled reliance on CDR and net-negative emissions (as enshrined in the Paris Agreement) and the practical instruments that could deliver such outcomes.

Achieving CDR and net-negative emissions at scale may itself pose severe macroeconomic challenges. If poorly managed, such efforts could open systemic risk channels and prove fiscally untenable. Insights from the financial sector, environmental law, and monetary policy could offer valuable starting points, as these domains have long grappled with similar idiosyncratic and macro-level risks, as well as the management of long-dated environmental liabilities, e.g., for mine-site reclamation or nuclear waste disposal.

These gaps motivated me to develop an economic policy framework based on intertemporal Carbon Removal Obligations (CROs). However, the thesis does not follow the conventional structure of surveying a settled literature to identify gaps and then proposing solutions. Instead, it reflects a process of co-evolution within a dynamic and uncharted field. We conceptualized and refined the CRO approach, outlined a practical pathway for implementation, and situated it within long-term net-negative scenarios, thereby addressing the research questions below.

### 1.5.2. Research Questions

The research questions arise sequentially from the central problem examined in this thesis: conventional contemporaneous carbon policy instruments are poorly suited to governing net-negative emissions. If net-negative emissions are to be achieved, intertemporal policy instruments become relevant. Such instruments, however, raise new questions concerning uncertainty, commitment, and enforcement. Moreover, the thesis investigates whether the need for net-negative emissions may extend over much longer time horizons than is commonly assumed, thereby strengthening the relevance of intertemporal approaches.

#### 1. **Financing and fairness**

How can CDR, especially net-negative emissions, be financed through intertemporal instruments that uphold the PPP and EPR/EER?

#### 2. **Enforcement and incentive problems**

How can instruments be designed to overcome the core problems of intertemporal carbon trade, including, enforcement of carbon debt, default risk of carbon debtors, time inconsistency, adverse selection, and moral hazard?

#### 3. **Mitigation deterrence**

Under what conditions do removals substitute for (rather than complement) near-term abatement, and how can policy architecture minimize such mitigation deterrence?

#### **4. Rationale for financialization**

Is there a defensible efficiency and enforcement rationale for financializing removal obligations versus simpler deposit or tax-fund models?

#### **5. Implementation design**

How can a framework based on financialized removal obligations be implemented in practice?

#### **6. Price and delivery risk**

How can such a framework manage core uncertainties of intertemporal carbon trade, price risk (removal cost paths) and delivery risk (project failure, permanence)?

#### **7. Institutional architecture**

What institutions can oversee intertemporal obligations and manage macroeconomic and idiosyncratic risks associated with CDR, while maintaining democratic accountability?

#### **8. Long-run perspective and policy sequencing**

What is a plausible post-2100 trajectory for CDR and net-negative emissions, and what is the role of removal obligations in this long-term perspective? How should CDR policy be sequenced, from near term through mid-century and beyond this century, to build markets, infrastructure, and institutions?

## **1.6. Thesis structure**

This thesis contributes to the emerging field of economic governance for net-negative emissions by developing, step by step, a coherent framework for intertemporal carbon policy centered on CROs. A literature review is provided in Chapter 2. Each of the substantive Chapters thereafter build on previous Chapters and addresses one aspect of this overarching

objective, together forming an integrated research sequence. Chapters 3-6 move from conceptual foundations (defining carbon debt and proposing CROs) through analytical and quantitative modelling (social-planner model and pricing properties), to policy design, legal implementation and institutional blueprint. Finally, CROs are situated within centuries-long net-negative futures resulting from a stabilization target for time lagged climate impacts, inferred from a recent advisory opinion of the International Court of Justice (ICJ). Chapter 7 synthesizes these insights, comparing CROs with other proposals, and providing an outlook beyond issued discussed in Chapters 3-6.

To support quantitative exploration, the thesis develops an emulator of complex IAMs that treats technological uncertainty as “inter-model uncertainty” between complex IAMs. This is a methodological contribution, an initial step toward an IAM paradigm that goes beyond stylized IAMs like DICE, however which does not treat future technologies as perfectly known. Because it is methodological rather than central to the thesis’s core claims, the published working paper is presented in Annex 1. Annex 2 documents the authors’ contributions for each paper. Annexes 3-6 contain Supplementary Information for Chapters 3-6.

## **Chapter 2 – Literature review of net-negative instruments**

Existing proposals for incentivizing net-negative emissions are reviewed. Because the literature is thin, the review gives proportionally more space to the few existing proposals. Chapter 7 revisits these designs and compares their features with the CRO framework. Notably, when work on this thesis began, these proposals had not yet been published and therefore did not shape the original conception of CROs.

## **Chapter 3 – Conceptualization of carbon debt and its intertemporal management**

Peer-reviewed journal article: J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).

Chapter 3 develops the concept of carbon debt and its intertemporal management, initially in interaction with an ETS. It outlines how CROs could be introduced within the EU-ETS. In a simple analytical setting, an “interest on carbon debt” (also labeled an “atmospheric rental fee” or “premium” in other chapters) is introduced as a cost item for emitters. This mechanism incentivizes an earlier scale-up of CDR to limit temperature overshoot, thereby challenging the notion that CDR inevitably leads to mitigation deterrence and overshoot. The “interest” functions as an overshoot penalty, serving as a stylized proxy for the real costs associated with climate overshoot and management of its reversal.

## **Chapter 4 – Social planner implementation and pricing paths**

Publicly available working paper: J. Bednar, A. Baklanov, J. Macinante, The carbon removal obligation: Updated analytical model and scenario analysis. IIASA Working Paper WP-23-001 (2023); <https://pure.iiasa.ac.at/id/eprint/18572/>.

Chapter 4 extends Chapter 3 to a social planner setting, co-developed with Artem Baklanov. It provides a proof of concept showing how optimal emissions, removals, and respective marginal cost paths from a constrained planner problem can be translated into a private compliance-cost minimization problem through maturity schedules and flow or stock-based premium payments. In this way, the chapter demonstrates that the stylized “interest on carbon debt” introduced in Chapter 3 need not be imposed exogenously, but can reflect shadow values associated with constraints such as limited removals capacity or restrictions on net-negative emissions. Scenario analysis illustrates how different technological assumptions and policy constraints imply different price trajectories and therefore different CRO maturities and premia. The chapter thus serves as a bridge between the conceptual framework of Chapter 3 and the more applied institutional design developed in Chapter 5.

## **Chapter 5 – Refined policy design and implementation blueprint**

Peer-reviewed journal article: J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).

Chapter 5 builds on the insights from the social-planner model and introduces revisions to the initial concept of CROs presented in Chapter 3. In particular, it proposes a shift from net-emissions accounting to gross emissions and removals accounting, elaborating on the implications and advantages of this approach, a topic revisited in Chapter 7. A key consequence of this shift is the reduced role of the ETS once the carbon budget is exhausted (which explains the paper’s title “Beyond emission trading [...]”), as the trading of removals becomes fully separated from the ETS. In addition, Chapter 5 presents a detailed legal and institutional blueprint, developed in collaboration with a legal scholar (Justin Macinante), outlining how carbon debt can be financialized through CROs.

## **Chapter 6 – Net-negative futures beyond 2100**

Article submitted to peer-reviewed journal: J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries.

Chapter 5 examines whether there is a rationale for extending net-negative emission trajectories beyond the year 2100 – the typical cutoff point in current climate mitigation scenarios, where the continuation of net negative emissions remains unclear. Extension to net negative futures beyond 2100 has crucial implications for how long intertemporal removal obligations can serve to finance CDR. The analysis centers on time-lagged climate impacts as a key metric for assessing climate change, rather than the 1.5°C temperature goal of the Paris Agreement. These delayed impacts, such as sea-level rise and permafrost thaw, are among the most severe, unfold over longer timescales, and continue to intensify even under 1.5°C scenarios. We argue that the recent advisory opinion of the International Court of Justice (ICJ) could be interpreted as implying an obligation to stabilize time-lagged impacts at the lowest attainable levels. This interpretation would inherently necessitate net-negative emission pathways extending well beyond the 21st century. Such a long-term commitment may ultimately exceed the scope of intertemporal instruments like the proposed CRO.

## **Chapter 7 – Synthesis and conclusions**

This final chapter compares CROs with the alternative proposals reviewed in Chapter 2 and identifies desirable design features of intertemporal carbon policy instruments. It examines whether the financialization of carbon debt offers an effective mechanism for enforcing intertemporal obligations and for mobilizing additional funding for CDR projects. The chapter concludes with a sequenced, long-term CDR policy strategy that addresses the challenges discussed in Chapter 6 and provides insights into the institutional architecture and the role of government in implementing such a framework.

## 2. Literature review of net negative instruments

Several jurisdictions now signal intent to move beyond net zero. The European Climate Law sets a binding target of climate neutrality by 2050 and states the Union shall aim for “negative emissions thereafter.” In Europe, Sweden, Finland, Denmark, Switzerland and Germany are among the states planning to move into net-negative territory. Yet concrete operational pathways remain sparse, and the EU-ETS cap trajectory remains misaligned with 1.5°C-consistent carbon budgets. This section reviews policy instruments proposed in the literature to generate and govern net negative emissions. It complements the preceding review of instruments for the net zero transition and focuses on how to create durable, financeable obligations to reverse overshoot after net zero is reached.

A useful starting point is to distinguish contemporaneous from intertemporal carbon policy designs. It is argued that contemporaneous designs, like those introduced in Section 1.4, are not well suited to enable net negative emissions. Contemporaneous instruments raise funds at the time emissions occur, e.g., through carbon pricing, sufficient to pay for removals in the same period. Alternatively, as discussed in Section 1.4.2, mandates could be imposed to directly link emissions with removals at the same time. Intertemporal instruments, by contrast, bank present revenues from carbon pricing for future removals, or they assign to present emitters a forward obligation to finance or physically deliver removals in the future.

There are several reasons why intertemporal designs should be prioritized to finance net negative emissions. First and foremost, they help maintain fiscal sustainability. Once emissions turn net negative, conventional carbon pricing flips from a source of public revenue to an ongoing public expenditure, potentially imposing prohibitive budgetary burdens just as net negative emissions must scale. This coincides with the time when public budgets will already be constrained by greater climate impacts and adaptation needs. Alternatively, a purely contemporaneous, emitter-financed approach – either through carbon pricing or mandates – is problematic because the entire net negative burden is shifted onto a shrinking set of residual emitters with few remaining abatement options. In effect, it bets on the continued existence of those residual emitters to pay for future removals exceeding their own emissions.

Intertemporal designs encourage regulators and emitters to adopt a forward-looking perspective, explicitly factoring future removal costs into today’s decisions about whether to emit (and remove later) or abate. They build on well-established regulatory principles, reflecting how environmental responsibility is already structured in many policy domains. The PPP, embedded for example in EU primary law (TFEU Art. 191(2)) and long promoted by the OECD (23), holds that polluters should bear the costs of preventing and remedying

environmental harm. Extending this logic, EPR has been implemented in some jurisdictions (e.g., waste electronics, batteries, and packaging in the EU) to shift end-of-life costs onto producers. An intertemporal removal obligation operationalizes EPR (or EER (2)) by assigning to current emitters a liability to finance or deliver the future removals corresponding to their built up atmospheric “waste carbon stocks”.

Two broad archetypes of intertemporal instruments have emerged, but actual proposals typically sit along a continuum between them. The first approach keeps responsibility for net-negative emissions largely within the public domain, relying on long-term procurement by governments or dedicated agencies to meet removal targets. The proposed funding vehicle includes earmarking current carbon tax or ETS revenues to finance future net removals, with funds managed over time either as escrow or in a manner similar to pension or sovereign wealth funds as introduced in ref (18) (see Chapter 3). The Dutch Scientific Climate Council mentions this as one of the options to finance CDR intertemporally in the Netherlands (24), and a similar strategy has been proposed for Taiwan (25). By requiring contributions from today’s emitters, governments can avoid shifting the entire burden of future removals onto taxpayers once emissions have largely ceased.

The public-interest spirit of this approach is well suited to the broader CDR policy objectives (as outlined in Section 1.3.1), particularly the internalization of social and environmental impacts of CDR deployment. Historically, such public provisioning echoes the way many energy systems were organized for decades as state monopolies or vertically integrated public utilities. However, current policy trends point in a different direction, emphasizing reliance on markets for price discovery. This reflects the view that competitive markets, through decentralized investment and experimentation, are better equipped than public agencies to reveal the true costs and optimal trajectories of CDR deployment far in the future. Public institutions are often seen as facing informational disadvantages, which risks locking in inefficient allocation of resources. While concerns about public-sector inefficiency are often either ideological or self-fulfilling (26), there are genuine political-feasibility and funding risks with a purely public, pre-funded approach. Because any funding gap from misestimation ultimately falls on the public budget, prudent policymakers would be incentivized to over-charge to cover uncertainty in future removal costs, an approach that can be hard to sustain politically over electoral cycles. In addition, earmarked public funds might be politically exposed. Reserves built up for future net negative emissions may be diverted to address more immediate pressures such as health crises, defense expenditures, or urgent climate-related spending on adaptation and loss-and-damage.

The second archetype is based on intertemporal carbon markets. Obligations are placed directly on emitters through forward instruments that enforce future removals. The rationale

for this approach is dynamic efficiency and accountability. The actors responsible for emissions decide how to optimize between abating now and removing later, they bear liability if they defer emission reductions, and in doing so generate a transparent and predictable pipeline of future demand for removals required to channel investments in CDR ramp-up today. In other words, emitters are incentivized to become forward-looking in their compliance decisions. This logic is particularly salient for upstream fossil fuel majors and other large emitters, which are both materially linked to the geological and atmospheric carbon stocks and financially capable of underwriting forward removal obligations (and many are already engaging in CDR through offtakes and investments). Importantly, the mere prospect of liability for delivering future removals can potentially change current behavior and accelerate emission reductions, beyond what a purely public route might achieve, even if, in a first-best benchmark, public and market approaches could be outcome-equivalent.

Challenges of intertemporal markets include long-term commitment and enforcement issues, time inconsistency (e.g., deferral of mitigation based on speculation of future softening of climate targets), moral hazard (e.g., emitters taking on obligations they may not plan to meet, or lobbying for cancellation of obligations), adverse selection (stronger moral hazard for emitters with limited ability to deliver removals), exposure to price and technology uncertainty (with systemic risks if future removal costs are misestimated), and potential speculative bubbles around anticipated technologies (7). These risks imply the need for credible institutions to issue and enforce obligations, and for careful integration with the broader policy objectives outlined in Section 1.3. Moreover, attempting to assign or enforce obligations long after emissions occurred is increasingly impractical. Limited liability, mergers and exits mean many historic emitters will no longer exist. For intertemporal instruments to generate credible net negative outcomes, early introduction is essential; the longer implementation is delayed, the smaller the share of (historical) emissions that can feasibly be brought under enforceable obligations.

Hence, the goal of intertemporal market-based instruments is not to outsource the “abate-now versus remove-later” decision to improve dynamic cost-effectiveness entirely to an unregulated market, but to support decision making with financial discipline and assurance mechanisms. The remainder of this section reviews the few principal proposals within the market-based archetype. A comparison across several dimensions with the CRO introduced in Chapters 3-5 is undertaken in Chapter 7.

## 2.1. Intertemporal clean-up certificates within the EU-ETS

Lessmann et al. (21) propose augmenting the EU-ETS with clean-up certificates, that is, rights to emit CO<sub>2</sub> now with the obligation to remove the same amount later. In their analytically tractable ETS model, the social planner's (or regulator's) optimization problem depends on two key parameters. First, the size of carbon debt ( $D$ ), which represents the cumulative amount of future net-negative emissions to be delivered and equals the total number of clean-up certificates introduced into the ETS. Second, the degree of additionality ( $\lambda$ ), which determines how much of the clean-up certificate issuance substitutes for existing allowances (raising ambition) versus how much is added on top, thereby increasing intertemporal flexibility but also mitigation deterrence.

Because of the no-arbitrage conditions, the auction price of a clean-up certificate equals the ETS allowance price minus the discounted cost of future removal. To manage liability and moral-hazard risk, the framework assumes a collateral priced at the present value of the removal cost; thus, collateral + certificate price = allowance price. Under exogenous technological progress and an implicitly assumed overshoot cap, the market then selects an efficient intertemporal abatement path including removals.

An important methodological deviation from typical mitigation scenario assessments is that the authors do not primarily ask how to implement a given climate target at least cost. Instead, they evaluate clean-up certificates also against second-order, or political-economy, objectives of various interest groups – raising ambition and lowering cumulative damages (environmental groups), reducing compliance costs/prices (firms and consumers), and increasing public revenues (governments) – to identify feasible improvements over the status quo. In other words, the proposal is judged on whether it delivers a politically realistic Pareto-type gain, even if it does not fully align with the most ambitious temperature pathways. Relative to a baseline calibrated to an EU-ETS-wide net-zero-by-2050 cap with no net negative phase, the authors identify compromise regions in which all three objectives improve simultaneously, notably when roughly half of the clean-up certificates replace allowances and half are added on top. These conclusions are sensitive to assumed technological progress. Faster cost declines widen the compromise set; with little or no technological progress, “win-win-win” reforms vanish.

The paper addresses two main vulnerabilities of intertemporal designs. First, because discounting and expected cost declines make later removal cheaper, a future regulator may be tempted to extend the compliance horizon (a type of time inconsistency). Second, firms might default on future removal obligations. To mitigate both, the authors propose delegating implementation to a Carbon Central Bank (see also Section 1.4.1.1) with a narrow mandate,

independence from electoral cycles, and authority to set collateral and enforcement rules, acting, in effect, as lender of last resort for carbon debt. The proposal, however, does not elaborate in detail on the role of collateral – specifically, how the potentially substantial funds held as collateral would be managed or how collateral levels should be determined under uncertainty, which would naturally call for over-collateralization (as discussed in Section 2.3 below).

## 2.2. Atmospheric CO<sub>2</sub> Removal Deposits (ACORDS)

While ref (21) provides a transparent social-planner model with a no-arbitrage link between today's carbon price and discounted future marginal removal costs, Lyngfelt et al (22) present a similar concept without explicit formalization, which makes it hard to compare with other proposals. Emitters pay a per-ton CO<sub>2</sub> deposit into a publicly overseen fund, which can be redeemed only upon certified removal. The associated deposit receipts can trade on a secondary market. Pricing is derived from a simple present value analysis of future deposit redemption. Deposits grow at the risk-free rate  $r$ , while market participants discount net redemption value (deposit value minus marginal removal cost) at a, supposedly, risk-adjusted rate  $i$ . When  $i > r$ , the net present redemption value rises for a period and then falls, implying an optimal redemption window rather than redemption as late as possible. Hence, the present price of deposit receipts is introduced as the discounted net redemption value at the optimal redemption time. However, a low initial deposit fee can push redemption far into the future. Likewise, a later re-evaluation that lowers the discount rate (e.g., after uncertainty subsides) can shift the optimal redemption later in time.

The proposal does not discuss the roles and origins of the different interest and discount rates used. Moreover, on scope and policy integration, the text is ambiguous about whether ACORDs should finance all removals or only net negative emissions, implicitly leaving room for other instruments to handle contemporaneous compensation of residual emissions with CDR. The paper sketches an ETS linkage where, if interpreted correctly, an allowance is tied to an ACORD-type obligation, akin to clean-up certificates, though ref (21) distinguishes certificates from allowances. Here, auctioned allowances appear to function directly as “rights to emit now and remove later.” In the paper's EU illustration, redemption timing is assumed rather than optimized or rule-bound, underscoring that fee calibration, maturity control, and quantity governance are not specified as policy variables nor modeled within the framework. The authors do identify operational risks, including political diversion of funds, imprudent investment of funds, and strategic delay of removals, and propose governance mitigants such as an independent trust structure and depositor representation on the investment board. The proposal would be materially strengthened by formalization and further discussion of fee-

setting considerations, quantity controls, maturity caps, etc. Without such governance instruments substantial deterrence remains likely.

### 2.3. Carbon shares based on the Social Cost of Carbon (SCC)

Whereas clean-up certificates and the CRO introduced in Chapter 3 are framed within a cost optimization framework with a carbon budget constraint, Lemoine's carbon shares approach (19, 20) targets social welfare maximization by explicitly internalizing climate damages, aligning with US practice that centers policy on the SCC. In the social welfare or cost-benefit setting, firms abate current emissions and remove atmospheric CO<sub>2</sub> until marginal abatement or removal costs equal marginal social benefits from avoiding or removing these emissions, as measured by the SCC. Here, the SCC is defined as the present value sum of the entire future stream of marginal damages from an additional ton of CO<sub>2</sub> along the optimal emissions path.

The carbon shares instrument is engineered to replicate the incentives of an ideal stock tax delivering socially optimal emission reductions and removals over time. Such a stock charge levies payments each period a ton remains in the atmosphere and ceases once it is removed, directly rewarding removals when they are socially valuable (see also discussion about stock-storage charges proposed for temporary removals in Section 1.4.4). However, contrary to a situation where providers of temporary removals are rewarded, commitment issues and liability risks remain under stock charge models where emitters need to pay for atmospheric carbon storage. Emitters may be unable or unwilling to honor liabilities in the future, for example due to exit, bankruptcy, or restructuring. Moreover, anticipation of non-payment of future charges creates a moral hazard.

To address these commitment and liability risks within a stock-pricing framework, the proposed policy requires an upfront bond to be placed by the emitter for each ton of CO<sub>2</sub> equal to the worst-case SCC, defined as the supremum over admissible damage realizations. In return, the regulator issues a tradable carbon share tied to that ton, with a face value backed by the bond. Each period, the regulator deducts the stock charge from the face value, which equals the realized contemporaneous marginal damage from leaving the ton of CO<sub>2</sub> in the atmosphere. This deliberate "over-collateralization" using the worst-case SCC ensures that even under adverse damage realizations the system remains fully funded, avoiding potential calls on public budgets.

The regulator also updates its worst-case SCC estimate as new information arrives from observed losses and new SCC projections. Whenever that worst-case estimate falls, the

regulator pays the reduction to the current share-holder as a dividend and marks the carbon share's face value down accordingly. These dividend payments refund the initial over-collateralization over time. Over the life of the share, the initial bond is exactly exhausted by the sum of period damage charges (which finance realized damages) and dividends (which return funds that ultimately prove unnecessary). Hence, in present value, charges plus dividends equal the bond.

If holders remove a ton of CO<sub>2</sub> from the atmosphere, they redeem the remaining face value, and the carbon share is retired. In equilibrium, removal occurs when the marginal cost of removing a ton of CO<sub>2</sub> equals the present value of the expected future period damage charges that would be avoided by removing. If removals were cheaper than the present value of charges, arbitragers would buy shares, remove, and redeem, thus increasing the marginal removal costs until equivalence; and vice versa. This replicates the first-best removal schedule implied by an ideal stock tax.

Moreover, the equilibrium market price of a carbon share equals the present value of its expected future dividends generated by downward revisions in worst-case SCC. Because the bond equals the worst-case SCC at issuance, and because the present value sum of all future dividends and all future charges must exactly exhaust that bond, the expected present value of dividends paid over the life of the share equals the worst-case SCC minus the expected SCC. The emitter's net upfront outlay is therefore the bond minus the market value of the share, which equals the expected SCC, hence, restoring first-best incentives for emission reductions.

To update the worst-case SCC between periods, it is assumed that moderate realizations of damages (informing the stock charge) would lead to downward correction over time. In a distant future, the worst case converges with the realized SCC through consecutive corrections as all uncertainties are revealed. In a state of the world close to the worst case, dividends are small and period charges consume most of the bond; in a less extreme state of the world, period charges are smaller and more of the bond is repaid through dividends. Either way, the face value is driven to zero as damages are charged and uncertainty shrinks, or earlier if the ton is removed and the share is retired.

While the other proposals primarily require long-horizon projections of removal costs to function, this framework's core information requirement is the future path of marginal climate damages. Those expectations determine marginal costs of removals and their timing through the no-arbitrage condition. Moreover, they enter the valuation of carbon shares through expectations about future worst-case revisions towards the expected value. Period charges

can be anchored in realized losses combined with damage attribution science, which is arguably less informationally demanding than forecasting the entire future damage stream each year. Like any SCC-based policy, the instrument is sensitive to how the SCC and the worst-case SCC are constructed, including choices about discounting, the scope of counted damages (for example, global versus domestic damages), socioeconomic baselines, and damage curvature. Refs (19, 20), moreover, introduce a notion of uncertainty absent in the other proposals. While ref (21) sets the collateral equal to discounted removal costs (which are assumed to be perfectly known), the carbon shares instrument is initially over-collateralized at the worst-case SCC, acknowledging potential outcomes above the expected value.

## 2.4. Carbon Removal Obligations

The primary objective of the CRO framework as introduced in Chapters 3 to 5 below is reduction of gross CO<sub>2</sub> emissions and incentivizing removal pathways that exceed residual CO<sub>2</sub> emissions in the long run. This is achieved by an obligation to remove initially emitted CO<sub>2</sub> at a given maturity, combined with a stock charge on CO<sub>2</sub> temporarily retained in the atmosphere (the “carbon debt interest rate” or “CRO premium”). To achieve removals, CROs function like balance-sheet provisions (27) that accumulate with an entity’s emissions and are settled by delivering verified removals. Similar to existing environmental liabilities (e.g., performance bonds for mine site rehabilitation (28)), the obligation is supported by step-in guarantees arranged by a CRO-issuing intermediary in return for a commercial premium or interest. Given the scale of involved financial flows, stocks and risks (see Section 7.3.1), the proposed framework is overseen by a monetary-policy-like authority that manages repayment capacity of carbon debt and associated systemic risk channels. Thus, the CRO framework combines elements from

- a) carbon policy (emission control),
- b) financial assurance to manage environmental liabilities as well as
- c) monetary policy to address system-level challenges.

The basic structure of the CRO is similar to the other proposed instruments (Sections 2.1-2.3), which can be summarized by starting from the simplest design and layer features:

- a) Emitters pay into a fund today; the fund finances removals later (tax-fund system (24)).
- b) Emitters pay into a fund today (collateral/deposit); emitters redeem deposit upon certified removal; otherwise the fund pays for removals (clean-up certificates (21)).

- c) Emitters pay into a fund (collateral/receipt) and receive a transferable receipt (or share); the receipt-holder redeems the deposit upon certified removal, otherwise the fund pays for removals (ACORDS (22), carbon shares (19)).

Within this framework, the distinctive value of each proposal lies in the features it adds beyond the basic intertemporal mechanism. It should be noted that ACORDS are not formally developed within a social-planner setting and are less elaborated than the other instruments. For the purposes of comparison, they are therefore treated as equivalent to clean-up certificates with the additional feature of tradable deposit receipts. A comprehensive comparison of all instruments is provided in Chapter 7 after the detailed introduction of CROs.

### 3. Conceptualization of carbon debt and its intertemporal management

Based on the peer-reviewed journal article: J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).

For Extended Data Figures and Tables referenced in the text, refer to Annex 3. For Supplementary Information (SI) cited in the text, please see the online publication, as the volume of material exceeds what can be included within this thesis.

#### 3.1. Abstract

The remaining carbon budget for limiting global warming to 1.5°C will likely be exhausted within this decade (29, 30). Carbon debt (31) generated thereafter will need to be compensated by net negative emissions (32). However, economic policy instruments to guarantee potentially very costly net CDR have not yet been devised. Here, we propose novel intertemporal instruments to provide the basis for widely applied carbon taxes and emission trading systems to finance a net negative carbon economy (17). We investigate an idealized market approach to incentivize repayment of previously accrued carbon debt by establishing emitters' responsibility for net carbon removal through 'Carbon Removal Obligations' (CROs). Inherent risks, such as the default risk of carbon debtors, are addressed by pricing atmospheric CO<sub>2</sub> storage through interest on carbon debt. In contrast to the prevailing literature on emission pathways, we find that interest payments for CROs induce substantially more ambitious near-term decarbonization complemented by earlier and less aggressive deployment of CDR. We conclude that CROs will need to become an integral part of the global climate policy mix if we are to ensure the viability of ambitious climate targets and an equitable distribution of mitigation efforts across generations.

## 3.2. Introduction

Delivering on the many national and corporate net-zero emission pledges will likely require gross removal of atmospheric CO<sub>2</sub> on top of conventional emission reductions (33, 34). To achieve the Paris Agreement, global gross CO<sub>2</sub> removals will need to exceed gross residual emissions (32, 35) beyond mid-century (29, 36). The resultant net negative emissions compensate carbon debt (37) accrued by CO<sub>2</sub> emissions overshooting the remaining carbon budget (38, 39). Carbon debt is projected to amount to roughly the equivalent of nine years of global pre-COVID emissions according to the IPCC's 1.5°C 'middle of the road' scenario P3/S2 (29) (Extended Data Table 1). Such large-scale deployment of carbon-dioxide removal (CDR) is controversial mainly for the implied economic and technological risks (40–44) and environmental impacts (45, 46); and because reliance on CDR in mitigation scenarios often goes hand-in-hand with a substantial shift of the mitigation burden to future generations (14).

Here we would like to point to a fundamental economic problem associated with the existing climate mitigation scenario assessments, aiming to inform international climate negotiations. Existing economic policy instruments for emission control are inadequate to incentivize a global transformation towards a net negative carbon economy without imposing excessive fiscal burden from 2050 onwards: Currently envisaged carbon tax schemes would turn into public subsidies under net negative emissions with potentially prohibitive fiscal implications (17). Emission trading schemes (ETS), on the other hand, are presently designed to handle positive emission caps only. Negative emissions are merely treated as offsets, implying that CO<sub>2</sub> emissions from one point in time cannot be compensated by an equivalent quantity of negative emissions at another point in time, as required by most mitigation scenarios. Crucially, we observe that pricing the depletion of the remaining carbon budget is fundamentally different to pricing overshoot emissions after the budget's depletion, which has profound implications for the consistent earmarking of accrued revenues from a price on CO<sub>2</sub>.

We argue that establishing emitters' responsibility for carbon debt is a prerequisite to ensuring viable net negative carbon futures. Carbon debt could therefore be treated similar to financial debt including interest payments on physical liabilities, or 'Carbon Removal Obligations' (CROs), to internalize the inherent risks. Based on this idealized global carbon policy proposal motivated by the IPCC's mitigation scenarios, our numerical results address the shortcomings of the existing climate mitigation literature (47). Despite the conceptual character of this study, we establish profound implications for national carbon policy, which is strongly influenced by the IPCC's global mitigation pathways in many high-emitting countries (48).

### 3.3. Carbon pricing for net negative emissions

Integrated Assessment Models (IAMs) provide global carbon price paths serving as a proxy for a wider range of cost-effective climate policy options to achieve specified greenhouse gas (GHG) mitigation goals (36). Such carbon prices typically increase exponentially with the interest rate as a consequence of the Hotelling rule, which defines the intertemporally optimal extraction schedule and price of a non-renewable resource (49, 50), such as the carbon budget. If understood as a global common, revenues generated from pricing its depletion should consistently add to public budgets, for instance to compensate for the associated welfare impacts which may be unfairly distributed across society. However, in scenarios where the carbon budget is overshoot and subsequently replenished, the budget can no longer be regarded as a non-renewable resource. In this case, the Hotelling rule lends itself to an ‘intertemporal interpretation’ for carbon policy: Revenues from carbon pricing after the budget’s depletion can be invested at the market interest rate to finance net carbon removal later in the century. Because marginal abatement costs increase at the market interest rate, this calculation is exact under perfect foresight conditions, as assumed in most IAMs, if the retained funds purchase net negative emissions at marginal costs later on. Because emitters pay for future net CDR through the carbon price, this intertemporal interpretation is compatible with the Polluter Pays Principle. The resultant intertemporal financial transfer thereby addresses concerns of intergenerational equity because public budgets in the near-term no longer spuriously benefit from pricing an already-depleted resource, whilst future generations thereafter are forced to replenish the carbon budget through other sources, such as income, sales or payroll taxes. According to the ‘conventional interpretation’, revenues from carbon pricing are merely treated as contemporaneous additions to public budgets, with no clear earmarking of accrued funds. Crucially, since both approaches are simply interpretations of the same underlying carbon price paths, emitters also pay the discounted future costs of net emission removal in case of the conventional interpretation. However, in the absence of consistent earmarking, the financial viability of net CDR in the second half of the 21<sup>st</sup> century is highly doubtful (17), and intergenerational equity remains unaccounted for.

To operationalize a future net negative carbon economy, carbon tax revenues could be partially retained and transferred over generations to finance net CDR in the style of a nuclear decommissioning trust fund or a sovereign wealth fund. The value of such a global net carbon removal fund is potentially enormous, yet in the range of comparable funds, peaking at roughly 100% of global GDP in the median of SSP scenarios compatible with RCP1.9 (51) (Figure 2). For comparison, Norway’s large sovereign wealth fund has passed 250% of national GDP (52). Given this order of magnitude, intermediate investment portfolios could be a game

changer to lift CDR out of the pilot phase even before payout of the fund. However, protecting financial resources from diversion for other purposes as political environments change, or as public finances get stressed, will surely be extremely challenging. For instance, sovereign borrowing to cushion the impacts of the COVID-19 pandemic meant that by the end of 2020 OECD governments' debt-to-GDP ratio had increased by about 13.4 percentage points (53). Severe crises in the future might induce considerable pressure for governments to appropriate savings originally reserved for net CDR.

The success of a net CDR fund also depends on the appropriate choice of several inherently uncertain parameters, including future abatement costs. If costs and other socio-economic parameters are not estimated in line with the precautionary principle, or if regulators are reluctant to adequately reflect future carbon removal in near-term price instruments, insufficient financial resources would be collected as observed for nuclear decommissioning (54). Because carbon debt and associated risks would be mutualized by a net CDR fund, missing financial resources would need to be replenished by public budgets.

### 3.4. Dynamic emission trading

Emission trading with fully liberalized banking and borrowing of allowances can be regarded as a response to these concerns. Decentralized decision making and price determination in a competitive market is believed to improve efficiency by leveraging the ability of carbon markets to determine cost-effective time paths of mitigation (55). In an idealized global scheme, the remaining carbon budget would be distributed over time resulting in positive emission caps for consecutive auctioning periods. Emitters would decide in each period what fraction of their CO<sub>2</sub> emissions to compensate by allowances and how much carbon debt to generate for compensation by future allowances – or future CDR in the absence of a positive emission cap. Effectively, emitters generating carbon debt would remain liable for the timing and delivery of net negative emissions (Figure 3) and can therefore balance present against future abatement based on individual expectations, such as those concerning technological breakthrough. Stranded assets can be avoided by harmonizing abatement investments with natural renewal cycles of capital; and fluctuations in the business cycle can be addressed. Fixed price schedules under a carbon tax imply lower costs for hedging risks related to the long-run costs of negative emissions and low-carbon investments. However, increased intertemporal flexibility in emission trading stabilizes prices – which reflect discounted future marginal abatement costs – compared to currently implemented ETS with no intertemporal trade of allowances (56, 57). At least in principle, this ETS arrangement allows emitters to develop optimal investments over longer time horizons, increasing the dynamic efficiency of emission trading. While emission caps can be overshoot, the quantity of cumulative emissions remains

exactly controlled under an ETS with intertemporal trade of carbon debt, which is, more generally, the main advantage of cap-and-trade schemes over carbon taxes. If caps no longer directly control emission reductions, they can be set to equitably distribute ETS revenues over time. However, as the carbon budget diminishes rapidly – the 1.5°C compatible budget is projected to become depleted roughly within the next 10 years (29) – the importance of carbon debt management increasingly outweighs the requirement of an adequate temporal distribution of the remaining carbon budget.

Privately managed carbon debt within an ETS also has considerable drawbacks: the enforcement of carbon debt, assessment of creditworthiness of emitters, the potential for speculation on future softening of emission targets and subsequent deferral of mitigation (*time inconsistency*) – which is stronger the lower the solvency of emitters (*adverse selection*) – and the resultant incentive to lobby for cancellation of carbon debt (*moral hazard*) are crucial obstacles that explain why such intertemporal mechanisms are severely restricted in currently implemented ETS (55). Moreover, intertemporal trade of carbon debt by means of forward and futures markets trading negative emissions over potentially long periods at a fixed price is perceived as infeasible, given the deep uncertainty in the parameters guiding a large-scale CDR rollout (58).

### 3.5. Carbon Removal Obligations

Intertemporal emission trading would necessarily come at the cost of considerable regulation to address these drawbacks. We argue, however, that practices from the financial industry and monetary policy could be leveraged to reduce risks and adaptively balance potentially competing interests of economic development and climate mitigation by treating carbon debt in a similar fashion as a financial debt obligation, and thereby invoking an interest on carbon debt. Economic growth, aggregate demand for carbon debt and individual financial ratings of debtors would define a general base rate, individual markups, term structures and debt maturities. To assure its physical conservation and exert control over its aggregate level, carbon debt would initially be issued at the base rate by managing authorities, e.g., Central Banks, towards which commercial banks would be held liable in case of insolvent debtors. Commercial banks, or their equivalents, would issue debt to emitters and, assisted by rating agencies, assess and hedge their insolvency risk by determining individual markups on the base rate. Carbon debt would enter firms' balance sheets as physical liability in tonnes CO<sub>2</sub> – a Carbon Removal Obligation, for which interest payments would be due (Extended Data Figure 7a). This chain of legal liabilities across layers of public and private actors reduces the moral hazard that governments would ultimately pick up the bill for net emission removal, and limit issuance of CROs to debtors reluctant to fulfill (interest) obligations. Individual interest

markups would also balance the market's push for adverse selection and incentivize a debt transfer from agents losing ground under stringent climate policy to low-risk agents; or lead to more near-term abatement (see Results) if risks are deemed non-insurable. The rate controls carbon price volatility (Extended Data Figure 1) and therefore directly impacts on price-risk costs of scheduled abatement investments. More generally, interest and debt maturities would need to reflect the speculative nature of CDR, leading to short – but potentially renewable – repayment terms and elevated rates in the near-term.

For intertemporal emission trading to work efficiently, for instance to reduce issues of time inconsistency and price volatility, emission caps would need to be credibly announced as early as possible. By consequence, regulators would lose the flexibility of adapting caps as new knowledge concerning the Earth system becomes available. In an idealized global scheme emission caps need to reflect exactly the remaining carbon budget. Budget uncertainties related to issuing of carbon debt, like those of permafrost thaw following a temperature overshoot (30), could be hedged by collecting risk funds through base rate payments and by incentivizing more ambitious emission reductions to minimize the risk of climate feedbacks (see Results). Such uncertainties should remain manageable by risk reserves, allowing for the budget to be replenished by drawing on risk funds rather than requiring a downwards correction of scheduled emissions caps. In the best case, uncertainties and base rates would decrease over time as updated carbon budget estimates converge to a value within the expected range of the previously announced budget. However, new findings might realistically also lead to exceeding the capabilities of risk management, requiring a combined effort of future generations to counter potentially abrupt climate change. Management of physical risks therefore remains limited to what is presently perceivable and realistically quantifiable.

**Box 1: Hypothetical implementation of a CRO-ETS in the European Union (EU) and beyond.**

The EU's total carbon debt amounts to 22.5 Gt CO<sub>2</sub> already by 2050, or roughly 7 years (59) of present CO<sub>2</sub> emissions\*, according to the 1.5°C-compatible mitigation scenarios LIFE and TECH from the European Commission (COM) (60). In line with the Union's net zero GHG target for 2050, CO<sub>2</sub> emissions must turn net negative already by 2043 (61). Despite the lack of any adequate mechanism to do so, sectors currently covered by the EU-ETS will therefore need to deliver 50Mt CO<sub>2</sub>eq net GHG removal by 2050 in the more ambitious 1.5-TECH scenario. CDR volumes are expected to grow after 2050 in line with the economy-wide net negative GHG emissions objective already enshrined in the EU Climate Law. Beyond 2050, negative caps in the EU-ETS (62) will require significant public

funding, which is likely to obstruct the implementation of ambitious net-CO<sub>2</sub> removal targets. With CROs in place, overburdening of public budgets can be avoided.

We envision the following scenario: With the revision for Phase IV of the EU-ETS initiated in 2021, the linear reduction factor of emission caps is brought in line with the COM's long-term cumulative net-CO<sub>2</sub> 'target' of 26 Gt CO<sub>2</sub>\*\* while the scheme is gradually extended to full sectoral coverage. The implied increase of the reduction factor is balanced by a simultaneous phase-in of CROs, and carbon debt management is added to the European Central Bank's (ECB) portfolio. The ECB issues debt to commercial banks at a base rate, which in turn issue debt to firms participating in the EU-ETS charging individual markups depending on firms' financial ratings. To be able to repay the ECB despite defaulting debtors, banks would have to develop their own CDR portfolios. The resultant increase of CDR supply and expertise in assessing carbon debt risks induces development of a wider variety of CRO-products, with different maturities. For securing the long-term supply with fossil fuels in hard-to-transition sectors, like long-haul aviation and shipping (63, 64), large energy firms would be incentivized to develop CDR for counterbalancing residual emissions (65). Alternatively, accrued carbon debt would be transferred to other agents, such as wealthy – potentially non-EU – tech firms, with presumably low credit risk and a proclivity for mitigation technology (66). For CDR suppliers (67, 68) CROs are the basis of a business case, and because negative emissions do not have to be delivered immediately, CROs simultaneously act like loans to finance development.

It may be that global implementation of a CRO-ETS under the UNFCCC, as conceptualized in this article, is not realistic for the time being. However, given the potential opportunities for the financial sector and CDR investors, as well as the implications for public finance, non-EU countries with ambitious climate targets and (pilot-) ETS schemes, like China, Japan, South Korea, Quebec or California (69), would likely be under pressure to liberalize intertemporal trade of carbon debt, and thereby establish responsibility for overshoot emissions. The EU-wide rollout would therefore be followed by attempts to actively influence regulation globally (e.g., via 'regulatory export' (70)) and subsequent linkage with other national and regional schemes (71).

*\*All numbers provided here include the United Kingdom (UK) and emissions from land use, land use change and forestry (LULUCF). Carbon debt for compensation in the 2050-2100 period is determined by subtracting the 2018-2100 budget from the higher 2018-2050 budget. Budgets are average values from the 1.5-TECH and LIFE scenarios. Annual emissions in 2018 amount to 3.14 Gt CO<sub>2</sub>(72).*

### 3.6. Climate mitigation under carbon debt

In IAMs abatement costs are discounted at the market interest rate, implying a cost advantage for abatement in the distant future vis-à-vis near-term decarbonization in net present value terms. The interest rate is therefore a key driver of carbon debt accrual in IAMs (15, 73). This ‘discounting effect’ is balanced by imposing interest on carbon debt. Longer CRO maturities imply lower net present costs for CDR. Simultaneously carbon debt interest is paid over a longer period, compensating for these gains. When the market rate of interest and the carbon debt interest rate ( $r_d$ ) coincide, the gains from discounting are balanced exactly, as we analytically show in the Methods. In Figure 4 we illustrate the sensitivity of 2°C-compatible global mitigation pathways to interest on carbon debt, with rates constant over the 2020-2100 period ranging from  $r_d = 0$  to  $r_d = 0.08$ . For each rate, 13 scenarios are computed based on different SSPs and IAMs used to calibrate the marginal abatement cost (MAC) curves of our model (Extended Data Table 2).

To illustrate by comparison, only the two extreme cases,  $r_d = 0$  and  $r_d = 0.08$ , are depicted in panels a-d of Figure 4. Crucially, when  $r_d = 0.08$ , the cumulative emission target is achieved without accrual of carbon debt in the median path, implying that emissions remain at the net zero level once achieved. This is accomplished by contemporaneous compensation of residual CO<sub>2</sub> from fossil fuels and industry (‘FFI’) with negative emissions from bioenergy with carbon capture and storage (‘BECCS’) and land use change. Complete decarbonization of FFI emissions is, however, not cost-effective due to the high marginal costs of emission reductions from hard-to-abate sectors. Remarkably, net negative emissions of individual scenarios in panel a turn back to zero before 2100, thereby minimizing the “problem of phasedown” (74). With reduced reliance on net negative emissions marginal costs are higher in the near-term due to the more rapid reduction of FFI emissions and ramp-up of BECCS, but significantly lower in 2100 (panel b). Panel e shows a reduction of total carbon debt  $D$  as  $r_d$  is gradually increased. Carbon debt risks are therefore greatly reduced at a moderate cost increase of below 12.5% in more than 75% of scenarios where  $r_d > 0.02$ .

A similar analysis is performed for the 1.5°C global warming target; however, direct air capture and storage (DACs) is added to the mitigation technology mix, represented by 6 different DACs-specific MAC curves with low, medium and high costs as well as low and high-capacity limits. This results in a set of 78 scenarios for each rate  $r_d$ . Not surprisingly, the higher the potential for DACs to be deployed, the larger the level of  $D$ , when  $r_d = 0$ . By contrast, when

interest is invoked, this discounting effect is reversed and scenarios with large-capacity low-cost DACS simultaneously exhibit the lowest levels of  $D$ , see Extended Data Figure 2. The pathways in Figure 5 show baseline (panels a and b) and reduced  $D$  (panels c and d) scenarios for those scenarios that achieve at least a 30% reduction of  $D$  compared to their associated baselines. See Extended Data Figures 3-5 for 5%, 15% and 45%, respectively. For illustration, we interpret the CRO-ETS baseline scenarios, where  $r_d = 0$ , as conventional ETS scenarios because both schemes are theoretically equivalent in terms of the resultant emission profiles while they imply a qualitatively different timing of financial flows.

Despite the earlier ramp-up of DACS in panel c, causing emissions to turn net zero around 2050, an emission overshoot appears to be inevitable if warming is to be limited to 1.5°C. Remaining net negative emissions might cause problems of phasedown in 2100, unless CRO maturities are further extended to allow for a smooth transition towards net-zero; or more net negative emissions are needed to stabilize the climate in the 22<sup>nd</sup> century (75). Hence, median  $D$  equals to roughly 7 years of 2019 global net emissions in panel c. Yet, the role of CDR changes considerably: without considering risks, CDR seems to justify late-century compensation of carbon debt. In this case median  $D$  is equivalent to about 11 years of 2019 global net emissions, with compensation starting roughly 10 years later in panel a. However, when risks are accounted for by imposing interest, CDR supports a rapid decrease of net emissions by balancing residual emissions. Controversially, the availability of cheap and large-scale CDR options, like DACS, is key in 1.5°C scenarios with reduced reliance on carbon debt accrual. As illustrated by the pie-charts in panel d, the share of high capacity DACS scenarios among feasible scenarios with respect to the 30% reduction requirement grows to 81% (50% in the underlying set) and the share of low cost DACS scenarios to 54% (33% in the underlying set). Should CDR not become readily available as asserted in IAMs (76–78), this would be reflected in an elevated carbon debt interest rate, incentivizing emission reductions provided by other sources, such as replacement of fossil with renewable energy sources in hard-to-abate sectors – even if this leads to much higher costs.

### 3.7. Impact on financial flows in time

Figure 5, moreover, illustrates the distribution of annual mitigation cost shares, including investments in emission reductions and negative emissions (red and yellow shades) and the financial flows associated with ETS allowances and interest for CROs (blue shades). The share of abatement costs for emission reductions ('ABM') and negative emissions ('RES' and 'NNE') incurred in the near- versus the long-term increases with larger levels of  $r_d$ ; compare Figure 5d to Extended Data Figures 3d-5d. Here, CROs with interest induce a more equitable temporal distribution of these cost items, in sum peaking at 2.4% in panel d compared to 4.5%

of GDP in panel b. This is partly because the CRO-ETS requires carbon debtors to reserve financial resources early in the century, and such funds earn interest until they are spent for net negative emissions ('NNE', yellow). By contrast, NNE expenditures in panel b are incurred at the time of net carbon removal and would need to be funded by public sources in the absence of intertemporal financial transfers. Note that here we show average abatement costs. If marginal costs are paid by incentivizing net CDR on a market, public expenditures are much higher; see for comparison Figure 2. Pricing overshoot emissions under a conventional ETS, moreover, implies much larger revenues ('ETS', light blue) than under the CRO-ETS, where emission caps reflect exactly the remaining carbon budget. Median total discounted abatement costs, excluding ETS costs and interest costs ('INT'), increase from 1.6% to 2.0% of GDP when interest is invoked within the CRO-ETS. Median interest costs in these scenarios are substantial, peaking at above 1.3% of GDP, and 0.4% to 1.5% in the Extended Data Figures 3-5. These numbers are, however, highly uncertain and will need to be determined considering the viability and scalability of near-term CDR options and other emission reduction technologies.

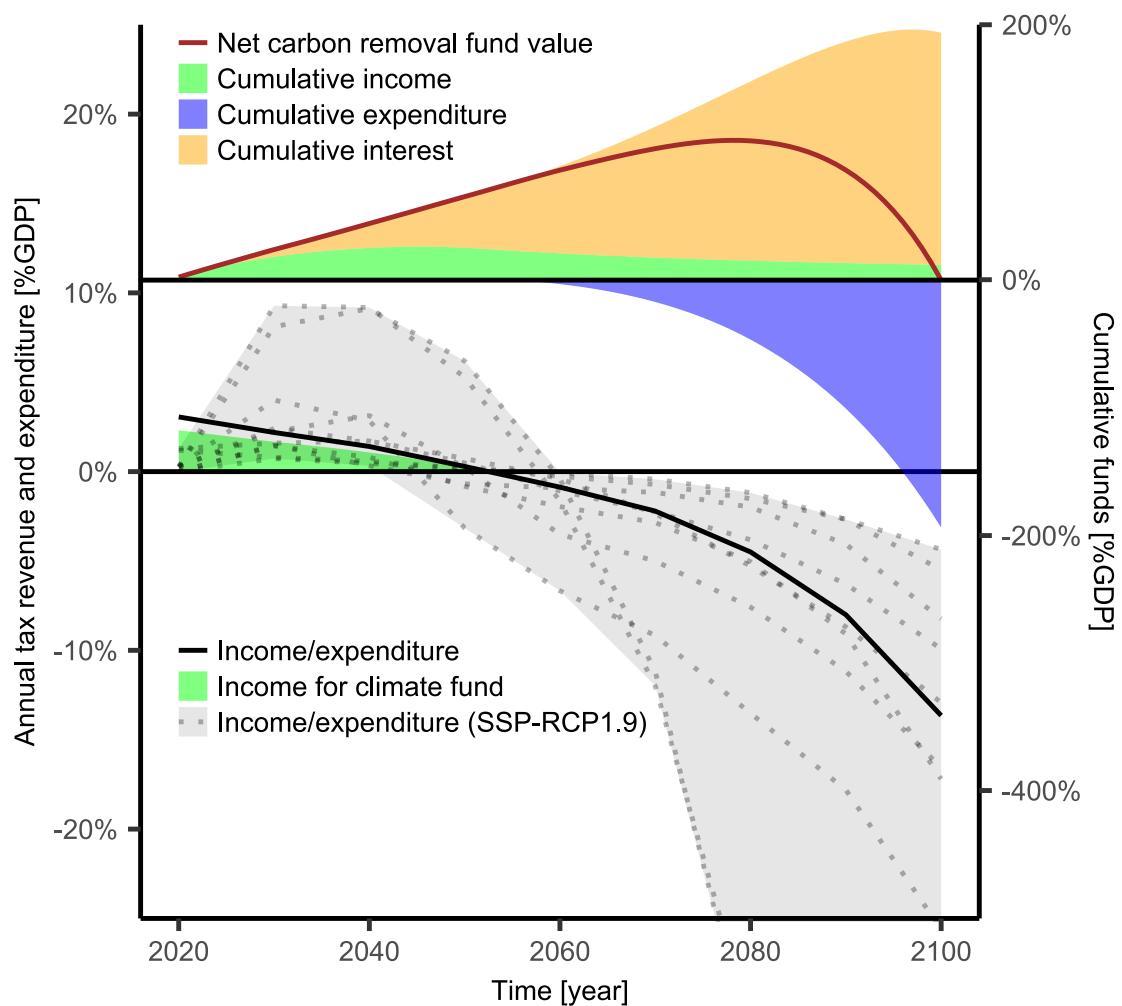
Enlarging IAM CDR-portfolios to reduce technological risks and environmental impacts would likely lead to further burdening of future generations in scenarios if CDR remains primarily a motivation for reducing net present costs by accrual of carbon debt. This is especially problematic if such results trickle down via the IPCC and international climate negotiations into national target setting because no viable mechanisms for carbon debt repayment have entered the policy debate at the moment. Simultaneously, mitigation pathways with reduced carbon debt heavily rely on CDR, requiring that risks be appropriately managed. Similar pathways result from lowering the market interest rate in IAMs (15) or from adequately setting intermediate climate targets or constraints on net emissions (47). However, such measures would individually not resolve the more profound issue of finance of net negative emissions discussed here.

### 3.8. Conclusion

In view of the rapid depletion of the global carbon budget CROs appear indispensable for any robust climate mitigation framework. While emitters under a combined tax-fund system pay upfront for net carbon removal, debtors in a CRO-ETS individually manage their financial resources. The implied flexibility for emitters also bears the largest drawback of intertemporal emission trading, if public bailout of carbon debtors becomes necessary. To minimize such risks 'conservation of carbon debt' needs to take top priority by controlling the total amount of carbon debt and by establishing liability across several layers of actors. Risk management under a CRO-ETS relies on imposing interest on carbon debt. For higher and risk adjusted

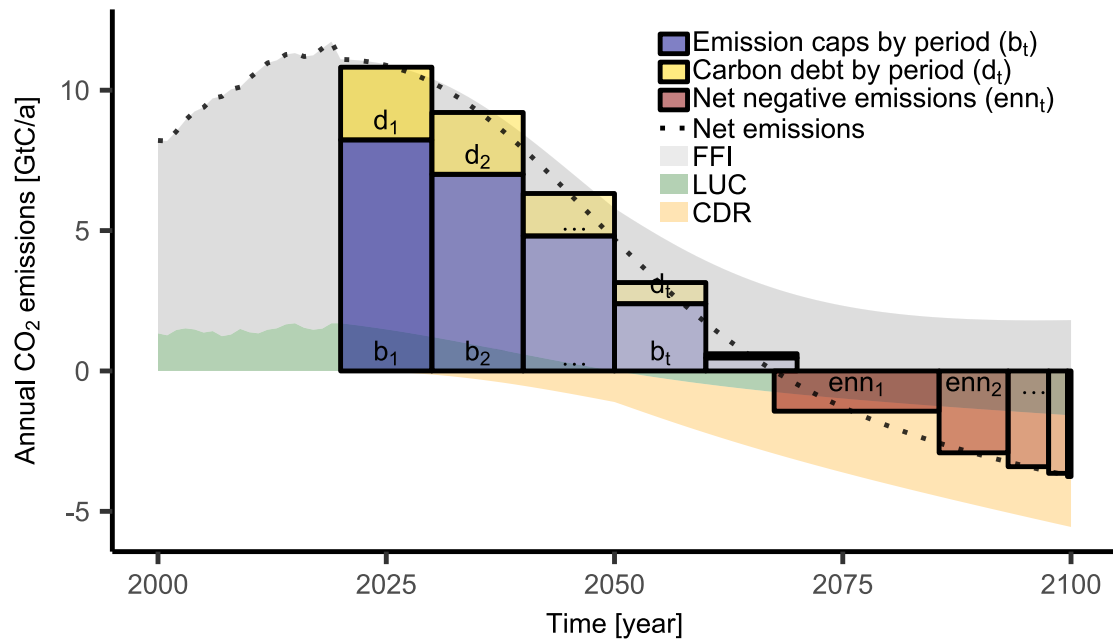
carbon debt interest rates, net negative emission investments no longer benefit from net present cost gains when mitigation is deferred to the distant future. By implication, CDR under a CRO-ETS will need to prove its viability vis-à-vis conventional emission reduction options already in the near-term. This will promote bottom-up CDR market development with the attendant benefits of price discovery, earlier technological learning, testing of scalability and identification of socio-environmental co-benefits and hazards, and ultimately, eliminating the uncertainties surrounding CDR.

### 3.9. Figures

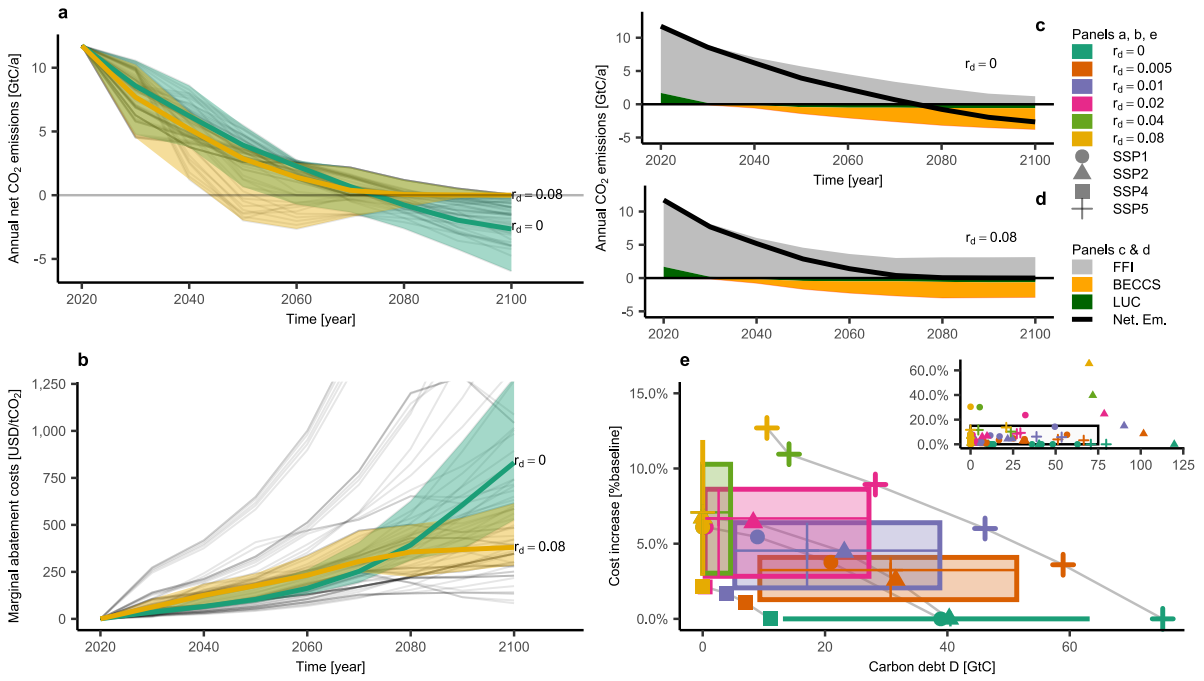


**Figure 2: Idealized global tax scheme with net carbon removal fund.** Lower figure (left hand side axis): Public income and expenditure from a tax on net emissions expressed as GDP percentage. Hotelling-compatible (exponential) carbon prices from SSP-RCP1.9 scenarios are multiplied by net emissions and divided by GDP (grey dashed lines). An idealized income/expenditure curve (black solid line) was derived from these scenarios using a strictly exponential median carbon price, median net emissions and GDP. Instead of reserving 100% of tax revenues after depletion of the carbon budget, we assert that a fraction  $\phi = 0.76$  of revenues are earmarked for net

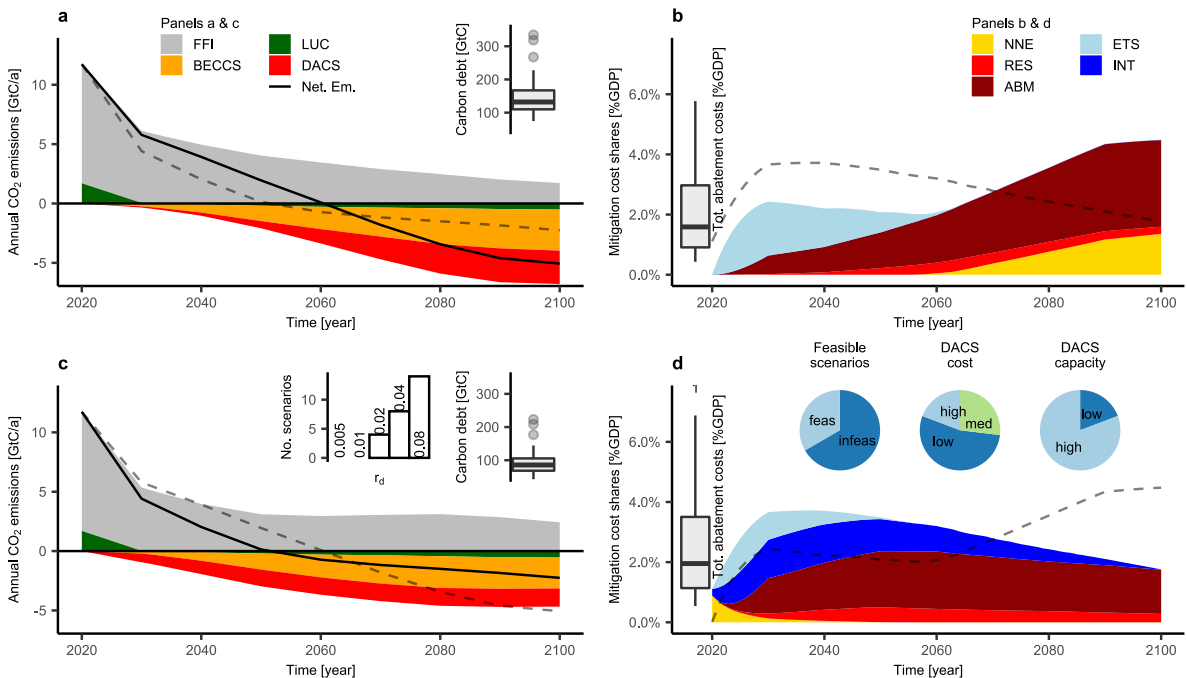
carbon removal, however, already from 2020 onwards. This share of income (green area) would need to be accrued into a net carbon removal fund invested at the market rate of interest to account for later expenditure when net emissions turn negative. See Methods for a definition of  $\phi$ . Upper figure (right hand side axis): Cumulative payments into the net carbon removal fund (green) and interest (orange) in theory pay exactly for cumulative tax expenditure (blue), such that the fund's net value (brown solid line) gets exhausted as the warming target is achieved in 2100.



**Figure 3: Idealized emission trading system (ETS) with intertemporal trade of carbon debt.** Illustrative 2°C pathway with gross carbon emissions from fossil fuels and industry (FFI), land use change (LUC), and non-specified sources of carbon-dioxide removal (CDR) including the schematic architecture of idealized global intertemporal emission trading. ETS emission caps  $b_t$  are obtained by distributing the carbon budget in tranches over consecutive periods. The amount by which emission caps  $b_t$  are exceeded by net emissions is conceptualized as 'carbon debt' ( $d_t$ ). In this idealized illustration,  $d_t$  is compensated later by corresponding net negative emissions ( $enn_t$ ) such that  $d_t = -enn_t$ . In a conventional ETS emission caps would be set to  $b_t + d_t$ , and  $enn_t$  would have to be incentivized by public subsidies. Historical emissions are from (79).



**Figure 4: 2°C (RCP2.6) mitigation scenarios for a range of interest rates on carbon debt.** Panel a: Net CO<sub>2</sub> emissions of all scenarios with  $r_d = 0$  (turquoise) and  $r_d = 0.08$  (yellow), including geometric median paths (bold solid lines) and min to max ranges (shaded areas). Panel b: Marginal abatement costs of scenarios with  $r_d = 0$  (turquoise) and  $r_d = 0.08$  (yellow). Bold solid lines indicate geometric medians, shaded areas indicate 25-75% interquartile ranges. Panels c ( $r_d = 0$ ) and d ( $r_d = 0.08$ ): Geometric median net emissions as in panel a, including gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS) and land use change (LUC). Panel e: Total discounted abatement costs (net present value, including interest costs) expressed as percentage cost increase compared to the baseline ( $r_d = 0$ ) are shown as function of total carbon debt D. The boxes indicate 25-75% interquartile ranges around median values of costs and D. Symbols linked by grey solid lines indicate medians grouped by SSPs. The entire dataset is shown in the upper-right corner, where each scenario is reflected by a symbol, grouped by SSPs (symbol type) and  $r_d$  (color).



**Figure 5: 1.5°C (RCP1.9) pathways under a conventional ETS (panels a and b) compared to a CRO-ETS (panels c and d).** Panels a and c: Geometric median net emissions (solid line) and gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS), land use change (LUC) and direct air capture and storage (DACs). Net emissions from panel a are also displayed in panel c (dashed line) and vice-versa. Total carbon debt  $D$  is shown as box-and-whiskers plot. Boxes indicate the 25-75% interquartile range around median values (bold line), whiskers indicate min to max ranges, points mark the outliers. Panels b and d: Annual mitigation costs as GDP percentage, including the share of average abatement costs attributed to emission reductions (ABM), to compensation of residual emissions by CDR (RES) and to net negative emissions (NNE) as well as expenditures for allowances (ETS) and interest costs (INT). Total mitigation costs (i.e.,  $ABM+RES+NNE+ETS+INT$ ) from panel d are also displayed in panel b (dashed line) and vice-versa. Box-and-whiskers plots show total discounted abatement costs (i.e.,  $ABM+RES+NNE$ ) as GDP percentage, the number above the chart indicates out-of-range outliers. Pie charts in panel d summarize properties of the underlying set of scenarios (see Methods). The distribution of  $r_d$  in CRO-ETS scenarios is depicted in panel c.

## 3.10. Methods

### 3.10.1. Basic analytical setup

Emission reductions induced by a CRO-ETS are quantified using a Hotelling-type optimization problem (see ref (15) for an analytical solution of the model). A global social planner is tasked to implement emission reductions at minimum costs to meet a cumulative emission target, i.e., the remaining carbon budget  $B$ , by  $T=2100$  ( $t_0=2020$ ). Exogenously given baseline emissions  $E_{base}$  i.e., future emission paths based on ‘business-as-usual’ climate policy assumptions, are reduced by a fraction  $a$  to obtain net emissions  $e$ :

$$e(t) = E_{base}(t) * (1 - a(t)). \quad [1]$$

Total abatement costs  $c_{tot}$  are discounted at the market interest rate  $r$  to obtain the net present value of total abatement costs, which is minimized:

$$\min_{a(t), c_{tot}(t, a(t))} \int_{t_0}^T c_{tot}(t, a(t)) * \exp(-r * (t - t_0)) dt, \quad [2]$$

subject to:

$$\int_{t_0}^T e(t) dt = B. \quad [3]$$

Integrating over marginal abatement costs  $MAC(a)$  gives the cost per ton  $CO_2$  for an instantaneous emission reduction of  $a$  compared to the baseline. Consequently, total abatement costs  $c_{tot}$  are defined as:

$$c_{tot}(t, a(t)) = E_{base}(t) * \int_0^{a(t)} MAC(t, \tilde{a}) d\tilde{a}. \quad [4]$$

Assume that under an idealized CRO-ETS a constant fraction  $1-\phi$  of net positive emissions  $e_{NP}$  is equivalent to a (continuous) emission cap  $b$ , i.e., the amount of conventional emission allowances issued over time, and  $\phi < 1$  of  $e_{NP}$  equals carbon debt  $d$ , i.e., the quantity of CROs issued. Then  $\phi$  is defined as the ratio of cumulative net negative emissions  $e_{NN}$  to cumulative net positive emissions  $e_{NP}$ :

$$\Phi = \frac{\int_{t_0}^T e_{NN}(t) dt}{\int_{t_0}^T e_{NP}(t) dt}, \quad [5]$$

and net negative emissions and net positive emissions equal the negative and positive parts of net emissions ( $e_{NP}, e_{NN} > 0$ )

$$e_{NN}(t) = \begin{cases} -e(t), & e(t) < 0 \\ 0, & e(t) \geq 0 \end{cases}, \quad [6]$$

$$e_{NP}(t) = \begin{cases} e(t), & e(t) > 0 \\ 0, & e(t) \leq 0 \end{cases}. \quad [7]$$

Carbon debt  $d$  and the continuous emission cap  $b$  are defined as:

$$d(t) = \Phi * e_{NP}(t), \quad b(t) = (1 - \Phi) * e_{NP}(t), \quad [8]$$

and total carbon debt  $D$  is obtained by integration over the planning horizon  $T$  (see [ 5 ] and [ 8 ]):

$$D = \int_{t_0}^T d(t) dt = \int_{t_0}^T e_{NN}(t) dt. \quad [9]$$

Consequently, we can write  $\phi$  as:

$$\Phi = \frac{D}{B + D}. \quad [10]$$

By implication, a fraction  $\varphi$  of cumulative net positive emissions overshoots  $B$  and thereby generates  $D$ , and a fraction  $1 - \varphi$  depletes the budget  $B$ .

Instead of exogenously imposing ETS emission caps,  $\varphi$  allows us to endogenously compute caps  $b$  and carbon debt  $d$  to conceptualize the intertemporal allocation of carbon debt such that debt is solely compensated by net negative emissions  $e_{NN}$ . Based on that we can compute a ‘physical repayment term’  $T_R$  linking the timing of net positive to net negative emissions (see [ 12 ]). CROs in this idealized ETS therefore represent a long-term intertemporal net transaction for financing net negative emissions. This aggregate can be regarded as a proxy for a multitude of smaller carbon debt transfers over shorter timeframes possible in real ETS implementations where CROs can be compensated by (gross) carbon removal, issuance of new CROs or allowances at a later point in time.

Average abatement costs are obtained from total abatement costs by dividing by the abated quantity of CO<sub>2</sub>:

$$c_{avg}(t, a(t)) = \frac{c_{tot}(t, a(t))}{a(t) * E_{base}(t)} \quad [ 11 ]$$

Next, we introduce interest payments which are due for carbon debt  $d$  over the repayment term  $t \rightarrow t + T_R(t)$ , i.e., from issuance of the CRO until its retirement (see Extended Data Figure 11b-e).  $T_R$  is implicitly defined as:

$$\int_{t_0}^t d(\tau) d\tau = \int_{t_0}^{t+T_R(t)} e_{NN}(\tau) d\tau, \quad [ 12 ]$$

and instantaneous interest payments are obtained by multiplication of the quantity of CO<sub>2</sub> for which CROs have been issued ( $d = \varphi * e_{NP}$ ) and the average abatement costs,  $c_{avg}$ , the moment of retirement of the CRO,  $t + T_R(t)$ , with the interest rate on carbon debt  $r_d$ :

$$i_{inst}(t) = d(t) * c_{avg}(t + T_R(t), a(t + T_R(t))) * r_d. \quad [ 13 ]$$

Integrating and discounting instantaneous interest payments over the repayment term  $T_R$  gives the total net present interest costs at  $t$  for carbon debt  $d(t)$ :

$$i_{tot}(t) = i_{inst}(t) * \int_t^{t+T_R(t)} \exp(-r * (\tau - t_0)) d\tau. \quad [14]$$

Now we add interest costs to the standard objective function [ 2 ] to obtain the optimization problem for a CRO-ETS:

$$\min_{a(t), c_{tot}(t, a(t)), i_{tot}(t)} \int_{t_0}^T (c_{tot}(t, a(t)) * \exp(-r * (t - t_0)) + i_{tot}(t)) dt. \quad [15]$$

### 3.10.2. Mitigation cost discounting

If we set  $r = r_d$ , the objective function can be written as (see [SI3](#)):

$$\min_{a(t), e_{NP}(t), d(t), c_{avg}(t, a(t))} \int_{t_0}^T (d(t) * c_{avg}(t + T_R(t), a(t + T_R(t))) + (E_{base}(t) - e_{NP}(t)) * c_{avg}(t, a(t))) * \exp(-r * (t - t_0)) dt. \quad [16]$$

Crucially, instead of pricing  $e_{NN}$ , carbon debt  $d$  is now paid for the moment it is created, however, at the average (undiscounted) future costs during removal at  $t+T_R$ , which is due to our definition of interest costs in [ 13]. This is because when  $r = r_d$  interest payments exactly compensate the cost reduction in net present value terms from discounting. The second term,  $E_{base}(t) - e_{NP}(t)$  equals emission reductions in the net positive / net zero domain. These reductions can be achieved by a mix of CDR, low carbon- and zero carbon technologies, however CDR is deployed only to offset contemporaneous emissions and not to recapture CO<sub>2</sub> released earlier.

Intuitively,  $r_d$  therefore controls to what extent cost discounting becomes a driver for accruing carbon debt. If  $r_d$  equals the market interest rate future costs  $c_{avg}$  at  $t+T_R$ , driven by technological learning and the aggregate demand for abatement  $a$  in  $t+T_R$  determine whether the carbon debt route ( $d$ ) proves competitive vis-à-vis instantaneous emission reductions ( $E_{base} - e_{NP}$ ). However, if  $d$  is reduced,  $e_{NP}$  needs to be reduced simultaneously to meet the emission target (less carbon debt leads to higher demand for near-term emission reductions, thus an increase of near-term marginal costs). Because near-term emission reductions potentially include CDR, technological and socio-environmental learning associated with CDR is induced earlier, leading to a reduction of uncertainty, which is key for operating in the net

negative domain later in the century. In this article we provide some intuition about the dynamic effects of invoking an interest on carbon debt, but do not determine optimal risk-reducing rates, which could – but do not necessarily need to – coincide with market interest rates. We expect, however, under circumstances where physical and financial risks associated with carbon debt are managed by appropriately setting an interest rate on carbon debt, that  $r_d$  is driven by the market interest rate: In our model, an increase in the market interest rate induces deferral of mitigation due to discounting, leading to higher quantities of  $D$ , thereby also to an increase of risks, and finally the necessity to correct  $r_d$  upwards to account for the increased risks.

### 3.10.3. Assessing the value of carbon debt

Note that net present cost gains from discounting are only cancelled exactly if the market interest rate is invoked on abatement costs at  $t+T_R$ . Costs are known in our model, but potentially impossible to determine in the context of real emission control policy. Therefore, given their liability for issued debt, managing authorities and financial institutions need to estimate the financial value of carbon debt as basis for interest payments and CRO maturities. The incentive to correctly value debt has a societal benefit of gradually reducing uncertainty with respect to CDR and other technologies relied on at large scales in mitigation scenarios. Importantly, by prudently valuing debt, issuing bodies assure the quality of price signals on carbon markets, instead of relying on the carbon price to value debt. In fact, carbon prices on its own are insufficient benchmarks for valuing debt. For instance, large demand for carbon debt would lead to a lower carbon price if this were not balanced by an increase of  $r_d$ , which in turn would lead to an undervaluation of risks.

### 3.10.4. Supply and demand of CROs

Supply of allowances under a pure ETS is completely inelastic, whereas supply in a tax system is infinitely elastic. By contrast, the supply of CROs (adding to the supply of allowances) is finitely elastic. Generally, the supply curve is increasing because the larger the demand for CROs, the more abatement is required in the future, making future abatement and thus CROs more expensive. Because total discounted interest costs ( $i_{tot}$ ) are reflected in the supply curve, by valuing carbon debt and setting the rate  $r_d$  accordingly, debt issuing bodies can partly control its slope. The slope, however, determines the level of price volatility, e.g., resulting from a demand shock, as depicted in Extended Data Figure 1. By implication, price volatility is largest in a pure ETS, and zero in a tax system. By increasing interest costs in a CRO-ETS, the potential for volatile prices increases, and vice versa. On the other hand, net emissions are fixed in an idealized ETS, and subject to demand fluctuations in a tax system. In a CRO-

ETS the cumulative quantity of net emissions is fixed, however, only if default risks are adequately managed.

### 3.10.5. Numerical solution of the model

The model used to solve the CRO optimization problem [ 15 ] is based on marginal abatement cost curves (MACCs, see [ 4 ]) derived from scenarios reported in the SSP scenario database (51, 80). MACCs are derived for each IAM and Shared Socioeconomic Pathway (SSP) by combining and fitting a curve to carbon prices from different Representative Concentration Pathways (RCPs) in each time step. For instance, a MACC in 2040 for a specific IAM/SSP configuration is composed of the carbon prices reported for RCP1.9-RCP6.0. The set of parameters of each IAM/SSP configuration of our model is therefore composed of net emissions from the baseline scenario ( $E_{base}$ ), the interest rate  $r$  (derived from the slope of log carbon prices), the carbon budget  $B$  derived from the sum of net emissions compatible with specific climate targets and 8 MACCs for the period from 2030 to 2100, i.e., one per decade. We fix abatement rates  $a$  during optimization where no MACCs could be derived because reported prices  $p_i$  are (close to) zero over the whole range of  $a_i$ , i.e., in 2020 for all configurations; for IMAGE/SSP2 in 2030; for IMAGE/SSP3 in 2030 and 2040; for IMAGE/SSP5 in 2030. Where abatement is fixed, costs are set to zero. Moreover, for the 1.5°C and 2°C case studies carbon budgets were corrected using historical emission data (79) (scenarios reported in the SSP database start in 2005 or 2010 and were exceeded by estimated net emissions in the past decades). Baseline emissions in 2020 were replaced by the projection for 2019 in (79).

We fit the inverse of the generalized logistic function (81) to log prices  $p_i$  as reported in the SSP database. Abatement rates  $a_i$  are computed by subtracting net emissions in a scenario with climate target from net emissions in the baseline scenario and dividing by the baseline. The index  $i$  denotes different RCPs within the same IAM/SSP configuration and the same year (see [SI2.1](#) for the cost curves of all IAM/SSP configurations):

$$\ln(p_i) = P + \frac{1}{k} * \ln \left( \frac{1}{v} * \left( \left( \frac{L - A}{a_i - A} \right)^v - 1 \right) \right). \quad [ 17 ]$$

MAC are therefore a power law defined on the interval  $\{a \in \mathbb{R} | L < a < A\}$ :

$$MAC(a_i) = b * \left( \frac{1}{v} * \left( \left( \frac{L - A}{a_i - A} \right)^v - 1 \right) \right)^c, \quad [18]$$

where  $b = \exp(P)$  and  $c = \frac{1}{k}$ . An interpretation of the parameters is provided in Extended Data Figure 8a.  $L \approx 0$  (subject to model fitting) and  $A = \max(a_i) + \varepsilon$  (such that  $a$  can become  $\max(a_i)$  without  $MAC(a)$  becoming  $inf$ ), i.e.,  $A$  is set to the maximum abatement (plus  $\varepsilon = 0.01$ ) observed in each decade for each IAM/SSP configuration because this level cannot be exceeded. For numerical reasons, however,  $a$  is also constrained by  $A$  during optimization such that  $a < A$ .

In most IAMs carbon prices are either imposed exogenously as driver of mitigation (e.g., in the recursive dynamic models AIM/CGE or GCAM4) or prices are derived after optimization from Lagrange multipliers of emission caps (e.g., in the intertemporal optimization models MESSAGE-GLOBIOM, WITCH-GLOBIOM or REMIND-MAgPIE). In these cases carbon prices typically increase exponentially with the interest rate, as explained by the Hotelling-rule (49, 50). In heavily constrained detailed process-based IAMs, intertemporally optimal carbon prices are a good proxy of marginal costs, however, they do not necessarily reflect MACs exactly in each point of time, as a consequence of growth constraints or caps on total deployment levels of specific mitigation technologies. This is also the case here because we limit  $a < A$  with an additional constraint and we fix  $a$  where no MACCs could be derived, implying that  $MAC$  and carbon prices (derived from the Lagrange multiplier of the budget constraint [ 3 ]) don't necessarily coincide.

We compare  $MAC$  and carbon prices from our model with carbon prices as reported for the individual scenarios in the SSP database for all models, SSPs and RCPs (see [SI2.2](#)). Reported carbon prices in the database for AIM/CGE do not follow an exact exponential curve because these prices reflect marginal costs from the SSP1 scenario which was initially constrained by emission caps to obtain the climate target. Then prices were manually scaled and imposed on other SSP scenarios to achieve the respective climate targets (82). Therefore, AIM/CGE prices are better replicated by our model's  $MAC$  than by carbon prices. The same is true for the IMAGE framework, which contains simulation as well as optimization components and does not report Hotelling-type carbon prices.

Furthermore, we show abatement costs for all SSPs, IAMs and RCPs computed with our model (see [SI2.3](#)). Because abatement costs are not explicitly reported in the database, we compare costs from our model with close proxies, i.e., GDP loss and consumption loss in SSP scenarios. For GCAM4 and IMAGE GDP loss and consumption loss are either not reported or losses are close to zero. For GCAM4 we therefore added abatement costs for some scenarios as reported in the supplementary information of ref (83), which are well replicated by our

model. No comparable data could be retrieved for the IMAGE model. For the other IAMs our model's abatement costs mainly coincide with consumption loss. Net CO<sub>2</sub> emissions are also compared for all SSPs, IAMs and RCPs (see [SI2.4](#)).

Abatement rates  $a$  cannot exceed  $A$ , hence only IAM/SSP configurations with RCP1.9 data are used for our 2°C case studies because more ambitious mitigation under a CRO-ETS requires our model to partly operate in the 1.5°C abatement domain to achieve 2°C. Therefore, 13 IAM/SSP parameter sets of our model are used for the case studies: AIM/CGE (SSP1 and SSP2), GCAM4 (SSP1, SSP2 and SSP5), IMAGE (SSP1), MESSAGE-GLOBIOM (SSP1 and SSP2), REMIND-MAGPIE (SSP1 and SSP2 and SSP5), WITCH-GLOBIOM (SSP1 and SSP4); i.e. 6 parameter sets for SSP1, 4 for SSP2, 1 for SSP4 and 2 for SSP5 (see Extended Data Table 2). All 2°C scenarios are shown graphically in [SI1.1](#) and numerically in [SI1.2](#).

### 3.10.6. Scenarios for direct air capture and storage

For our 1.5°C (RCP1.9) case study, additional sources of abatement are required to assess compatible pathways of more ambitious mitigation than suggested by RCP1.9 scenarios. We therefore add direct air capture and storage (DACS) to the mitigation portfolio, however, we treat this technology in a stylized manner as completely stand-alone and independent of other abatement technologies (e.g., the energy needs for DACS are assumed to be met by additional local renewable sources which do not interfere with the ramp-up of renewable energy as part of conventional abatement). DACS is less controversial than bioenergy with carbon capture and storage (BECCS) with respect to land use and has potentially limited environmental impacts compared to other large scale CDR options (44), making it more independently scalable. However, capital and energy requirements are uncertain and potentially enormous. Costs range between 20 and 1000 USD/tCO<sub>2</sub> (44, 46, 84–86), and potentials for CDR range from 0.5-5 GtCO<sub>2</sub>/a in 2050 to 15-40 GtCO<sub>2</sub>/a in 2100 (46), however, these potentials are mainly constrained by cost considerations rather than biophysical limits (87). Here we derive 6 idealized MACCs for DACS covering 3 cost ranges and 2 maximum abatement rates (see Extended Data Figure 8b). Instead of modifying the MACCs derived from SSP scenarios to account for DACS, we add  $a_{DACS}$  to

[ 1 ]:

$$e(t) = E_{base}(t) * (1 - a(t) - a_{DACS}(t)). \quad [ 19 ]$$

and change total costs in [ 4 ] to:

$$c_{tot}(t, a(t)) = E_{base}(t) * \left( \int_0^{a(t)} MAC(t, \tilde{a}) d\tilde{a} + \int_0^{a_{DACs}(t)} MAC_{DACs}(\bar{a}) d\bar{a} \right). \quad [20]$$

Moreover, marginal abatement costs are always required to be equal:

$$MAC(t, a(t)) = MAC_{DACs}(a_{DACs}(t)). \quad [21]$$

To obtain a detailed technology downscaling of sources and sinks of CO<sub>2</sub> (fossil fuels and industry, including residual emissions from carbon capture and storage; BECCS and land use emissions) we interpolate linearly between the closest abatement levels reported in the SSP database, i.e.,  $a_i < a < a_{i+1}$  (again,  $i$  denotes different RCPs within the same IAM/SSP configuration and the same year) and add DACS after the interpolation.

### 3.10.7. 1.5°C scenarios for Figure 5

For Figure 5 the set of all 468 scenarios (13 IAM/SSP parameter sets, 6 rates  $r_d$  and 6 DACS parameters sets) is filtered for scenarios achieving at least a 30% reduction of D compared to their baselines, i.e., where  $r_d = 0$ . For scenarios depicted in Extended Data Figures 3-5 this reduction of D needs to be at least 5%, 15% and 45%, respectively. From scenarios with different rates  $r_d$  but otherwise identical parameters, only the lowest rate is kept, resulting in a potential set of 78 scenarios, of which 26 are feasible regarding the 30% carbon debt reduction requirement in Figure 5. Hence, in panels c and d geometric median pathways of 26 scenarios where  $r_d > 0$  are compared to the associated 26 baselines in panels a and b where  $r_d = 0$ . Baselines are interpreted as ‘conventional ETS’ scenarios, which are in terms of emission paths equivalent to CRO-ETS scenarios with  $r_d = 0$ . All underlying scenarios are shown graphically in [S11.3](#) and numerically in [S11.4](#)., abatement and interest costs are illustrated in Extended Data Figure 6 for all scenarios.

### 3.10.8. A note on technological learning

Technological learning in most IAMs is either exogenous, i.e., purely time dependent, or induced by learning-by-doing, which is strongly backed by empirical evidence. However, learning is best perceived as a complex interplay between R&D, learning-by-doing and

different types of spillovers (88), which only few models attempt to fully address. The MACCs derived here from SSP scenario results reflect learning rates in the IAMs used to generate these scenarios, resulting in typically decreasing marginal costs over time for similar abatement rates. Therefore, learning in our model is exogenous (purely time dependent), which is one of the main caveats of this model, because fixed learning rates over time imply an incentive to wait until abatement becomes cheaper. More ambitious near-term mitigation under a CRO-ETS, however, would likely lead to earlier cost reductions than reflected in the model. Due to the complexity of learning and the simplicity of our model we disregard DACS related technological change.

## 4. Social planner implementation and pricing paths

Based on the publicly available working paper: J. Bednar, A. Baklanov, J. Macinante, The carbon removal obligation: Updated analytical model and scenario analysis. IIASA Working Paper WP-23-001 (2023); <https://pure.iiasa.ac.at/id/eprint/18572/>.

The Supplementary Information referenced in this chapter is provided in Annex 4.

### 4.1. Abstract

The framework for carbon removal obligations (CROs), introduced in Chapter 3, consists of two core mechanisms: (1) the principal CRO mechanism obliges the emitter of a tonne of CO<sub>2</sub> to remove a tonne of CO<sub>2</sub> from the atmosphere at maturity of the CRO; and (2) the CRO pricing instrument imposes a premium ('CRO Premium') on carbon debt, defined as the emissions overshooting the remaining carbon budget. The CRO Premium thus adjusts carbon price levels induced by the principal CRO mechanism to alter the emission profile according to some prespecified preferences.

This technical chapter amends and extends the analytical CRO model in two fundamental ways: (1) instead of net emissions we consider gross emissions as basis for carbon debt creation, and gross removals for its compensation. This extends the scope of the principal CRO mechanism and is the basis for disentangling the emission trading system (ETS), that Chapter 3 relies on, from the CDR market; and (2) we introduce the methodology defining the CRO Premium.

We deploy the updated analytical framework using a simple numerical model to compute a set of illustrative climate mitigation pathways. Along these scenarios we assess the potential benefits from setting separate targets for emissions reductions and carbon removals – a possibility that results from the disentanglement of the ETS and the CDR market.

### 4.2. Introduction

Carbon Removal Obligations (CROs) were introduced in Chapter 3 to resolve a fundamental policy failure associated with climate mitigation scenarios that rely on large scale carbon dioxide removal (CDR) to reverse the overshoot of a previously missed climate target. The CRO framework consists of two core mechanisms: (1) the principal CRO mechanism obliges the emitter of a tonne of CO<sub>2</sub> to remove a tonne of CO<sub>2</sub> from the atmosphere later at maturity of the CRO; and (2) the CRO pricing instrument imposes a premium ('CRO Premium') on carbon debt, defined as the emissions overshooting the remaining carbon budget. The CRO

Premium adjusts carbon price levels induced by the principal CRO mechanism to alter the emission profile according to some prespecified preferences, e.g., to achieve a net-zero target for 2050.

Here we present an update of the analytical model of Chapter 3, consisting of two main improvements: (1) Instead of net emissions we consider gross emissions as basis for carbon debt creation, and gross removals for its compensation. This extends the scope of the principal CRO mechanism and is the basis for disentangling the emission trading system (ETS) that Chapter 3 relies on from the CDR market, implying that the ETS can be phased out up to the point where the remaining carbon budget becomes depleted. (2) We develop the fundamental methodology to define the CRO Premium.

The paper is structured as follows: section 4.3 introduces the updated analytical CRO framework (notably the novel CRO pricing instrument); section 4.4 explains the numerical model for applying the analytical framework and in section 4.5 we discuss the updated framework based on a set of illustrative climate mitigation scenarios.

### 4.3. Analytical CRO framework

We follow the convention that parameters use uppercase letters, and the free variables (controls) are denoted by  $\alpha$  and  $\mu$ .

#### 4.3.1. Definition of the constrained abatement cost minimization problem

Assume that  $\alpha$  and  $\mu$  are abatement rates (see Chapter 3 for the definition of abatement rate), where  $\alpha$  represents ERs and  $\mu$  reflects CDR. The convex cost function associated with these abatement rates is defined as  $f_c(t, \alpha(t), \mu(t)) = E(t) \left( \int_0^{\alpha(t)} f_\alpha(t, a) da + \int_0^{\mu(t)} f_\mu(t, a) da \right)$ , where  $f_\alpha$  and  $f_\mu$  are marginal cost functions and  $E$  reflects baseline emissions.  $B$  denotes the remaining carbon budget, i.e., the cumulative net emissions until  $T=2100$  compliant with a given target for warming in 2100. Moreover,  $T_0 \leq t \leq T$ . We aim to find an optimal solution, denoted by  $\alpha^*$  and  $\mu^*$ , of the problem

$$\min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \int_{T_0}^T f_c(t, \alpha(t), \mu(t)) \exp(-R(t - T_0)) dt, \quad [22]$$

subject to (s.t.)

$$\int_{T_0}^T E(t)(1 - \alpha(t) - \mu(t))dt \leq B, \quad [23]$$

$$v_i(t, \alpha(t), \mu(t)) \leq 0 \forall t, i = 1, \dots, m \quad [24]$$

$$w_j(t, \alpha(t), \mu(t)) = 0 \forall t, j = 1, \dots, n \quad [25]$$

where  $v_i$  reflects a set of  $m$  inequality constraints and  $w_j$  a set of  $n$  equality constraints. These constraints represent additional policy targets, like those for gross emissions, gross removals, or net removals as defined in Table 2 below. Based on this problem we derive the CRO pricing instrument in two steps: The first reformulation replaces the constraints [ 24 ] and [ 25 ] by carbon price paths for gross emissions and removals. The second reformulation merges these price paths to obtain a single pricing instrument for carbon debt.

#### 4.3.2. First reformulation of the problem

Let us assume that  $\alpha^*$  and  $\mu^*$  exist and are known, and that they represent piecewise continuous functions. Based on the optimal solution we define  $P_\alpha(t) = f_\alpha(t, \alpha^*(t))$  and  $P_\mu(t) = f_\mu(t, \mu^*(t))$ . We call  $P_\alpha$  the price of ERs and  $P_\mu$  the price of CDR.

Let us denote gross emissions by  $e(t) = E(t)(1 - \alpha(t))$  and gross removals by  $r(t) = E(t)\mu(t)$ . As demonstrated in the Supplementary Information (Annex 4) we can reformulate the problem in [ 2 ]-[ 25 ] by adding to the objective function [ 2 ] the price paths of ERs and CDR, imposed on gross emissions and removals, respectively. With this reformulation we can omit constraints [ 23 ] to [ 25 ] and get

$$\min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \int_{T_0}^T \left( f_c(t, \alpha(t), \mu(t)) + P_\alpha(t)e(t) - P_\mu(t)r(t) \right) \exp(-R(t - T_0)) dt, \quad [26]$$

which yields the same optimal solution  $(\alpha^*, \mu^*)$  as the problem in [ 2 ]-[ 25 ].

### 4.3.3. Second reformulation towards the CRO model

Again, let us assume that  $\alpha^*$  and  $\mu^*$  exist and are known, and that they represent piecewise continuous functions. Based on the optimal solution let us define a temporal distribution of the carbon budget  $B_\alpha$ , such that  $\int_{T_0}^T B_\alpha(t) dt = B$  and  $0 \leq B_\alpha(t) \leq E(t)(1 - \alpha^*(t))$ . We denote carbon debt by  $d(t) = e(t) - B_\alpha(t)$ , i.e., gross emissions overshooting the temporal distribution of the carbon budget. The repayment term  $g: [T_0, T] \rightarrow [0, T - T_0]$  ties carbon debt and gross removals. It reflects the time span between creation of carbon debt at a specific date and its compensation through gross removals. It therefore establishes a link between CRO issuance and maturity. We denote this idealized representation of a ‘time to maturity’ of a CRO by  $t'$ . We define the term structure function for the CRO Premium as  $f_s(t, t') = P_\alpha(t) - P_\mu(t + t') \exp(-Rt')$ ,  $0 \leq t' \leq T - t$ , i.e., the difference between the price of ERs at  $t$  and the price of CDR at maturity  $t + t'$ , expressed in present value terms at  $t$ .

As we show below, the problem in [ 27 ]-[ 30 ] also yields the same optimal solution  $(\alpha^*, \mu^*)$  as the previous problems.

$$\min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \int_{T_0}^T (f_c(t, \alpha(t), \mu(t)) + f_s(t, g(t))d(t)) \exp(-R(t - T_0)) dt, \quad [ 27 ]$$

s.t.  $\forall t \in [T_0, T]$

$$d(t) \geq 0, \quad [ 28 ]$$

$$\int_{T_0}^T d(\tau) d\tau = \int_{T_0}^T r(\tau) d\tau, \quad [ 29 ]$$

$$\int_{T_0}^t d(\tau) d\tau = \int_{T_0}^{t+g(t)} r(\tau) d\tau. \quad [ 30 ]$$

Note that the CRO Premium function  $f_s$  is imposed on carbon debt  $d$  rather than gross emissions/removals. The additional constraints [ 24 ] and [ 25 ] are fully reflected by  $f_s$ . Moreover, [ 8 ] reflects the principal CRO mechanism, i.e., that carbon debt needs to be compensated by gross removals, which replaces the carbon budget constraint in [ 23 ]. To

apply the CRO Premium function  $f_s$ , creation of carbon debt (CRO issuance) needs to be linked to its compensation (CRO maturity), as in [ 30 ]. Compared to Chapter 3, the principal CRO mechanism covers gross removals  $r$ , i.e., all CDR activities, implying that the CDR market supplying the required removal units is solely linked to the CRO framework (and not the ETS as in Chapter 3). The ETS, or another conventional carbon pricing scheme, is limited to emissions which need to comply with the time-distributed carbon budget  $B_\alpha(t)$ . Therefore,  $B_\alpha(t)$  could be understood as the emission caps of the ETS.

Now let us show the steps that lead from [ 26 ] to [ 27 ]. We denote the set of all solutions of [ 26 ] by  $\Omega = \arg \min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \int_{T_0}^T \left( f_c(t, \alpha(t), \mu(t)) + P_\alpha(t)e(t) - P_\mu(t)r(t) \right) \exp(-R(t - T_0)) dt$ .

Note the simple fact that  $\arg \min_x f(x) = \arg \min_x (f(x) + K)$  where  $K$  is a constant. Then by subtracting the constant  $\int_{T_0}^T P_\alpha(t)B_\alpha(t) \exp(-R(t - T_0)) dt$  from the objective function in [ 26 ], we obtain that

$$\Omega = \arg \min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \left( \int_{T_0}^T \left( f_c(t, \alpha(t), \mu(t)) + P_\alpha(t)e(t) - P_\mu(t)r(t) \right) \exp(-R(t - T_0)) dt - \int_{T_0}^T P_\alpha(t)B_\alpha(t) \exp(-R(t - T_0)) dt \right).$$

We simplify the expression to obtain

$$\begin{aligned} \Omega &= \arg \min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \int_{T_0}^T \left( f_c(t, \alpha(t), \mu(t)) + P_\alpha(t)(e(t) - B_\alpha(t)) - P_\mu(t)r(t) \right) \exp(-R(t - T_0)) dt \\ &= \arg \min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \int_{T_0}^T \left( f_c(t, \alpha(t), \mu(t)) + P_\alpha(t)d(t) - P_\mu(t)r(t) \right) \exp(-R(t - T_0)) dt. \end{aligned}$$

Next, let us recall the Theorem in Chapter 3, which assumes that  $\phi \int_{[0,1]} x(t)f(t + T_R(t))dt = \int_{[0,1]} y(t)f(t)dt$ . Here, because of [ 29 ],  $\phi = 1$ . Moreover, we apply the Theorem by inserting  $x(t) = d(t)$ ,  $y(t) = r(t)$ ,  $f(t) = P_\mu(t) \exp(-R(t - T_0))$ , and for the repayment term  $T_R(t) = g(t)$ . We therefore obtain  $\int_{T_0}^T d(t) P_\mu(t + g(t)) \exp(-R(t + g(t) - T_0)) dt = \int_{T_0}^T r(t) P_\mu(t) \exp(-R(t - T_0)) dt$ , hence,

$$\begin{aligned}
\Omega &= \arg \min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \int_{T_0}^T \left( f_c(t, \alpha(t), \mu(t)) \right. \\
&\quad \left. + (P_\alpha(t) - P_\mu(t + g(t)) \exp(-Rg(t))) d(t) \right) \exp(-R(t - T_0)) dt \\
&= \arg \min_{\alpha(t), \mu(t) \in \mathbb{R}^+} \int_{T_0}^T \left( f_c(t, \alpha(t), \mu(t)) + f_s(t, g(t)) d(t) \right) \exp(-R(t - T_0)) dt.
\end{aligned}$$

#### 4.3.4. The CRO Premium function

The CRO Premium function in present value terms is defined as  $\hat{f}_s(t, t') = (P_\alpha(t) - P_\mu(t + t') \exp(-Rt')) \exp(-R(t - T_0))$ . Assume that  $g^*$  is the repayment term associated with the optimal solution  $(\alpha^*, \mu^*)$ , then  $\hat{f}_{g^*}(t) = (P_\alpha(t) - P_\mu(t + g^*(t)) \exp(-Rg^*(t))) \exp(-R(t - T_0))$  is the cost-effective (optimal) CRO Premium path (red dashed line in Figure 7 a2-e2). This setting implies two scenarios for implementation of the CRO framework. For the scenario analysis in section 4.5 we assume that maturities are defined by the regulator, i.e.,  $g$  is fixed to the optimal solution  $g^*$  in [ 6 ]. In this case it is required that emitters at issuance of CROs know the CDR cost function at CRO maturity. If  $g$  is not fixed by the regulator, the CRO Premium at each time depends on the set of all possible maturities, i.e., the single CRO Premium curve  $\hat{f}_{g^*}(t)$  is replaced by a CRO Premium term structure  $\hat{f}_s(t, t')$ . In this case emitters at one point in time also need to correctly anticipate the behavior of future emitters in response to their own actions. We expect that a real-world implementation would be a mix of the constrained maturities and subsequent CRO Premium  $\hat{f}_{g^*}(t)$  and the fully unconstrained case  $\hat{f}_s(t, t')$ , for instance, by limiting CRO maturities within reasonable bounds (e.g., up to 25 years).

#### 4.3.5. The 'carbon debt interest rate'

Note that [ 27 ] is similar to the objective function of the analytical CRO problem formulation in Chapter 3. By comparing the original model in Chapter 3 with the updated model here one can easily derive a carbon debt interest term structure from  $\hat{f}_s$ . The carbon debt interest rate in the analytical model in Chapter 3 is imposed on the average removal costs at the time of CRO maturity, which is used as a proxy for the capital amount of (physical) carbon debt. Instead, imposing the carbon debt interest rate on either the spot market price or a CDR price index with reduced volatility might be feasible – at least until the CDR market is sufficiently

mature to provide future and forward contracts (58). Crucially, the capital amount of carbon debt influences the financial position of CRO holders, hence, their default risk.

#### 4.4. Numerical framework

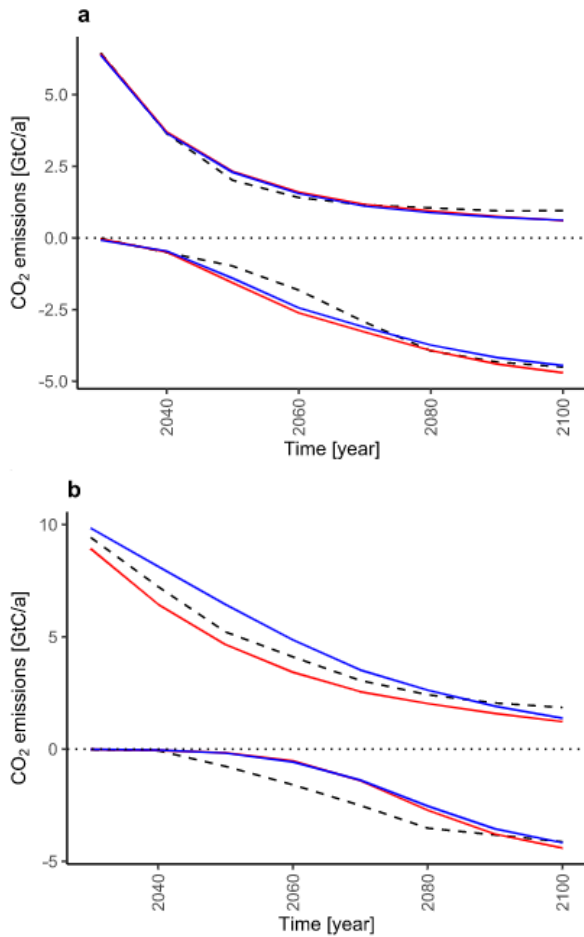
Similar to Chapter 3 we calibrate marginal abatement cost curves (MACCs) based on the marker scenario for SSP2 from the integrated assessment model (IAM) MESSAGE-GLOBIOM, including the scenarios for RCP 1.9, 2.6 and 3.4 (51, 80). The MACC for ERs is defined as

$$f_{\alpha}(t, \alpha(t), \alpha) = \frac{D_{\alpha}}{(1 + A_{\alpha}(t))^{M_{\alpha}}} \left( \frac{\alpha(t)}{U_{\alpha}(t) - \alpha(t)} \right)^{C_{\alpha}}. \quad [31]$$

Note that the functional form and underlying calibration procedures for the ER abatement rate  $\alpha$  and the CDR abatement rate  $\mu$  are identical, hence, only  $\alpha$  is referred to explicitly here. For  $\alpha$  we use gross emission reductions as fraction of baseline emissions  $E$ ; for  $\mu$  we use gross removals as fraction of  $E$ , whereas for  $f_{\alpha}$  and  $f_{\mu}$  we use the same reported carbon prices. Cumulative ERs (or cumulative removals for  $\mu$ ) are defined as  $A_{\alpha}(t) = \int_{T_0}^t \alpha(\tau)E(\tau)d\tau$ .  $M_{\alpha}$  defines the level of endogenous technological change due to learning-by-doing, which can be expressed more intuitively as progress ratio  $L_{\alpha} = 2^{-M_{\alpha}}$ , where  $L_{\alpha}$  indicates the fraction of initial marginal costs after doubling  $A_{\alpha}(t)$ .  $D_{\alpha}$  and  $C_{\alpha}$  are the standard power law coefficients.  $U_{\alpha}(t) = \frac{\bar{U}_{\alpha}}{1 + \exp(K_{\alpha}(t - I_{\alpha}))}$  is an upper bound of abatement following a logistic function, with the curve's maximum value at  $\bar{U}_{\alpha}$ , the inflection point  $I_{\alpha}$  and the steepness of the curve  $K_{\alpha}$ .  $U_{\alpha}(t)$  aims to reflect ramp-up constraints in the underlying IAM. However, since  $f_{\alpha}(t, \alpha(t)) \rightarrow \infty$  for  $\alpha(t) \rightarrow U_{\alpha}(t)$ , cost reduction can also be achieved exogenously (learning over time) by the gradual increase of the upper bound of abatement.

We calibrate two sets of cost curves, with low and high progress ratios (high and low endogenous learning potential),  $L_{\alpha} = 0.65$  and  $L_{\alpha} = 0.95$ , respectively, which corresponds to the range given in ref (89). Note that overall technological change is similar for the two sets of cost curve parameters. If the potential for endogenous technological change is high ( $L_{\alpha} = 0.65$ ), then exogenous, purely time-dependent cost reductions through  $U_{\alpha}(t)$  are low, and vice-versa.

We first fit the MACC model for fixed  $L_\alpha$  and  $U_\alpha(t) = \max(\alpha(t))$ , to determine  $D_\alpha$  and  $C_\alpha$ . Then we fix these parameters to determine  $\bar{U}_\alpha$ ,  $K_\alpha$  and  $I_\alpha$ . In Figure 6 we compare the gross emissions and removals pathways from the SSP RCP1.9 and RCP2.6 pathways with pathways resulting from our calibration.



**Figure 6. Gross emissions (above zero) and removals (below zero) of the climate mitigation scenarios from MESSAGE-GLOBIOM based on SSP2 (black dashed line), compared to output of the model used for this study. The model was calibrated using the data from these scenarios. Red solid lines are emission profiles resulting from high endogenous learning potentials, blue lines are emission profiles with low endogenous learning potentials. Marginal abatement costs were fixed to the reported carbon price for RCP 1.9 in panel a, and for RCP 2.6 in panel b.**

The MACC parameters, shown in Table 1, define marginal costs in USD/tonne C. Integration of  $f_\alpha$  and  $f_\mu$  to obtain  $f_c$  is done numerically during optimization. Note that because  $C_\alpha \in \mathbb{R}^+$ , the domain of  $f_\alpha$  is generally constrained to  $[0, U_\alpha]$ .

Table 1. Parameters of the marginal abatement cost curves (MACCs) for the ER abatement rate  $\alpha$  and CDR abatement rate  $\mu$ , for a high endogenous technological learning potential represented by a low progress ratio  $L = 0.65$ , and a low learning potential with  $L = 0.95$ .

Parameters of the marginal abatement cost curves				
	$L = 0.65$		$L = 0.95$	
	$f_\alpha$	$f_\mu$	$f_\alpha$	$f_\mu$
$D$	1724	7384	329	1327
$C$	1.67	0.88	0.96	0.53
$M$	0.621	0.621	0.075	0.075
$\bar{U}$	0.99	0.20	0.98	0.19
$K$	-0.14	-0.36	-0.17	-0.13
$I$	2021	2033	2024	2041

We use a remaining global carbon budget of  $B = 400$  Gt CO<sub>2</sub> for the 2020-2100 period, which reflects a 67% likelihood of limiting warming to below 1.5°C (90). For the temporal distribution of the carbon budget, we use  $B_\alpha(t) = 0.8 E(t)(1 - \alpha^*(t)) \exp(-Q(t - T_0))$  where  $Q$  is set such that  $\int_{T_0}^T B_\alpha(t) dt = B$ . The additional targets underlying the scenarios, which are represented by the inequality constraints [ 24 ], are defined in Table 2. The model is solved in ten-year time steps, like the underlying data. We compute four sets of scenarios by using all possible combinations of the two sets of cost function parameters. The scenarios for  $L_\alpha = L_\mu = 0.65$  are shown and discussed in section 4.6, whereas the other scenarios are illustrated in section 4.7. From the solution of [ 2 ]-[ 25 ] and using the MACCs [ 31 ], the optimal CRO Premium path  $\hat{f}_g^*$  is determined by using spline interpolation between the ten-year time steps.

For the theorems in the Supplementary Information (Annex 4) to apply we need to assume that learning (hence cumulative ERs  $A_\alpha(t)$  and removals  $A_\mu(t)$ ) are fixed to the optimal paths for the reformulation of the original problem towards the problem in [ 26 ]. For this, the standard assumption underlying carbon taxes is sufficient: emitters at each point in time abate to the level where marginal costs equal the price. Learning then follows as a result defining ERs and CDR according to that logic.

Table 2. Targets underlying the climate mitigation scenarios as constraints for gross emissions, gross removals, and net removals.

Climate mitigation scenario	Target for emissions and removals
1 Standard	None
2 Rapid decarbonization	$e(t) \leq 1 + 11 \exp(-0.1(t - T_0))$
3 Limit CDR	$r(t) \leq 2$
4 Phase out CDR	$r(t) \leq 5 \exp(-0.05(t - T_0 - 40))$
5 Phase out net removals	$e(t) - r(t) \geq -5 \exp(-0.05(t - T_0 - 40))$

## 4.5. CRO-based climate mitigation scenarios

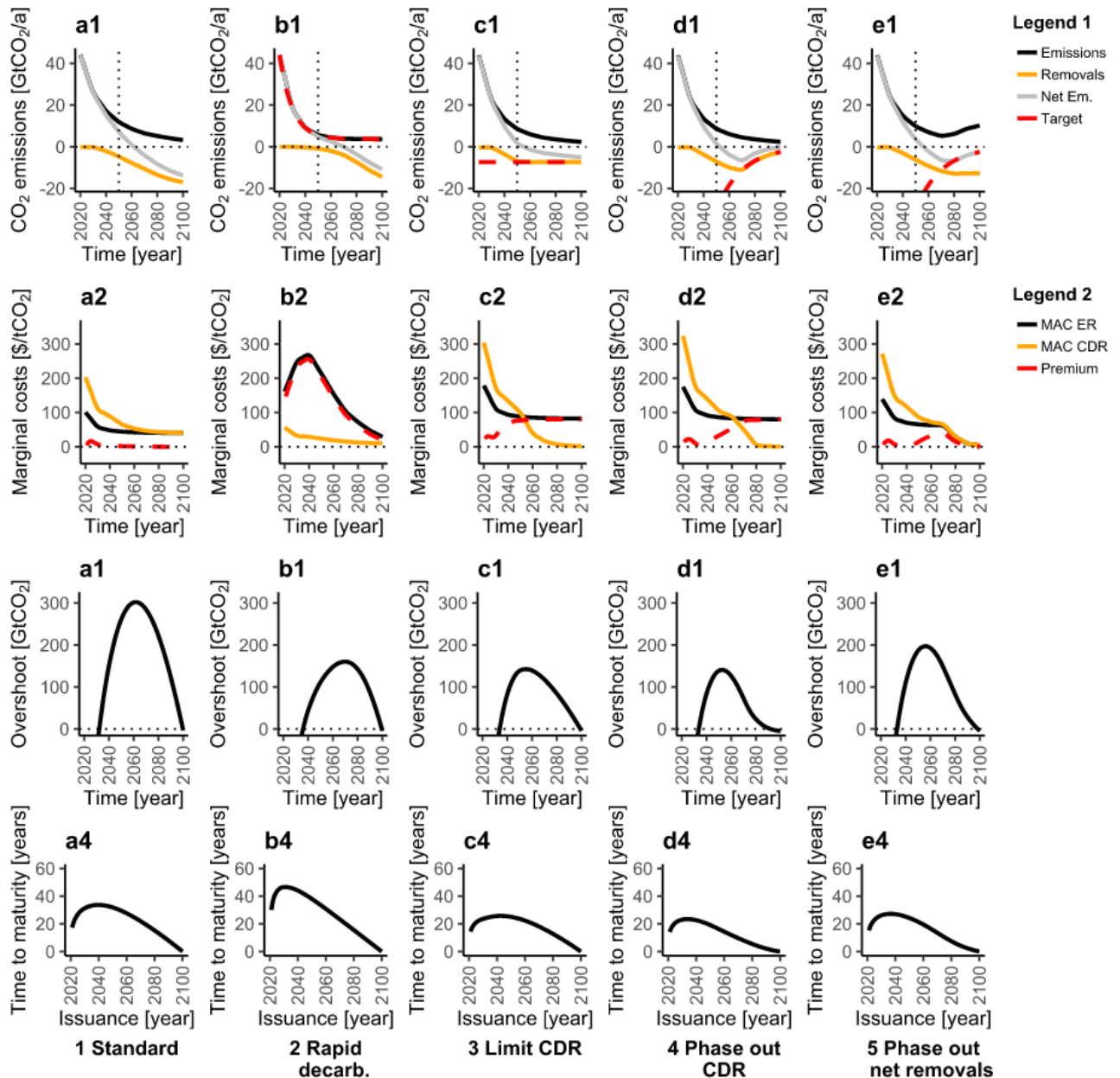
The separation of ERs and CDR in the model described in section 4.3 enables the CRO pricing instrument to separately control price and quantity levels of ERs and CDR. This section, hence, investigates two drivers of divergent price levels, including policies with separate targets for CDR and ERs (35, 91), as well as endogenized technological change. It further illustrates the CRO Premiums required to induce these price levels. The analysis is based on a set of idealized 1.5°C climate mitigation scenarios shown in Figure 7, similar to the archetypes in (14). The scenarios are based on the analytical model in section 4.3, computed with the numerical model in section 4.4. Each of the scenarios reflects a plausible target for either gross emissions, gross removals or net removals, as described in Table 3. To assess the feasibility and implications of the different targets, the mitigation scenarios are qualitatively compared with each other along a set of indicators in Table 4. The first set of indicators summarizes the long-term convergence of price and emission levels, with implications for mitigation beyond the achievement of the carbon budget target in 2100. The second set of indicators shows changes of policy costs compared to the ‘standard scenario’ as well as the aggregated financial flows resulting from CRO Premium payments as percentage share of policy costs. The third set of indicators quantifies in various ways the level of near-term ambition associated with the mitigation scenarios.

## 4.6. Results

Emission profiles of the mitigation scenarios including a representation of the additional emission or removal targets are shown in panels a1-e1; the associated price paths for ERs and CDR as well as the trajectories of CRO Base Premiums in panels a2-e2 of Figure 7. Panels a3-e3 show cumulative carbon emissions overshooting the carbon budget. Issuance

of CROs is linked to their maturities in the repayment term structures shown in Figure 7 a4-e4.

For the scenarios presented in Figure 7 the endogenous learning potentials for CDR and ERs are high ( $L_\alpha = L_\mu = 0.65$ ), and exogenously imposed cost reductions ('learning over time') are low. A sensitivity analysis with respect to the share of endogenous versus exogenous learning is carried out. Hence, Figure 7 is replicated for the resultant scenarios in Figure 8-Figure 10.



**Figure 7. Climate mitigation scenarios based on a 1.5°C carbon budget (400GtCO<sub>2</sub>) and additional targets for gross emissions and removals, as well as net removals.** Panels a1-e1: Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). The respective targets (red dashed line) are defined as upper or lower bounds. Panels a2-e2: Present value marginal cost paths of conventional emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO premium (red dashed line). The CRO premium is defined as the present value of marginal costs of ERs at issuance

of the CRO minus the present value CDR price at maturity. Panels a3-e3: Cumulative CO<sub>2</sub> emissions above the carbon budget. Panels a4-e4: The repayment term structure links the issuance of CROs to their maturities.

Table 3. Description of climate mitigation scenarios

Climate mitigation scenario	Scenario description
1. Standard	Emission and price profiles are based solely on cost effectiveness considerations, i.e., there are no policy targets other than the carbon budget constraint.
2. Rapid decarbonization	A reduction target is imposed on gross emissions to achieve a fast transformation towards zero carbon technologies. No separate target is defined for CDR, which is ramped-up late in the century for overshoot reversal.
3. Limit CDR	Gross removals are limited at 7.3 GtCO <sub>2</sub> /a (=2 GtC/a) to reduce CDR specific risks and environmental impacts. The constant CDR level is better compatible with CDR capital renewal cycles and reduces the ‘problem of phasedown’(74).
4. Phase out CDR	CDR is deployed only temporarily, because the long-term goal is to achieve full decarbonization of emitting sectors. Therefore, a phase-out target is imposed on gross removals towards 2100, which minimizes the problem of phasedown.
5. Phase out net removals	A phase-out target is imposed on net removals such that gross emissions and removals are balanced by 2100, and price levels converge. CDR continues to play a role beyond 2100, hence, residual emissions are permitted to grow if cheap CDR options are available for offsetting.

A single Hotelling price path for both, CDR and ERs, is used as a guideline by many detailed process-based IAMs to determine or define carbon price paths. Such a single price, which increases at the market interest rate, would be induced by a CRO Premium equaling zero. However, the scope of the Hotelling rule (50) is in fact very limited (92). Even in the standard mitigation scenario in Figure 7a, where no target other than the carbon budget was imposed, prices increase at a lower rate than the market interest rate<sup>2</sup>. This is a consequence of endogenized technological change: to leverage the high learning potentials of CDR and ERs, both need to ramp-up faster than suggested by the Hotelling rule. To achieve this, initial prices need to be high, but then increase at a lower rate than the market interest rate to balance the initial growth burst. By contrast, in Figure 8 technological learning is almost independent of past ERs and removals, roughly resulting in a single Hotelling price path for CDR and ERs. In the long run, CDR and ER prices need to converge to a single Hotelling price also in Figure 7a, as learning potentials become depleted.

Note that the CRO Premium in Figure 7 a2-e2 (red dashed line) is generally positive, although the CDR price exceeds the price of ERs in four of the scenarios. Extended negative CRO

<sup>2</sup> Note that prices in Figure 7 are shown in present value terms, i.e., they are discounted at the interest rate.

premium periods are observed in Figure 9, where endogenous learning potentials of ERs are much smaller than of CDR. In this case, the negative CRO Premiums can be regarded as a public subsidy to assist a fast CDR ramp up and to induce learning-by-doing. However, such periods of 'CRO subsidies' are negligible as long as achievable endogenous learning rates of CDR and ERs are positive and in the same order of magnitude.

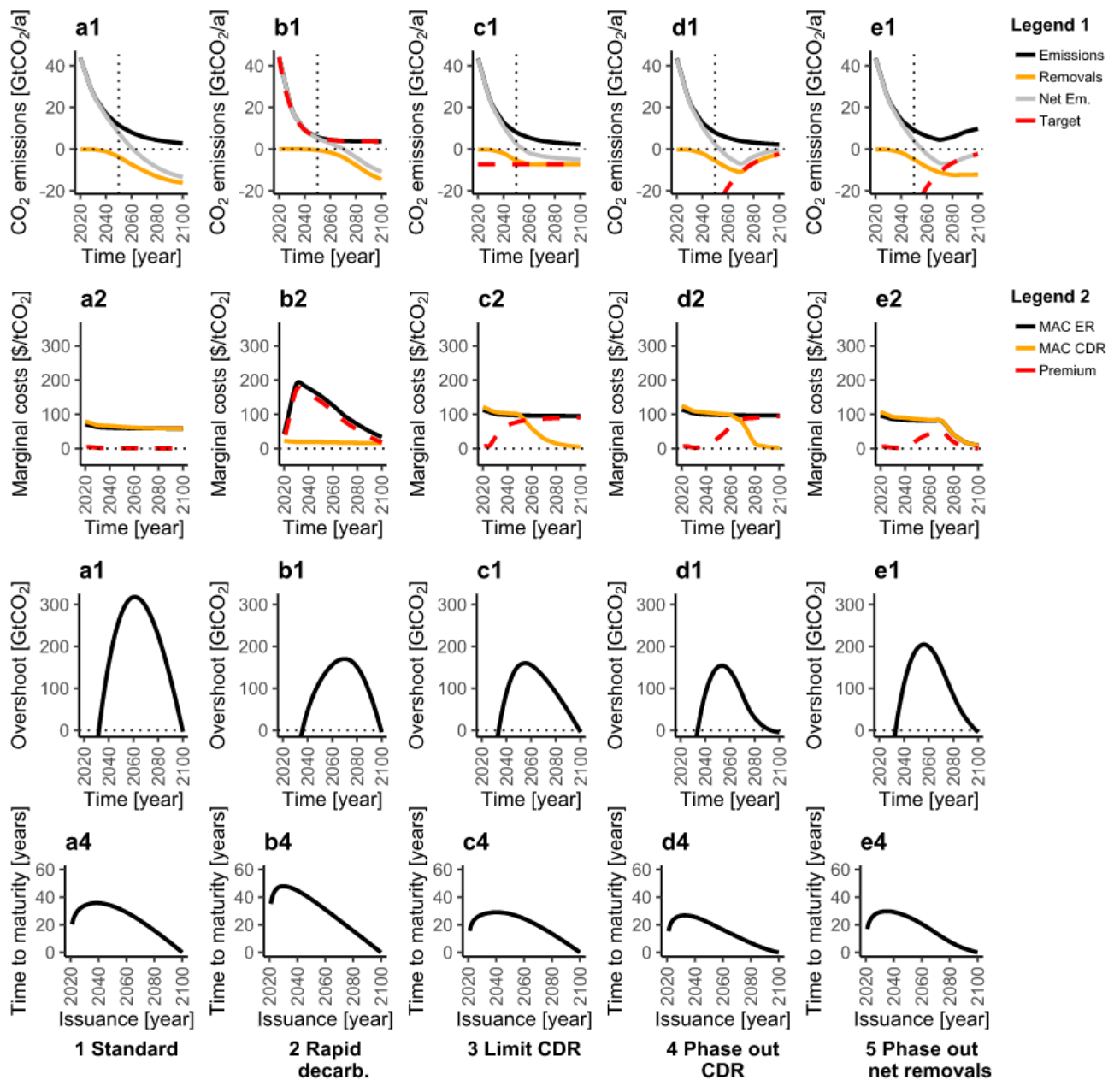
Table 4. Quantification of specific characteristics of the climate mitigation scenarios in Figure 2. Color scales indicate a value judgement, 'bad' (red) or 'good' (green). The yellow scale indicates low to high numbers where a judgement based on 'good' and 'bad' is not possible. Indicator 1.1 (Price convergence): Is necessary beyond 2100 to phase out the intertemporal CRO mechanism and gradually replace it with a contemporaneous mechanism for balancing gross emissions with removals. Indicator 1.2 (Emissions convergence): Net emissions converging to zero reduces the 'problem of phasedown'(93) once the climate target has been achieved. In scenarios where emissions do not converge, CDR assets might become stranded at larger scale. Indicator 2.1 (Policy costs) reflects the change of total present value abatement costs compared to the standard scenario. Indicator 2.2 (CRO Premium) quantifies total present value CRO Premium times the number of CROs issued as fraction of the total present value abatement costs of each scenario. Indicator 3.1 (CDR to ERs until 2050) reflects the ratio between total gross removals and emission reductions until 2050. Indicator 3.2 (CDR to ERs after 2050) reflects the ratio between total gross removals and emission reductions after 2050. Indicator 3.4 (Net zero year) shows the year where net emissions become negative. Indicator 3.5 (Max overshoot) equals the maximum level of cumulative net emissions from 2020 onwards above the carbon budget, as in Figure 2 a3-e3. Indicator 3.6 (Budget depletion year) Year where the remaining carbon budget becomes depleted. Indicator 3.7 (Max time to maturity) illustrates the maximum time to maturity derived from the repayment term structure in Figure 2 a4-e4.

Indicators		Climate mitigation scenarios				
		1 Standard	2 Rapid decarbonization	3 Limit CDR	4 Phase out CDR	5 Phase out net removals
1 Convergence	1.1 Price convergence	yes	yes	no	no	yes
	1.2 Emissions convergence	no	no	no	yes	yes
2 Costs	2.1 Policy cost	0%	+82%	+41%	+49%	+19%
	2.2 CRO Premium	9%	114%	78%	44%	27%
3 Near-term ambition	3.1 CDR to ERs until 2050	0.060	0.008	0.087	0.091	0.079
	3.2 CDR to ERs after 2050	0.182	0.098	0.110	0.110	0.177
	3.3 Total abatement until 2050 to after 2050	0.22	0.27	0.26	0.26	0.25
	3.4 Net zero year	2062	2070	2055	2053	2056
	3.5 Max overshoot	302 GtCO2	160 GtCO2	142 GtCO2	141 GtCO2	197 GtCO2
	3.6 Budget depletion year	2032	2036	2034	2034	2033
	3.7 Max time to maturity	34 Years	47 Years	26 Years	23 Years	27 Years

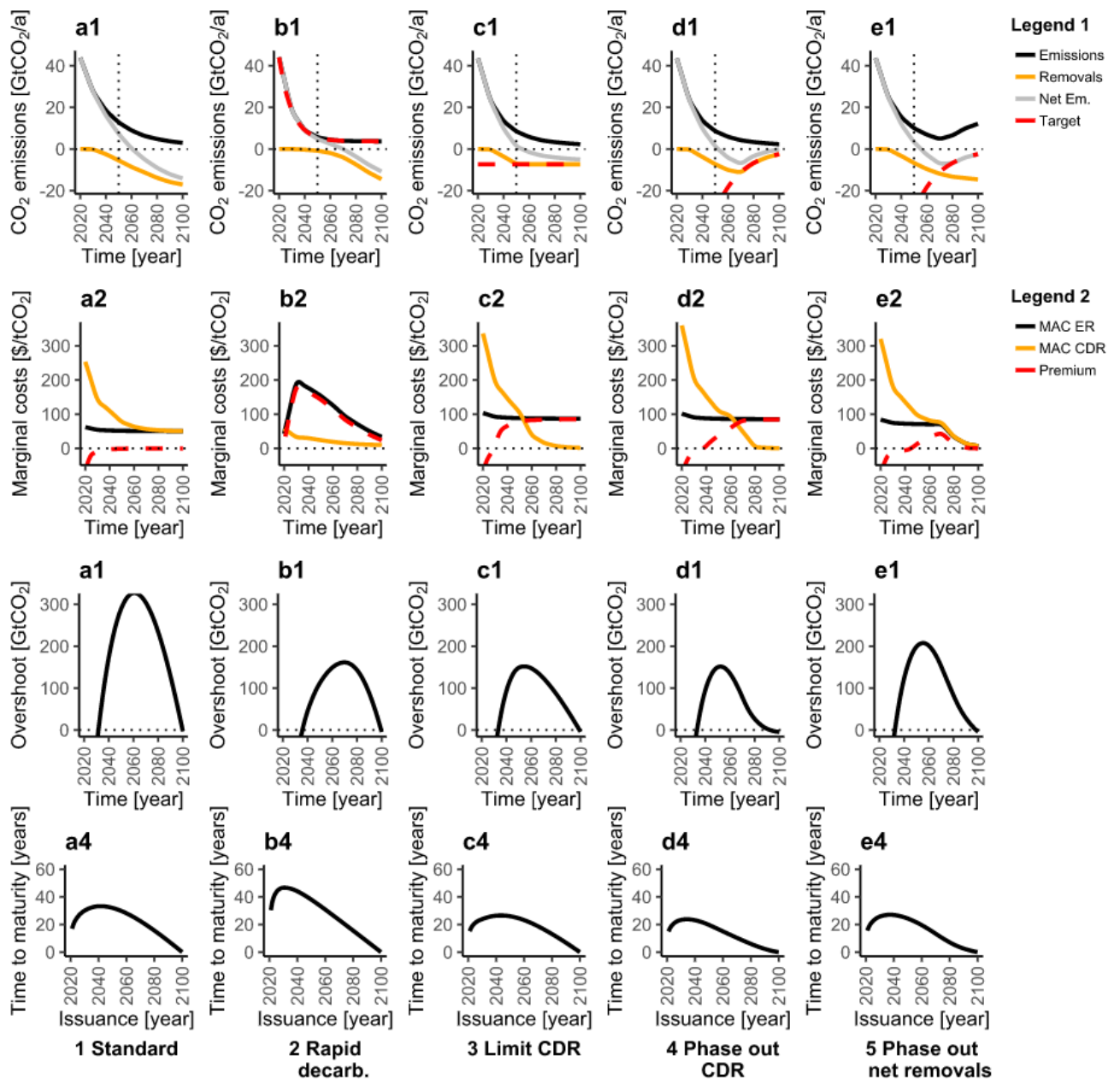
Figure 7 shows that policies with separate targets rely on different price levels for ERs and CDR. From the set of targets underlying the scenarios, those limiting gross removals (scenarios 3 and 4) show considerably more near-term ambition than the standard scenario. However, these scenarios are also significantly more costly (indicator 2.1 in Table 4), with CRO pricing strategies relying on a positive Premium in the long run to suppress CDR. Generally, more near-term ambition has a positive impact on the net zero year (indicator 3.4 and timing of the peak of the overshoot in Figure 7 a3-e3) and the maximum overshoot level (indicator 3.5 and peak of the overshoot in Figure 7 a3-e3), which implies earlier carbon debt repayment, hence, reduced maturities (indicator 3.7 and Figure 7 a4-e4). This is beneficial, both, from an overshoot risk and contract risk perspective. A reduced overshoot and considerable delay of the carbon budget depletion (indicator 3.6) can also be achieved by inducing a rapid decrease of gross emissions (scenario 2). However, without the support of near-term CDR, policy costs are high, and the net zero year is delayed. Long maturities and large financial flows from CRO pricing might impede operationalization of this scenario by means of the CRO framework. Notably, of all policies, the phase-out of net removals (scenario 5), i.e., a policy based on a net emissions target (94), appears to balance best between costs and ambition. Moreover, it is the only scenario characterized by convergence of prices as well as emissions and could therefore be sustained beyond 2100 with relatively little policy intervention.

## 4.7. Sensitivity analysis

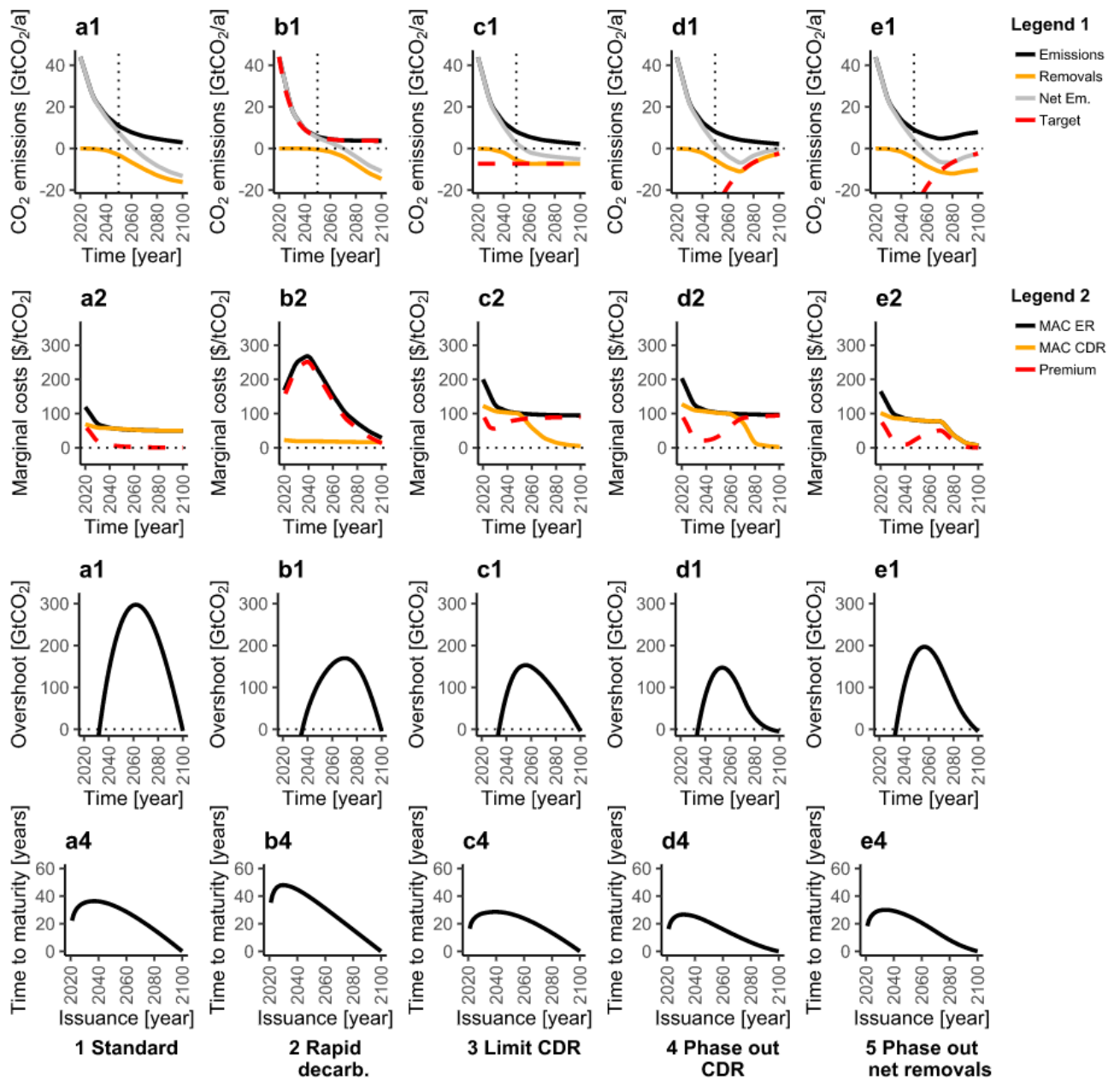
We perform a sensitivity analysis of the climate mitigation scenarios with respect to the degree of endogenous technological learning. The scenarios with high endogenous learning potentials for emission reductions (ERs)  $\alpha$  and carbon dioxide removal (CDR)  $\mu$  with progress ratios  $L_\alpha = L_\mu = 0.65$  are shown in Figure 7, whereas the other scenarios are illustrated. Figure 8 shows scenarios with low endogenous learning potentials ( $L_\alpha = L_\mu = 0.95$ ), cost reductions are mainly imposed exogenously as function of time. Figure 9, endogenous learning is low for ERs ( $L_\alpha = 0.95$ ) and high for CDR ( $L_\mu = 0.65$ ), whereas in Figure 10 endogenous learning is high for ERs ( $L_\alpha = 0.65$ ) and low for CDR ( $L_\mu = 0.95$ ).



**Figure 8. Low endogenous learning potentials for emission reductions and removals. Climate mitigation scenarios based on a 1.5°C carbon budget (400GtCO<sub>2</sub>) and additional targets for gross emissions and removals, as well as net removals.** Panels a1-e1: Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). The respective targets (red dashed line) are defined as upper or lower bounds. Panels a2-e2: Present value marginal cost paths of conventional emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO premium (red dashed line). The CRO premium is defined as the present value of marginal costs of ERs at issuance of the CRO minus the present value CDR price at maturity. Panels a3-e3: Cumulative CO<sub>2</sub> emissions above the carbon budget. Panels a4-e4: The repayment term structure links the issuance of CROs to their maturities.



**Figure 9. Endogenous learning is low for emission reductions and high for removals. Climate mitigation scenarios based on a 1.5°C carbon budget (400GtCO<sub>2</sub>) and additional targets for gross emissions and removals, as well as net removals.** Panels a1-e1: Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). The respective targets (red dashed line) are defined as upper or lower bounds. Panels a2-e2: Present value marginal cost paths of conventional emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO premium (red dashed line). The CRO premium is defined as the present value of marginal costs of ERs at issuance of the CRO minus the present value CDR price at maturity. Panels a3-e3: Cumulative CO<sub>2</sub> emissions above the carbon budget. Panels a4-e4: The repayment term structure links the issuance of CROs to their maturities.



**Figure 10. Endogenous learning is high for emission reductions and low for removals. Climate mitigation scenarios based on a 1.5°C carbon budget (400GtCO<sub>2</sub>) and additional targets for gross emissions and removals, as well as net removals.** Panels a1-e1: Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). The respective targets (red dashed line) are defined as upper or lower bounds. Panels a2-e2: Present value marginal cost paths of conventional emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO premium (red dashed line). The CRO premium is defined as the present value of marginal costs of ERs at issuance of the CRO minus the present value CDR price at maturity. Panels a3-e3: Cumulative CO<sub>2</sub> emissions above the carbon budget. Panels a4-e4: The repayment term structure links the issuance of CROs to their maturities.

## 5. Refined policy design and implementation blueprint

Based on the peer-reviewed journal article: J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).

The Supplementary Information referenced in this chapter is provided in Annex 5.

### 5.1. Abstract

According to most climate mitigation scenario assessments, limiting global warming to 1.5-2°C in the long run will not be possible without the extensive deployment of carbon dioxide removal (CDR) from the atmosphere. CDR is required for drawing down and achieving net-zero CO<sub>2</sub> emissions by mid-century. Thereafter, CO<sub>2</sub> removals will likely need to exceed residual CO<sub>2</sub> emissions, resulting in net negative emissions. A policy framework based on Carbon Removal Obligations (CROs) has been proposed by the authors to respond to concerns about the financial and fiscal viability, the lack of incentives for CDR uptake, as well as the physical and technological risks associated with any climate mitigation scenario that relies on large scale CDR. Here we propose an updated and improved CRO policy framework, consisting of two core elements: the ‘principal CRO mechanism’ obliges emitters of a tonne of CO<sub>2</sub> to remove a tonne of CO<sub>2</sub> at the time of maturity of the CRO. On top of this obligation, CRO holders need to pay a fee. This ‘CRO pricing instrument’, introduced in detail here, is used by regulators to steer the carbon emissions and removals pathways. Our update suggests that markets for CDR under the CRO framework should operate independently from markets for emission reductions (ERs), such as emission trading schemes. Moreover, we argue that carbon policies governing ERs become obsolete upon the depletion of the remaining cumulative carbon budget, if a CRO policy framework is implemented. We then propose a blueprint for legal implementation of the CRO policy framework in which central banks as regulators and commercial banks as CRO issuing entities allocate CROs via mechanisms similar to the way in which private financial borrowing and debt are dealt with. It is concluded that the CRO framework could be implemented by a package of three instruments: an enactment of primary legislation; development of a national or international standard; and secondary legislation to adopt the standard and implement the primary legislation. Details of these three proposed instruments are elaborated. Taking advantage of

the concept of incorporating CROs into financial debt, they build on traditional roles of existing institutions, applying mechanisms that are familiar and well understood, thus streamlining climate mitigation into the main economy.

## 5.2. Introduction

Many countries – representing more than two thirds of global GDP – and numerous international corporations, have pledged to achieve net zero carbon emissions by mid-century (33, 34). However, the 6<sup>th</sup> assessment report of the Intergovernmental Panel on Climate Change (IPCC) highlights that the 1.5°C threshold will likely be surpassed already in the mid-2030s – even if immediate emission reduction measures were implemented globally (95). At the current rate of greenhouse gas (GHG) emissions to the atmosphere, the remaining cumulative (RC) global carbon budget<sup>3</sup> to stay within an average global surface temperature increase of 1.5°C by 2100, will be consumed within the next decade, if not sooner (96). More specifically, the global RC carbon budget for a 50 % likelihood to limit global warming to 1.5, 1.7, and 2°C has, respectively, reduced to 105 GtC, 200 GtC, and 335 GtC from the beginning of 2023, equivalent to 9, 18, and 30 years from 2022 onwards and assuming 2022 emissions levels (97).

To limit warming to 1.5-2°C in the long run, most model-based assessments agree that carbon dioxide removal (CDR) from the atmosphere will be needed at large scale (98). A variety of mechanisms have been proposed for this, including measures like afforestation and reforestation, and technological options such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). Climate mitigation scenarios assessed by the IPCC foresee two different time horizons for such CDR deployment in the context of stringent climate goals: in the near to medium-term the role of CDR is to support emission reductions (ERs)<sup>4</sup> for achieving net zero CO<sub>2</sub> emissions by mid-century. In the long run, CDR needs to exceed residual emissions from sectors remaining hard to decarbonize (64), in order to achieve net CO<sub>2</sub> removals or net negative emissions (99), as illustrated in Figure 11a. Net CO<sub>2</sub> removals reduce atmospheric carbon stocks and can induce a cooling of the planet, if other GHG emissions also decline sufficiently (100). In that case, even 1.5°C can still be met by 2100 despite the temporary overshoot of the target.

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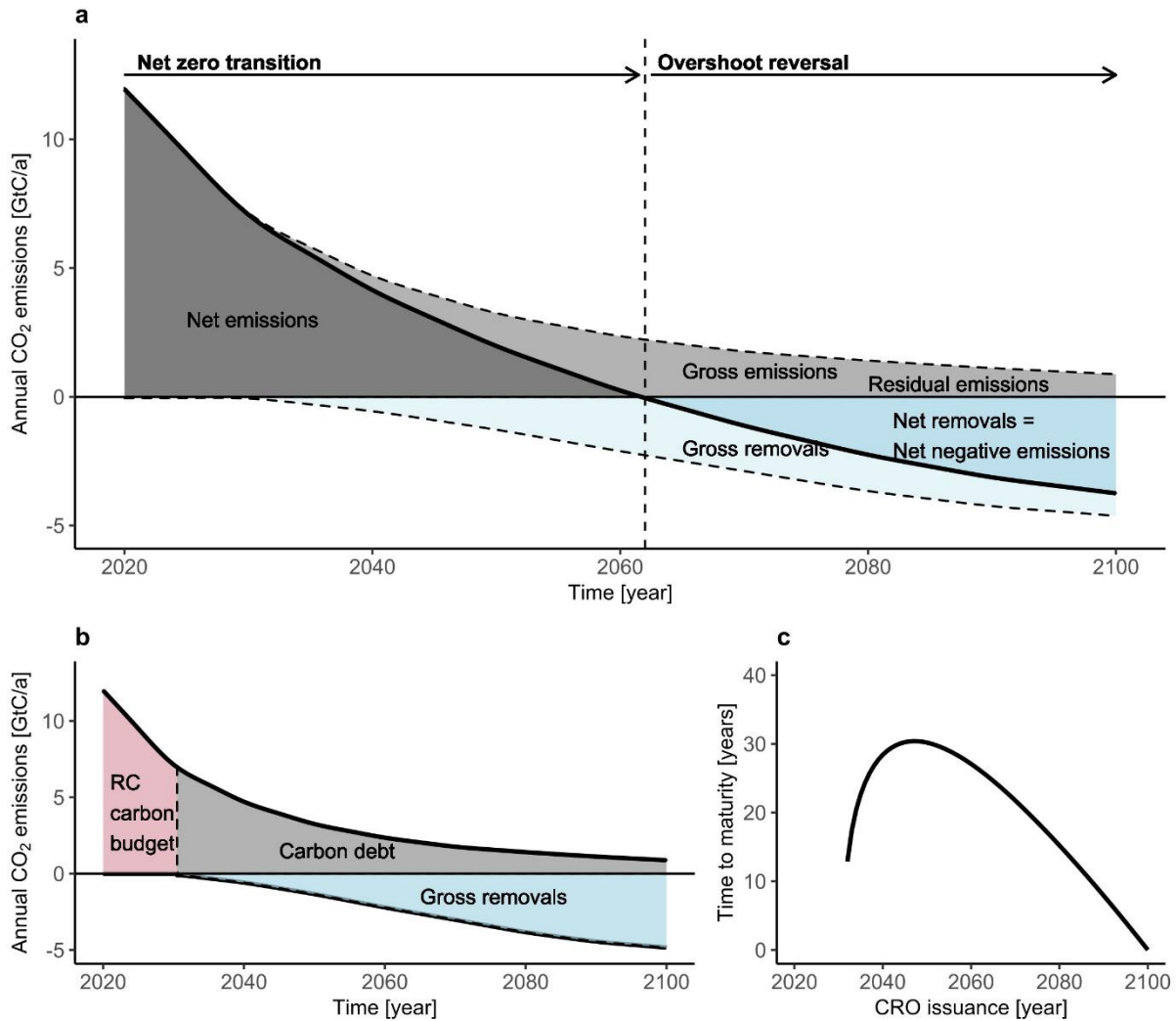
<sup>3</sup> The remaining cumulative (RC) carbon budget represents the cumulative net emissions quantity until 2100 compatible with a specific warming threshold, such as 1.5°C.

<sup>4</sup> Emission reductions compared to a baseline scenario might include carbon capture and storage (CCS) but do not include any atmospheric carbon removals.

Chapter 3 addresses the long-term role of CDR based on a rationale of intergenerational fairness, proposing regulatory arrangements that introduce the carbon removal obligation (CRO). They argue that emitters causing the overshoot of the RC carbon budget need to remain liable for delivering the net carbon removals required to reverse the overshoot in the second half of the century. Furthermore, they contend that the price of temporary atmospheric carbon storage – comparable to temporary CO<sub>2</sub> storage through afforestation – can be quantified and should rightfully be shouldered by emitters. In the absence of such an intertemporal mechanism that enforces the polluter pays principle (PPP), net removals would become a ‘public waste management task’, potentially imposing a huge fiscal burden on future generations on top of the growing climatic impacts (17). On the other hand, fully decarbonizing the global economy before overshooting the 1.5°C warming target, would require radical measures (101) which will likely not be achieved within this narrow time frame.

The CRO policy framework is appealing for a couple of reasons: first, it allows CDR-based climate change mitigation to be streamlined into the economy using the existing principle of interest-bearing financial debt. By taking this approach, emitters are not only legally obligated to ensure carbon removals, but are also mandated to make payments as long as their CO<sub>2</sub> emissions persist in the atmosphere. In this way, the PPP is upheld and enforced (102). It is expected that this scheme can attract significant private capital as the basis for the robust functioning of a CDR market in the near-term. Second, CRO pricing ensures that near-term ERs and CDRs are not compromised by the possibility of net removals later in the century. In other words, it reduces the moral hazard that would likely lead to mitigation deterrence (7) if contracting a CRO were for free. CRO pricing thus assures that – where possible – CDR is deployed in addition to, and not instead of, ERs.

This chapter builds on, amends and extends the mechanisms conceptualized in Chapter 3. Moreover, it provides a concrete roadmap for the implementation of the overall CRO policy framework, as proposed herein. We proceed as follows: In section 5.3 we revisit the scope of the principal CRO mechanism as envisaged in Chapter 3. Moreover, we explain the CRO pricing instrument, for which an analytical model has been developed (see Chapter 4). In section 5.4 we begin to explore possible legal frameworks, instruments and mechanisms that might enable implementation of the CRO policy framework, so as to facilitate operationalization of a negative carbon economy. We set out conclusions in section 5.5.



**Figure 11. Key terms and concepts: Gross and net emissions, gross removals, net negative emissions, remaining cumulative carbon budget, carbon debt and time to maturity.** Panel a: Elements characterizing a carbon emissions pathway. Net CO<sub>2</sub> emissions (opaque grey area) equal gross emissions (all grey areas) minus gross removals (all blue areas). Net emissions coincide with gross emissions in the near future until carbon dioxide removal (CDR) is ramped up. When gross emissions equal gross removals, net zero CO<sub>2</sub> emissions are achieved (vertical dashed line). Beyond net zero, gross removals exceed gross emissions, resulting in net negative emissions or net carbon removals (opaque blue area). Net emissions deplete the remaining cumulative (RC) carbon budget, whereas net removals replenish an overshoot RC carbon budget. Gross emissions which remain hard-to-abate in the long-term are labeled residual emissions. ‘CDR’ is a general term which comprises gross removals and net negative emissions, or the underlying technologies and practices, depending on the context. Panel b: Elements characterizing the CRO framework. Carbon debt is generated by gross emissions once the RC carbon budget has been depleted, here around 2030. Carbon debt is compensated intertemporally by gross removals. Panel c: The repayment term structure shows the time to maturity in years as a function of the date of issuance for the profile in panel b. For an analytical definition see Chapter 4.

### 5.3. The updated CRO

The CRO policy framework consists of two elements: the principal CRO mechanism and a CRO pricing instrument. The transition from the proposals in Chapter 3 to that proposed in this chapter with respect to these elements is demonstrated in section 2 in the Supplementary

Information (Annex 5). Here we elaborate on the elements of the CRO policy framework, as now proposed.

### 5.3.1. Theoretical considerations

The principal CRO mechanism is executed by CRO issuing entities and dictates that for every tonne of CO<sub>2</sub> emitted as ‘carbon debt’, a CRO is issued to the emitter. We classify emissions that exceed the RC carbon budget as this carbon debt<sup>5</sup>, as in Figure 11b. CROs in turn oblige emitters to remove an equivalent amount of CO<sub>2</sub> upon the CRO’s maturity (see Figure 12). Hence, CROs are issued at the time of emission and remain with emitters until CRO maturity. At maturity, emitters must possess removal units (13) for CRO cancellation, purchased on a CDR market or obtained via certified ‘in-house’ CDR operations. It is expected that removal units are traded competitively on a CDR market, ensuring CDR implementation at the lowest cost by capable entities at CRO maturity.

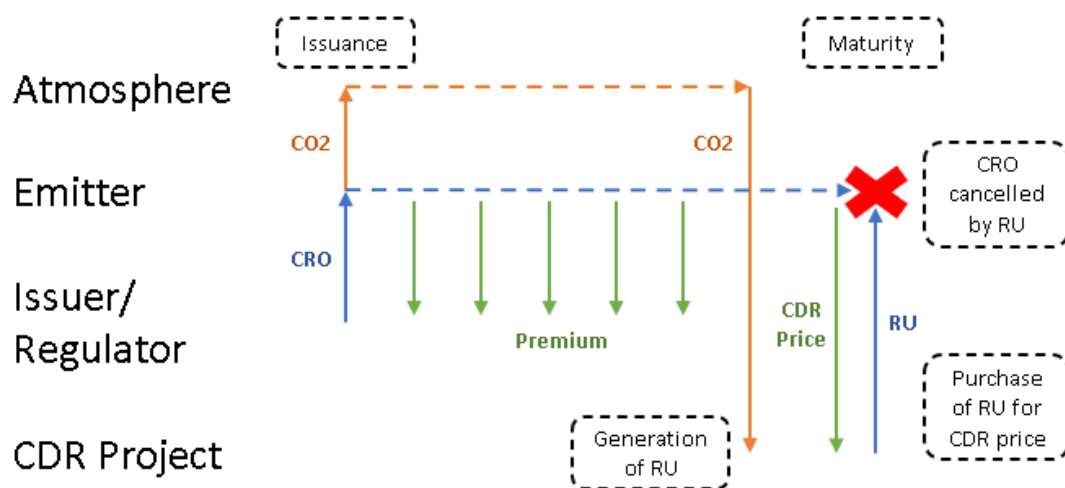
The CRO pricing instrument, on the other hand, encompasses the delineation and application of an apt CRO Premium, a two-stage process conducted by separate entities (elaborated in section 5.4). Initially, the regulator sets the CRO Base Premium (e.g., in EUR per tonne CO<sub>2</sub>) as a financial incentive to steer the emissions pathway. Subsequently, commercial CRO issuers impose emitter-specific Commercial Premiums atop this base and determine maturity profiles. Determination of these parameters aims to minimize idiosyncratic risks, as issuers remain liable for CDR deployment if CRO-holders default. Moreover, Premium payments financially compensates issuers for these risks taken. The maturity profiles and Commercial Premiums reflect the emitter’s financial position: a stronger position may warrant longer maturities and potentially lower Premiums, while a weaker position might see shorter maturities and higher Premiums. This approach ensures that emitters have a clear basis for deciding whether to reduce emissions or secure CROs. The total Premium may manifest as a financial interest rate, termed originally a ‘carbon debt interest rate’ (18), a periodic fee, or, at its simplest, a one-off payment by the emitter upon the CRO’s issuance (illustrated in Figure 13). While Figure 11c presents an idealized repayment term structure derived from a typical mitigation scenario, it is essential to understand that this aggregate pattern emerges from the combined individual maturity settings of all emitters. Due to variations in individual settings reflecting financial risk considerations, the real-world aggregate repayment trajectory might differ substantially from what current mitigation scenarios suggest.

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<sup>5</sup> In this manuscript, we equate gross emissions to carbon debt, essentially positing an RC carbon budget of zero. Thus, we consider the CRO framework’s initiation to align with the RC carbon budget’s exhaustion (refer to Figure 1b). Nonetheless, there exist compelling arguments for initializing the CRO framework before this depletion, as detailed in the Supplementary Information (Annex 5).

The principal CRO mechanism paired with the CRO pricing instrument defines the ERs' marginal costs at CRO issuance and the CDR price upon the CRO's maturity: under idealized perfect foresight conditions within the CRO framework, emitters would reduce emissions until ERs' marginal costs equate to CRO-associated marginal costs – the present value sum of future marginal removal costs and the CRO Premium. A Premium increase for a set maturity period would reduce CRO demand, resulting in fewer issued CROs and diminished removal demand at maturity, hence lowering the CDR price at maturity<sup>6</sup>. Fewer CROs being issued implies more ERs in the near-term, and elevated ERs' marginal costs.

The principal CRO mechanism presumes a CDR market's existence but not one for ERs. An ERs market could conceivably coexist with the CRO framework, given conditions delineated in Supplementary Information (Annex 5), Section 2. Separation of the CDR market permits divergent marginal costs between CDR and ERs, attributed to factors like different technological learning rates (see Figure 13c). This separation paves the way for individual target determination for ERs and CDR (see Figure 13d), a potentially beneficial strategy for various reasons (35), encompassing political factors (61, 91). Target setting coupled with technological learning rate variations are elaborated upon in section 5.3.2 scenarios.



**Figure 12. Graphical illustration of the CRO framework.** At the time of emission, an Issuer issues a CRO to the emitter, held until maturity. By maturity, emitters must own a removal unit (RU), generated by CDR projects and traded on a CDR market or directly generated by certified in-house operations of the emitter. The CRO is canceled against an RU at maturity. Between issuance and maturity, emitters pay a Premium, serving to 1) reduce emitter-specific (idiosyncratic) risks, 2) guide the emissions and removals paths, and 3) potentially allocate revenues towards mitigating future loss & damage or adaptation needs related to temporary atmospheric CO<sub>2</sub> stocks. In the figure, dashed boxes indicate actions or events; green arrows denote financial flows; blue arrows represent the exchange of CROs and RUs; and orange arrows depict physical CO<sub>2</sub> fluxes.

<sup>6</sup> Compare the two scenarios in Figure 13 for an illustration of that effect.

The principal CRO mechanism ensures that gross emissions and removals in total stay within the RC carbon budget, whereas CRO pricing plays a crucial role in determining how ERs and removals contribute over time to achieving this goal. The purpose of defining a Base Premium is thus to incentivize gross emission and removal pathways that are in line with a broader set of climate policy targets and/or risk considerations. Furthermore, revenues generated from Base Premium payments, conceptualized as compensation for temporary atmospheric CO<sub>2</sub> storage, can be effectively allocated to mitigate loss and damage attributable to these additional temporary CO<sub>2</sub> stocks, or to the resultant adaptation needs. This allocation contributes to the realization of intergenerational climate equity goals, aligning with suggestions posited in Chapter 3

In terms of steering emissions and removals paths, intermediate targets (47) such as achieving net zero CO<sub>2</sub> emissions by 2050, could be induced by appropriately imposing a time dependent Base Premium. Similarly, the Base Premium can be utilized to discourage emitters from obtaining CROs that would result in exceeding a specified threshold for removals at a given CRO maturity, as depicted in Figure 13b. In this manner, the Base Premium can serve as an incentive for a soft upper limit on removals. This might reduce the overshoot (Figure 13f) and the associated risks, recognizing that it is still unclear whether from technological, environmental, and economic perspectives CDR can be deployed at the required scale to reverse the overshoot (14, 41, 44, 46). More sophisticated CRO pricing strategies could be targeted at internalizing the physical risks associated with an overshoot by quantifying the likelihood and impact of climatic feedbacks, such as the melting of ice sheets, permafrost thaw (30), or other tipping points (103). If such feedbacks lead to additional warming, for instance through CO<sub>2</sub> outgassing from permafrost soils, they would put at risk the attainability of the temperature target even if cumulative emissions complied with the RC carbon budget – which the principal CRO mechanism aims to assure.

The analytical model introducing the CRO pricing mechanism is explained in Chapter 4. One way of determining the CRO Base Premium is through modeling of the properties of the processes relevant for climate mitigation in the physical, technological, and socio-economic environment, as well as the consideration of additional climate targets, such as net zero CO<sub>2</sub> emissions by 2050. The CRO Base Premium is then derived ex-post from marginal abatement cost paths – a method which is fully compatible with the model-based practice adopted by many regulators and scientific communities to compute carbon prices, for which countless examples exist in the climate economic literature. On the basis that the assumptions underlying such numerical models are valid, the CRO Base Premium can be imposed to adjust price levels of ERs and CDR which then incentivize the preferred behavior among emitters

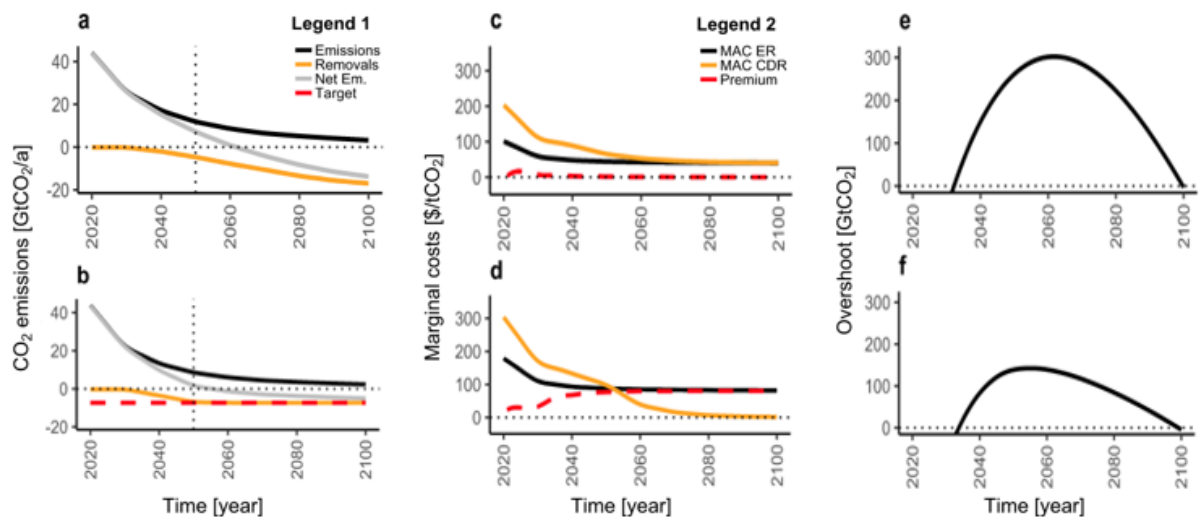
and the CDR industry. Realistically, an adaptive approach will be required to adjust the CRO Base Premium iteratively using model-based estimates backed by carbon market observational data, and considering other factors that determine a socially desirable mitigation pathway. The CRO Commercial Premium is determined by the issuing entities based on normal credit risk evaluations (104), which the analytical CRO model does not address.

### 5.3.2. CRO based climate mitigation scenarios

Chapter 4 also sets out a detailed scenario analysis based on a simple numerical model with technological change represented by 'learning-by-doing'. Two of the scenarios are illustrated in Figure 13, including a scenario where CDR is capped at 2 GtC/year (7.3 GtCO<sub>2</sub>/year) in panels b, d and f. Important conclusions for the integration of CDR into carbon policy schemes can be drawn from the scenario analysis: First, the initially high costs of CDR options like BECCS and DACCS compared to ERs is one of the frequent arguments used against CDR integration into ETSs. An ETS would require additional financial resources to cover that price gap between ERs and CDR, or else fail to stimulate innovation and early uptake of CDR (62, 105). A similar situation applies for the scenarios in Figure 13, where the price of CDR exceeds that of ERs. However, according to the principal CRO mechanism, ERs at CRO issuance always compete with CDR at maturity<sup>7</sup>. This time lag increases the competitiveness of CDR and even allows for charging a positive CRO Base Premium in almost all of the examined pathways in Chapter 4, instead of the need for additional funding an ETS would have to supply. Second, allowing the price levels to diverge is not only the prerequisite for separate target setting for ERs and CDR, as in Figure 13b. It also leads to a more cost-effective pathway than is achievable under a policy scheme requiring a single price. Even in the absence of additional constraints for emissions and/or removals as in Figure 13a, price levels diverge due to endogenous technological change. A generalization towards sectoral CRO pricing, which considers the different learning rates and inertias in CDR portfolios, the emitting sectors as well as their abatement options, would likely further improve flexibility and cost effectiveness.

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<sup>7</sup> This is in some ways similar to the mechanism described in Rickels et al. (2021).



**Figure 13. Climate mitigation scenarios based on a 1.5°C RC carbon budget (400GtCO<sub>2</sub> from 2020 onwards). For the full range of scenarios see Chapter 4.** The left column (a, c, e) reflects a standard mitigation scenario, whereas the right column (b, d, f) illustrates a scenario where gross removals were capped at 2 GtC/a, similar to the scenario archetypes in ref (14). Panels a & b: Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). In panel b gross removals were capped at 2 GtC/a (red dashed line). Panels c & d: Present value marginal cost paths of emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO Base Premium (red dashed line). The CRO Base Premium is defined as the present value of marginal costs of ERs at issuance of the CRO minus the present value CDR price at maturity. Capping gross removals implies a larger CRO Premium in panel d than in panel c. Panels e & f: Cumulative CO<sub>2</sub> emissions above the RC carbon budget. The upper bound for gross removals reduces the overshoot of the RC carbon budget and associated risks.

## 5.4. Legal frameworks, instruments and mechanisms for implementation

While recognizing that other approaches may be possible, this section aims to illustrate relatively straightforward legislative actions to provide for implementation of the CRO policy framework envisaged in the preceding section. In the proposed implementation scenario, central banks as regulators and commercial banks as CRO issuing entities have roles to play in the allocation/distribution of CROs to emitter entities, via mechanisms similar to those dealing with private financial borrowing and debt.

### 5.4.1. Initial discussion

Carbon debt is treated as financial debt in the balance sheets of emitters, represented by CROs. For example, each tonne of CO<sub>2</sub> emissions equals one CRO. Like financial debt, CROs accrue interest, referenced herein as the CRO Premium. The CRO Base Premium is determined by the central bank. The CRO Commercial Premium is determined by the commercial CRO issuer bank for their customer-emitter entities based on normal credit risk

evaluations, terms and conditions including collateral. CRO Premium payments might be hypothecated in part to a fund for specific future purposes<sup>8</sup>, just as a sovereign fund might be. CROs are discharged by the CRO holder acquiring and surrendering/retiring removal units generated by a CDR project.

Elements for implementation of the proposed CRO policy framework thus include:

- i. a legal obligation for prescribed legal entities to report their emissions;
- ii. the date when the RC carbon budget is defined to be expended (or a process to determine a temporally distributed instantaneous (TDI) carbon budget, as explained in the Supplementary Information in Annex 5);
- iii. emissions overshooting the RC or TDI carbon budget being defined in law as carbon debt that must be included by prescribed legal entities in their financial accounts (e.g., in the balance sheet);
- iv. carbon debt being subject to a financial CRO Premium – both for the commercial banks and the banks’ emitter-customers that are prescribed legal entities;
- v. carbon debt being extinguished by prescribed legal entities acquiring and retiring removal units;
- vi. removal units being generated and issued by CDR projects;
- vii. provision for funds generated by CRO Base Premium payments on the commercial banks’ accounts with the central bank – and perhaps also a portion of the CRO Commercial Premium payments by the emitter entities to their issuer commercial banks – to be hypothecated against future climate change management risks; and
- viii. carbon debt not being able to be written off, but rather needing to be paid off. Thus, in the case of an insolvent emitter, any outstanding carbon debt will need to be paid off by the CRO issuing entity (i.e., commercial bank that issued it).

By treating carbon debt the same as any other business debt, the CROs on the emitter’s balance sheet would need to be taken into account when considering the emitter’s solvency. This underscores the need for an established marketplace for removal units to be functioning robustly, well before CROs become applicable, so that liability can be ascertained and budgeted for by emitters. There would also be other relevant regulatory provisions to be taken into account, for instance, such as the rules against insolvent trading.

Moreover, the CRO policy framework, as proposed in Chapter 3 holds that ‘...To assure its physical conservation and exert control over its aggregate level, carbon debt would initially be issued at the base rate by managing authorities – for example, Central Banks – to which

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<sup>8</sup> For instance, the funds might be targeted at reducing future climate change risks, as hypothesized in Chapter 3; or for addressing welfare distributional issues associated with carbon pricing.

commercial banks would be held liable in case of insolvent debtors'. This gives rise to two points.

First, central banks, (for example, the Bank of England), control money supply and can create 'base money' through open market operations (e.g., buying or selling government bonds). However, for the most part, commercial banks take deposits and use these deposits to lend to borrowers (subject to central bank requirements to maintain a fractional reserve to cover depositor repayments): this increases the money supply beyond the base money issued by the central bank (see refs (107, 108)). It is proposed to adapt these concepts and approach to the issuance of CROs. Thus, we propose commercial banks will issue CROs to reflect the level of a customer's emissions; they will apply their normal credit risk evaluation to set the rate of interest they charge; they will need also to maintain a reserve with the central bank to cover – not repayments – but the risk that their customer does not honour the CRO, as in such a case, that obligation falls to the commercial bank as issuer.

Second, a question arises whether the role envisaged for central banks would come within their respective mandates. In this respect, analysis shows 'significant differences in central bank mandates' (109), highlighting also that 'central banking activities depend in practice not only on the formal mandate, but also its interpretation, which can be ambiguous'.<sup>9</sup> Ref (109) found there is 'a particularly strong case for central banks to respond to climate change risks as part of core macro-financial stability mandates', however, going beyond this to use its powers to actively 'green' the financial system and economy, would depend on a central bank's legal mandate. They conclude that, rather than a central bank intervening to address market externalities, the preferred solution would be removing that market failure, for example, by a carbon pricing mechanism that internalizes the social cost of carbon emissions.<sup>10</sup> These authors note that the Bank of England (BoE) under Mark Carney had accusations of 'mission creep' levelled against it in relation to its stance on climate risks, notwithstanding the terms in which the objectives for the BoE's Monetary Policy Committee were set out (i.e., to support the government's economic policy and objectives for growth) and Carney's support for carbon pricing. Thus, such concerns could be addressed through government policy and legislation, by providing for internalization of the social cost of carbon through carbon debt/CROs. Giving effect to such a government policy, the BoE (or other central bank) would not be straying far

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<sup>9</sup>Ref (109), section 2. The authors made detailed analysis of 135 central bank mandates and compared them to arrangements and responsibilities adopted by the central banks in practice.

<sup>10</sup> The Proposal and the framework for implementation in this paper advocate this via introduction of carbon debt and the CDR market.

from traditional core roles of safeguarding financial stability and supporting wider economic objectives.<sup>11</sup>

A further initial observation is that, in terms of climate policy developments and, in particular, emissions mitigation policy development, the suggestions in this paper could integrate with a carbon border adjustment mechanism (CBAM) just as readily as an ETS could do. Determining the emissions, resulting from production of the relevant imported goods would be the same, irrespective of whether the mechanism to attach a price to those emissions (that is, the carbon border adjustment) was done through an ETS or by issuing CROs.

#### 5.4.2. CRO framework functioning

The CRO policy framework introduces a demand side (carbon debt/CROs) and a supply side (removal units), thus intimating the formation of a market ('CDR market').

##### 5.4.2.1. Demand side

Under the CRO policy framework, obligations to accurately measure emissions from economic activities above a minimum threshold would need to be mandatory across all sectors of the economy or, at least, all those sectors whose emissions are considered significant enough to generate carbon debt and as a result, be included in the legal framework. These measurement and reporting obligations imply a role for a registry, or alternatively, the obligations could be integrated into an expanded corporate financial reporting regime.<sup>12</sup> The service providers and other existing infrastructure for measuring, reporting and auditing CO<sub>2</sub> emissions would need to be scaled up to ensure capacity for a significantly expanded role. Apart from reporting standards, accreditation of reporting and verification services providers would improve outcomes.

Recognizing that a parallel operation of conventional carbon pricing and the CRO framework would be possible during a transition phase, as discussed in Section 2 in the Supplementary

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<sup>11</sup> While reference is to the Bank of England, the principle could be extrapolated to other central banks and their mandates. Additionally, there is scope for broader consensus through bodies such as the Financial Stability Board (FSB), Bank for International Settlements (BIS), and the Network for Greening the Financial System (NGFS).

<sup>12</sup> There are increasing public policy developments in this respect taking place already, for instance: (a) the International Sustainability Standards Board (ISSB), established at COP26 to develop a comprehensive global baseline of sustainability disclosures for the capital markets, launched a consultation on its first two proposed standards. One sets out general sustainability-related disclosure requirements (Exposure Draft IFRS S1) and the other specifies climate-related disclosure requirements (Exposure Draft IFRS S2), see (110); (b) The U.S. Securities and Exchange Commission announced proposed rules to require disclosures about a company's governance, risk management, and strategy with respect to climate-related risks. Moreover, the proposal would require disclosure of any targets or commitments made by a company, as well as its plan to achieve those targets and its transition plan, if it has them (98).

Information (Annex 5), here we follow the approach that once the RC carbon budget for Paris Agreement alignment is exhausted, then:

- i. emissions = carbon debt;
- ii. one metric tonne CO<sub>2</sub>/CO<sub>2</sub>e emissions = one CRO.

By defining carbon debt as a financial debt, corporate and financial market regulators also would have roles in addition to central and commercial banks and these are roles they are assuming already (110). In relation to a mechanism for CRO allocation, accounting, auditing and related management, commercial banks would set up CRO accounts for their emitter-customers (based on the last annual reported emissions) just as they might normally set up deposit accounts for those emitter-customers if they were borrowing money.

The central bank would require each commercial bank to hold a 'reserve' account facility with it on which it would charge a CRO Base Premium (interest at a base rate). The mechanism through which the CRO Base Premium, or 'cost' of the carbon debt, is charged to commercial banks, would be determined by the central bank. By way of illustration, for instance, a commercial bank's CRO reserve account facility with the central bank might be charged Base Premium interest to reflect the amount of CROs issued by that commercial bank to its emitter-customers. Thus, it would reflect pricing of the risk to the central bank of the commercial bank failing to acquire the equivalent amount of removal units that would be required to discharge the issued CROs. For example, calculation of the CRO Base Premium – in addition to the modelling aspects discussed in section 5.3.1 – might be based on the spot contract for removal units, or even a forward contract (e.g., 3-month futures contract) with daily reconciliation.

For their customer-emitter entities, the CRO Commercial Premium would be determined by the CRO issuer bank, based on normal credit risk evaluations. A possible mechanism for issuing CROs is shown diagrammatically in Figure S2 in the Supplementary Information (Annex 5).

Emitters with CROs on their balance sheet for which they must pay a CRO Premium would need, in accordance with their obligations to repay the carbon debt, to acquire units generated by projects that remove CO<sub>2</sub> from the atmosphere.<sup>13</sup> Thus, the need to repay carbon debt, in accordance with the conditions of the CROs on the emitter entity's balance sheet, will drive demand for removal units and hence, funding for development of CDR projects to generate the removal units. Recognizing the demand, it is anticipated that banks and other financiers will fund CDR projects that generate removal units for purchase by holders of CROs.

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<sup>13</sup> For simplicity, referred to here as CDR projects generating removal units.

#### 5.4.2.2. Supply side

Minimum technical, assurance, governance and management requirements would be introduced by a standard for CDR projects, with the aim not only to ensure integrity and quality of outcomes, but also to foster a role for a class of professional managers, who would be tasked to ensure CDR projects continued to satisfy those requirements.<sup>14</sup> The requirements would address technical characteristics such as delivery risk and quality/integrity risk (e.g., permanence; saturation risk; timing of removals; leakage risk; long-term management requirements; co-benefits; as well as a number of other characteristics).<sup>15</sup>

In addition to legal governance of CDR delivery and quality/integrity risk, requirements might also include the standard of project management to be maintained; and accounting and cost coverage requirements (see Table S4, Supplementary Information in Annex 5). These elements could generate disclosure and transparency requirements, with the entities managing the projects obliged to provide information on project performance and risk issues, project structure and response mechanisms for any risks, thus further encouraging development of the professional standard of management.

Standard-based removal units would facilitate a smoother running, more efficient physical market for purchasers by reducing transaction costs for emitter entities needing to satisfy and remove CROs from their balance sheet. The removal units could be transacted more readily using a Master Agreement with transaction specific matters (parties, volume, price) dealt with in a term sheet, thereby reducing the legal complexity and transaction costs.<sup>16</sup> A more efficiently operating market might be expected to encourage greater participation, facilitating more competitive cost reductions and a more rapid scaling up of the CDR project sector.

CDR projects generate removal units, minimum requirements for which could be prescribed by regulation (applying the national, or an international standard: see the Supplementary Information in Annex 5). The removal units, notwithstanding meeting the commitments set out in the standard and regulation, would nevertheless demonstrate different characteristics, depending on the method applied by the project (e.g., delivery risk based on permanence, and saturation risk; tonnage removal units per annum; scheduling of delivery). Importantly, elements such as co-benefits (including features that may not avail themselves to being priced

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<sup>14</sup> In terms of the length of this project management commitment, there is a clear parallel with the role performed by pension fund managers.

<sup>15</sup> The aim would be that each project would generate removal units equal to or better than a minimum regulatory requirement, which would be based on a national standard or, ideally, an international standard for such.

<sup>16</sup> Similar approach to that of the International Swaps and Derivatives Association (ISDA) Master Agreement.

directly, but nevertheless add to the value of the project and removal units generated by it, e.g., environmental improvement, biodiversity enhancement) would be taken into account. Thus, not only would different methods generate removal units with price differences in the market, but any co-benefits would also give projects differing profiles and so be factored into the removal unit pricing according to the preferences of the various market actors.

### 5.4.3. Interaction of public and private sector actors

It will be critical that an established marketplace is functioning robustly well before CROs are required to be included in emitting entities' financial accounts. For this to occur, there needs to be significant scaling up of CDR projects; and an initial learning-by-doing period of CDR market operation. These two aspects are complementary and could be part of the transitional measures governments put in place to foster development of the CDR market. Putting in place the necessary legal instruments that give rise to binding financial commitments would be an integral initial part of this process.

Thus, the primary initiative to implement the CRO policy framework will need to come from government. All the same, the process of implementation could generate significant engagement with the private sector, in particular with private finance facilitating rapid scaling up of the CDR sector, as well as generating substantial revenue for hedging future risk (through CRO Premium payments on carbon debt being set aside for that purpose).<sup>17</sup>

In relation to the finance sector, for example, if commercial banks have the role envisaged by the Proposals, by 'extending CRO credit' to their emitter-customers, a new financial market would be created, including potential for subsequent securitization of portfolios of CROs to free up capital.<sup>18</sup> Similarly, to the extent that the banks and lenders extend debt finance to the project owners/developers, another financial market would be generated, again including potential for the initial lenders to securitize loan portfolios to free up capital.

The opportunities for these secondary markets suggest potential private sector interest. Equally, developments such as these could promote greater transparency, since performance reporting, delivery, quality/integrity and other matters would need to be defined in commercial documents (for example, prospectuses, regulated by corporate law) in relation to any

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<sup>17</sup> There are parallels in the financing of nuclear waste management, for example see: World Nuclear Association, *National Policies and Funding (112)*; and OECD Nuclear Energy Agency *(113)*; and also the building of sovereign wealth funds. On the other hand, historic failures in many jurisdictions to provide for mine site rehabilitation provide examples of cost legacies left for future generations of taxpayers.

<sup>18</sup> As a matter of policy, governments may be reluctant to have commercial banks move the responsibility for the CROs held by their customers off the bank balance sheets by securitizing, unless certain elements of obligation remain with the bank or are adequately provided for through parallel mechanisms.

secondary markets, providing an additional layer of governance screening. Development of a class of management professionals could encourage growth and governance in the CDR sector.

The public sector and private sector roles, and how they might interact, are illustrated in Table S2, in the Supplementary Information in Annex 5.

#### 5.4.4. Legal implementation of the CRO policy framework

Clearly, implementation of the CRO policy framework needs to be initiated by government. While other sectors, particularly the private financial sector, will have important roles, as a first step, adoption of policies and legislative action are needed to set the course for and incentivize such fundamental changes.

All the same, as outlined here, the legislative actions required could be relatively straightforward. Subject to resolution of some preliminary elements, the legal framework envisaged could be implemented by a package of three instruments:

- i. an enactment of primary legislation;
- ii. development of a national (or international) standard; and
- iii. secondary legislation (a regulation) to adopt the standard and implement the primary legislation.

For these purposes, it is herein contemplated that the jurisdiction where the framework is being implemented is the United Kingdom. All the same, the three instruments could be adapted to fit the lawmaking arrangements of other jurisdictions. Details of the three instruments for implementation of the legal framework envisaged by the CRO policy framework are illustrated in text and related Tables S3, S4 and S5, in the Supplementary Information (Annex 5).

The preliminary elements to be resolved would be first, the specific temperature increase target: e.g., 1.5°C, 1.7°C, 2.0°C or another; second, the global RC carbon budget to stay within that target given a specific likelihood; third, when the global RC carbon budget will be expended, based on the rate of emissions; and consequently, agreement on the date when emissions = carbon debt (or on TDI carbon budget and parallel operation of the CRO framework, as discussed in Section 2 in the Supplementary Information in Annex 5).

Notwithstanding the usual free rider and leakage problems, while there is no reason why an individual government could not make a determination of these elements for its own policy purposes, it would clearly be better for there to be regional or, ideally, multilateral or broad international determinations on a consistent basis. All the same, apart from the first, which involves a specific choice (although, to some extent, already resolved by commitments of

governments to align with the Paris Agreement target), these elements would resolve themselves with the passage of time.

## 5.5. Discussion and conclusion

The CRO policy framework sets out mechanisms by which substantially more ambitious near-term decarbonization complemented by earlier deployment of CO<sub>2</sub> removal technologies might be achieved. This mechanism is innovative not only in its intention to place the climate change mitigation pricing levers in the hands of the traditional managers of financial and price stability, namely central banks, but more so, for the corollary of integrating climate change mitigation response management far more into the economic mainstream, treating carbon debt as financial debt, hence accounting for the externality of carbon emissions as part of core economic and financial management. In so doing, it begins to address a fundamental of climate change policy, namely the question of intergenerational equity, by the application of the PPP. The legal basis of the PPP will be further extended as climate targets become legally binding in many countries (33). In line with this principle, the implementation of the CRO policy framework requires relatively straight-forward legislative measures, to adjust existing legal structures.

The proposed CRO policy framework implies that conventional carbon pricing through ETSs or carbon taxes will become obsolete in the near-term as the RC carbon budget becomes depleted. Rather than seeking to integrate CDR into ETSs (114, 115), which is associated with several technical difficulties (105), policymakers should strive for intertemporal mechanisms such as the CRO framework. The implied potential for separate price levels for CDR and ERs might entail efficiency gains if endogenous technological change is considered.

We have illustrated that CRO pricing fully builds on existing modeling practices, which need to be further improved to get a better understanding of joint Earth system, socio-economic and technological risks. Details remain to be further elaborated and teased out, including additional attribution mechanisms for overshoot risks, as well as the integration of non-CO<sub>2</sub> GHGs. Moreover, the degree of public involvement in a framework that builds on markets and privately held removal obligations needs to be further investigated.

Section 5.4 adds substance by offering the outline of one possible pathway for implementation. The proposed CRO policy framework sets out a demand side (carbon debt) and a supply side (CO<sub>2</sub> removal units), thus intimating the creation of a CDR market. In so doing, it points to a way in which the CDR sector can be scaled up to the degree necessary if the limits on global warming targeted by Paris Agreement Parties are to be achieved. The primary initiative must come from government putting in place policies and legal instruments to generate confidence

that a robust CDR market is in place before carbon debt and removal obligations take effect. While inter-jurisdictional collaboration and consistency (for instance, in the case of the Standard, being under the aegis of the International Organization for Standardization) always holds out the possibility for better outcomes, the framework, instruments and mechanisms outlined could be applied initially on a jurisdiction-by-jurisdiction basis without detriment to the potential for development of a global CDR market in the longer term.

We conclude that the CRO policy framework characterizes feasible and necessary mechanisms to respond to the increasing evidence and warnings, in particular from the IPCC, of the need to drawdown CO<sub>2</sub> emissions and scale up removals, if average global surface temperature is to be stabilized within the targets envisaged by the Paris Agreement.

## 6. Net-negative futures beyond 2100

Based on the article submitted to peer-reviewed journal: J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries.

Supplementary Figures and Tables are illustrated in Annex 6.

### 6.1. Abstract

In July 2025, the International Court of Justice (ICJ) affirmed that States must prevent significant harm to the environment, including the climate system. Some of the most critical climate impacts, such as sea level rise (SLR) and permafrost thaw (PFT), will intensify for centuries even under 1.5–2 °C stabilization. In the terms expressed by the ICJ, we argue a duty exists to pursue stabilization of impacts at the lowest attainable levels.

Using ensembles from a coupled integrated assessment and earth system model emulator, we show that achieving this requires sustained global net-negative CO<sub>2</sub> emissions well beyond the 23rd century. Crucially, delayed mitigation does not increase carbon debts as under overshootable temperature-based targets, but instead increases long-term impacts, the likelihood of extreme outcomes, and shifts mitigation burdens further to future generations.

These findings suggest that Paris targets are milestones, not endpoints, and that sustained carbon removal must become a structural element of future climate governance. In the ICJ's terms, this points to a plausible legal trajectory toward recognizing sustained global carbon removal obligations. Robust frameworks to define and fairly distribute these obligations, both among nations and across generations, are essential yet currently absent from international climate governance.

### 6.2. Introduction

On 23 July 2025, in response to a 2023 request from the United Nations General Assembly (116), the International Court of Justice (ICJ) issued its seminal Advisory Opinion on the Obligations of States in respect of Climate Change (117). The ICJ was of the unanimous opinion that climate treaties impose binding obligations on States to protect the climate system and wider environment from human-induced greenhouse gas emissions, and that under customary international law they must exercise due diligence and use all means at their disposal to prevent activities within their jurisdiction or control causing significant harm to either (ref (117), para 457). Unfortunately, the Court addressed the temporal scope of these

obligations only obliquely. Yet many of the most severe and irreversible climate impacts are projected to continue to grow well after 2100, even under successful temperature stabilization within the 1.5-2°C target range of the Paris Agreement. Here, we demonstrate that stabilizing these time-lagged impacts requires sustained net-negative emissions well beyond the 23rd century. This suggests that carbon dioxide removal (CDR) is not a transitional tool to limit or reverse global warming, but a structural necessity for preventing long-term climate harm through time-lagged impacts, which raises profound implications for the legal, ethical, and institutional architecture of future climate governance.

While global mean temperature serves as a useful proxy for many climate-related impacts, and is commonly used in integrated assessment models (IAMs) to estimate instantaneous economic losses (118), some of the most critical climate impacts are time-lagged and continue to grow for centuries even if global temperatures stabilize at 1.5°C (119). Many of these impacts exhibit hysteresis or are effectively irreversible on human timescales (120). Notable examples include large-scale ecosystem shifts (121), permafrost thaw (PFT) (30), the loss of polar ice sheets, and the resulting contributions to sea level rise (SLR) (122), as well as emerging evidence of persistent continental drying (123).

SLR poses a major threat to coastal infrastructure and economies, with damage and adaptation costs projected to reach hundreds of billions of dollars annually (124). While globally binding limits for SLR have not been identified, hard limits to adaptation are already evident for low-lying island states facing permanent inundation. In many other regions, soft limits, such as inadequate funding, weak governance, and limited access to technology, may be hard to overcome (125). Permafrost, on the other hand, covers approximately 20-25% of the Northern Hemisphere's land area and stores nearly twice the amount of carbon currently in the atmosphere (126). Its thaw and the subsequent release of CO<sub>2</sub> and methane via enhanced microbial decomposition creates a potent carbon feedback to global warming and directly increases climate risks globally. For local communities, it further contributes to the destabilization of buildings, roads, and other infrastructure; the disruption of water systems; and increased risks of landslides and erosion (127). It also presents a potential biohazard due to the release of long-dormant pathogens from previously frozen soils (128, 129).

### 6.3. From temperature overshoot to impact stabilization

The ICJ's opinion notes that '... the specific character of the risk of significant harm to the climate system is indisputably established. The best available science, as presented by the IPCC, confirms that cumulative GHG emissions are the primary source of risks arising from anthropogenic climate change' (ref (117), para 137), and addresses in detail the relevant

scientific background (ref (117), paras 72-87). SLR and PFT thus are illustrative examples of ‘significant harm’ that disproportionately affect vulnerable populations and future generations. Since the Paris Agreement, climate policy has centered on a temperature goal range of 1.5°C to 2°C. Scenarios assessed by the IPCC show that achieving the 1.5°C target is, in most cases, only possible after temporarily overshooting and returning to that threshold. For time-lagged impacts, however, we argue that the relevant objective is not staying below or returning toward a predefined threshold, but rather the stabilization of impacts at the lowest attainable level. Once higher impact levels have been reached and adaptation measures implemented, such as infrastructure relocation or coastal protection, further removals may yield diminishing returns, as reversing these physical processes may be slow, uncertain, or economically unjustified. Hence, we argue that for time-lagged impacts, the clear inference is that prevention of significant harm, as articulated by the ICJ, means avoiding escalation rather than enabling later reversal.

Stabilizing such time-lagged impacts requires sustained net-negative emission futures, however, the duration and scale of future net removals needed to achieve impact stabilization remains uncertain. To explore this, we assess how choices and limitations we face today shape the scale and persistence of required net-negative emission futures, their effectiveness in limiting SLR and PFT, and the resulting trajectories of residual time-lagged harm across generations. To this end, we develop four mitigation scenarios that reflect plausible technological or deployment constraints resulting from currently observed and emerging implementation delays (see SM Methods and Table S1). In addition to the Full Portfolio (FullP) scenario, which includes the unconstrained suite of technological options typically modeled in detailed process-based (dp-) IAMs (4, 118), we explore three scenarios with potential mitigation shortfalls: The Final Energy Reduction Failure (FERF) scenario reflects slower near-term emission reductions. The Storage and Removal Constrained (StoRC) scenario imposes limits on both CO<sub>2</sub> storage expansion and the total capacity of BECCS and DACCS deployment. The Multiple Failures (MultiF) scenario combines both sets of limitations. Despite the imposed constraints, all scenarios remain ambitious: they assume near-term peak of emissions, continued rapid renewable expansion, at least partial availability of all typical dp-IAM technologies, the AFOLU sector acting consistently as a carbon sink, as well as a prolonged period of net-negative emissions to reverse temperature overshoot and stabilize long-term impacts.

Scenarios are generated using an emulator of dp-IAMs (see Annex 1). Each scenario comprises 14 emissions trajectories, based on distinct combinations of parameter sets derived from dp-IAMs and DACCS cost assumptions. These trajectories are propagated through the Earth system emulator Pathfinder (130), producing broad ensembles of physical states of the

world (SoWs) that reflect joint physical and technological uncertainties (see 6.7 Methods). In each SoW, net-negative emissions are phased out once the relevant impact metric stabilizes at its lowest attainable level. The resulting net-negative phase is therefore the shortest possible duration required to stabilize and maintain impacts, given the SoWs' underlying technological and physical parameter sets (see 6.7 Methods).

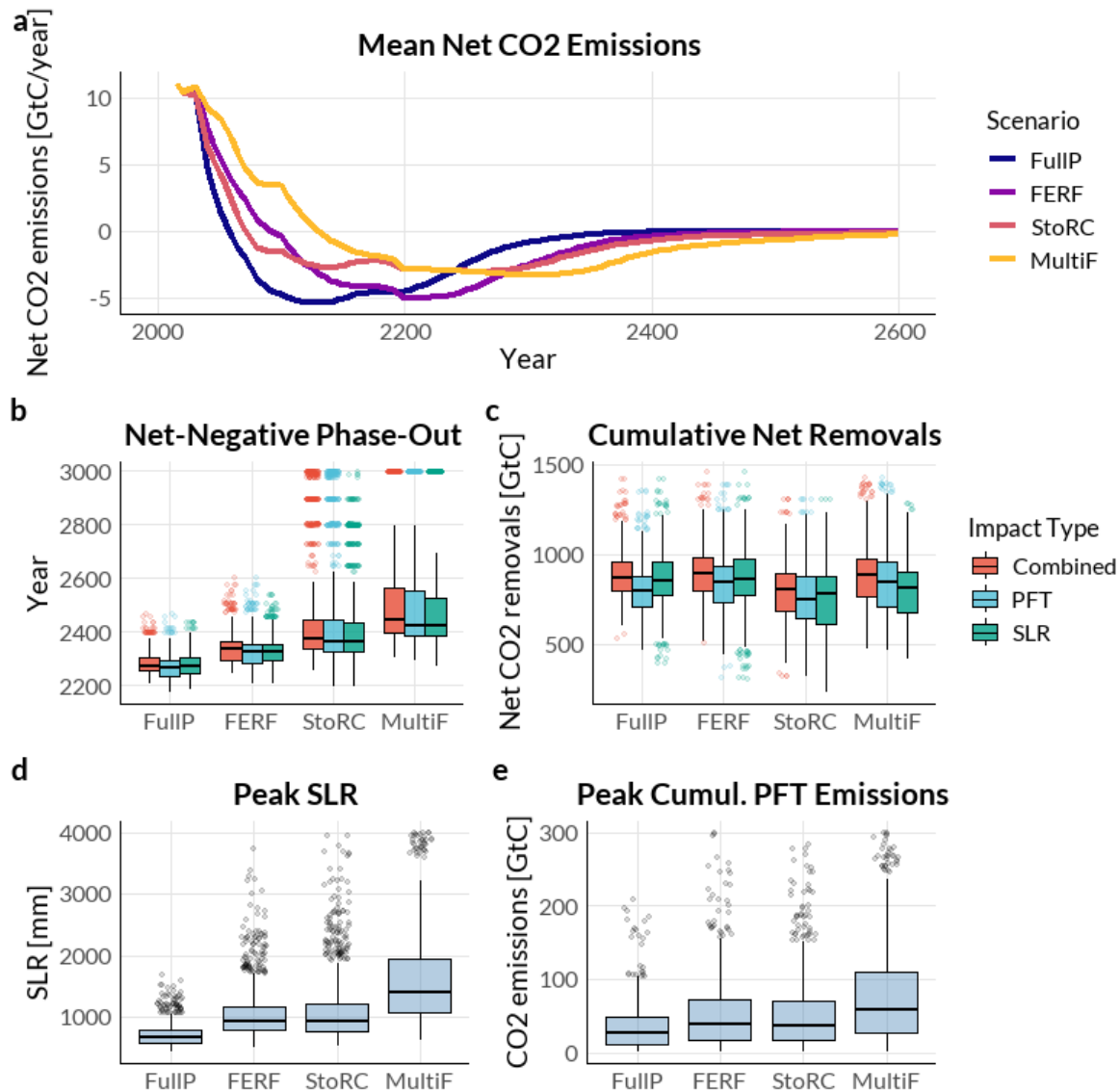
## 6.4. How implementation constraints shape net-negative futures

We find that, in all scenarios, net-negative emissions must be sustained far beyond the 23rd century – even under optimistic assumptions (Figure 14a). Remarkably, stabilization timelines for SLR and PFT are very similar, and neither consistently dominates in determining the length of the net-negative phase: in approximately 41% of SoWs, SLR stabilization requires longer net-negative emissions; in 31%, PFT dominates; and in 28%, both impact metrics stabilize around the same time. Consequently, comparing phase-out distributions for each impact separately versus jointly shows that when stabilization of both impacts is required, the resulting distribution shifts toward later phase-out dates (Figure 14b). Within each scenario, the range of phase-out dates spans roughly two centuries, reflecting the deep joint physical and technological uncertainties underlying the duration of the impact stabilization process. Notably, the uncertainty increases with the number of implementation constraints imposed (compare Figure 14b and Table S1 in Annex 6).

Despite differences in the duration and depth of net-negative emissions, the median cumulative amount of net removals remains notably consistent across scenarios, at below 1000 GtC (Figure 14c). Therefore, within the range of our scenarios, mitigation delays have a comparably small effect on the total amount of net removals required for impact stabilization.

## 6.5. Mitigation delays drive impacts and risks

This limited sensitivity of cumulative net carbon removals to earlier implementation delays and the resulting larger overshoot is in stark contrast with the logic underlying temperature targets. To achieve a temperature goal, for instance by keeping cumulative net CO<sub>2</sub> emissions within a specified carbon budget, implies that delays in near-term mitigation translate directly into larger net-negative requirements, or carbon debts, later on (as conceptualized in Chapter 3). Here, however, net removals either contribute more to lowering long-term impact levels or to offsetting higher near-term emissions at the cost of increased peak SLR and PFT when early mitigation is weaker.



**Figure 14: Comparison of four idealized mitigation scenarios and their implications for long-term net-negative CO<sub>2</sub> emissions and time-lagged impacts, specifically global mean sea level rise (SLR) and cumulative CO<sub>2</sub> emissions from permafrost thaw (PFT).** The FullIP scenario includes the full portfolio of mitigation options typically modeled in dp-IAMs, including DACCS. The FERF scenario assumes reduced progress in decreasing final energy intensity, resulting in fewer emission reductions. The StoRC scenario constrains CO<sub>2</sub> storage growth and limits the total deployment of BECCS and DACCS. The MultiF scenario combines the limitations of both FERF and StoRC. For a detailed description of the scenarios, see Table S1 and the Methods. Panel a shows the mean annual net CO<sub>2</sub> emission pathways for each scenario. Panel b displays the distribution of net-negative emissions phase-out dates, defined as the point at which either SLR, PFT, or both impacts are stabilized. Panel c presents the distribution of cumulative net CO<sub>2</sub> removals across scenarios. Panels d and e show the distributions of peak SLR and peak cumulative CO<sub>2</sub> emissions from PFT, respectively. Note, in panel d, 0.3% and 4.4% of data points are larger than 4000mm in the StoRC and MultiF scenarios, respectively. In panel e, 0.1%, 0.4% and 2.4% of data points are larger than 300 GtC in the FERF, StoRC and MultiF scenarios, respectively. All distributions are illustrated as box-and-whisker plots, where the box represents the interquartile range (25th–75th percentile), the horizontal line indicates the median, and the whiskers extend to the most extreme values within 1.5 times the interquartile range.

This effect of mitigation delay on peak SLR and peak cumulative CO<sub>2</sub> emissions from PFT is shown in Figure 14d–e, where FullIP yields the lowest outcomes, MultiF the highest, and FERF

and StoRC result in similar intermediate levels. Notably, permafrost emissions are projected to cause around 5% of the cumulative net CO<sub>2</sub> removal burden, but could exceed 30% in higher impact scenarios (Figure S8). The similarity of impact levels between FERF and StoRC suggests that modeled shortfalls in emission reductions as well as CDR play equally critical roles in shaping time-lagged impacts. Regardless of cause, shortfalls in mitigation not only lead directly to elevated physical harm, but also to a wider spread in projected outcomes, indicating an increased risk of extreme SoWs. In short: delays in mitigation do not just increase harm – they make outcomes more unpredictable and harder to govern.

## 6.6. Does harm prevention imply removal obligations?

The ICJ notes that the ultimate objective of the UNFCCC is to achieve ‘stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system’ (ref (117), para 197) and that mitigation lies at the heart of that objective (ref (117), para 200). It seeks to achieve this by limiting emissions and by preserving and enhancing sinks and reservoirs of GHGs (ref (117), Ibid). Further, the temperature goal in the Paris Agreement is aimed at enhancing implementation of the UNFCCC and its objective (ref (117), paras 223 and 225).

However, in contrast to previous studies focusing on temperature stabilization, our results suggest that a deep and sustained net-negative emissions phase is a structural requirement of any strategy that seeks to limit long-term climate harms. This highlights that, for time-lagged impacts, the Paris Agreement targets for the 21st century are best understood as milestones rather than endpoints on the pathway to long-term stabilization. Achieving the Paris targets is neither sufficient to halt impact growth, nor does failure to meet them – an increasingly likely scenario given current implementation gaps and inadequate Nationally Determined Contributions (6) – mark the end of viable climate response. There is, however, limited scope for future compensation of delayed mitigation through net removals. We illustrate that, for time-lagged impacts, mitigation shortfalls translate directly into increased residual harm, a higher likelihood of extreme outcomes, as well as a redistribution of mitigation burdens towards future generations.

In relation to the issue of temporality, significantly, the ICJ opined that States ‘... are subject to the duty to prevent significant harm either where no harm has yet been caused but the risk of future significant harm exists, or where some harm has already been caused and there exists a risk of further significant harm (ref (117), para 274).’ Related to this, the ICJ found that ‘[I]t is necessary to take into account the risks which current activities might pose in the future, including in the long term. In any case, the degree of a given risk of harm is always an

important element for the application of the due diligence standard: the higher the probability and the seriousness of possible harm, the more demanding the required standard of conduct (ref (117), para 275).’ As such, in the terms expressed by the ICJ, it is argued that there is a plausible legal trajectory toward recognizing long-term responsibilities for sustained global net CO<sub>2</sub> removals in order to limit harm from time-lagged climate impacts.

Regardless, an exclusive policy focus on rapid emission reductions, without accounting for the structural need for sustained net-negative emissions, is insufficient to prevent long-term harm. The economic implications of maintaining such a net-negative economy for centuries, particularly in the absence of scalable, low-cost CDR, however, raise foundational concerns about intra- and intergenerational equity and legal responsibility. Therefore, robust legal frameworks to define and fairly distribute carbon removal obligations, both among nations and across generations, will be essential. Such frameworks are currently absent from existing international legal instruments and have yet to be meaningfully addressed in international climate negotiations, despite their importance as a cornerstone for designing any future architecture of long-term climate responsibility.

## 6.7. Methods

### 6.7.1. Basic model description

The emulator model used to generate mitigation scenarios is described in detail in Annex 1. It is based on dynamic abatement cost functions and incorporates ten abatement options spanning the energy, industry, and AFOLU sectors. The model is calibrated using standardized mitigation scenarios from seven dp-IAMs.

Two of these dp-IAMs provide distinct DACCS cost parameterizations: a high-cost variant from REMIND-MAgPIE and a low-cost variant from WITCH. These DACCS cost assumptions are recombined with the seven parameter sets for the remaining abatement options, resulting in 14 distinct parameter sets. The model takes an exogenous carbon price trajectory as input. In line with current NDCs (6), prices are set to keep mean net CO<sub>2</sub> emissions of the unconstrained scenario roughly constant from 2020 to 2030. The carbon price then rises to USD 300 per tCO<sub>2</sub> by 2040 and increases at 5% annually thereafter, leading to a decline in mean net CO<sub>2</sub> emissions beginning in 2030.

As described in Annex 1, we extend scenario time horizons to the year 3000 in order to evaluate time-lagged impacts. Each scenario contains 14 emissions trajectories, corresponding to the 14 parameter sets. Each emission trajectory is propagated through the Earth system model emulator Pathfinder (130), yielding 100 realizations of physical

uncertainty per trajectory. This results in  $14 \times 100 = 1400$  distinct SoWs per scenario, each representing a unique pathway of temperature, SLR, PFT, and other physical variables. Mean and uncertainty ranges of selected metrics over time are shown in Figures S1-S4.

### 6.7.2. Impact stabilization approach

In a stylized form, time-lagged impacts such as the contributions of Arctic ice sheet, Greenland ice sheet and glacier melt to sea level rise, as well as the thawed part of permafrost carbon, can be represented by

$$\frac{dH}{dt} \sim \frac{1}{\tau} (\hat{H}(T) - H)$$

where  $H$  is the realized time-lagged impact (SLR and cumulative CO<sub>2</sub> from PFT),  $\hat{H}(T)$  is the long-run equilibrium level implied by current temperature, and  $\tau$  is the adjustment timescale. As long as temperatures are brought down after peaking through sustained net-negative emissions,  $\hat{H}(T)$  declines and the realized impact can be limited. The impact stabilization level determined in this analysis is the point  $H^*$  where  $H$  and  $\hat{H}$  meet, i.e., where  $\frac{dH}{dt} = 0$ . Limiting impacts to a lower level  $H^*$  therefore means cooling faster or reducing peak warming.

Stabilization of long-term impacts is assessed through a brute-force approximation implemented via simulation: The emissions trajectory in each SoW is fixed, except for the length of the net-negative emissions phase, which is varied. Shorter net-negative phases may lead to continued impact growth through 3000, while longer phases may result in peaking and eventual stabilization or reversal of SLR and PFT within the modeled time frame.

We define impact stabilization as the shortest net-negative phase for which the relevant impact (SLR, PFT, or both) peaks and (at least) remains constant thereafter. Conceptually, this corresponds to minimizing cumulative net-negative emissions subject to a constraint on peak impact levels.

This procedure is applied independently to each of the 1400 SoWs per scenario. As a result, each scenario yields distributions of net-negative phase-out dates, cumulative net removals, and peak impact levels, as presented in Figure 14. Note that SLR could not be stabilized in 0.07% of StoRC and 0.21% of MultiF SoWs, and PFT could not be stabilized in 2.8% of StoRC and 8.4% of MultiF SoWs. For these SoWs we assume the level of the impact metric, as well as net-negative phase-out in the year 3000, which introduces a bias in the upper ends of distributions shown in Figure 14.

### 6.7.3. Deployment constraints

While the expansion of renewable energy, particularly solar PV, is breaking records (131), progress in reducing the economy's energy intensity (132) and scaling up of CO<sub>2</sub> storage and carbon dioxide removal (CDR) remains off track compared to ambitious mitigation scenarios assessed by the IPCC (1, 4). Reducing final energy demand relative to a baseline through a mix of efficiency improvements, electrification, and behavioral change is among the most effective levers for cutting emissions. However, emerging sources of consumption, such as data centers (133) and increased cooling needs (134), along with rebound effects (135), slow down the reduction of the energy intensity.

Moreover, CDR and carbon capture and storage (CCS) continue to face persistent structural challenges. The capital-intensive nature of CCS infrastructure requires complex coordination across the value chain, which hampers investment, while project failure rates remain high (136, 137). BECCS and DACCS remain costly (138, 139), and large-scale BECCS deployment might be constrained by a set of terrestrial planetary boundaries (140). As a result, the CDR sector currently remains dominated by non-durable options like afforestation and reforestation (1).

The deployment constraints applied in this study are summarized quantitatively in Table 1. These are stylized, top-down assumptions rather than bottom-up estimates derived from detailed sectoral analysis. None of the limits are particularly stringent in absolute terms, though they may appear conservative relative to some high-end mitigation scenarios in the literature.

#### 6.7.3.1. Final energy constraint

Due to the recent slowdown in the decoupling of energy consumption from economic growth (132) we assume that scenarios under this constraint follow baseline assumptions, which essentially reflect a continuation of historical trends (see Figure S5).

#### 6.7.3.2. Bioenergy constraint

To represent sustainability constraints on bioenergy deployment, we impose an upper limit of 250 Mha for dedicated bioenergy crops, roughly the equivalent of half the Amazon forest, and more than twice the EU cropland. This value lies between the ~1000 Mha used in some high-end dp-IAM scenarios used for calibration, and the 51 Mha maximum identified under stringent planetary boundary conditions (140). Across parameter sets, this results in a range of 81 to 154 EJ of annual primary bioenergy supply (see Figure S6), which is broadly consistent with the 100 EJ per year bioenergy cap adopted in the EMF27 and EMF33 protocols to reflect food security and land-use sustainability concerns (141).

#### 6.7.3.3. DACCS constraint

In light of concerns about the unsustainable energy requirements associated with large-scale DACCS deployment (142, 143), we impose an upper limit on DACCS energy consumption equivalent to 5% of baseline global final energy demand (see Figure S7) – approximately the current energy use of global civil and freight aviation. For comparison, in the high-end scenarios used to calibrate our model, DACCS energy consumption reaches approximately 22% of baseline final energy demand in REMIND-MAGPIE and around 8% in WITCH scenarios.

#### 6.7.3.4. Geological CO<sub>2</sub> storage constraint

To constrain CO<sub>2</sub> storage availability, we use the 110 MtCO<sub>2</sub> yr<sup>-1</sup> estimate for 2030 from the “current plans and 76% failure rate” scenario in (136). From this initial level, we assume logistic growth with a 15% annual rate, reflecting the early phase of deployment and consistent with historical growth rates of other technologies (144).

## 7. Synthesis and discussion

This Chapter is structured as follows: Sections 7.1 and 7.2 compare the CRO framework with the other instruments introduced in Chapter 2. Section 7.1. focuses on issues including, how proposals tackle mitigation deterrence, temporary vs. durable removals, financing of early-stage high-cost CDR, integration of climate damages, and distributional impacts. Section 7.2 focuses specifically on the pivotal question of commitment and enforcing intertemporal obligations and is therefore treated separately. Section 7.3 adopts a more exploratory and normative perspective and looks beyond the issues examined in Chapters 3 to 6, exploring broader implications for the role of government in market development, institutional design, and the long-term sequencing of CDR policy. The Chapter concludes by outlining possible pathways for future research.

### 7.1. Comparison of proposed instruments

Clean-up certificates (21) require emitters to purchase the right to emit now and remove later through an ETS-based auction, while posting collateral. At the time of removal the emitter finances the operation and redeems the collateral, which grows at the risk-free rate. ACORDS (22) operate similarly, however, collateral/deposit receipts can be traded. Similarly, under carbon shares (19), the emitter posts a bond upon emission and receives a tradable share with face value equal to the bond. A carbon stock tax tied to realized marginal damages is deducted from the bond over time, shrinking the share's face value, and the remaining value is redeemed to the shareholder upon verified removal. CROs record a liability on the emitter's balance sheet at the time of emission. Collateral may be required under credit policy or regulation. A stock charge is paid while the carbon remains in the atmosphere, and the CRO holder ultimately finances removal and releases any collateral upon completion. Revenues from the CRO stock charge have been proposed for earmarking to loss-and-damage finance, although a formal integration with a SCC framework, as for carbon shares, has not been established.

#### 7.1.1. Market context and integration with other instruments

ACORDS and clean-up certificates remain anchored to an ETS, which continues to operate, even after the depletion of allowances, to manage contemporaneous offsetting of residual emissions with removals. CROs can run in parallel to an ETS, but the volume of ETS allowances must not exceed the carbon budget that constrains cumulative net emissions, which is much less than currently envisaged allowances in the EU-ETS, for instance. Crucially,

the ETS itself does not govern CDR in a CRO framework as proposed in Chapter 5. Once allowances are depleted, the CRO framework operates independently, as the obligation to remove at a specified maturity induces a shadow price for emissions, sufficient to incentivize reductions. Carbon shares, by contrast, function like a “re-arranged” SCC-based carbon tax that can incentivize net-negative emissions without drawing on public budgets and are therefore not coupled to any companion instrument.

Hence, ACORDS and clean-up certificates operate with a removals market that is fully integrated into the ETS, which in parallel services the redemption of those instruments. Both ACORDS and carbon shares feature secondary markets in which the instrument (or derivatives of the instrument) are traded, providing liquidity for emitters, risk-sharing among investors, and price discovery on expected net redemption values and marginal damage trajectories, according to neoclassical theory. By contrast, CROs rely on a CDR market that is separate from emissions trading. The instrument itself is not traded, however, secondary markets may emerge via financialization of CROs with similar expected benefits (see Section 7.2).

### 7.1.2. Mechanisms to control pathways or cumulative variables: quantity-versus price-led designs.

One central design choice is whether policy directly fixes quantities or indirectly steers them through prices. While equivalent in idealized textbook settings, quantity-led designs leave prices to the market and thus inherently uncertain in reality, while price-led designs fix prices and let realized quantities respond, introducing uncertainty on the quantity side. A related distinction is whether instruments govern cumulative outcomes or time-paths, and whether they target gross (emissions, removals) or net (net emissions, net-negative emissions) variables.

The tax-fund system is fully price-led and therefore guides net emissions only indirectly, without guaranteeing cumulative net emissions targets (unless additional public funds are provided if a shortage in CDR financing occurs). Clean-up certificates and ACORDS, when layered over an ETS that auctions allowances consistent with a carbon budget, strictly constrain cumulative net emissions to stay within that budget because any emission above the cap must be matched by a subsequent removal. Allowances and certificates issued period by period shape the path to net zero, whereas post-net-zero outcomes depend on holders' preferred timing of retiring certificates through removals. Cumulative net-negative emissions are thus governed by the number of certificates, while gross removals are not directly fixed because the ETS allows contemporaneous balancing of residual emissions with removals.

CROs, again under an ETS aligned to a carbon budget, strictly constrain cumulative net emissions. The prescribed removal schedule (CRO maturity) coupled with a price led instrument (the stock charge on atmospheric carbon), provides incentives to follow specific pathways of gross emissions and gross removals. Carbon shares can be understood as primarily price-led, as there are no quantity restrictions. However, the price is not fixed by the regulator, it is established through trading influenced by a combination of realized period damages and expected future damages.

### 7.1.3. Information requirements

Each instrument allocates the burden of forward-looking beliefs differently. In the tax-fund system, regulators must forecast the time paths of marginal abatement costs to set emission prices appropriately and to time removals efficiently. Under carbon shares, emitters form expectations about the marginal damage path to price emissions, while shareholders must anticipate marginal damage paths to infer future stock charges, which determine removal timing and marginal costs. Supervising entities need to measure damage realizations and update the worst-case present value of remaining damages that drives dividends and asset valuation. These expectations are naturally conditional on the emissions trajectory shaped by abatement. Accordingly, carbon shares likely impose the heaviest expectation-formation burden among the instruments.

Clean-up certificates and ACORDs require holders to form expectations about the time path of marginal removal costs to price emissions and schedule removals efficiently. Although not explicitly discussed in refs (21, 22), a parallel informational burden falls on regulators to calibrate collateral correctly. If collateral is set to the discounted expected cost of future removals (as in ref (21)), and regulators share the same expectations as emitters, then emitters are indifferent between “emitting now” and “abating now”. By contrast, if collateral is set below that value, emitters perceive an incentive to emit and never remove. The system then effectively reverts to a tax-fund mechanism; however, the fund will be insufficient to cover removals and public budgets must fill the gap. This is precisely why carbon shares adopt over-collateralization.

CROs require supervising and intermediary entities to anticipate the time paths of marginal abatement and removal costs to set efficient repayment terms (maturities) and stock charges. By contrast, emitters must form expectations only about marginal removal costs at the mandated maturity to price present emissions correctly. The use of collateral is further discussed in Section 7.2.

#### 7.1.4. Deterrence

CDR-induced deterrence arises in various forms (3), including (i) contemporaneous substitution, where removals displace emission reductions within the same period, and (ii) intertemporal substitution, where current emission reductions are deferred in expectation of future removals. ACORDS and clean-up certificates leave the timing of removals to emitters and/or instrument holders. Evolving price paths then guide private decisions toward an “optimal” removal date, but no rule directly governs timing. Clean-up certificates nevertheless cap the cumulative volume of net-negative emissions via the number of certificates issued, thereby limiting how much carbon debt can accumulate over time, while remaining agnostic about how long the debt remains outstanding. Contemporaneous substitution is determined by potential quantity controls in the ETS, as discussed in Section 1.4.1.1.

CROs address the timing margin directly. Regulated intermediaries issue CROs with prescribed maturities, creating enforceable deadlines for when emissions must be counterbalanced by removals. This can be used as guardrail to control the degree of intertemporal substitution by narrowing the window for CDR delivery. Unlike clean-up certificates, however, CROs do not cap total carbon debt explicitly but rely on a price instrument (the stock charge) to control the demand for issued CROs.

#### 7.1.5. Identification of beneficial design features

The primary objective of CROs, clean-up certificates, and ACORDS is to constrain cumulative net emissions to a specified non-negative carbon budget. In a stylized setting with textbook assumptions, the proposals would yield similar outcomes. By contrast, carbon shares are explicitly welfare-maximizing in theory. By internalizing climate damages, they aim to discover the optimal net emissions pathway without prescribing an explicit emissions target. However, carbon budgets can be chosen to align with modeled welfare optima, and it is very likely that welfare-maximizing pathways are tightly constrained near or below 1.5 °C because climate risks escalate sharply beyond that threshold (145, 146).

Unlike other instruments, carbon shares remain operational even if CDR proves infeasible at scale. In that case, the posted bond would be depleted to pay for realized damages, and not for removals. To ensure coverage under all circumstances, the bond is initially set to the worst-case SCC, which is expected to decline over time as uncertainties resolve, allowing carbon shares to pay positive dividends. However, it remains unclear whether a definable worst case exists, whether it can be estimated reliably, or whether its value would indeed decline.

The proposal makes a valuable contribution by addressing how to set collateral under uncertainty, resolving it through initial over-collateralization and subsequent gradual reimbursement. Although the other deposit-based proposals, including the tax-fund system, don't explicitly discuss this, they would also have to over-collateralize, i.e., charge more than the discounted expected value of removal costs to operate reliably under uncertainties and provide the right incentives. However, the implied transactions based on worst-case collateralization could be macroeconomically large and potentially unrealistic, undermining political feasibility of implementation.

All proposed instruments, except carbon shares, would face systemic failure if large-scale removals were unavailable. As argued in Chapter 5 and further discussed in Section 7.3.2, CROs, clean-up certificates and ACORDS, however, presuppose at least a minimal functioning removals market, allowing entities to price risks and to inform their "abate versus emit" decisions, which hinge critically on expectations of future removal costs.

The information requirements are large for all proposed instruments, but naturally largest for carbon shares. CROs limit the forward-looking burden for emitters by fixing maturities. Although, according to neoclassical theory, decentralizing the decision when to remove could improve dynamic efficiency, this is a guardrail viewed as necessary to prevent deterrence through intertemporal substitution. Additional guardrails would need to be established for clean-up certificates / ACORDS to address deterrence.

Among the instruments, CROs as proposed in Chapters 4 and 5 are unique in explicitly allowing separate targets and price trajectories for removals and for emissions. By contrast, clean-up certificates, carbon shares, and ACORDS implicitly equate the marginal cost of removals with the marginal cost of abatement, thereby adhering to the standard logic of cost-effectives in climate mitigation pathways. However, many advantageous features result from allowing separation:

First, clean-up certificates and ACORDS effectively govern CDR by two instruments, i.e., including the ETS, thus adding regulatory complexity. Second, the interval between net emissions and net removals is longer than that between gross emissions and gross removals, implying longer instrument maturities and thus potentially greater exposure to idiosyncratic and macroeconomic risks (see Figure S1 in Annex 5). Third, because CROs encompass gross removals, i.e., all CDR, the aggregate demand for removals is fixed years in advance of delivery. CDR developers therefore do not need to form expectations about residual demand to balance hard-to-decarbonize sectors, which increases planning certainty and reduces investment risk.

Forth, from a dynamic-efficiency perspective, higher present value marginal removal costs early on are advantageous to admit high-cost CDR options and accelerate learning-by-doing for cost reductions (see Chapter 4 as well as Section 5.3.2), and lower later to reduce welfare distributional impacts. Efficient emission reduction price paths, by contrast, are often modeled to grow at the interest rate, i.e., remain roughly constant in present value terms. If privately owned CDR projects are remunerated at the same carbon price as emissions reductions in a single market, they can accrue windfall profits, amplifying regressive distributional effects (147). Decoupling the price paid for removals from the (often higher) post-2050 marginal cost of abatement by separation of markets can help constrain CDR rents and associated inequality impacts. Empirically, modest deviations from the cost-effective “equal-price” path, via stronger emphasis on emission reductions and less CDR through separated markets, prices, and/or targets, incur only small efficiency losses, while reducing reliance on CDR and limiting fiscal exposure to large public CDR payouts (16).

While separation of emission reductions from removals is a distinctive and advantageous feature of CROs, the architectures of clean-up certificates and ACORDS can be adapted to deliver similar separation. However, doing so would diminish the ETS’s role in steering mitigation relatively soon, a prospect that may be politically unattractive for some policymakers.

Finally, CROs as well as carbon shares are based on a stock charge architecture. As discussed in Section 1.4.4, this naturally accommodates temporary removals. CDR rewards stop upon reversal thereby incentivizing owners of temporary removal projects to prudently manage reversal risks. Hence, CROs should ultimately be extinguished only with permanent removals in line with the “like-for-like principle”; however, regulation could allow suspension of the stock charge (base premium) for CRO holders who maintain verifiable temporary removals. This does not resolve the additionality challenge for temporary removals, and it requires continuous monitoring to detect reversals, hence integration of temporary removals would require high-quality, persistent MRV. However, this architecture ensures that the full potential of permanent and temporary CDRs is deployed, while maintaining environmental integrity.

A crucial question not discussed here concerns how the different proposals envision the enforcement of intertemporal obligations, which is discussed in the next Section (7.2). Beneficial design features, including considerations about enforcement, are summarized in Table 5.

Table 5. Beneficial design features of intertemporal policy instruments and institutional arrangements, as discussed in Sections 7.1 and 7.2.

Design feature	Expected benefits of design choice
<p><b>Gross-emissions-gross-removals accounting:</b></p> <p>Obligations are imposed on gross emissions and thus cover all removals. There is no ETS-based contemporaneous offsetting of residual emissions with removals.</p>	<ul style="list-style-type: none"> <li>• Reduced regulatory complexity;</li> <li>• Separate path control of emissions and removals;</li> <li>• Shorter maturities;</li> <li>• Improved CDR demand forecasts;</li> <li>• Positive distributional and learning effects</li> </ul>
<p><b>Managed maturities:</b></p> <p>Regulators prescribe maturities of obligations instead of leaving this decision to emitters / instrument-holders.</p>	<ul style="list-style-type: none"> <li>• Reduced information requirement for instrument holders;</li> <li>• Guardrail against deterrence;</li> <li>• Improved CDR demand forecasts</li> </ul>
<p><b>Stock-charge:</b></p> <p>A carbon stock-charge is imposed on CO<sub>2</sub> temporarily parked in the atmosphere.</p>	<ul style="list-style-type: none"> <li>• Seamless integration of temporary removals;</li> <li>• Compatibility with provision-style treatment of carbon debt;</li> <li>• Potential integration with realized damages</li> </ul>
<p><b>Emitter-specific pricing:</b></p> <p>The costs associated with obtaining the right to “emit now and remove later” depends on the financial position of the emitter to reflect default risk.</p>	<ul style="list-style-type: none"> <li>• Counterbalanced adverse selection;</li> <li>• Reduced system level risk by managed idiosyncratic risks;</li> <li>• Improved allocative efficiency</li> </ul>
<p><b>Flexible collateral:</b></p> <p>Various types of collateral are used (including lien on assets, cash margins, guarantees) instead of one-size-fits-all deposit. Interplay between collateral and emitter-specific pricing is considered.</p>	<ul style="list-style-type: none"> <li>• Reduced capital immobilization;</li> <li>• Increased flexibility to reduce risk exposure;</li> <li>• Improved political feasibility</li> </ul>

## 7.2. Enforcement of intertemporal obligations

Here it is discussed whether financialization of carbon debt is a suitable way to manage commitment and liability risks, i.e., the risk that firms emit today but never fund removals later, relative to the two proposed alternatives: simple collateral (21) and collateral (deposits) with tradable receipts (22). Financialization here means converting a legal removal obligation into a bankable liability that is priced, monitored, and backstopped within the regulated financial system. This would integrate removal delivery within the financial system’s risk management

by relying on financial market discipline mechanisms, credit risk management instruments and macro prudential management to make non-performance visible and costly, and to channel capital into CDR project finance.

Akin to performance bond-like instruments (28), a CRO is booked as debt on the issuer's balance sheet and accrues interest (the commercial premium described in Chapter 5) until maturity, when the obligation is extinguished by retiring RUs. Enforcement of the obligation is shifted to regulated, supervised and well-capitalized intermediaries whose solvency and conduct are already policed by banking and financial regulation. CROs would thus be accounted for as a provision with uncertain future outlay (27), measured at the present value of the expected RU purchase and accreted over time while premiums are recognized as period expenses in the CRO-holders profit and loss (P&L) accounts. Hence, the provision is updated each reporting date for changes in estimated removal costs and the discount rate, subject to external audit. The periodic unwinding of the discount (accretion) is recognized in P&L as a finance cost until settlement. For intermediaries CROs are off-balance sheet contingent obligations to step in if the issuer defaults, which generate a stream of revenue for the risks taken.

### 7.2.1. Risky firms are disincentivized to emit

As a liability, the CRO affects the issuer's financial position, i.e., it raises leverage, potentially tightens covenants, and thereby reduces borrowing headroom (including the ability to take on additional CROs), but it does not necessarily immobilize working capital (cash). The CRO relies on dynamic risk-based pricing and ongoing monitoring which can, in theory, align abatement incentives intertemporally. Riskier firms face higher CRO premiums and are thus incentivized to abate more, whereas stronger firms secure lower premiums. Covenants defined in the terms and conditions of the CRO (e.g., on borrowing limits, or debt ratios) allow early intervention and adjustment of pricing when conditions deteriorate. This could improve allocative efficiency by ensuring carbon debt is built up only by companies which have plans and capacity to deploy removals.

### 7.2.2. Funds for risk hedging are channeled into CDR

In theory, and if well designed, financialization could help free up capital through various mechanisms, and channel additional capital into CDR project finance. Because intermediaries carry an exposure that is best hedged by securing future CDR supply, capital might be naturally channeled into RU offtake. This includes, for example, the proposed requirement for

intermediaries to hold prudential loss-absorbing buffers (CDR reserves at the central bank) sized to CRO exposure. Moreover, equity requirements for intermediaries, tied to risk-weighted CROs they issued, might be imposed by supervisors (e.g., central banks), who would likely recognize hedges through forward CDR offtakes as credit-risk mitigation. Because intermediaries observe the maturity profile of the obligations they issue, they can prioritize projects whose CDR delivery aligns with those dates. This “asset-liability matching” may reduce price and availability risk and thereby stabilize their exposure. The resulting lower risk weight on the intermediary’s residual exposure frees regulatory capital, which could be redeployed to finance additional CDR projects.

If a CRO is secured by a lien on assets, the pledged assets are encumbered, i.e., they can’t be sold or re-pledged, strengthening enforcement without immediately reducing cash liquidity. However, it can still constrain liquidity indirectly by blocking asset sales and limiting additional borrowing. Other collateral options include a parent-company guarantee or a cash margin (28, 148), with the latter directly immobilizing cash. Where collateral is used to secure exposures, re-margining, i.e., the periodic top-up or release of collateral as risk changes (for example, rising CDR prices or a deterioration in the CRO holder’s credit quality), helps ensure that posted collateral continues to cover current exposure. This is to avoid initial over-collateralization to address uncertainties.

Finally, CROs can be securitized via a synthetic capital-relief trade, provided strong safeguards are in place (149). The intermediary aggregates a diversified portfolio of guarantees (i.e., contingent removal obligations) and transfers a defined slice of loss risk to investors in return for a coupon. Investor capital, e.g., from insurers, pension funds, public development institutions, and specialist credit funds, is deployed against that portfolio risk and earns yield, typically with collateral and downgrade protections. Because genuine risk is transferred, the intermediary’s required regulatory capital on that portfolio is reduced. In turn, the freed capacity can support additional RU forward purchases or CDR project finance. However, such risk transfer should only be implemented if it can be ensured that it does not ultimately undermine step-in liability and therefore the environmental integrity of CROs.

### 7.2.3. Enforcement through deposits

A deposit model secures performance of removal obligations by parking cash collateral in an interest-earning escrow-like deposit, and releasing it only once certified removals occur. This instrument is transparent and comparably simple to implement, but it is intrinsically static. Deposit levels do not update with changing removal costs or firm risks, and there is no step-in party beyond the posted funds. Deposits also immobilize capital for long periods and may

not create a financing pipeline for removal projects through risk hedging. Allowing tradable deposit receipts adds useful features, including liquidity for emitters, risk-sharing among investors, and some price discovery about expected redemption values, but it does not, by itself, supply a creditworthy backstop (like a capitalized intermediary) or enable risk-based collateralization. Trading shifts who holds the claim; it does not change that capital remains immobilized and that the program lacks a supervised step-in counterparty if costs exceed deposits.

The picture changes if collateral is no longer held in escrow but placed in a risk-taking public trust or investment fund. If the fund invests only in low-risk cash equivalents (e.g., short-dated sovereign bonds), it does little to ease the underlying capital immobilization. If, instead, it invests in riskier assets or directly in CDR projects, it becomes an underwriter of project risks. In practice, that pushes the arrangement toward similar monitoring, and risk-management apparatus required for financialized obligations, as the fund must ensure that deposits plus accrued time value is available for redemption when removals are delivered. Further research is needed to clarify the risks and opportunities of this option.

#### 7.2.4. Financialization risks and opportunities

Compared to static deposit regimes, the main advantages of financialization include emitter-specific pricing and the potential for limiting the need for large up-front capital transfers and subsequent capital immobilization. Moreover, introducing removal obligations in the financial mainstream could reduce the risk of policy reversal. Since most CDR produces no marketable co-product, a policy reversal would likely extinguish CDR deployment far more quickly than it could, for example, derail renewable energy when subsidies are discontinued.

However, financialization introduces intermediation costs expressed in premiums, operational complexity and might reduce transparency. Moreover, it may create systemic risk channels through mispriced delivery risk, or procyclical tightening during stress, which could transmit shocks through the intermediaries' and investors' balance sheets. This could be amplified by a "too big to fail" moral hazard for financial intermediaries, which operate on an implicit state guarantee. Distributional concerns might arise because risk-based pricing tends to raise costs for smaller or younger firms. Also, small financial intermediaries might face higher costs for capacity building in carbon debt management than larger competitors (21).

Some of these risks relate to the financial sector more broadly, amid ongoing debates about whether the financial system in its current form adequately serves the real economy and what reforms are needed to make it more effective. Cooperative and stakeholder-owned institutions, as well as public development banks might be a good benchmark (150). Moreover, many of

the associated systemic risks are, in principle, manageable with standard macro-prudential tools. A central-bank-operated reserve facility and base premiums can lean countercyclically (raising buffers in booms, easing in stress), and stress testing can reveal vulnerabilities under shocks to removal costs, policy, or default rates. Other tools that might be applied by supervisors include risk-based equity requirements, relaxation or strengthening of maturity limits, as well as system-level caps on total carbon debt/obligations issued.

In conclusion, deposits, with or without tradable receipts, remain attractive where simplicity, transparency, and tight public control are the main objectives. The case for financialization generally strengthens with scale, which is projected to be massive (Section 7.3.1). As carbon debt grows large relative to corporate balance sheets and public budgets, costs of static deposits grow.

## 7.3. Discussion

This section offers an outlook beyond the analyses in Chapters 3 to 6, synthesized in Sections 7.1 and 7.2. It addresses the magnitude of system-level carbon debt and the question of where along the value chain (producers, emitters, consumers) such obligations should fall. It argues that building a functioning removals ecosystem will require a strong governmental role, paired with independent institutions that insulate obligation systems from day-to-day politics. It also considers international cooperation and non-adoption of the CRO framework. Drawing on these insights, it proposes a multi-decade sequencing of CDR policy. The section concludes by outlining limitations and avenues for future research.

### 7.3.1. Costs of carbon debt and who should pay

Removal costs under CROs are incurred at maturity. While estimates of total annual removal costs are typically in the single-digit range of global GDP (2), the associated financial flows and implied redistribution might be substantially larger if emissions and removals are priced at a uniform carbon price derived from a steep marginal abatement cost curve (17). Until costs are incurred, CROs sit as liabilities on emitters' balance sheets, and the balance-sheet impact depends on accounting. If treated as provisions (27), the discounted present value of the expected future RU cost is booked.

A back-of-the-envelope sizing illustrates the macro orders of magnitude. Suppose global carbon debt accrues for 25 years before removals exist at scale, i.e., peak cumulative uncompensated carbon debt is assumed around 2050. Since emissions need to be declining until mid-century, assume an average global accrual rate of 20 GtCO<sub>2</sub>/year. Peak outstanding

carbon debt is thus about 25 times 20 = 500 GtCO<sub>2</sub> in 2050. At average removal costs of \$100/tCO<sub>2</sub> (low) or \$500/tCO<sub>2</sub> (high), the book value without discounting (i.e., proxying an upper bound estimate where all CROs are due in 2050) is \$50T (low) or \$250T (high). With today's world GDP at about \$110T and growing at 2% for 25 years ( $\approx$  \$180T in 2050), these correspond to about 28% (low) and 139% (high) of GDP in the year 2050.

If, instead, we assume an average 20-year maturity for the obligations and a 3% real discount rate, the book values are 15% (low) and 77% (high) of GDP in the year 2050, respectively. For context, global debt in 2024 was about 236% of GDP ( $\approx$  143% private, 93% public), with most debt in capital-intensive, non-financial sectors, like real estate (151). Hence, if removal costs are high and maturities are short, peak carbon debt could approach the scale of today's global private debt, underscoring a substantial macroeconomic challenge and the need for macro-prudential tools and strong independent institutions. Whether and under what conditions these magnitudes are manageable for involved entities is subject to ongoing research.

This thesis does not resolve the distributional question of who pays for carbon debt, which remains a core topic for future research. Still, several guideposts are clear. First, equity principles widely discussed in the literature, for example in IPCC AR5 (36), which provides a transparent normative basis for allocating obligations within a jurisdiction. These include responsibility (historical contribution to emissions), capability (ability to pay), and equality (avoiding disproportionate burdens on low-income households). Second, for feasibility of the CRO framework, implementation should prioritize highly capitalized entities with demonstrable ability to pay and manage long-dated liabilities (e.g., major fossil-fuel suppliers, energy utilities, and heavy industry). For margin-constrained and trade-exposed entities, CROs might need to be coupled with competitiveness safeguards to avoid de-industrialization, and subsequent carbon leakage.

Operationally, the obligation should attach where emissions are verifiable, non-overlapping, and enforceable. This is typically at the point of release (large point sources), the first placing of fossil carbon into the economy (upstream fuel suppliers), or at customs entry (for imports). These compliance points minimize double counting and simplify monitoring and enforcement. For fossil fuel importers, import licenses would need to be tied to a CRO account at an intermediary and non-compliance would lead to its suspension. Moreover, importers would need to have a locally incorporated entity that can grant security over domestic assets or post cash as collateral.

This concept could be extended to an “intertemporal carbon storage obligation (iCSO)”, whereby all carbon embodied in fossil products extracted, produced, or imported into a jurisdiction must ultimately be returned to geological storage. This iCSO could also require that a gradually increasing fraction must already be stored at the time those fossil products enter the economy, in line with the CSO/CTBO discussed in Section 1.4.2. This increasing near-term quota could help ensure a credible and timely ramp-up of storage capacity, while remaining volumes are settled through longer-dated maturities. As part of such a framework, obligated entities could also be required to demonstrate that sufficient proved, commercially viable, and contractually secured geological storage capacity exists to cover 100% of the carbon placed into the economy – analogous to how extractive firms demonstrate access to economically recoverable reserves – even if actual injection occurs progressively over time in line with the maturity schedule of the intertemporal obligation.

A broader fairness issue concerns actors who benefit from a fossil-based economy without directly emitting at the compliance point (for example, large financial institutions or digital platforms with low scope-1 emissions). CROs are not well suited to obligate such indirect beneficiaries without introducing overlap and double counting. If society wishes these actors to contribute, complementary fiscal instruments, such as profit-based contributions, windfall mechanisms, or surcharges linked to financing of carbon-intensive outputs, are the appropriate tools. Accrued revenues could for example be used to address distributional impacts, e.g., from increased energy bills, or they could be earmarked to a removal trust that finances CDR projects.

### 7.3.2. Institutions and role of government

A common limitation of the instruments reviewed is their intertemporal information requirement. They require reliable information that today does not exist. Firms must form views about future removal costs or marginal climate damages to decide whether to abate now or emit and remove later; regulators or financial intermediaries must price collateral, set maturity, and manage default risk over decades; policymakers must quantify technology, permanence, and MRV risks to calibrate rules. With no deep removals market yet in place, these expectations are necessarily fragile. In short, the policy challenge is not only to choose an instrument, but to create the market and knowledge base those instruments presuppose, beyond the challenges named in the introduction.

Building that ecosystem is a multi-sector, multi-decade task because CDR is heterogeneous and embedded in many existing policy domains (see Section 1.3), and because of the broader environment with progressing climate change and increasing global tensions. The CDR

challenge, as outlined in Chapter 6 might be comparable with the Apollo Program or the Manhattan Project, only at a global scale with considerably harder co-ordination challenges.

Chapter 5 pointed out the critical role of government to establish a functioning CDR market. Given the complexity, costs and timescales of the challenge, a mission-oriented state perspective suggests a way forward (26), at least at national or regional scale. An interministerial “war room” could reduce fragmentation and shorten feedback cycles to align functions that otherwise move on incompatible timelines and in different governance domains. This includes all the elements discussed in Section 1.3, like research and innovation, project permitting, land and ocean governance, energy, industrial and infrastructure policy, CO<sub>2</sub> transport and storage planning, standards, MRV, and so on.

From this perspective, rather than acting only as facilitators and redistributors, governments would need to behave as entrepreneurial, risk-taking investors with a strategic long-term vision (152). In the CDR context that could include establishing or co-owning removal enterprises (with the benefit of addressing distributional aspects at the root (147)), capitalizing shared commons such as CO<sub>2</sub> transport and storage hubs, funding and operating MRV, sponsoring university and other research programs that de-risk methods and train the workforce, running testbeds and field trials with open data, and even establishing public or stakeholder-owned intermediaries if removal obligations are to be financialized, as well as coordination of all these tasks between public and private stakeholders.

However, a strong public role, which is inherently political and democratic, also requires institutional designs for rule-based execution and stewardship of long-lived funds and obligations that benefit from operational independence, expert oversight, and insulation from day-to-day politics. Hence, most proposals agree that funds and commitments that must persist across electoral cycles, like escrowed deposits, financialized obligations, long-dated CDR offtake contracts, prudential buffers etc., are best delegated to an independent, statute-anchored body with a narrow mandate, transparent rules, and hard accountability (reporting, audits, judicial review). This mirrors the logic of monetary governance (as suggested for CROs) and reflects the idea of a Carbon Central Bank with politically set objectives but technically executed operations. Such an entity should be empowered to act counter-cyclically, apply expert standards, supervise intermediaries, etc., while remaining accountable to elected institutions through clearly defined oversight and periodic mandate reviews.

In short, scaling up CDR and sustaining it over long time horizons will likely require a strong governmental role, complemented by independent institutions that shield established systems from political cycles.

### 7.3.3. Political default and international coverage

Chapters 3 and 6 touch on CROs as international instruments, especially for addressing historical carbon debt and responsibility for climate change, but this thesis does not analyze that dimension in detail. Instead, CROs are proposed primarily as domestic or regional economic carbon policy instruments. Hence, they do not, by themselves, resolve the international cooperation problem of climate change. However, there are two risks which CROs might help address: political default, that is, the prospect that a government walks away from accumulated obligations within its jurisdiction; and non-compliance by jurisdictions that choose not to adopt obligation frameworks at all. The first is a credibility question, the second is a leakage and fairness question.

Embedding CROs in the financial mainstream raises the domestic cost of exit. Once CRO liabilities sit on corporate balance sheets, intermediaries hold prudential reserves, RU offtake contracts are signed, and CDR projects are financed, dismantling the regime is no longer an opportunistic political decision. It would impose visible balance-sheet impacts, trigger contractual remedies, and carry rating and funding consequences for firms and intermediaries. In other words, “policy default” is a decision to force losses on identified creditors and counterparties. Credibility can be strengthened by statutory entrenchment and operational independence, as discussed above. Countercyclical tools help avoid procyclical stress that might otherwise catalyze political exit in downturns.

Non-participation by other states is often seen as a collective-action problem with freeriding, though this point of view has been challenged (153). CROs, however, are not different from other climate policies in this respect. They operate where enacted, and it is likely that some industrialized countries will need to lead in implementation. Beyond the border, familiar trade instruments are needed to limit leakage and protect against loss of competitiveness. Jurisdictions can pair CROs with border carbon adjustments (see Chapter 5) or other penalties/benefits associated with market access to internalize the cost of unmanaged carbon in trade. This can be arranged within climate clubs (154, 155) where club incentives (e.g., preferential access; technology sharing; mutual recognition or shared development of RU quality standards, financial regulation, or institutional architectures; linking of obligation markets) are paired with penalties for non-members (e.g., coordinated border adjustments; trade barriers), to curb freeriding, increase exist costs and thus make coalitions more durable.

### 7.3.4. Sequencing of CDR policies

The Paris architecture has always implicitly relied on large-scale removals, yet current CDR deployment is far from trajectories consistent with Paris-aligned pathways, heightening the likelihood of substantial overshoot. Chapter 6 argued that sustained net-negative emissions may be required well beyond this century to stabilize certain climate risks. Depending on the magnitude of overshoot, it could be desirable to push temperatures below 1.5°C in the long run to stabilize time-lagged impacts, such as sea-level rise or permafrost thaw, and to lower the probability of extreme outcomes.

While earlier adoption of intertemporal removal obligations is generally advantageous, because the instrument enables more ambitious climate goals via the obligations issued, there is likely to be scope for introducing such instruments even after the depletion of the 1.5°C-compatible carbon budget. Given insufficient progress in climate change response and the current trajectory toward a 2.5-3°C overshoot (6), the feasible scope and implementation horizon for reversal instruments, such as CROs, are correspondingly expanded.

A plausible sequencing of CDR deployment begins with a government-led phase focused on scaling removal capacity, including infrastructure and MRV systems. In this stage, simple registry-based intertemporal obligation systems could be introduced, grounded in the PPP and EPR, alongside the establishment of independent, statute-anchored public authorities tasked with overseeing carbon debt at the system level.

However, large up-front collateral requirements could undermine the political feasibility of such a program. Enforcement mechanisms should therefore be strengthened gradually, in step with the growing capacity to deliver CDR at scale. Governments must take the lead in creating these conditions, while enterprises should be encouraged to participate and view the transition as an economic opportunity, not a constraint.

Ultimately, once the CDR ecosystem can support it, i.e., when reliable price paths and robust MRV systems are in place, carefully regulated financialization of carbon debt could follow. Converting removal obligations into bankable liabilities, issued by supervised intermediaries, priced through risk-based premia, and hedged via forward removal offtakes, can improve risk management and mobilize larger pools of private capital for CDR project finance. Because financialization increases operational complexity and introduces new systemic channels, it must be accompanied by strong macro-prudential safeguards.

In the long run net negative steady state, as sketched out in Chapter 6, intertemporal obligations will eventually become depleted, yet a persistent demand for net negative emissions may remain. Following the phase of intertemporal compensation of carbon debt, whose primary purpose is to develop methods, mature technologies, and scale supply with

the aid of responsible emitters, a normalization of CDR needs to occur. In that regime, removal rates remain constant, and unit costs decline relative to a larger economy and energy system. At that point, CDR can be institutionalized as a utility-like public service, funded through broad bases (e.g., energy bills or general revenue). Alternatively, products could be mandated to become carbon negative, making CDR “just another input” in the supply chain.

In sum, by sequencing from public-led scale-up to supervised financialization and ultimately a normalized utility-like service, CDR can be made scalable, capable of sustaining net negative emissions for as long as climate stability demands.

### 7.3.5. Summary, limitations, and future research

This thesis develops a coherent framework for financing and governing net negative emissions through intertemporal CROs. It advances several strands of contribution. First, it establishes conceptual foundations by formalizing carbon debt and proposing CROs as enforceable intertemporal liabilities aligned with established principles of environmental economics. Second, it provides analytical and quantitative results in a social-planner setting, demonstrating how distinct price trajectories for gross emissions and gross removals can implement efficient paths and how policy constraints shape those paths. Third, it offers a refined policy, legal, and institutional blueprint. Fourth, it extends the analysis to a long-run time horizons, situating CROs within post-2100 net negative futures motivated by stabilizing time-lagged climate impacts. These elements are synthesized to provide an in-depth stocktake of proposed net negative instruments in Chapter 7. It is suggested that future improvements of intertemporal designs should focus on the points outlined in Table 5. It is concluded that a mix of known elements from economic carbon policy, financial assurance governance and monetary policy, which constitute the CRO framework, best address the immense challenge ahead of us.

Several limitations should be acknowledged. The modelling is necessarily stylized and abstracts from political-economy frictions, heterogeneity, and detailed distributional incidence. Quantitative exploration is designed to illuminate mechanisms rather than to forecast point values. Uncertainty around removal costs, learning, permanence, and delivery risk remains only partially captured and calls for explicit stochastic treatments. The institutional and legal implementation blueprint adapts concepts from financial regulation which requires further tailoring to address the specifics of carbon debt. Moreover, the proposed financialization of CROs is introduced by analogy and not based on explicit quantitative modelling. The thesis also does not fully formalize how optimal maturities, rollover constraints, and premium-setting rules would be determined under strategic interaction between regulators, intermediaries, and emitters, nor how Base Premium adjustments should respond to model uncertainty or time-

inconsistency risks. Finally, intertemporal equity and welfare distributional questions are not sufficiently quantified and merit deeper empirical analysis.

Several immediate avenues for further research appear especially valuable. The first concerns the manageability of financialized carbon debt for CRO holders and intermediaries. Here, case-based work on large emitters and prospective financial intermediaries can clarify how CRO liabilities interact with firm balance sheets and risk management, what collateralization and default waterfalls are workable, and which supervisory metrics most effectively bound risk. Related work should examine how maturity choice can be disciplined when delegated to private intermediaries, how rollover incentives can be contained, and how pricing rules can better align private incentives with socially desired emissions-removals pathways, including overshoot discipline and intertemporal efficiency. This work would also need to characterize systemic channels using macro-prudential tools. Agent and network-based contagion analysis and climate-financial stress testing can be adapted to CRO markets to probe the propagation of shocks from removal-cost spikes, technology failures or permanence events, and to test the stabilizing roles of risk mitigation measures discussed in the synthesis. Another avenue is to clarify the interface between removal obligations and claims for loss and damage, conceptualized but not formalized in Chapters 3 and 5. It is worth exploring whether participation in a well-designed removal-obligation regime could be recognized within existing doctrines governing attribution, responsibility, and remedies.

Taken together, these extensions would help convert the thesis' proof-of-concept into an empirically grounded and institutionally robust policy architecture.

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# ANNEX 1

A Reduced-Complexity Model of Process-  
Based IAMs

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## **Abstract**

This working document presents the development and calibration of abatement cost functions for a reduced-complexity integrated assessment model (IAM). A total of ten cost functions, partially linked to one another, are developed and calibrated based on complex process-based IAMs. This design allows the reduced-complexity model to replicate scenarios produced by more detailed IAMs while running significantly faster. The improved computational efficiency enables the exploration scenarios based on multiple parameter sets, each representing a complex IAM, to provide a robust representation of technological uncertainty.

The final model is versatile, functioning either as an optimization tool (e.g., for cost minimization under a temperature target or welfare maximization when linked to a Ramsey growth model like DICE) or as a simulation tool that takes a carbon price path as input. It is important to note that this document focuses solely on the cost functions, which form the model's core, as well as some exploratory model extensions. Other components, such as climate or economic modules, can be easily linked using existing models.

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# 1 Model description

## 1.1 Model variables and index sets

In this model, various variables are indexed by specific categories to represent different aspects of energy use, emissions, and costs. Below, we define each variable along with its respective index set. A summary of the model is provided in ANNEX B.

### 1.1.1 Primary energy $W_i$

Represents the quantity of primary energy. The index  $i$  belongs to the set of primary energy types  $\mathcal{I} = \{\text{foss}, \text{nbr}, \text{bio}, \text{nuc}, \text{trad}\}$ , where:

- $W_{\text{foss}}$ : Primary energy from fossil fuels
- $W_{\text{nbr}}$ : Primary energy from non-biomass renewables
- $W_{\text{bio}}$ : Primary energy from biomass
- $W_{\text{nuc}}$ : Primary energy from nuclear
- $W_{\text{trad}}$ : Primary energy from traditional biomass

### 1.1.2 Final energy $F$

Represents the quantity of final energy and encompasses all end-use energy types without differentiation. Abatement in final energy is denoted by the index  $fe$ .

### 1.1.3 Other emitting sectors

Emitting sectors other than the energy sector include the industrial and Agriculture, Forestry, and Other Land Use (AFOLU) sectors, which are represented by the set  $\mathcal{N} = \{\text{ind}, \text{afolu}\}$ .

### 1.1.4 Emissions $E_j$

Represents emissions associated with different sectors. The index  $j$  belongs to the set  $\mathcal{J} = \mathcal{N} \cup \{\text{ener}\}$ , where:

- $E_{\text{ener}}$ : Pre-capture emissions from the energy system (i.e., emissions are aggregated as if no carbon capture were present)
- $E_{\text{ind}}$ : Pre-capture industrial process emissions (e.g., cement, steel)
- $E_{\text{afolu}}$ : Net emissions from AFOLU

### 1.1.5 Carbon capture $S_k$

Represents the amount of emissions captured and stored from the atmosphere and point sources, like fossil carbon capture and storage (CCS). The index  $k$  is associated with different capture and storage options, defined by the set  $\mathcal{K} = \{s\_foss, s\_bio, s\_ind, s\_dac\}$ , where:

- $S_{s\_foss}$ : Carbon capture via fossil CCS
- $S_{s\_bio}$ : Removals via bioenergy with CCS (BECCS)
- $S_{s\_ind}$ : Carbon capture via industry CCS
- $S_{s\_dac}$ : Removals via direct air CCS (DACCS)

### 1.1.6 Absolute abatement $A_m$

Represents reductions in emissions or increase of carbon capture compared to a baseline (but not expressed as fraction of baseline emissions). The index  $m$  belongs to the expanded set  $\mathcal{M} = \mathcal{I} \cup \mathcal{N} \cup \mathcal{K} \cup \{fe\}$ , where we have abatement through: emission reductions from primary energy substitution, industry and AFOLU emission reductions, carbon capture, as well as emission reductions from reducing final energy demand.

### 1.1.7 Marginal costs $P_m$ and total costs $C_m$

Represent the marginal and total cost associated with each type of emission reduction or carbon capture, respectively. The index  $m$  is the same as for  $A_m$  and uses the set  $\mathcal{M}$ .

## 1.2 Model parameters

### 1.2.1 Carbon intensity of fossil fuels $\beta_{foss}$

We define  $\beta_{foss}$  as the carbon intensity of fossil fuels. A simplifying assumption is made that  $\beta_{foss}$  is constant, although in reality it varies depending on the fossil fuel mix. This mix may differ especially between baseline and mitigation scenarios.

### 1.2.2 Conversion efficiencies $\eta_i$

Conversion efficiencies  $\eta_i$ , where  $0 < \eta_i < 1$ , represent the efficiency with which primary energy is converted into final energy. These parameters capture technological and systemic losses during the conversion process (e.g., electricity generation or refining). We assume these efficiencies remain constant, even as energy end-use patterns change. The index  $i$  is defined as in Section 1.1.1.

### 1.2.3 Fossil fuel substitution efficiencies $\sigma_i$

The fossil fuel substitution efficiency  $\sigma_i$  is defined as the ratio of the conversion efficiency of energy type  $i$  to that of fossil fuels:

$$\sigma_i := \frac{\eta_i}{\eta_{foss}}$$

This parameter allows comparisons of how efficiently alternative energy sources substitute for fossil fuels in delivering final energy.

### 1.3 Basic model structure

Net carbon emissions from the energy, industry, and AFOLU sectors are calculated as follows:

$$E_{\text{net}}(t) = \sum_{j \in \{\text{ener, ind, afolu}\}} E_j(t) - \sum_{k \in \{\text{s.foss, s.bio, s.ind, s.dac}\}} S_k(t),$$

where  $E_{\text{net}}(t)$  represents net emissions, and  $E_j(t)$  denotes emissions from different sectors (see Section 1.1.4). The term  $S_k(t)$  represents carbon capture from point sources or the atmosphere, as introduced in Section 1.1.5.

Pre-capture emissions from the energy sector,  $E_{\text{ener}}(t)$ , are calculated based on the primary fossil energy consumption  $W_{\text{foss}}(t)$  and the carbon intensity of fossil fuels,  $\beta_{\text{foss}}$  (see Section 1.2.1):

$$E_{\text{ener}}(t) = \beta_{\text{foss}} W_{\text{foss}}(t).$$

Final energy  $F(t)$  is defined as a linear function of the primary energy sources, weighted by their respective conversion efficiencies  $\eta_i$ , as defined in Section 1.2.2

$$F(t) = \sum_{i \in \{\text{foss, nuc, bio, trad, nbr}\}} \eta_i W_i(t).$$

From this relationship, the primary fossil energy consumption  $W_{\text{foss}}(t)$  can be expressed as:

$$W_{\text{foss}}(t) = \frac{1}{\eta_{\text{foss}}} \left( F(t) - \sum_{i \in \{\text{nuc, bio, trad, nbr}\}} \eta_i W_i(t) \right). \quad (1)$$

### 1.4 Baseline and mitigation scenarios

To distinguish between elements from the baseline and mitigation scenarios, we introduce a hat notation. For instance,  $\hat{W}_{\text{foss}}(t)$  represents the fossil primary energy in the baseline scenario. Initially, model variables are fixed to their baseline values, such that:

$$W_i(t_0) := \hat{W}_i(t_0) \quad \text{and} \quad F(t_0) := \hat{F}(t_0).$$

The same applies to carbon capture, so that:

$$S_k(t_0) := \hat{S}_k(t_0).$$

For internal consistency, the initial value of fossil primary energy,  $W_{\text{foss}}(t_0)$ , is calculated using Eq. (1).

## 1.5 Energy sector abatement

It is assumed that abatement can occur through reducing final energy  $F(t)$ , for example through increased efficiency or reduced demand, compared to a baseline; or by increasing other sources of zero-carbon primary energy  $W_i(t)$ , where  $i \in \{\text{nuc}, \text{bio}, \text{nbr}\}$ , compared to a baseline, thus substituting  $W_{\text{foss}}(t)$ . In this section, cost functions for reducing  $F(t)$  and increasing  $W_i(t)$  are introduced. Traditional biomass,  $W_{\text{trad}}(t)$ , does not represent a valid substitute for fossil fuels. It is phased-out in virtually all mitigation scenarios, with minor differences between individual scenario pathways. Moreover, the impact of carbon pricing on  $W_{\text{trad}}(t)$  is not obvious, hence, it is assumed that  $W_{\text{trad}}(t) := \hat{W}_{\text{trad}}(t)$ .

We define abatement,  $A(t)$ , compared to the baseline scenario as:

$$A(t) := \beta_{\text{foss}} \left( \hat{W}_{\text{foss}}(t) - W_{\text{foss}}(t) \right). \quad (2)$$

We define  $\Delta W_i(t) := \hat{W}_i(t) - W_i(t)$  and  $\Delta F(t) := \hat{F}(t) - F(t)$ . Because  $W_{\text{trad}}(t) := \hat{W}_{\text{trad}}(t)$ ,  $\Delta W_{\text{trad}}(t) = 0$ . From (1), it follows that:

$$\Delta W_{\text{foss}}(t) = \frac{\Delta F(t)}{\eta_{\text{foss}}} - \frac{\sum_{i \in \{\text{nuc}, \text{bio}, \text{nbr}\}} \eta_i \Delta W_i(t)}{\eta_{\text{foss}}}.$$

Furthermore, combining with 2,

$$A(t) = \beta_{\text{foss}} \left( \frac{\Delta F(t)}{\eta_{\text{foss}}} - \frac{\sum_{i \in \{\text{nuc}, \text{bio}, \text{nbr}\}} \eta_i \Delta W_i(t)}{\eta_{\text{foss}}} \right).$$

Using fossil fuel substitution efficiencies  $\sigma_i := \frac{\eta_i}{\eta_{\text{foss}}}$  (see Section 1.2.3), abatement can be attributed to different sources:

$$A_{\text{fe}}(t) := \frac{\beta_{\text{foss}} \Delta F(t)}{\eta_{\text{foss}}},$$

$$A_i(t) := -\beta_{\text{foss}} \sigma_i \Delta W_i(t), \quad i \in \{\text{nuc}, \text{bio}, \text{nbr}\}. \quad (3)$$

### 1.5.1 Cost functions for primary energy substitution

In an optimization setting, the model's objective function typically incorporates the total cost function – either directly, in the case of cost minimization, or indirectly through a utility function in an economic growth framework (e.g., welfare maximization in the DICE model). Here, we introduce such cost functions. Roughly speaking, we explain how a feasible path of  $W_i(\cdot)$  (equivalently,  $A_i(\cdot)$ ) produces paths of marginal costs  $P_i(\cdot)$ , and total costs  $C_i(\cdot)$ . In contrast, in ANNEX C we show how based on a carbon price path,  $P(\cdot)$  we can compute  $A_i(\cdot)$ ,  $P_i(\cdot)$  and  $C_i(\cdot)$ , a process used for the calibration of the model, and running the model in a simulation setting, rather than optimization.

Marginal abatement costs,  $P_i(t)$ , that capture the complex process of substituting fossil fuels with alternative primary energy sources are defined as (recall that  $\Delta W_i < 0$ ):

$$P_i(t) = \begin{cases} a_i(-\Delta W_i(t) + l_i \Delta W_i(t-1))^{b_i} + d_i, & \text{for } \Delta W_i(t) \leq l_i \Delta W_i(t-1) \\ d_i, & \text{for } \Delta W_i(t) > l_i \Delta W_i(t-1) \end{cases}$$

Using the definition for abatement,  $A_i(t) = -\beta_{\text{foss}}\sigma_i\Delta W_i(t)$ , we obtain:

$$P_i(t) = \begin{cases} \frac{a_i}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i} + d_i, & \text{for } A_i(t) \geq l_i A_i(t-1) \\ d_i, & \text{for } A_i(t) < l_i A_i(t-1) \end{cases} \quad (4)$$

The logic of the marginal cost function is as follows: Marginal costs remain constant at the floor level  $d_i$  when  $A_i(t) < l_i A_i(t-1)$ , but follow a power law when  $A_i(t) \geq l_i A_i(t-1)$ . The point at which marginal costs begin to follow a power law depends on previous abatement and the size of the lag parameter,  $l_i$ , where  $0 \leq l_i \leq 1$ , i.e., it is path-dependent. Larger abatement in the beginning leads to future cost functions capable of achieving greater abatement at lower average costs.

Moreover, in an optimization context, the following constraints are imposed:

$$W_i(t) \leq v_i(t), \quad (5)$$

$$A_i(t) \leq \beta_{\text{foss}}\sigma_i g_i + l_i A_i(t-1), \quad (6)$$

where  $v_i(t)$  is the maximum amount of  $W_i(t)$ , as discussed in Section 2.5; and  $g_i$  is a growth parameter further detailed in ANNEX C. Hence, primary energy  $W_i(t)$  cannot exceed  $v_i(t)$ ; and  $g_i$  and  $l_i$  together control the maximum growth of abatement by period.

To obtain total costs from the marginal cost function for the standard case, where  $A_i(t) \geq l_i A_i(t-1)$ , we integrate over abatement from 0 to  $A_i(t)$ . Note that from Eq. 2, it follows that  $A_{i,\min}(t) = 0$  for  $A_i(t) < l_i A_i(t-1)$ , and  $A_{i,\min}(t) = l_i A_i(t-1)$  otherwise:

$$\begin{aligned} C_i(t) &= \int_{A_{i,\min}(t)}^{A_i(t)} \left( \frac{a_i}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (\tilde{A}_i(t) - l_i A_i(t-1))^{b_i} + d_i \right) d\tilde{A}_i \\ &= \int_{l_i A_i(t-1)}^{A_i(t)} \frac{a_i}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (\tilde{A}_i(t) - l_i A_i(t-1))^{b_i} d\tilde{A}_i + \int_0^{A_i(t)} d_i d\tilde{A}_i. \end{aligned}$$

Hence, total costs for abatement from substituting fossil fuels are:

$$C_i(t) = \begin{cases} \frac{a_i}{b_i+1} \left( \frac{1}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i+1} \right) + d_i A_i(t), & \text{for } A_i(t) \geq l_i A_i(t-1) \\ d_i A_i(t), & \text{for } A_i(t) < l_i A_i(t-1). \end{cases}$$

Structurally, the cost functions derived for other types of abatement are almost identical with the ones introduced here.

## 1.5.2 Cost functions for final energy reduction

For final energy, the objective is to decrease energy use, as opposed to increasing a substitute for fossil fuels in the case of primary energy. Hence, the cost function differs from those for primary energy substitution in terms of the signs. Marginal costs for reducing final energy are defined as:

$$P_{fe}(t) = \begin{cases} a_{fe} \left( \frac{\eta_{\text{toSS}}}{\beta_{\text{toSS}}} \right)^{b_{fe}} (A_{fe}(t) - l_{fe}A_{fe}(t-1))^{b_{fe}} + d_{fe}, & \text{for } A_{fe}(t) \geq l_{fe}A_{fe}(t-1) \\ d_{fe}, & \text{for } A_{fe}(t) < l_{fe}A_{fe}(t-1) \end{cases} \quad (7)$$

Moreover, in an optimization context, the following constraints are imposed:

$$F(t) \geq v_{fe}(t),$$

$$A_{fe}(t) \leq \frac{\beta_{\text{toSS}}}{\eta_{\text{toSS}}} g_{fe} + l_{fe}A_{fe}(t-1).$$

Here,  $v_{fe}(t)$  is the minimum allowable amount of  $F_i(t)$ , as discussed in Section 2.5; and  $g_{fe}$  is a growth parameter, further explained in ANNEX C. As for primary energy substitution, to obtain total costs from the marginal cost function, we integrate over abatement:

$$C_{fe}(t) = \int_{A_{fe, \min}(t)}^{A_{fe}(t)} \left( a_{fe} \left( \frac{\eta_{\text{toSS}}}{\beta_{\text{toSS}}} \right)^{b_{fe}} (\tilde{A}_{fe}(t) - l_{fe}A_{fe}(t-1))^{b_{fe}} + d_{fe} \right) d\tilde{A}_{fe}.$$

Hence, the total costs are:

$$C_{fe}(t) = \begin{cases} \frac{a_{fe}}{b_{fe}+1} \left( \frac{\eta_{\text{toSS}}}{\beta_{\text{toSS}}} \right)^{b_{fe}} (A_{fe}(t) - l_{fe}A_{fe}(t-1))^{b_{fe}+1} + d_{fe}A_{fe}(t), & \text{for } A_{fe}(t) \geq l_{fe}A_{fe}(t-1) \\ d_{fe}A_{fe}(t), & \text{for } A_{fe}(t) < l_{fe}A_{fe}(t-1). \end{cases}$$

## 1.6 Industry and AFOLU sector abatement

Emissions from the industry and AFOLU sectors, as in Section 1.1.4, are denoted by  $E_j(t)$ , where  $j \in \mathcal{N} = \{\text{ind, afolu}\}$ . Abatement with respect to a baseline is given as  $A_j(t) := \hat{E}_j(t) - E_j(t)$ . We define marginal abatement costs in these sectors as:

$$P_j(t) = \begin{cases} a_j(A_j(t) - l_jA_j(t-1))^{b_j} + d_j, & \text{for } A_j(t) \geq l_jA_j(t-1) \\ d_j, & \text{for } A_j(t) < l_jA_j(t-1). \end{cases} \quad (8)$$

and impose the following constraints for optimization:

$$A_j(t) \leq v_j(t),$$

$$A_j(t) \leq g_j + l_jA_j(t-1).$$

Here,  $v_j$  represents the maximum allowable abatement in the industry and AFOLU sectors, further detailed in Section 2.5; and  $g_j$  is a growth parameter discussed in ANNEX C. As before, a total cost function can be derived by integrating over abatement:

$$C_j(t) = \begin{cases} \frac{a_j}{b_j+1} (A_j(t) - l_jA_j(t-1))^{b_j+1} + d_jA_j(t), & \text{for } A_j(t) \geq l_jA_j(t-1) \\ d_jA_j(t), & \text{for } A_j(t) < l_jA_j(t-1). \end{cases}$$

## 1.7 Carbon capture

Carbon capture, denoted by  $S_k(t)$  as introduced in Section 1.1.5, leads to abatement with respect to a baseline, represented by  $A_k(t) := S_k(t) - \hat{S}_k(t)$ . Because captured CO<sub>2</sub> cannot exceed the CO<sub>2</sub> produced during fossil fuel combustion, biofuel use, or industrial processes, we cap the amount of  $S_k(t)$  for  $k \in \{\text{s\_foss}, \text{s\_bio}, \text{s\_ind}\}$  as follows:

$$\begin{aligned} v_{\text{s.foss}}(t) &= f_{\text{s.foss}}^{\text{pot}}(E_{\text{ener}}(t)), \\ v_{\text{s.bio}}(t) &= f_{\text{s.bio}}^{\text{pot}}(W_{\text{bio}}(t)), \\ v_{\text{s.ind}}(t) &= f_{\text{s.ind}}^{\text{pot}}(E_{\text{ind}}(t)). \end{aligned}$$

The functions  $f_k^{\text{pot}}$  are explained in Section 2.4. Marginal costs of abatement through carbon capture are defined as:

$$P_k(t) = \begin{cases} a_k (A_k(t) - l_k A_k(t-1))^{b_k} + d_k, & \text{for } A_k(t) \geq l_k A_k(t-1) \\ d_k A_k(t), & \text{for } A_k(t) < l_k A_k(t-1). \end{cases} \quad (9)$$

Moreover, we impose the following constraints:

$$\begin{aligned} S_k(t) &\leq v_k(t), \\ A_k(t) &\leq g_k + l_k A_k(t-1). \end{aligned}$$

The maximum allowable carbon capture quantities,  $v_k$ , for  $k \in \{\text{s.foss}, \text{s.bio}, \text{s.ind}, \text{s.dac}\}$  are discussed in further detail in Section 2.5. The growth parameter,  $g_k$ , is discussed in ANNEX C. Following the same procedure as for primary energy substitution, total costs are computed by integrating over abatement. The total cost expression becomes:

$$C_k(t) = \int_{A_{k,\min}(t)}^{A_k(t)} \left( a (A_k(t) - l_k A_k(t-1))^{b_k} + d_k \right) dA_k,$$

which can be further broken down as:

$$C_k(t) = \int_{l_k A_k(t-1)}^{A_k(t)} a (A_k - l_k A_k(t-1))^{b_k} dA_k + \int_0^{A_k(t)} d_k dA_k.$$

The integration yields:

$$C_k(t) = \begin{cases} \frac{a_k}{b_k+1} (A_k(t) - l_k A_k(t-1))^{b_k+1} + d_k A_k(t), & \text{for } A_k(t) \geq l_k A_k(t-1) \\ d_k A_k(t), & \text{for } A_k(t) < l_k A_k(t-1). \end{cases}$$

## 1.8 Linking carbon price with marginal costs

A general assumption of economic efficiency is expressed as:

$$P_m(t) = P(t) \quad \forall m,$$

meaning that the marginal abatement cost  $P_m(t)$  is equal across all abatement options  $m$ . This reflects the calibration of the model to a unified carbon price, and it is recommended that this condition be upheld if the proposed cost functions are used in an optimization or simulation setting. However, due to the various constraints imposed on abatement, such as Eqs. 5 and 6, there are implied marginal cost caps and floors which vary between abatement options. Therefore, the condition,  $P_m(t) = P(t) \quad \forall m$ , is generally not met by the marginal cost functions introduced in Sections 1.5 through 1.7. In ANNEX C, and more specifically in C.1.1 we illustrate how marginal costs can be kept consistent with a unified carbon price  $P$ .

---

## 2 Model calibration

- **Data source:** We use data from the ENGAGE model intercomparison, available in the AR6 database. The scenarios are based on the socioeconomic pathway of SSP2.
- **Data structure:** The dataset is organized by model, scenario, and year. Different near-term policy assumptions, as well as overshoot and non-overshoot scenarios for the same carbon budget, are present. However, for calibration purposes, these distinctions are not considered.
- **Parameter sets:** A parameter set is calibrated for each complex IAM included in the dataset.
- **Component Calibration:** Each component, such as cost functions, is calibrated individually rather than optimizing parameters for the entire model simultaneously.
- **Notation:** Throughout this document, lowercase letters refer to variables from the dataset, while uppercase letters denote modeled variables used in the equations.
- **Abatement notation:** To prevent confusion with the cost function coefficients, abatement from the dataset is denoted by  $x_m(t)$ , defined as:

$$x_m(t) = \hat{e}_m(t) - e_m(t),$$

where  $\hat{e}_m(t)$  and  $e_m(t)$  represent baseline and mitigation scenario emissions from the dataset, respectively.

### 2.1 Data preparation and polishing

The following steps are applied prior to calibration to ensure consistent and meaningful data:

- **Scenario filtering:** We exclude
  - COVID-related scenarios, identified by “COV” in the scenario name,
  - Sensitivity analysis scenarios, identified by “NDCp”,
  - Scenarios with non-standard discount rates, identified by “DR”,
  - All scenarios from the COFFEE 1.1 and POLES ENGAGE IAMs due to data gaps and inconsistencies that could not be reliably corrected.
- **IAM-specific adjustments:**
  - For **GEM-E3\_V2021**, Carbon Sequestration|CCS|Biomass is missing from the AR6 database. We instead retrieve Primary Energy|Biomass|Modern|w/ CCS from the ENGAGE-native database and infer biomass sequestration using assumed capture efficiencies.
  - For **IMAGE 3.0** AFOLU emissions increase in mitigation scenarios compared to the baseline, which is incompatible with the defined cost functions. AFOLU emissions are therefore set to an average path of mitigation scenarios. Costs are assumed to be zero. The scenario EN\_INDCi2030\_1400f is removed because the reported carbon price is 0.

- For **WITCH 5.0**, we observe inconsistencies in CO<sub>2</sub> emissions in relation to fossil energy consumption. To correct this:
  - \* We add `Emissions|CO2|Industrial Processes` to `Emissions|CO2|Energy` and set industrial emissions to zero.
  - \* This adjustment ensures that pre-capture emissions (i.e., energy emissions plus captured emissions) remain non-negative in regional data and consistent with primary fossil energy use.
- We harmonize `Primary Energy|Biomass|Traditional` across scenarios by replacing scenario-specific trajectories with the median trajectory for each IAM across all scenarios. Traditional biomass is phased-out in all scenarios.
- **DACCS Energy Correction:** DACCS is only available in scenarios from the models WITCH 5.0 and REMIND-MAGPIE 2.1-4.2. The reported final and primary energy uses includes the energy consumed by DACCS. To avoid overestimating the energy actually used for economic activities, we correct final and primary energy by removing the share attributable to DACCS.

DACCS energy demand per tonne of CO<sub>2</sub> is assumed to be 6.9 GJ heat and 1.55 GJ electricity in WITCH 5.0, and 10 GJ heat and 2 GJ electricity in REMIND-MAGPIE 2.1-4.2, based on literature ([Realmonde et al. \[2019\]](#)) and model documentation ([PIK Potsdam Institute for Climate Impact Research](#)). From scenario data we infer that the energy carriers used to supply this demand differ: in WITCH 5.0, heat is assumed to be primarily provided by natural gas (80%, vs. 20% from hydrogen), whereas in REMIND-MAGPIE 2.1-4.2, it comes almost entirely from hydrogen (95%, vs. 5% from natural gas), which is itself produced from electricity and fossil fuels. Electricity for DACCS, including electricity used indirectly for hydrogen production, is assumed to come fully from NBRs in both IAMs, which is consistent with the high renewable shares observed in their DACCS-intensive scenarios.

The source shares for hydrogen (electricity vs. fossil) and the efficiencies of various conversion processes are either assumed or inferred directly from the scenario data. This allows us to attribute DACCS energy demand back to primary energy carriers.

We then correct both final energy (by subtracting the total DACCS energy demand) and primary energy (by subtracting the upstream energy used to supply DACCS heat and electricity). For WITCH 5.0, an additional correction is made to the accounting of fossil fuels with and without CCS, since gas used for DACCS appears to be reported inconsistently across those categories. We resolve this by reallocating gas energy and adjusting reported fossil CCS capture accordingly.

## 2.2 Carbon intensity

For the calibration of the carbon intensity of fossil fuels  $\beta_{\text{fossil}}$ , we use a simple linear regression model of the form:

$$e_{\text{ener}}(t) \sim \beta_{\text{fossil}} w_{\text{fossil}}(t)$$

where  $e_{\text{ener}}(t)$  denotes pre-capture emissions from the energy sector, and  $w_{\text{fossil}}(t)$  represents primary energy consumption from fossil fuels. The results for each IAM are summarized in Table 1.

Model	$\beta_{\text{foss}}$
AIM/CGE 2.2	68
GEM-E3_V2021	61
IMAGE 3.0	69
MESSAGEix-GLOBIOM_1.1	70
TIAM-ECN 1.1	65
REMIND-MAgPIE 2.1-4.2	70
WITCH 5.0	67

Table 1: Estimated carbon intensity of fossil fuels ( $\beta_{\text{foss}}$ ) in MtCO<sub>2</sub>/EJ for various IAMs

## 2.3 Energy conversion

We estimate the energy conversion efficiencies between primary energy,  $w_i(t)$ , and final energy,  $f(t)$ , with a linear regression model of the form:

$$f(t) \sim \sum_{i \in \{\text{foss}, \text{nuc}, \text{bio}, \text{trad}, \text{nbr}\}} \eta_i w_i(t).$$

However, estimating these conversion efficiencies individually for each IAM is challenging due to the high degree of multicollinearity between the primary energy sources. To overcome this, we employ a two-stage calibration approach:

### 2.3.1 Initial calibration using data from all IAMs

In the first stage, we combine data from all IAMs. This significantly reduces collinearity among the primary energy sources, with variance inflation factors (VIF) values below 5, indicating moderate but acceptable multicollinearity.

In this stage, we use a Bayesian linear regression approach to estimate the coefficients  $\eta_i$  for each primary energy source,  $w_i$ .

We assign uninformative priors (uniform distribution between 0 and 1) to most coefficients. The exception is nuclear energy, where we impose a prior between 0.7 and 0.9 due to its significantly smaller scale in scenarios compared to other energy sources, making the estimate unreliable. Moreover, for traditional biomass,  $w_{\text{trad}}$ , we follow the convention that primary and final energy are the same, fixing the parameter  $\eta_{\text{trad}}$  to 1 through the prior.

### 2.3.2 IAM-specific calibration using informative priors

In the second stage, we perform the calibration for each IAM separately. To address multicollinearity issues that arise when fitting the model to individual IAM data, we use informative priors based on the results from the first stage. The expected values (means) of the coefficients  $\eta_i$  from the initial calibration are used as the means of normal distributions as priors, with a narrow standard deviation of 0.01. This ensures that the estimates for each IAM remain consistent with the global calibration while allowing for model-specific variation. We keep the prior for nuclear energy uniform between 0.7 and 0.9.

Model	$\eta_{\text{bio}}$	$\eta_{\text{nbr}}$	$\eta_{\text{nuc}}$	$\eta_{\text{foss}}$
AIM/CGE 2.2	$0.53 \pm 0.01$	$0.78 \pm 0.01$	$0.82 \pm 0.05$	$0.68 \pm 0$
GEM-E3_V2021	$0.56 \pm 0.01$	$0.81 \pm 0.01$	$0.79 \pm 0.06$	$0.75 \pm 0$
IMAGE 3.0	$0.53 \pm 0.01$	$0.80 \pm 0.01$	$0.74 \pm 0.03$	$0.73 \pm 0$
MESSAGEix-GLOBIOM_1.1	$0.52 \pm 0.01$	$0.88 \pm 0.01$	$0.83 \pm 0.03$	$0.78 \pm 0$
TIAM-ECN 1.1	$0.53 \pm 0.01$	$0.80 \pm 0.01$	$0.82 \pm 0.05$	$0.74 \pm 0.01$
REMIND-MAgPIE 2.1-4.2	$0.53 \pm 0.01$	$0.76 \pm 0$	$0.83 \pm 0.05$	$0.78 \pm 0$
WITCH 5.0	$0.43 \pm 0.01$	$0.79 \pm 0.01$	$0.74 \pm 0.04$	$0.66 \pm 0$

Table 2: Estimated energy conversion efficiencies ( $\eta$ ) for various IAMs.

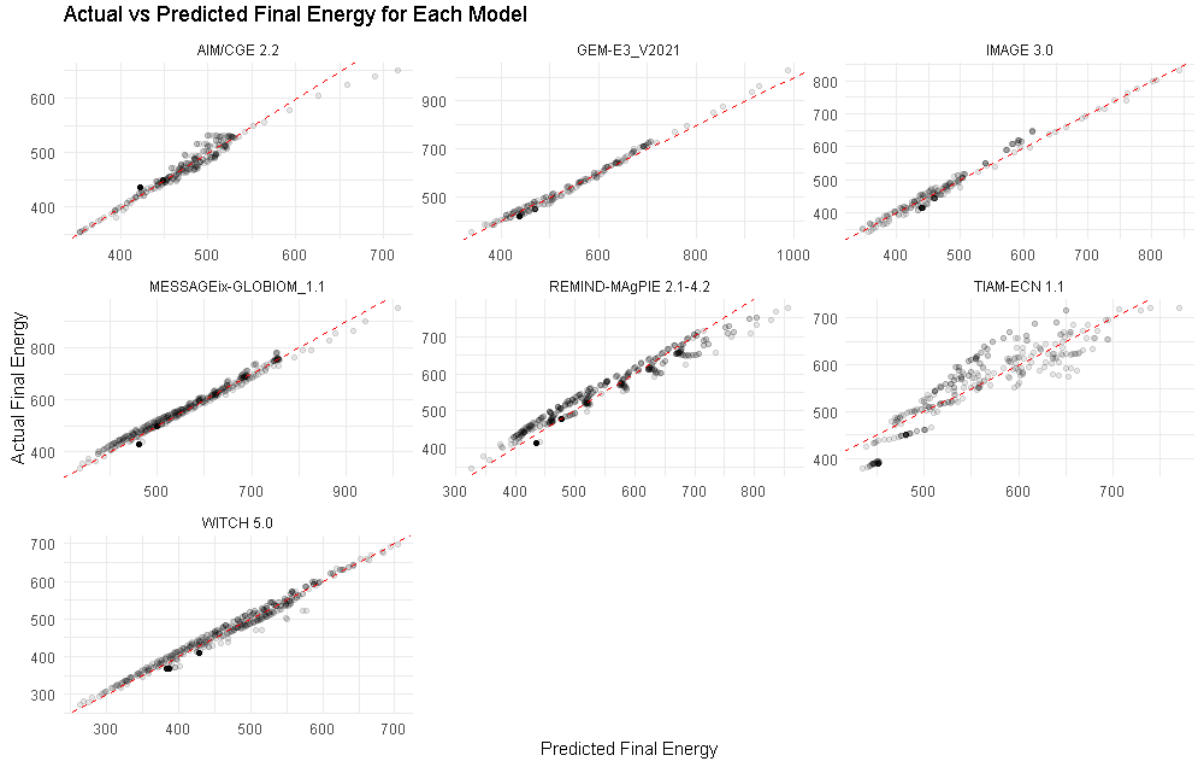


Figure 1: Actual vs. predicted final energy using energy conversion efficiencies ( $\eta$ ) Table 2

### 2.3.3 Results

The energy conversion efficiencies for each IAM are shown in Table 2. Actual versus predicted final energy is shown for each IAM in Figure 1.

The fossil fuel substitution efficiencies, denoted as  $\sigma_i := \frac{\eta_i}{\eta_{\text{foss}}}$ , are presented in Table 3. These efficiencies measure how effectively different energy sources can substitute for fossil fuels in terms of energy conversion.

## 2.4 Carbon capture potentials

We compute the potentials for bioenergy CCS and industry CCS by analyzing the maximum ratio of carbon captured to the corresponding primary energy or emissions in the dataset. The maximum ratios obtained for each IAM are summarized in Table 4.

Fossil CCS is modeled differently due to several factors. Unlike bioenergy, which increases with stricter climate policies, fossil fuel use generally declines, leading to the temporary deployment of fossil CCS

Model	$\sigma_{\text{bio}}$	$\sigma_{\text{nbr}}$	$\sigma_{\text{nuc}}$
AIM/CGE 2.2	$0.78 \pm 0.01$	$1.16 \pm 0.01$	$1.21 \pm 0.08$
GEM-E3 <sub>V</sub> 2021	$0.75 \pm 0.01$	$1.09 \pm 0.01$	$1.06 \pm 0.08$
IMAGE 3.0	$0.72 \pm 0.01$	$1.09 \pm 0.01$	$1.00 \pm 0.04$
MESSAGEix-GLOBIOM <sub>1.1</sub>	$0.67 \pm 0.01$	$1.12 \pm 0.01$	$1.06 \pm 0.04$
TIAM-ECN 1.1	$0.72 \pm 0.01$	$1.08 \pm 0.01$	$1.11 \pm 0.08$
REMIND-MAGPIE 2.1-4.2	$0.68 \pm 0.01$	$0.97 \pm 0.01$	$1.06 \pm 0.07$
WITCH 5.0	$0.65 \pm 0.01$	$1.20 \pm 0.01$	$1.12 \pm 0.06$

Table 3: Fossil fuel substitution efficiencies  $\sigma_i := \frac{\eta_i}{\eta_{\text{foss}}}$  for various IAMs.

in many scenarios until fossil point sources are phased out. Additionally, bioenergy is mostly used for BECCS, creating a clear link between bioenergy consumption and carbon capture, while fossil fuel end-uses are more diverse, making it harder to directly relate fossil fuel use to CCS potential. Although similar issues might arise with industrial emissions, fossil CCS is significantly larger in scale, allowing for a simplified approach to industry CCS.

We compute CCS potentials for each IAM as follows:

#### 2.4.1 Bioenergy CCS potential

We calculate the maximum ratio of carbon captured from bioenergy,  $s_{\text{bio}}$ , to primary bioenergy consumption,  $w_{\text{bio}}$ , over all time steps and over all scenarios for each IAM from the dataset and define bioenergy CCS potential,  $v_{\text{s.bio}}^{\text{pot}}$ , as:

$$v_{\text{s.bio}}^{\text{pot}}(t) = \max\left(\frac{s_{\text{bio}}}{w_{\text{bio}}}\right) W_{\text{bio}}(t)$$

Note,  $W_{\text{bio}}$  refers to the modeled value of bioenergy consumption, while  $w_{\text{bio}}$  is the dataset value of bioenergy consumption.

#### 2.4.2 Industry CCS potential

Similarly, we compute the maximum ratio of industrial CCS,  $s_{\text{ind}}$ , to industrial process emissions,  $e_{\text{ind}}$ , from the dataset and define the industry CCS potential,  $v_{\text{s.ind}}^{\text{pot}}$ , as:

$$v_{\text{s.ind}}^{\text{pot}}(t) = \max\left(\frac{s_{\text{ind}}}{e_{\text{ind}}}\right) E_{\text{ind}}(t)$$

Again,  $E_{\text{ind}}$  refers to the modeled value of industrial emissions, while  $e_{\text{ind}}$  is the dataset value of industrial emissions.

#### 2.4.3 Fossil CCS potential

In our empirical approach, the fossil CCS potential,  $v_{\text{s.foss}}^{\text{pot}}$ , is modeled as an increasing piecewise linear function of pre-capture energy system emissions,  $e_{\text{ener}}$ , as exemplified in Figure 2. This function is derived from the left-side increasing portion of the convex hull over the points  $(e_{\text{ener}}, s_{\text{s.foss}})$ . The function is constrained to prevent any positive intercept, ensuring that the CCS potential is zero when  $e_{\text{ener}} = 0$ .

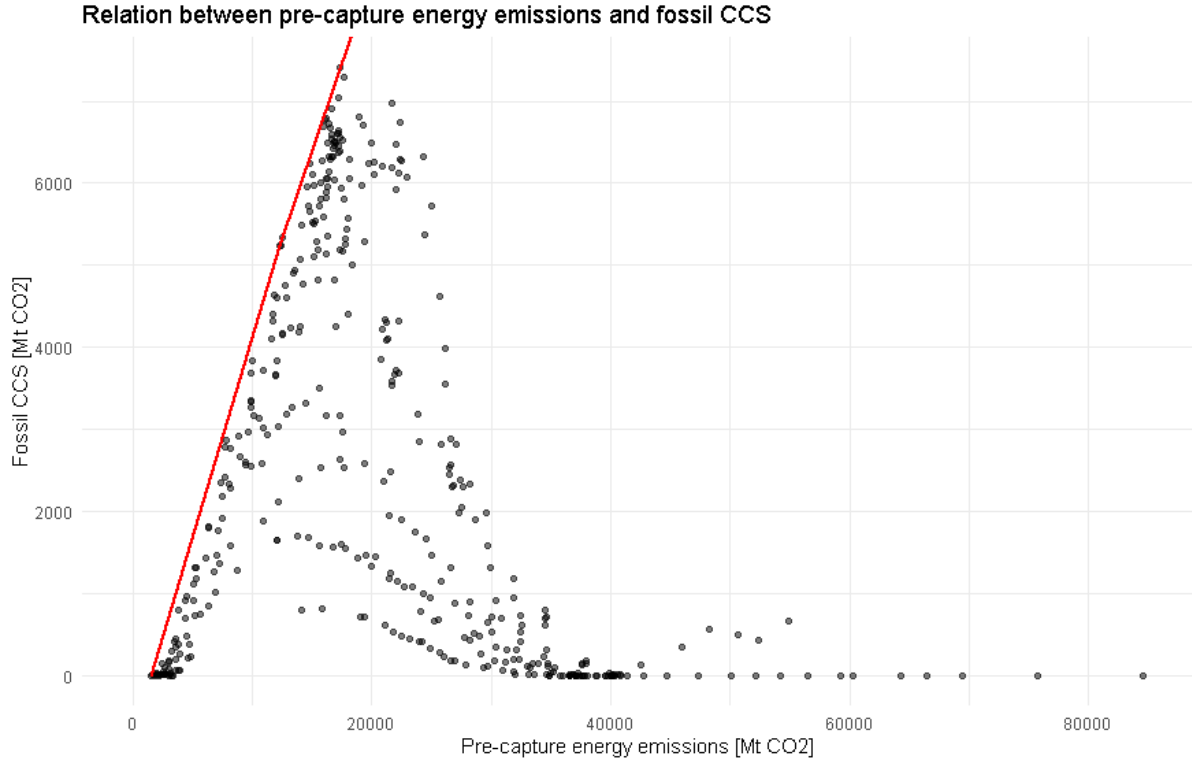


Figure 2: Red line is the fossil CCS potential for MESSAGEix-GLOBIOM 1.1

<b>Model</b>	$\max \left( \frac{s_{\text{bio}}}{w_{\text{bio}}} \right)$	$\max \left( \frac{s_{\text{ind}}}{e_{\text{ind}}} \right)$
AIM/CGE 2.2	63.5	0.359
GEM-E3_V2021	33.7	0
IMAGE 3.0	86.1	0.968
MESSAGEix-GLOBIOM_1.1	56.8	0.531
REMIND-MAgPIE 2.1-4.2	49.7	0.756
TIAM-ECN 1.1	66.0	0
WITCH 5.0	44.9	NA

Table 4: Maximum capture ratios for bioenergy with CCS and industry CCS from the dataset. A value of 0 indicates that there is no industry CCS in the data, while NA indicates that there are no industry emissions in the data. These ratios are used to calculate carbon capture potentials,  $v_{s_{\text{bio}}}^{\text{pot}}$  and  $v_{s_{\text{ind}}}^{\text{pot}}$ , based on modeled values of  $W_{\text{bio}}$  and  $E_{\text{ind}}$ .

## 2.5 Variable bounds

In this section, we define the variable bounds, denoted by  $v_m(t)$ , which are calculated as the maximum (or minimum) reported values within each time step, across all scenarios and for each IAM of the dataset. These bounds serve to constrain the potential range of key variables, ensuring that their modeled values remain within plausible limits over time. For instance, see the variable bounds for primary bioenergy in Figure 3. Note that the bounds for carbon capture are based on the potentials outlined in the previous section, hence, they depend on model variables.

The following relationships are used to determine the bounds for each time step  $t$ :

For primary energy, the bounds at each time step are:

$$v_i(t) = \max(w_i(t)), \quad i \in \{\text{nbr, bio, nuc}\},$$

For carbon capture, the bounds at each time step are:

$$v_k(t) = \min\left(\max(s_k(t), v_k^{\text{pot}}(t)), v_{\text{s\_dac}}(t)\right), \quad k \in \{\text{s\_bio, s\_foss, s\_ind}\},$$
$$v_{\text{s\_dac}}(t) = \max(s_{\text{s\_dac}}(t))$$

For abatement in the AFOLU and industry sectors, the bounds at each time step are:

$$v_{\text{ind}}(t) = \max(a_{\text{ind}}(t)),$$
$$v_{\text{afolu}}(t) = \max(a_{\text{afolu}}(t)).$$

Finally, for final energy, the bound at each time step is:

$$v_{\text{fe}}(t) = \min(f(t)).$$

## 2.6 Model validation

### 2.6.1 Energy and emissions

Table 5 reports the root mean square error (RMSE) and coefficient of determination ( $R^2$ ) for each parameter set (IAM), measuring the goodness of fit between modeled and reported net emissions under the reported carbon price scenarios.

Reported versus modeled values for primary energy, final energy, and emissions across all available abatement options are presented in Figures 9 through 15 in Appendix A for each parameter set (IAM) individually. The resulting net emissions pathway, derived from the combination of all model components, is also shown.

### 2.6.2 Average costs

Abatement costs are generally not explicitly reported for mitigation scenarios, and the calibration of cost functions in this model targets energy or emissions quantities rather than costs directly. To ensure

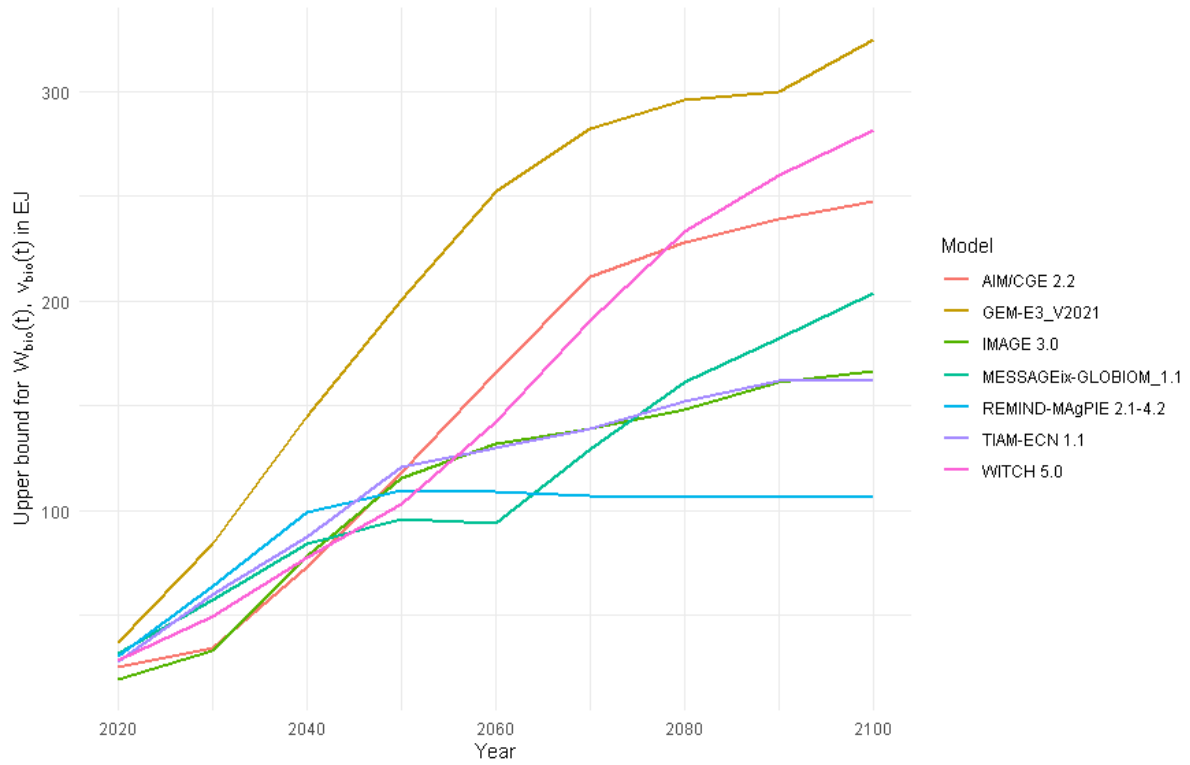


Figure 3: Upper variable bound for  $W_{\text{bio}}(t)$ .

Model	RMSE [GtCO <sub>2</sub> ]	R <sup>2</sup>
AIM/CGE 2.2	2.53	0.978
GEM-E3_V2021	2.67	0.974
IMAGE 3.0	3.89	0.951
MESSAGEix-GLOBIOM_1.1	5.11	0.926
TIAM-ECN 1.1	4.49	0.935
REMIND-MAgPIE 2.1-4.2	4.77	0.914
WITCH 5.0	2.31	0.977

Table 5: Goodness-of-fit metrics from comparing all reported scenario time series with modeled pathways for each IAM. RMSE and  $R^2$  values assess how well modeled net emissions match reported data under different carbon price scenarios, as illustrated in Figures 9 through 15.

consistency with external cost estimates, we impose soft lower bounds on the average cost of each abatement option. If the median of modeled average costs across scenarios for a given abatement option falls below its respective bound, a penalty is applied during calibration.

These bounds are median values estimated through visual interpretation of Figure SPM.7 in IPCC [2022]. However, two important limitations should be acknowledged. First, the categorization of abatement options in the IPCC figure does not align precisely with those used in our model. This mismatch is particularly evident in the treatment of final energy demand reductions, for which no meaningful bound could be derived. Second, the figure reports only cost ranges, and median values are not explicitly provided. The estimated medians, which serve as soft cost floors during calibration, are summarized in Table 6. The modeled average cost distributions are illustrated in Figure 4.

Abatement option	Est. Median	Low	High
Non-biomass Renewables	0	0	100
Nuclear	35	0	200
Bioenergy	80	20	200
AFOLU	50	0	200
Industry	35	0	200
CCS–Fossil	80	50	200
CCS–Bio	80	50	200
CCS–Industry	150	100	200

Table 6: Estimated median average costs in USD/tCO<sub>2</sub> for abatement options used in the model. A penalty is applied during calibration if the median modeled abatement cost falls below the estimated median. The lower and upper bounds represent the estimated ranges derived from IPCC AR6 WGIII Figure SPM.7.

Additionally, modeled total average abatement costs are compared against the reported consumption loss per ton of abated CO<sub>2</sub>, where available. While consumption loss is generally considered a reasonable proxy for abatement costs, this relationship does not hold for AIM/CGE 2.2, where reported consumption loss frequently exceeds the carbon price. In simpler economic models such as DICE, this would imply that average costs exceed marginal costs, a conceptually inconsistent outcome. The discrepancy may reflect model-specific assumptions or dynamics not fully reflected here. This comparison is illustrated in Figure 16 in Appendix A.

## 2.7 Non-CO2 radiative forcing

We estimate non-CO<sub>2</sub> radiative forcing  $r_{\text{nonCO}_2}(t)$  from fossil primary energy  $w_{\text{foss}}(t)$  via

$$r_{\text{nonCO}_2}(t) = \exp(\kappa + \gamma_1 w_{\text{foss}}(t) + \gamma_2 w_{\text{foss}}(t)^p).$$

Parameters are estimated per IAM and across all IAMs to inform parameter sets where no non-CO<sub>2</sub> radiative forcing was reported. The relationship  $w_{\text{foss}}(t)$  vs.  $r_{\text{nonCO}_2}(t)$  is shown in Figure 5. Model skill is shown in Figure 6, comparing reported and predicted  $r_{\text{nonCO}_2}(t)$ .

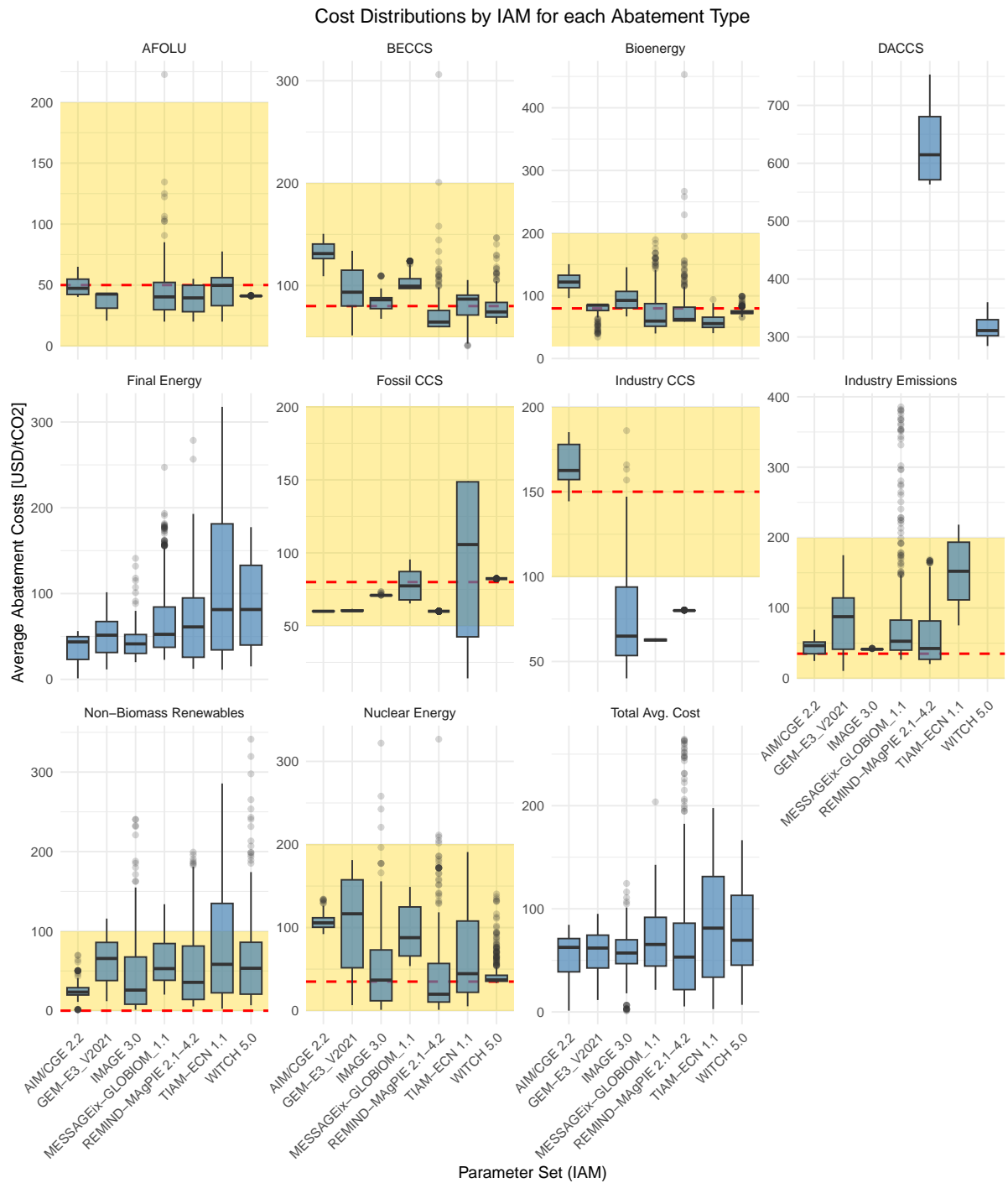


Figure 4: Distribution of average abatement costs by parameter set (IAM) across abatement types. Boxplots represent the interquartile range, median, and outliers of modeled cost estimates for each abatement option and IAM. Shaded yellow ribbons indicate the cost ranges, while the dashed line shows the soft lower cost bound as listed in Table 6. Panels are scaled individually for readability. This visualization supports the evaluation of whether models stay within plausible cost corridors for different abatement options.

## Data and exponential model

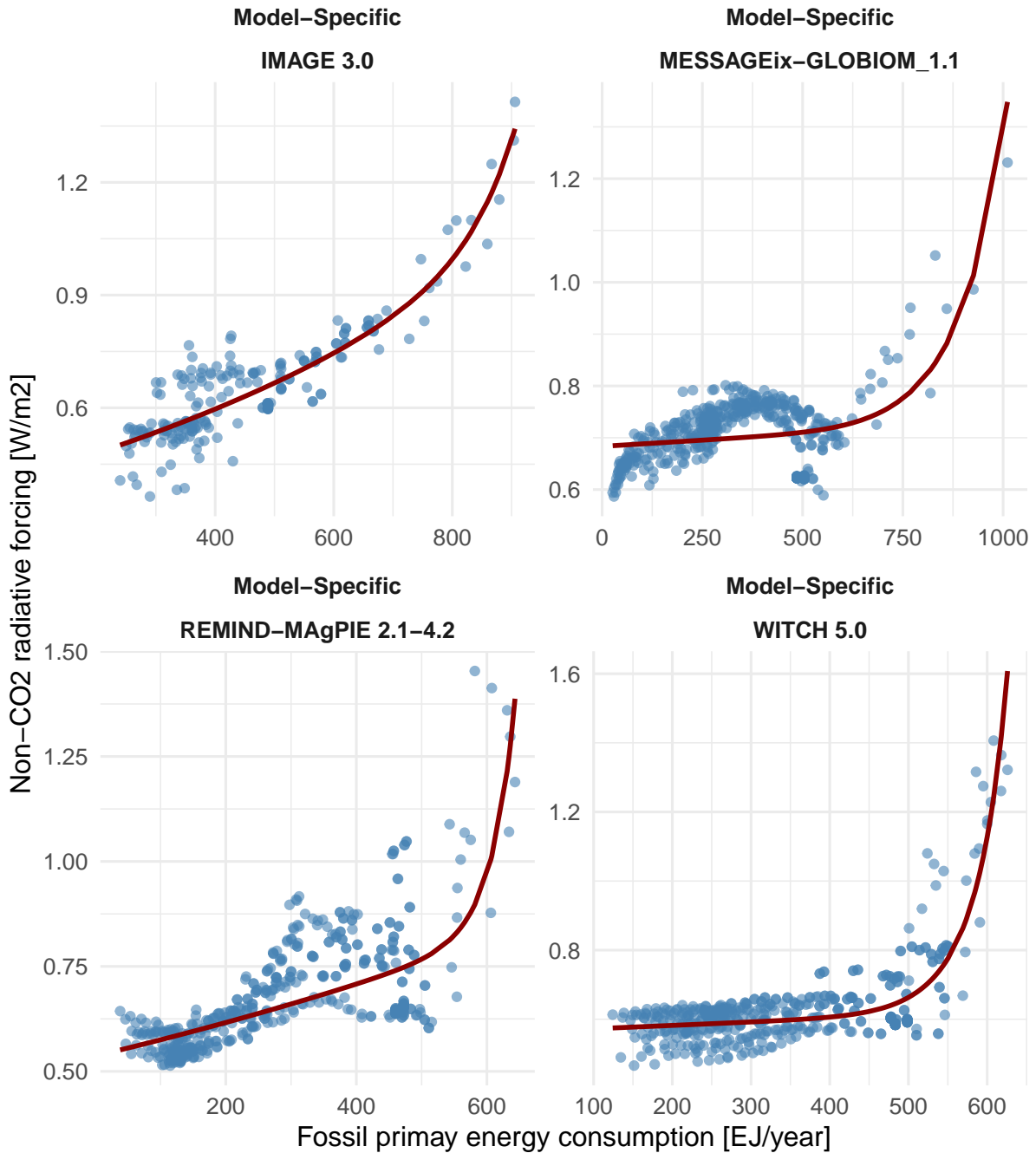


Figure 5: Relationship between fossil primary energy consumption  $w_{\text{foss}}(t)$  and non-CO<sub>2</sub> radiative forcing  $r_{\text{nonCO}_2}(t)$  with fitted exponential model.

## Observed vs. predicted non-CO<sub>2</sub> radiative forcing

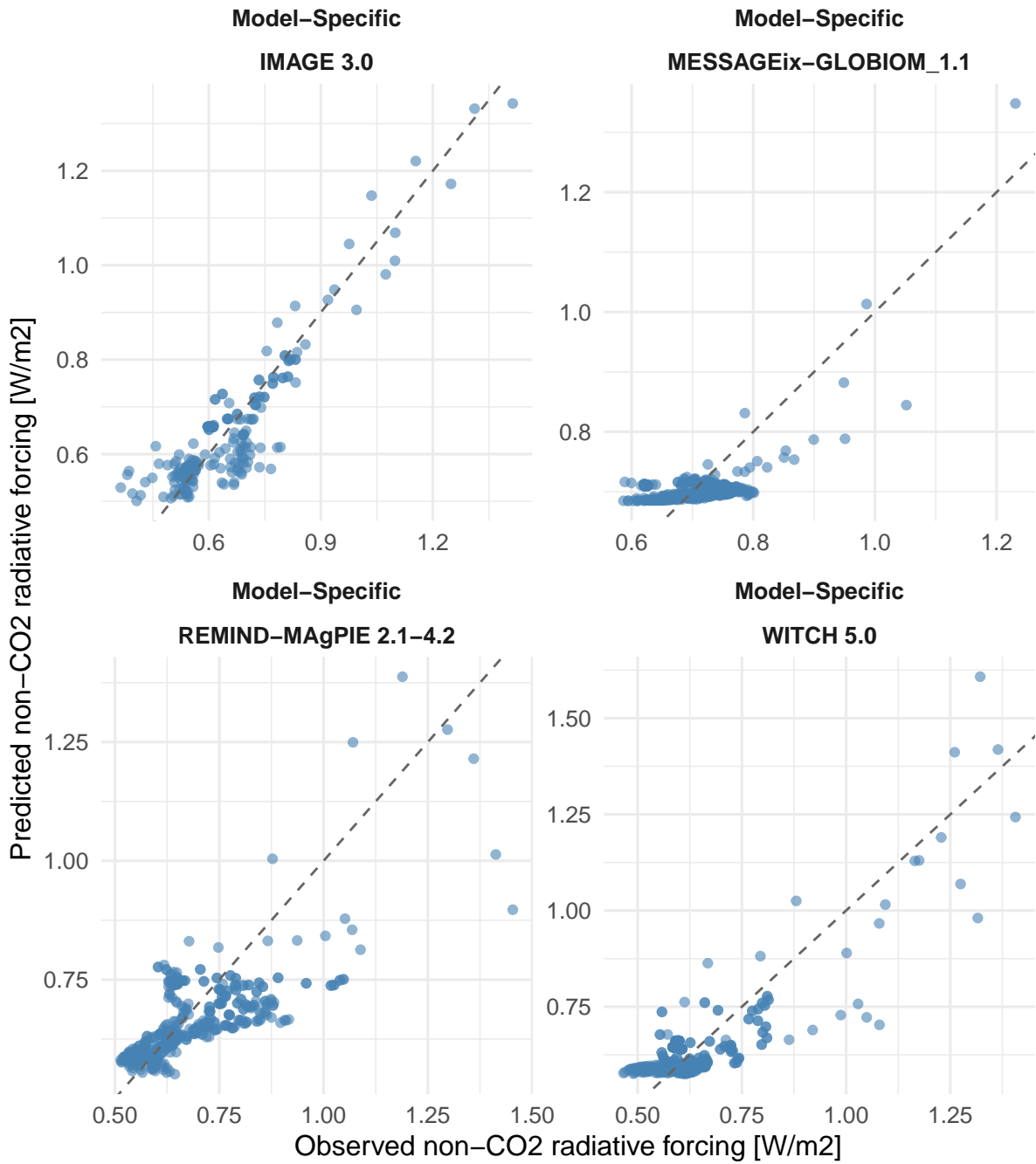


Figure 6: Observed versus predicted non-CO<sub>2</sub> radiative forcing  $r_{\text{nonCO}_2}(t)$  for individual IAMs.

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## 3 Exploratory model modifications

This section outlines a set of exploratory modifications to the calibrated model, aimed at extending its applicability beyond the scope of reported scenario data.

### 3.1 Integration of DACCS into all parameter sets

DACCS is incorporated as an abatement option into all model parameter sets, including those in which it was not originally reported. We use a lower-cost parameter set from WITCH 5.0 and a higher-cost parameter set from REMIND-MAGPIE 2.1-4.2 (see Figure 4). Each of these DACCS configurations is combined with the parameter set for all other abatement types from each IAM, resulting in a total of 14 model parameter sets (2 DACCS variants × 7 IAMs).

### 3.2 Extension of time horizon

The model's temporal scope is extended beyond 2100 to explore the long-term implications of mitigation strategies beyond the typical reporting window of IAMs. The key points of this extrapolation include:

- For consistency, the full range of abatement types is extrapolated beyond 2100. However, not all components continue to be modeled as functions of the carbon price, as they are before 2100.
- Fossil fuel emissions follow a predefined linear phase-out trajectory and are no longer price-responsive after 2100.
- Fossil fuel emissions serve as the basis for fossil CCS deployment, which continues to be determined by the carbon price, as in the pre-2100 period.
- Bioenergy and nuclear energy remain functions of the carbon price. Their deployment remains capped at the maximum levels observed between 2020 and 2100 in scenarios. Extrapolation requires an extension of baseline assumptions.
- Bioenergy serves as the basis for BECCS deployment, which continues to be determined by the carbon price.
- NBRs are assumed to meet the residual energy demand not covered by other sources, justified by their vast physical potential. NBRs are thus no functions of the carbon price post-2100.
- The baseline energy supply is extrapolated under the assumption that the fractional (i.e., relative) energy mix, such as the share of bioenergy in total primary energy, remains constant beyond 2100 at its 2100 level. This requires projecting total energy demand forward.
- Energy demand is extrapolated using a DICE-like approach in which energy demand is inferred from economic output, which itself is driven by exogenous projections of population and factor productivity growth.
- DACCS remains modeled as a function of the carbon price beyond 2100. However, the upper bound from the 2020–2100 period is imposed to reflect limits on deployment potential.

- The AFOLU sector, which typically acts as a net carbon sink before 2100 in most scenarios, is gradually phased toward net-zero emissions in the post-2100 period.
- Although long-term extrapolations inherently involve large uncertainty, several factors limit the spread between post-2100 trajectories:
  - Long-term net emissions are guided by residual fossil fuel emissions, as well as CDR.
  - Fossil fuel emissions follow a fixed phase-out path, independent of economic or policy assumptions. Bioenergy deployment, as basis for BECCS, is bounded by sustainability constraints commonly embedded in IAMs. In ambitious mitigation scenarios, these bounds are typically hit already before 2100. As a result, uncertainties in future GDP or energy demand affect only the timing at which upper limits of bioenergy are reached. Similarly, DACCS upper bounds from the 2020-2100 periods are maintained.
  - In other words, under a sufficiently high carbon price, such as one following a Hotelling-rule growth path, scenarios tend to converge toward similar long-run net-negative emissions trajectories.
- Modeled abatement costs are only credible for the period until 2100.

### 3.2.1 Extrapolation of population and economic output

We use a discrete-time Solow-style growth model to simulate economic output and capital accumulation with a fixed savings rate in the post-2100 period. This, in turn, is used to determine future energy demand. The model's production function, with output  $Y(t)$ , population  $L(t)$ , total factor productivity (TFP)  $\alpha(t)$  and capital elasticity  $\gamma$  is given by:

$$Y(t) = \alpha(t)L(t)^{1-\gamma}K(t)^\gamma$$

**Population extension for SSP2** Population trajectories are extended by blending the reported IAM-specific population projection for 2100,  $L(2100)$ , with an extended SSP2 population pathway,  $L_{SSP2}(t)$ , that runs to 2300. The scaling ratio

$$r_L = \frac{L(2100)}{L_{SSP2}(2100)}$$

is applied with a linearly decaying weight

$$w(t) = \frac{2300 - t}{200}$$

to yield

$$L(t) = L_{SSP2}(t) \cdot r_L^{w(t)}, \quad t > 2100.$$

This approach ensures asymptotically converging to the extended SSP2 trajectory by 2300.

The  $L_{SSP2}$  pathway was obtained from IIASA's POPJUS program. The series until 2100 follows the updated SSP population scenario in [K.C. et al. \[2024\]](#). For the extension to 2300, the same assumptions as to 2100 were maintained, with the exception that the fertility rate converges to 1.75 children per woman by the year 2200 for all countries, and the maximum life expectancy is set at 105 years for both sexes.

**Extrapolation of economic output** We first infer  $\alpha(t)$  by rearranging the production function using scenario data for output and population:

$$\alpha(t) = \frac{Y(t)}{L(t)^{1-\gamma}K(t)^\gamma}$$

Investment is derived from reported output and consumption,  $C(t)$ :

$$I(t) = Y(t) - C(t)$$

Capital then evolves according to the standard discrete-time capital accumulation equation, with capital depreciation  $\delta$ :

$$K(t+1) = (1 - \delta\Delta t)K(t) + \Delta t \cdot I(t)$$

We initialize capital in the first time step at 210 trillion USD (2010), based on data from the Penn World Table version 10.01 [Feenstra et al. \[2015\]](#).

We compute TFP  $\alpha(t)$  for capital elasticity  $\gamma = 0.35$ , as in [Leimbach et al. \[2017\]](#) for SSP2, and capital depreciation  $\delta = 0.1$ , as in [Barrage and Nordhaus \[2024\]](#). An exponential function is then fitted to the resulting TFP trajectories:

$$\alpha(t) = Ae^{bt}$$

To account for declining productivity growth post-2100, the estimated growth rate  $b$  is adjusted using an exponential decay:

$$b(t) = b \cdot e^{-\lambda(t-2100)}$$

TFP is then extrapolated recursively, following the logic of DICE 2023 ([Barrage and Nordhaus \[2024\]](#)), where the decline rate is set to  $\lambda = 0.0075$ :

$$\alpha(t) = \alpha(t-1) \cdot e^{b(t)}$$

The savings rate, defined as  $s(t) = \frac{I(t)}{Y(t)}$ , is assumed to converge linearly from its 2100 baseline scenario value to a fixed level of  $s = 0.20$  by 2200 after which it remains constant. This reflects a moderate, ‘middle-of-the-road’ investment level consistent with the SSP design principle of convergence to medium capital intensities. Using the Solow growth model, the savings rate, and the extrapolated TFP trajectories, we generate a set of economic growth pathways, presented in Figure 7.

### 3.2.2 Abatement post 2100

For all abatement options other than NBRs, cost functions and imposed upper bounds on abatement, as introduced in Section 2.5, are assumed to remain valid beyond 2100, and their baselines are accordingly extended. NBRs are expected to grow beyond any values observed in scenarios up to 2100 and are therefore determined using a different logic (see Section 3.2.3).

**Extrapolation of baselines** Extrapolation of baseline scenarios is required for all abatement options other than NBRs,. We begin by extending the baseline for total primary energy. Let  $\hat{W}(t)$  denote total primary energy consumption of baseline scenarios and  $Y(t)$  economic output as described in

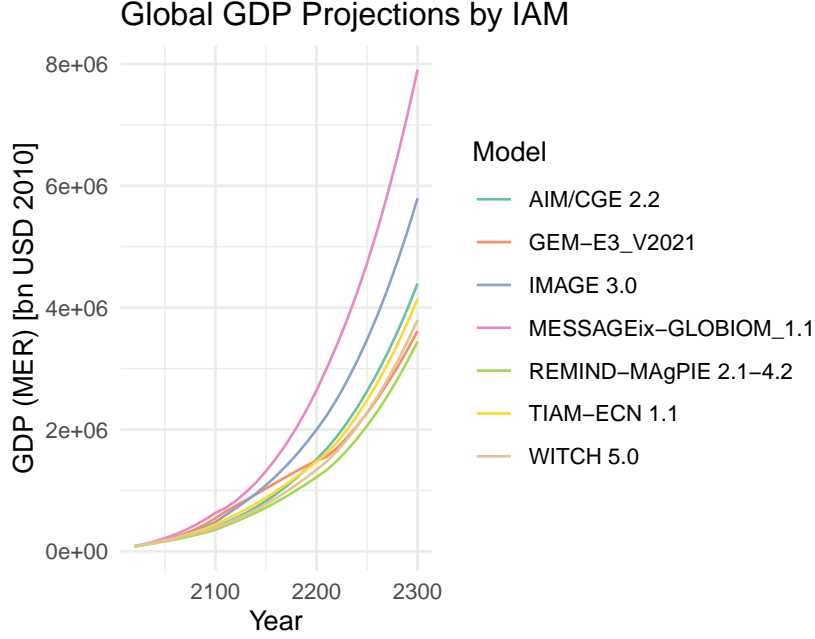


Figure 7: Extrapolated global GDP trajectories by IAM, in billion 2010 USD.

Section 3.2.1. We define the primary energy intensity

$$\phi(t) = \frac{\hat{W}(t)}{Y(t)}$$

using reported values for  $\hat{W}(t)$  and  $Y(t)$  over 2020–2100. We apply a hyperbolic decay function to extend primary energy intensity beyond 2100:

$$\phi(t) = \frac{\phi(2100)}{1 + \left( -\frac{\dot{\phi}(2100)}{\phi(2100)} \right) \cdot (t - 2100)},$$

where  $\dot{\phi}(2100)$  denotes the derivative at  $t = 2100$ . Combining the extended  $\phi(t)$ , as illustrated for all IAMs in Figure 8, with  $Y(t)$  yields the extended total primary energy path  $\hat{W}(t)$  up to 2300.

Primary nuclear and bioenergy shares of  $\hat{W}(t)$  are held constant at 2100 levels, implying proportional growth of  $\hat{W}_{\text{bio}}$  and  $\hat{W}_{\text{nucl}}$  with  $\hat{W}$  after 2100 until any predefined upper bounds (see Section 2.5) are reached.

Other baselines are extended as follows: Similar to energy intensity, industrial emissions intensity is extrapolated by fitting a log-linear relationship over 2020–2100, i.e.  $\log \frac{\hat{E}_{\text{ind}}(t)}{Y(t)} \sim t$ . AFOLU emissions are extended by first estimating a linear trend in emissions for the period after 2050, and then applying a logistic scaling factor  $(1 + \exp(0.1(t - 2150)))^{-1}$  to that trend, such that net (negative) AFOLU emissions smoothly transition towards net zero with an inflection point at 2150. Like industry emissions intensity, traditional biomass use,  $W_{\text{trad}}$ , is extrapolated using a log-linear fit. For industry CCS,  $\hat{S}_{\text{s.ind}}$ , and BECCS,  $\hat{S}_{\text{s.bio}}$ , the share relative to the baseline activity,  $\hat{E}_{\text{ind}}$  and  $\hat{W}_{\text{bio}}$ , respectively, is held constant at its 2100 value, subject to any applicable upper bounds. CCS on fossil fuels ( $\hat{S}_{\text{s.fossil}}$ ) is phased out after 2100 with the expectation that fossil fuels are being phased out (see Section 3.2.3). Note, however, that only few baseline scenarios feature CCS, and none of them feature DACCS. Final energy is extrapolated as  $\hat{F}(t) = \eta_{\text{tot}} \hat{W}(t)$ , where  $\eta_{\text{tot}}$  is the total final-to-primary energy conversion efficiency in 2100.

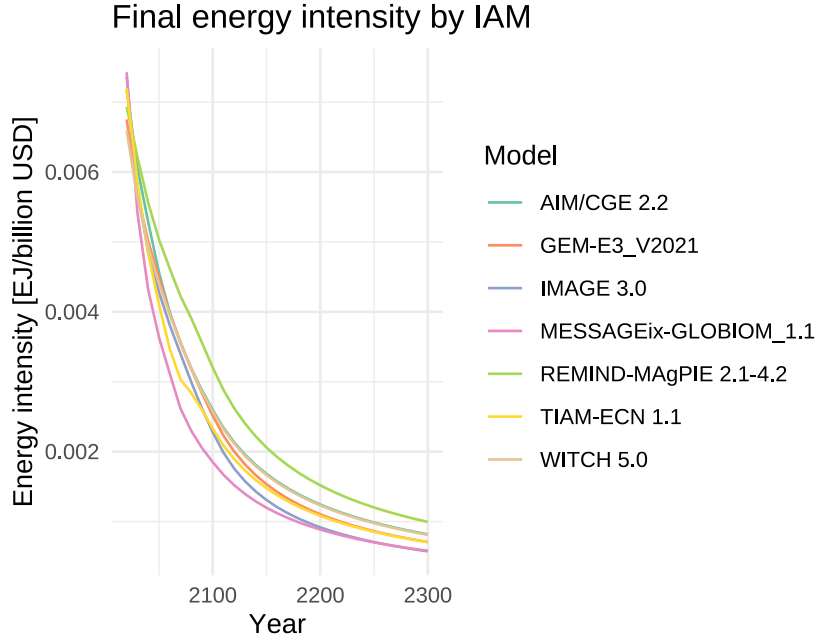


Figure 8: Extrapolated final energy intensity by IAM, in EJ / billion 2010 USD.

For ultra long-term projections beyond 2300, it is assumed that a steady state of net negative emissions will be achieved. That is, abatement options will operate at their maximum capacity. To hold net negative emissions at a constant level, baselines are fixed at their 2300 value after this date.

### 3.2.3 Extrapolation of primary energy

We define a linear phase-out of fossil primary energy  $W_{\text{foss}}(t)$ , starting from its value at time  $t_0 = 2100$ , denoted as  $W_{\text{foss}}(t_0)$ , and decreasing to zero by a specified end year. The phase-out proceeds at a constant rate and is expressed as:

$$W_{\text{foss}}(t) = \max \left( W_{\text{foss}}(t_0) \cdot \left( 1 - \frac{t - t_0}{t_{\text{end}} - t_0} \right), 0 \right)$$

where  $t \geq t_0$ . The formulation ensures that fossil energy use declines linearly to zero by the final year and remains zero thereafter.

Nuclear and bioenergy pathways are determined by using the marginal abatement cost functions under a specified carbon price path. As long as the imposed carbon price remains high enough, abatement via these options continues to grow until an upper bound is reached.

NBRs are assumed to fill the remaining energy demand not met by fossil fuels, bioenergy, or nuclear. The NBR contribution is calculated as the residual required to satisfy final energy demand, adjusted for conversion efficiencies:

$$W_{\text{nbr}}(t) = \frac{1}{\eta_{\text{nbr}}} \left[ F(t) - \sum_{i \in \{\text{bio}, \text{nuc}, \text{foss}, \text{trad}\}} \eta_i W_i(t) \right]$$

This approach is justified by the vast physical potential of renewable energy sources such as wind and solar, which are not assumed to be capacity-limited in this long-term extrapolation.

The fossil fuel phase-out trajectory, modulated by potential use of fossil CCS, effectively determines the gross emissions path. If fossil energy use is already low by 2100 (in a high-ambition scenario), it is likely that bioenergy and nuclear options have reached their maximum levels, implying that continued increases in energy demand will be met almost entirely by expanding NBR deployment. In this case, NBRs are already substantial in 2100 and continue to grow approximately in line with final energy demand, which itself depends on economic growth. In contrast, if fossil fuel use remains high in 2100 (a lower-ambition scenario), bioenergy and nuclear may still have room to grow post-2100, partially offsetting the reduction in fossil energy. However, NBRs will also have to expand more aggressively to fill the gap, yet starting from a lower level in 2100.

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## **A Additional Figures**

### Model Validation for AIM/CGE 2.2

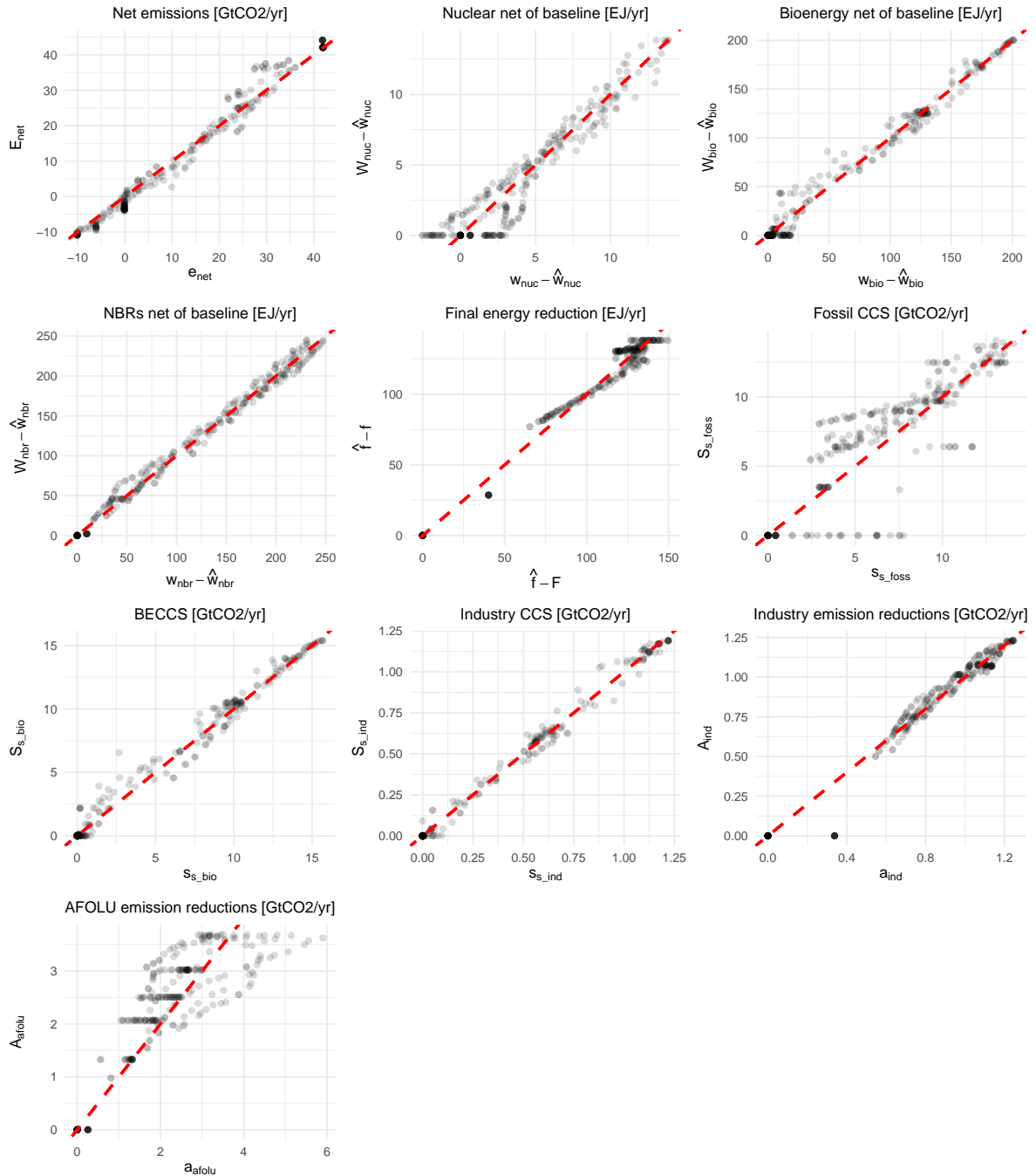


Figure 9: Model Validation for the AIM/CGE 2.2 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for GEM-E3\_V2021

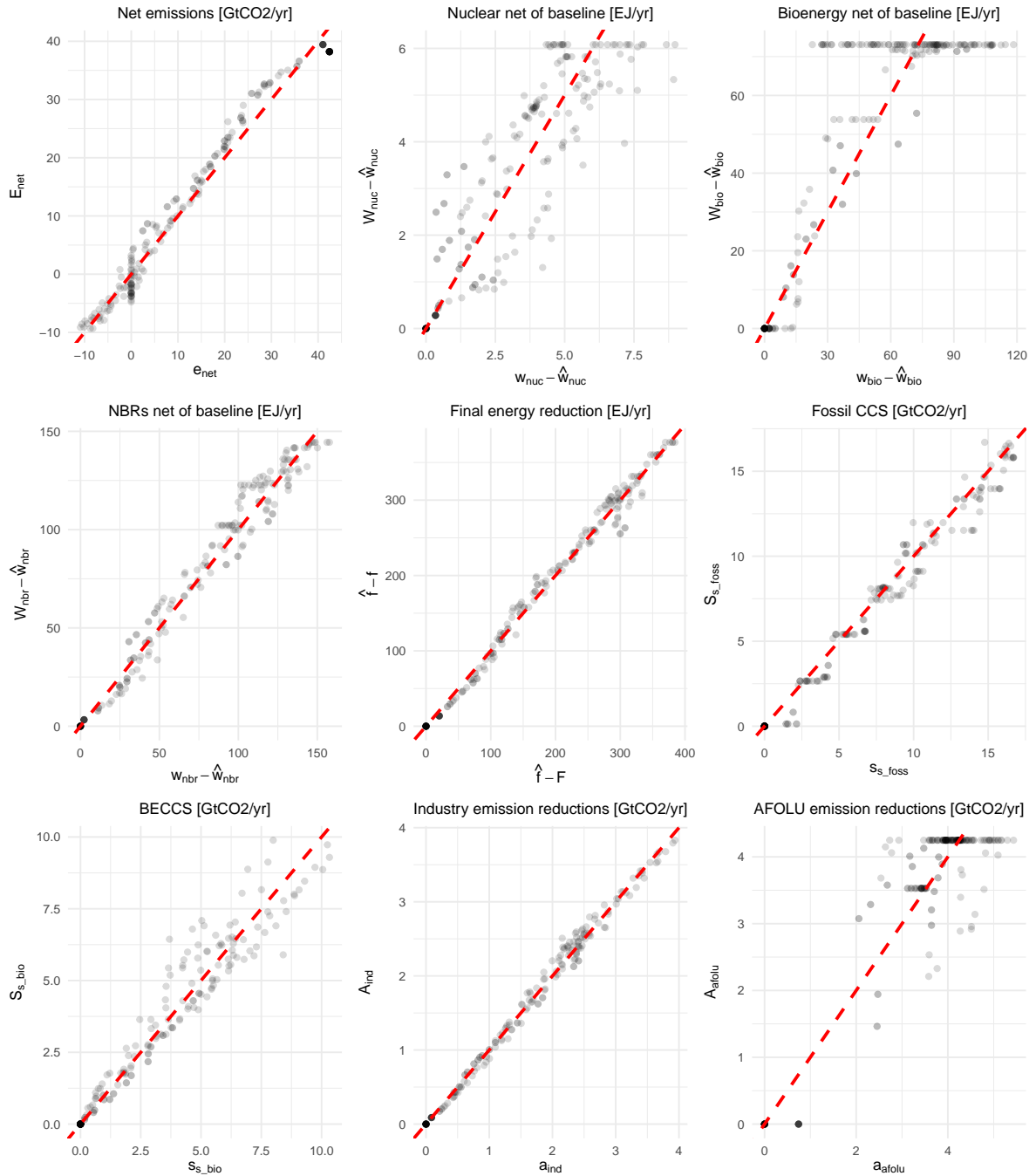


Figure 10: Model Validation for the GEM-E3 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for IMAGE 3.0

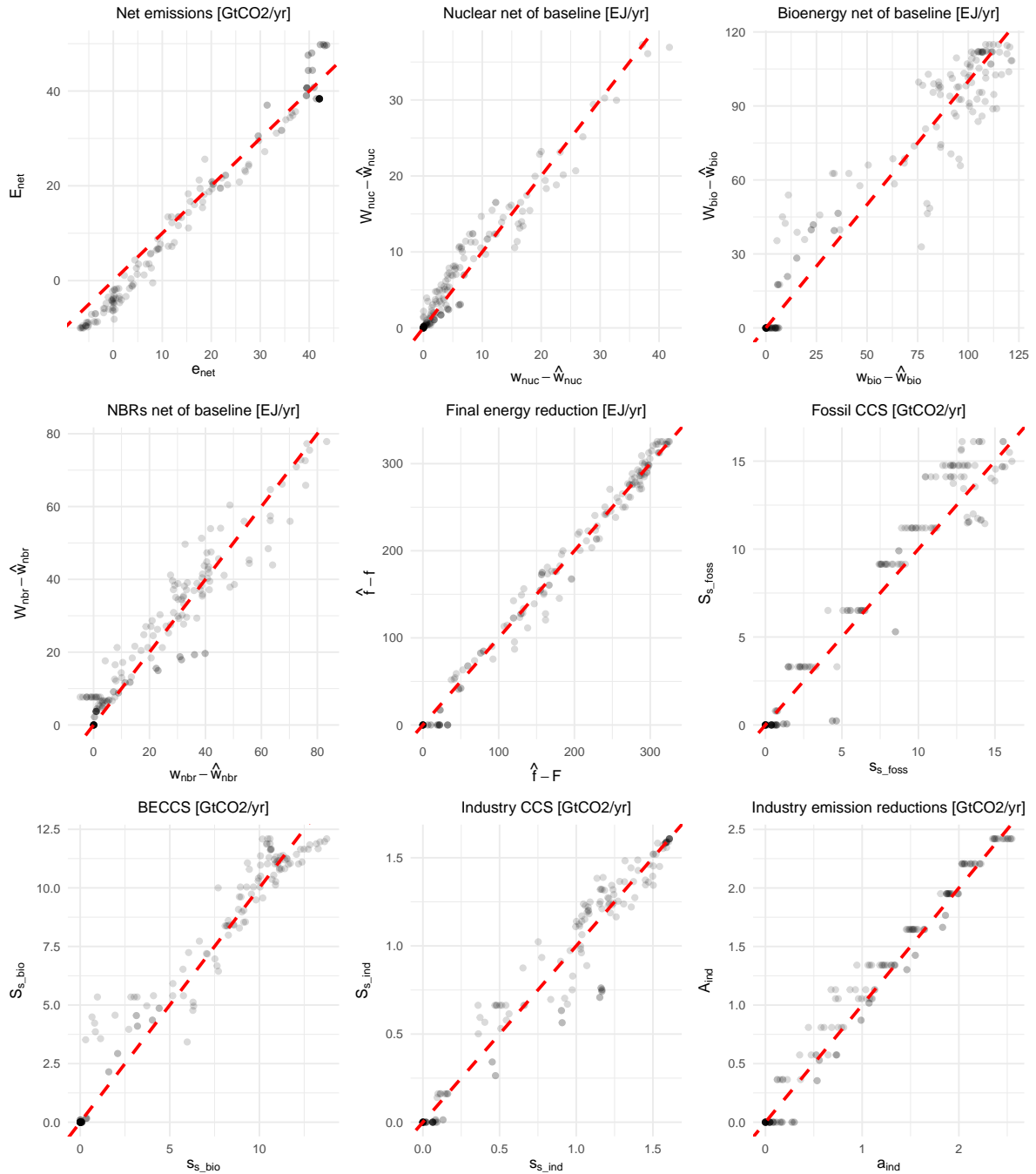


Figure 11: Model Validation for the IMAGE 3.0 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for MESSAGEix-GLOBIOM\_1.1

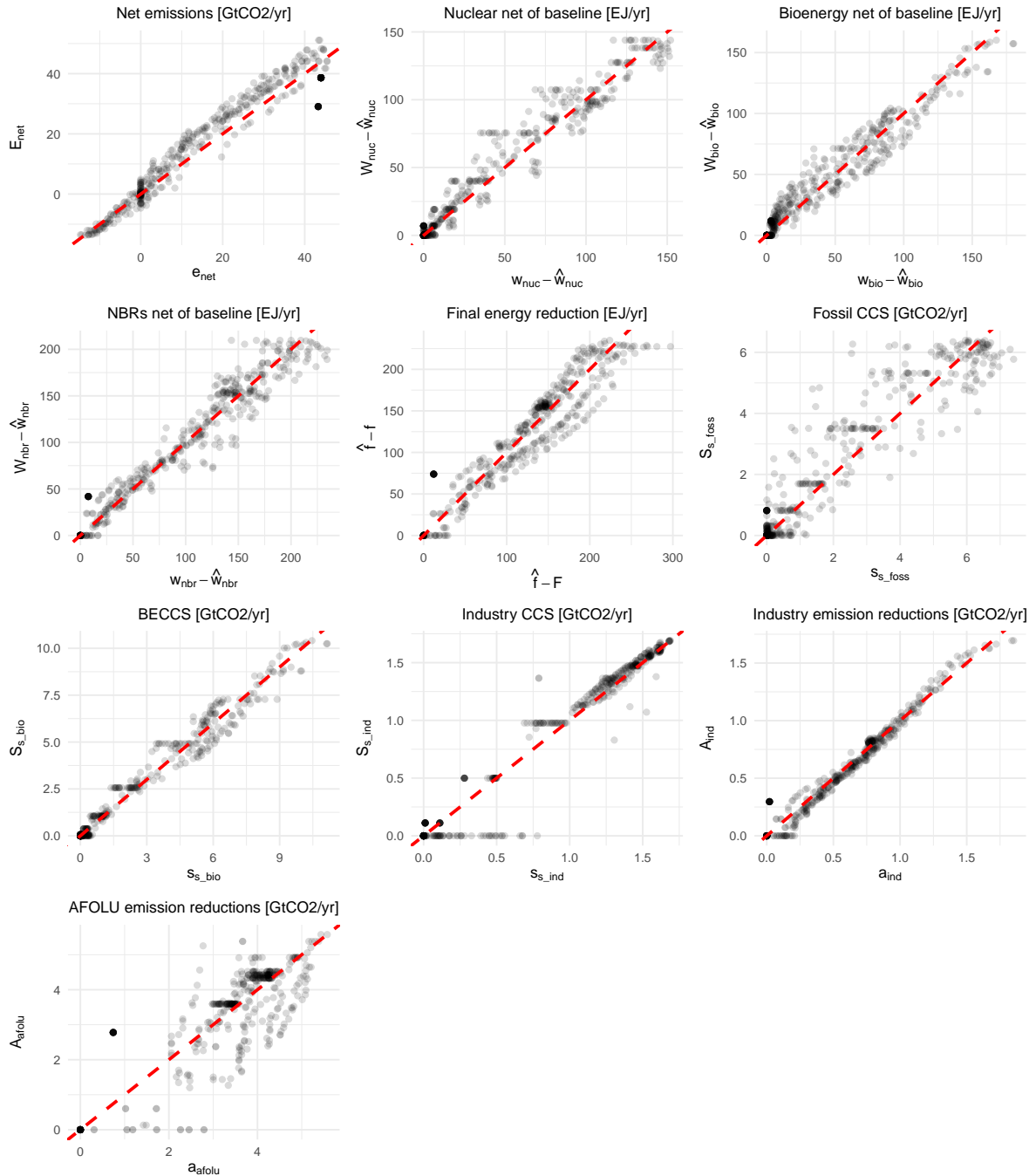


Figure 12: Model Validation for the MESSAGEix-GLOBIOM 1.1 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for REMIND-MAGPIE 2.1-4.2

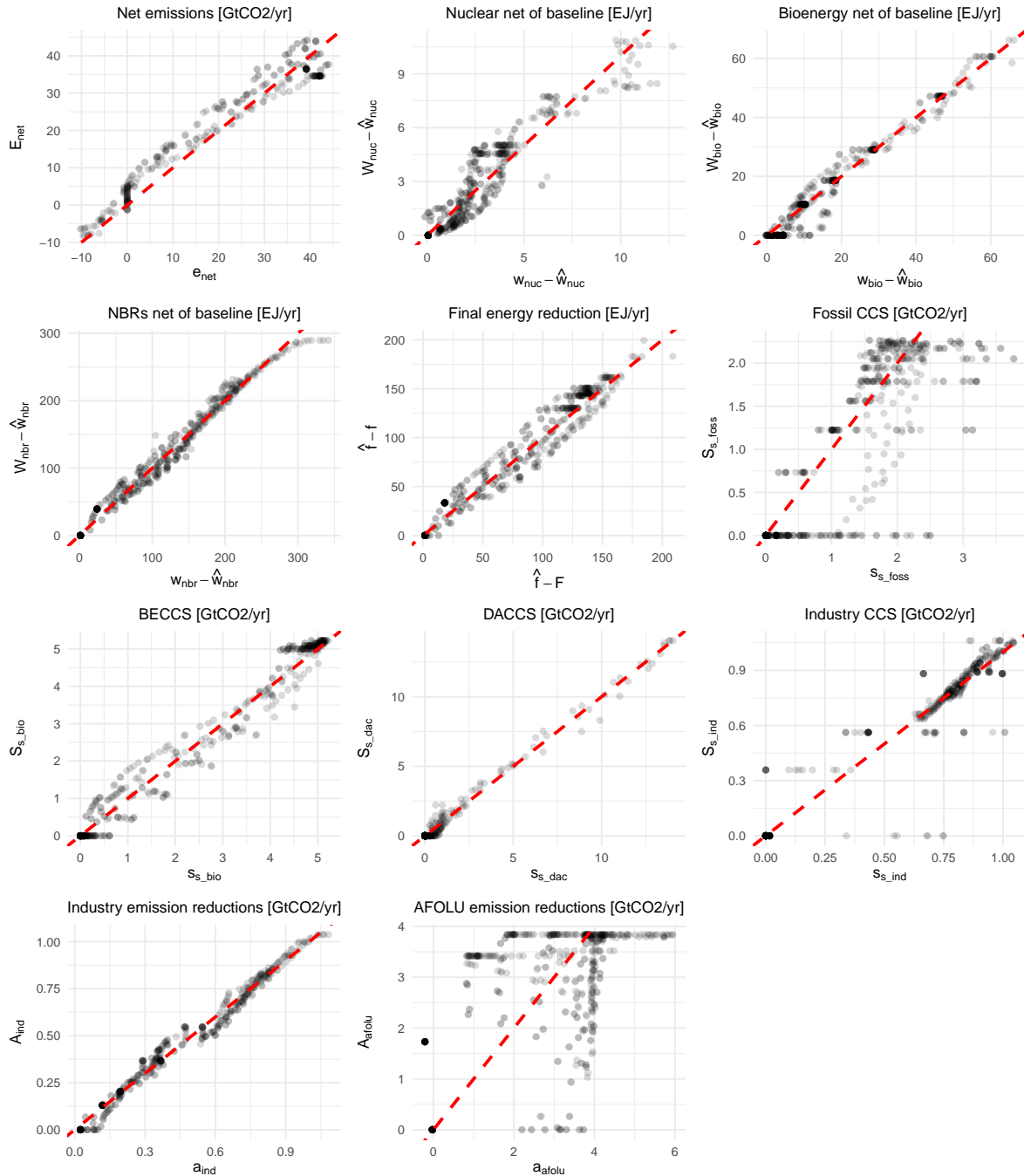


Figure 13: Model Validation for the REMIND-MAGPIE 2.1-4.2 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for TIAM-ECN 1.1

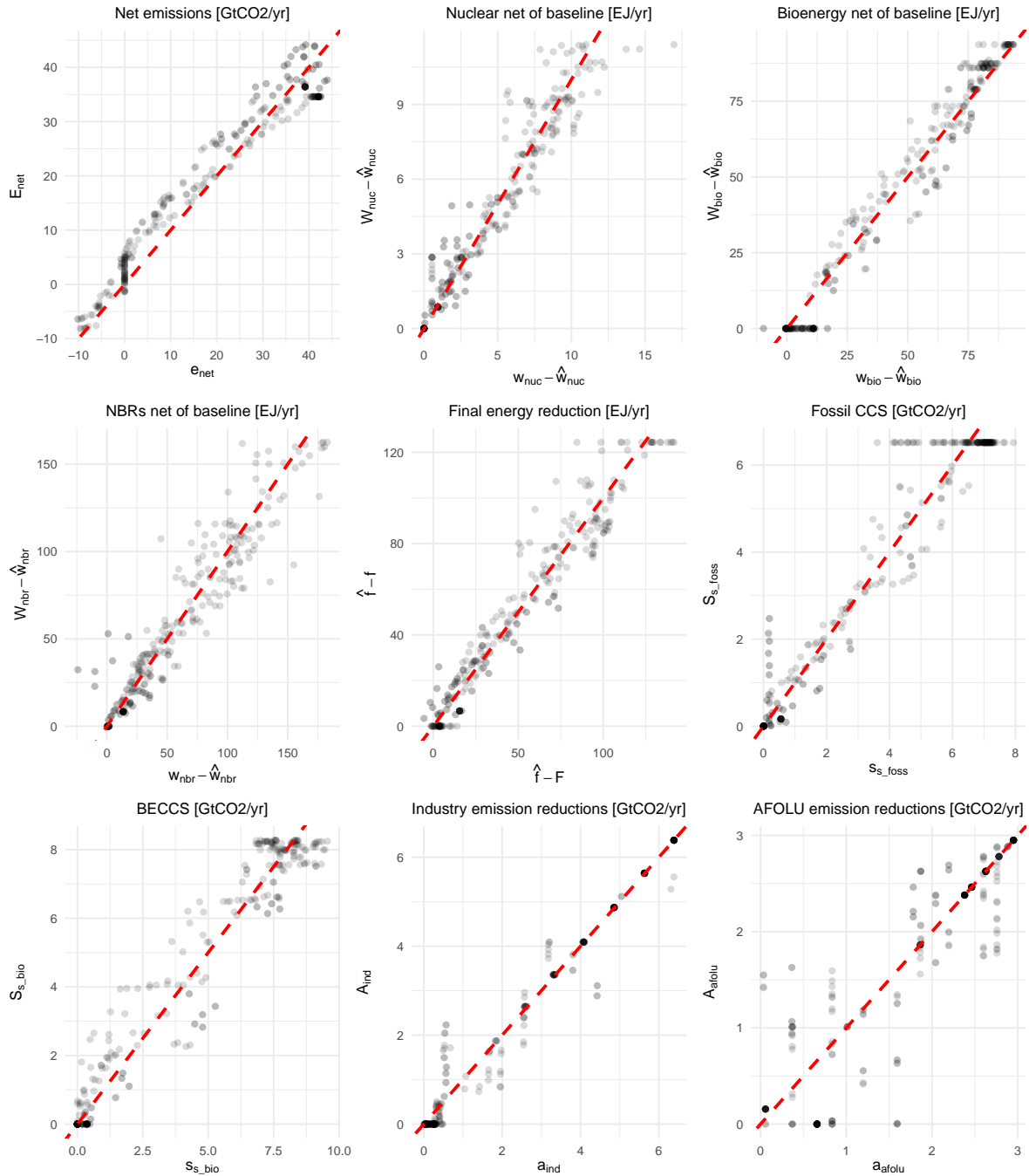


Figure 14: Model Validation for the TIAM-ECN 1.1 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for WITCH 5.0

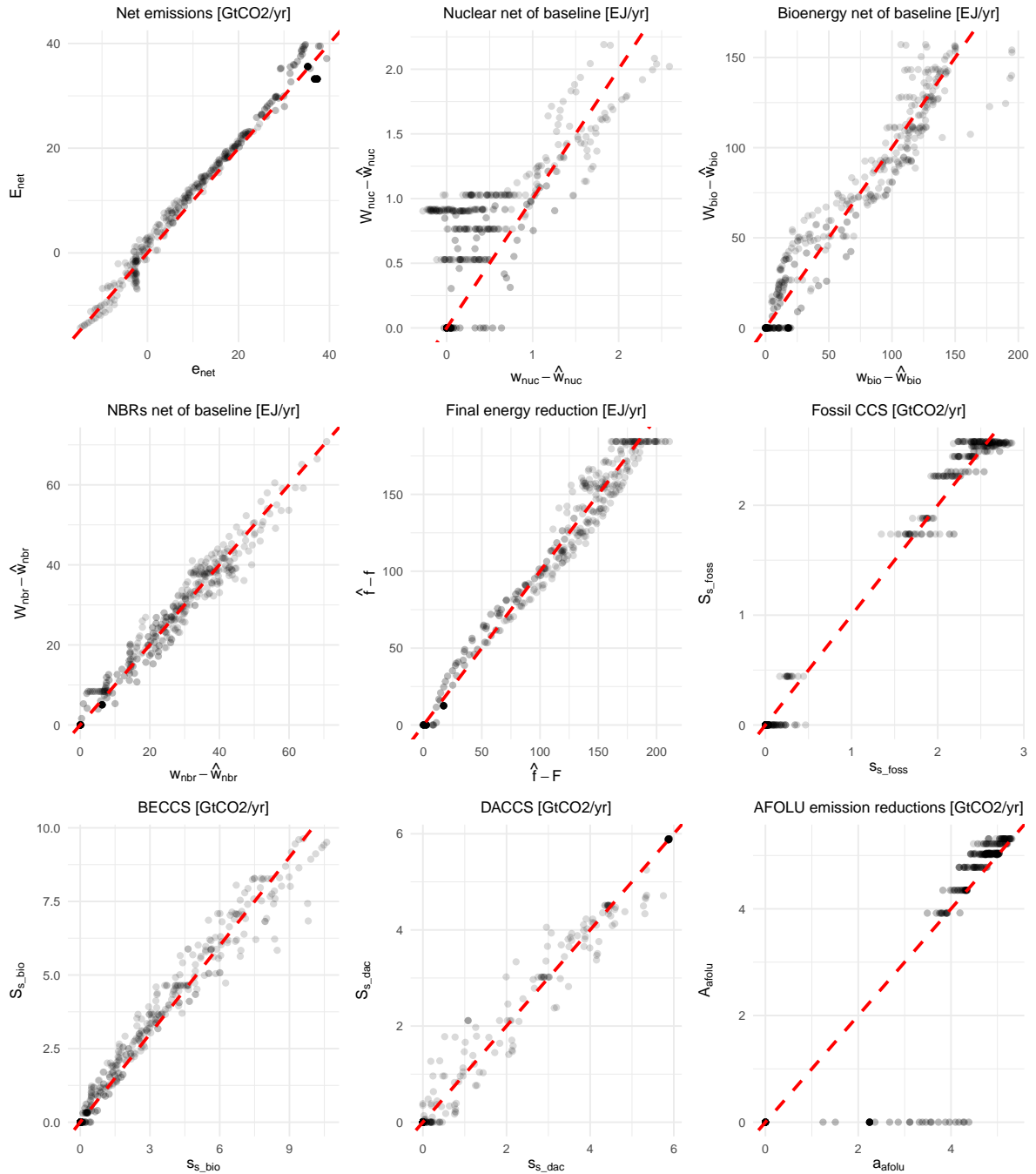


Figure 15: Model Validation for the WITCH 5.0 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

## Comparison of average abatement costs with consumption loss per tCO<sub>2</sub>

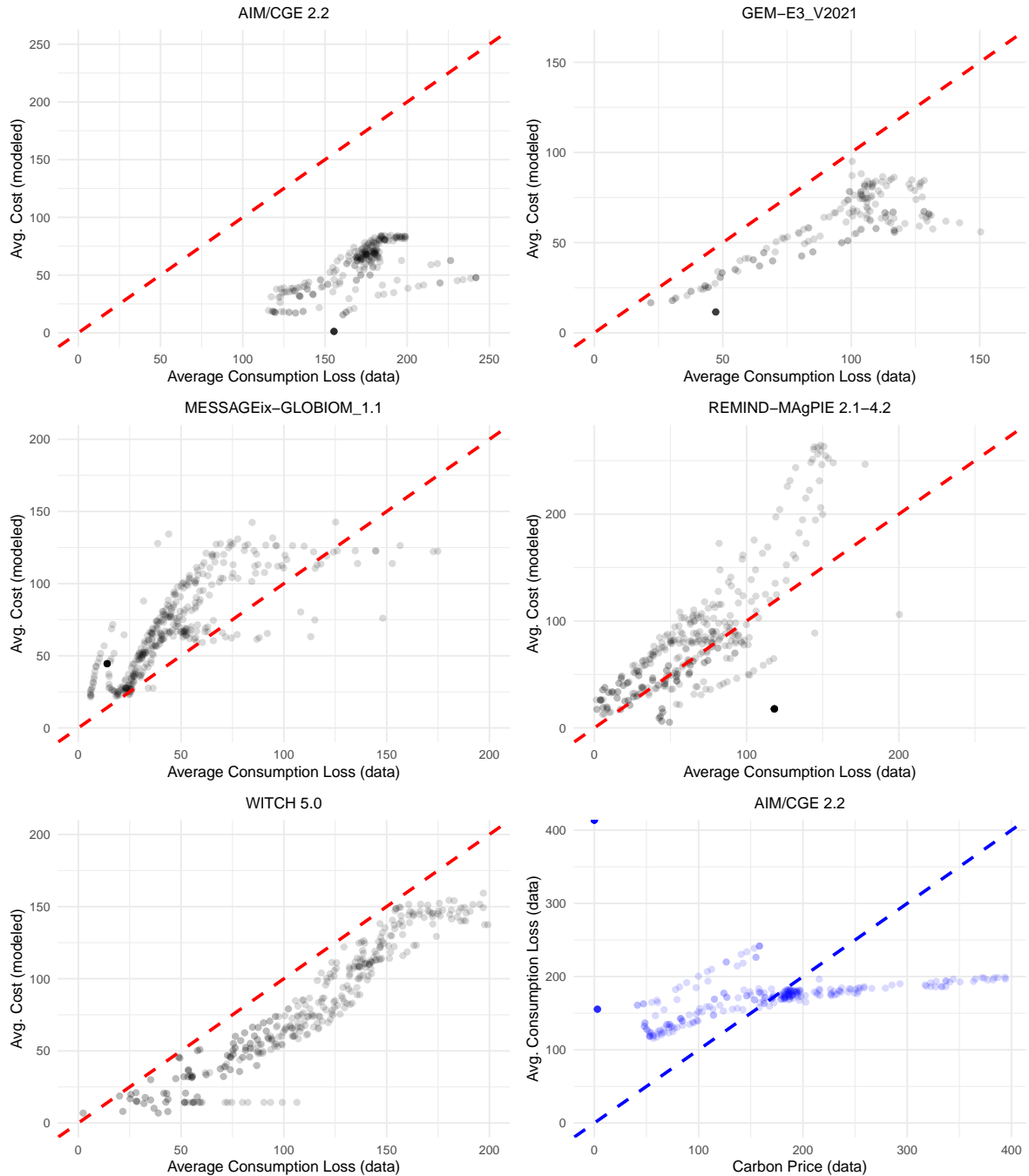


Figure 16: Reported consumption loss per tCO<sub>2</sub> versus modeled total average abatement costs. No consumption loss data are available for IMAGE 3.0 and TIAM-ECN 1.1. For AIM/CGE 2.2, reported consumption loss is also plotted against reported carbon prices (bottom right). If carbon prices represent marginal abatement costs and consumption loss per tCO<sub>2</sub> approximates average costs, then consumption loss should not exceed the carbon price. However, this condition is frequently violated for AIM/CGE 2.2, suggesting that consumption loss may not be a reliable proxy for average abatement costs in this case, which could explain the observed deviation from modeled estimates (top left).

## B Model overview

Symbol	Elements	Meaning
$\mathcal{I}$	{foss, nbr, bio, nuc, trad}	Primary energy types: fossil, non-biomass renewables, biomass, nuclear, traditional biomass
$\mathcal{N}$	{ind, afolu}	Sectors: industry, AFOLU (Agriculture, Forestry, and Other Land Use)
$\mathcal{J}$	$\mathcal{N} \cup \{\text{ener}\}$	Sectors: energy, industry, AFOLU
$\mathcal{K}$	{s.foss, s.bio, s.ind, s.dac}	Carbon capture types: fossil CCS, BECCS, industry CCS, DACCS
$\mathcal{M}$	$\mathcal{I} \cup \mathcal{N} \cup \mathcal{K} \cup \{\text{fe}\}$	Abatement options: primary energy types, industry, AFOLU, capture types, final energy reduction

Table 7: Index sets used in the model: symbols, elements, and meanings.

Symbol	Explanation	Units
$W_i$	Primary energy of type $i, i \in \mathcal{I}$	EJ/yr
$W_{\text{foss}}$	Primary energy from fossil fuels	EJ/yr
$W_{\text{nbr}}$	Primary energy from non-biomass renewables	EJ/yr
$W_{\text{bio}}$	Primary energy from biomass	EJ/yr
$W_{\text{nuc}}$	Primary energy from nuclear	EJ/yr
$W_{\text{trad}}$	Primary energy from traditional biomass	EJ/yr
$F$	Final energy	EJ/yr
$E_{\text{net}}$	Net emissions (all sectors)	GtCO <sub>2</sub> /yr
$E_j$	Pre-capture emissions from sector $j, j \in \mathcal{J}$	GtCO <sub>2</sub> /yr
$E_{\text{ener}}$	Pre-capture emissions from energy system	GtCO <sub>2</sub> /yr
$E_{\text{ind}}$	Pre-capture industrial process emissions	GtCO <sub>2</sub> /yr
$E_{\text{afolu}}$	Net emissions from AFOLU	GtCO <sub>2</sub> /yr
$S_k$	Carbon captured/stored via option $k$	GtCO <sub>2</sub> /yr
$S_{\text{s.foss}}$	Capture via fossil CCS	GtCO <sub>2</sub> /yr
$S_{\text{s.bio}}$	Removals via BECCS	GtCO <sub>2</sub> /yr
$S_{\text{s.ind}}$	Capture via industry CCS	GtCO <sub>2</sub> /yr
$S_{\text{s.dac}}$	Removals via DACCS	GtCO <sub>2</sub> /yr
$A_{\text{fe}}$	Abatement from reducing final energy	GtCO <sub>2</sub> /yr
$A_i$	Abatement from substituting fossil fuels with primary energy source $i$	GtCO <sub>2</sub> /yr
$\Delta W_i$	Change in primary energy $i$ vs baseline, $i \in \mathcal{I}$	EJ/yr
$\Delta F$	Change in final energy vs baseline	EJ/yr
$v_i(t)$	Upper bound on $W_i(t)$ , $i \in \mathcal{I} \setminus \{\text{foss}\}$	EJ/yr
$v_j(t)$	Upper bound on abatement in sector $j, j \in \mathcal{N}$	GtCO <sub>2</sub> /yr
$v_k(t)$	Upper bound on capture option $k, k \in \mathcal{K}$	GtCO <sub>2</sub> /yr
$v_k^{\text{pot}}(t)$	Technical capture potential of option $k, k \in \mathcal{K} \setminus \{\text{s.dac}\}$	GtCO <sub>2</sub> /yr
$v_{\text{fe}}(t)$	Lower bound on final energy	EJ/yr

Table 8: Model variables with brief explanation and units.

Energy and emission balance:

$$E_{\text{net}}(t) = \sum_{j \in \mathcal{J}} E_j(t) - \sum_{k \in \mathcal{K}} S_k(t); \quad (10)$$

$$E_{\text{ener}}(t) = \beta_{\text{foss}} W_{\text{foss}}(t); \quad (11)$$

$$F(t) = \sum_{i \in \mathcal{I}} \eta_i W_i(t). \quad (12)$$

Symbol	Meaning	Units
$\hat{\cdot}$	hat notation is used to distinguish between elements from the baseline and mitigation scenarios.	
$\hat{W}_i(t)$	Baseline primary energy of type $i, i \in \mathcal{I}$	EJ/yr
$\hat{E}_j(t)$	Baseline pre-capture emissions from sector $j, j \in \mathcal{N}$	GtCO <sub>2</sub> /yr
$\hat{S}_k(t)$	Baseline carbon captured/stored via option $k, k \in \mathcal{K}$	GtCO <sub>2</sub> /yr
$\beta_{\text{foss}}$	Carbon intensity of fossil fuels	GtCO <sub>2</sub> /EJ
$\eta_i$	Conversion efficiency from primary to final energy for type $i, i \in \mathcal{I}$	–
$\sigma_i$	Substitution efficiency of fuel $i$ vs fossil fuels, $i \in \mathcal{I} \setminus \{\text{foss}\}$	–
$d_i, u_i$	Marginal cost floor/ceiling for option $i, i \in \mathcal{I} \setminus \{\text{foss}\}$	USD/tCO <sub>2</sub>
$l_i$	Lag parameter for option $i, i \in \mathcal{I} \setminus \{\text{foss}\}$	–
$a_i, b_i$	Cost function coefficients for option $i, i \in \mathcal{I} \setminus \{\text{foss}\}$	see cost eq.
$g_i$	Growth parameter for max abatement change for option $i, i \in \mathcal{I} \setminus \{\text{foss}\}$	GtCO <sub>2</sub> /yr

Table 9: Model parameters with meanings and units.

Initial conditions and assumptions:

$$W_i(t_0) := \hat{W}_i(t_0), \quad (13)$$

$$F(t_0) := \hat{F}(t_0), \quad (14)$$

$$S_k(t_0) := \hat{S}_k(t_0), \quad (15)$$

$$\Delta W_{\text{trad}}(t) = 0. \quad (16)$$

Abatement:

$$\Delta W_i(t) := \hat{W}_i(t) - W_i(t), \quad i \in \mathcal{I}; \quad (17)$$

$$A(t) := \beta_{\text{foss}} \Delta W_{\text{foss}}(t); \quad (18)$$

$$\sigma_i := \frac{\eta_i}{\eta_{\text{foss}}}, \quad i \in \mathcal{I} \setminus \{\text{foss}\}; \quad (19)$$

$$A_i(t) := -\beta_{\text{foss}} \sigma_i \Delta W_i(t), \quad i \in \mathcal{I} \setminus \{\text{foss}\}; \quad (20)$$

$$\Delta F(t) := \hat{F}(t) - F(t); \quad (21)$$

$$A_{\text{fe}}(t) := \frac{\beta_{\text{foss}} \Delta F(t)}{\eta_{\text{foss}}}; \quad (22)$$

$$A_j(t) := \hat{E}_j(t) - E_j(t), \quad j \in \mathcal{N}; \quad (23)$$

$$A_k(t) := S_k(t) - \hat{S}_k(t), \quad k \in \mathcal{K}. \quad (24)$$

Marginal costs, total costs, and limits for abatement through primary energy substitution:

For  $i \in \mathcal{I} \setminus \{\text{foss}\}$

$$P_i(t) = \begin{cases} \frac{a_i}{(\beta_{\text{foss}} \sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i} + d_i, & \text{if } A_i(t) \geq l_i A_i(t-1) \\ d_i, & \text{if } A_i(t) < l_i A_i(t-1) \end{cases}; \quad (25)$$

$$C_i(t) = \begin{cases} \frac{a_i}{b_i + 1} \left( \frac{1}{(\beta_{\text{foss}} \sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i+1} \right) + d_i A_i(t), & \text{if } A_i(t) \geq l_i A_i(t-1) \\ d_i A_i(t), & \text{if } A_i(t) < l_i A_i(t-1) \end{cases}; \quad (26)$$

$$W_i(t) \leq v_i(t), \quad (27)$$

$$A_i(t) \leq \beta_{\text{foss}} \sigma_i g_i + l_i A_i(t-1). \quad (28)$$

Marginal costs, total costs, and limits for abatement through final energy reduction:

$$P_{\text{fe}}(t) = \begin{cases} a_{\text{fe}} \left( \frac{\eta_{\text{foss}}}{\beta_{\text{foss}}} \right)^{b_{\text{fe}}} (A_{\text{fe}}(t) - l_{\text{fe}} A_{\text{fe}}(t-1))^{b_{\text{fe}}} + d_{\text{fe}}, & \text{if } A_{\text{fe}}(t) \geq l_{\text{fe}} A_{\text{fe}}(t-1); \\ d_{\text{fe}}, & \text{if } A_{\text{fe}}(t) < l_{\text{fe}} A_{\text{fe}}(t-1) \end{cases}; \quad (29)$$

$$C_{\text{fe}}(t) = \begin{cases} \frac{a_{\text{fe}}}{b_{\text{fe}} + 1} \left( \frac{\eta_{\text{foss}}}{\beta_{\text{foss}}} \right)^{b_{\text{fe}}} (A_{\text{fe}}(t) - l_{\text{fe}} A_{\text{fe}}(t-1))^{b_{\text{fe}}+1} + d_{\text{fe}} A_{\text{fe}}(t), & \text{if } A_{\text{fe}}(t) \geq l_{\text{fe}} A_{\text{fe}}(t-1); \\ d_{\text{fe}} A_{\text{fe}}(t), & \text{if } A_{\text{fe}}(t) < l_{\text{fe}} A_{\text{fe}}(t-1) \end{cases}; \quad (30)$$

$$F(t) \geq v_{\text{fe}}(t), \quad (31)$$

$$A_{\text{fe}}(t) \leq \frac{\beta_{\text{foss}}}{\eta_{\text{foss}}} g_{\text{fe}} + l_{\text{fe}} A_{\text{fe}}(t-1). \quad (32)$$

Marginal costs, total costs, and limits for abatement in industry and AFOLU sector:

For  $j \in \mathcal{N}$ ,

$$P_j(t) = \begin{cases} a_j (A_j(t) - l_j A_j(t-1))^{b_j} + d_j, & \text{if } A_j(t) \geq l_j A_j(t-1); \\ d_j, & \text{if } A_j(t) < l_j A_j(t-1) \end{cases}; \quad (33)$$

$$C_j(t) = \begin{cases} \frac{a_j}{b_j + 1} (A_j(t) - l_j A_j(t-1))^{b_j+1} + d_j A_j(t), & \text{if } A_j(t) \geq l_j A_j(t-1); \\ d_j A_j(t), & \text{if } A_j(t) < l_j A_j(t-1) \end{cases}; \quad (34)$$

$$A_j(t) \leq v_j(t), \quad (35)$$

$$A_j(t) \leq g_j + l_j A_j(t-1). \quad (36)$$

Marginal costs, total costs, and limits for carbon capture:

For  $k \in \mathcal{K}$ ,

$$P_k(t) = \begin{cases} a_k (A_k(t) - l_k A_k(t-1))^{b_k} + d_k, & \text{if } A_k(t) \geq l_k A_k(t-1); \\ d_k A_k(t), & \text{if } A_k(t) < l_k A_k(t-1) \end{cases}; \quad (37)$$

$$C_k(t) = \begin{cases} \frac{a_k}{b_k + 1} (A_k(t) - l_k A_k(t-1))^{b_k+1} + d_k A_k(t), & \text{if } A_k(t) \geq l_k A_k(t-1); \\ d_k A_k(t), & \text{if } A_k(t) < l_k A_k(t-1) \end{cases}; \quad (38)$$

$$S_k(t) \leq v_k(t), \quad (39)$$

$$A_k(t) \leq g_k + l_k A_k(t-1). \quad (40)$$

## C Abatement functions

### C.1 Abatement functions for primary energy substitution

The marginal and total cost functions introduced in Sections 1.5 to 1.7 can be used to solve for abatement under a specified objective function in an optimization framework. In contrast, simulation and calibration require functions that directly determine abatement from an exogenous carbon price path  $P(\cdot)$ . Here, we introduce such abatement functions. In essence, we show how a given global carbon price path  $P(\cdot)$  generates a feasible trajectory for  $W_i(\cdot)$ , and thus for  $A_i(\cdot)$ , with the corresponding marginal costs  $P_i(\cdot)$  computed as described in Section C.1.1.

For computing pathways of primary energy sources, we define the following function:

$$W_i(t) = \min \left( \tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t), v_i(t) \right), \quad (41)$$

with

$$\tilde{P}_i(t) := \min(u_i, P(t)) - \min(d_i, P(t)),$$

where  $u_i \geq d_i$ . The parameters  $d_i$  and  $u_i$  denote the marginal cost floor and ceiling, below and above which the imposed carbon price has no effect on abatement. The parameter  $v_i(t)$  specifies the maximum achievable value of  $W_i(t)$  in each period. Recall that  $\Delta W_i(t) = -\frac{A_i(t)}{\beta_{\text{foss}} \sigma_i}$  (see Eq. 3). Moreover, we define the transformations  $\tilde{a}_i := a_i^{-1/b_i}$ ,  $\tilde{b}_i := 1/b_i$ , and  $g_i := \tilde{a}_i(u_i - d_i)^{\tilde{b}_i}$ .

#### Case A

Suppose

$$\tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t) \leq v_i(t).$$

Then,

$$W_i(t) = \tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t).$$

Let us now analyze  $\tilde{P}_i(t)$ .

**Case A.1** – Standard case ( $d_i < P(t) < u_i$ ), hence,  $\tilde{P}_i(t) = P(t) - d_i$ . Substituting yields:

$$W_i(t) - \hat{W}_i(t) + l_i \Delta W_i(t-1) = \tilde{a}_i (P(t) - d_i)^{\tilde{b}_i}.$$

Hence,

$$\left( \tilde{a}_i^{-1} (W_i(t) - \hat{W}_i(t) + l_i \Delta W_i(t-1)) \right)^{1/\tilde{b}_i} = P(t) - d_i,$$

and therefore,

$$P(t) = a_i (W_i(t) - \hat{W}_i(t) + l_i \Delta W_i(t-1))^{b_i} + d_i.$$

Substituting  $A_i(t) = -\beta_{\text{foss}} \sigma_i \Delta W_i(t)$  yields:

$$P(t) = \frac{a_i}{(\beta_{\text{foss}} \sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i} + d_i, \quad (42)$$

Thus, in this carbon price range,  $P_i(t) := P(t)$ .

**Case A.2** – Price ceiling ( $P(t) > u_i$ ) Here,  $\tilde{P}_i(t) = u_i - d_i$ . Inserting into Eq. 41 gives

$$A_i(t) = \beta_{\text{foss}}\sigma_i g_i + l_i A_i(t-1),$$

which represents the maximum feasible per-period growth (compare with Eq. 6). To determine the marginal costs at the maximum growth, we substitute this expression into Eq. 4 and obtain  $P_i(t) = u_i$ .

**Case A.3** – Price floor ( $P(t) < d_i$ ) Here,  $\tilde{P}_i(t) = 0$ . Then, again inserting into Eq. 41 gives

$$A_i(t) = l_i A_i(t-1).$$

This is a lower bound for abatement growth by period. Inserting this into Eq. 4 yields the marginal cost at the lowest possible growth,  $P_i(t) = d_i$ .

**Summary Case A** Given the condition

$$\tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t) \leq v_i(t),$$

we have shown:

- The lowest feasible abatement growth is given by  $A_i(t) = l_i A_i(t-1)$ .
- The largest feasible abatement growth is given by  $A_i(t) = \beta_{\text{foss}}\sigma_i g_i + l_i A_i(t-1)$ .
- Marginal costs satisfy:

$$P_i(t) = \frac{a_i}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i} + d_i.$$

So far, we have only considered the upper part of the marginal cost function in Eq 4.

## Case B

Suppose

$$\tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t) > v_i(t).$$

Then,

$$W_i(t) = v_i(t),$$

which reflects Eq. 5, and from which  $A_i(t)$  can be inferred:

$$A_i(t) = \beta_{\text{foss}}\sigma_i (v_i(t) - \hat{W}_i(t)). \quad (43)$$

### C.1.1 Link between carbon price and marginal costs

For **Case A**, we have established a relation between the price path  $P(t)$  and abatement-option-specific marginal costs  $P_i(t)$ :

$$P_i(t) = \begin{cases} P(t), & d_i \leq P(t) \leq u_i, \\ d_i, & P(t) < d_i, \\ u_i, & P(t) > u_i, \end{cases}$$

where  $P(t)$  is the globally imposed carbon price, while  $P_i(t)$  denotes the abatement-option-specific marginal cost. For **Case B**, abatement is trivially derived from Eq. 43, which can be used in Eq. 4 to determine  $P_i(t)$ . In **Case B**  $P_i(t)$  in any case diverges from  $P(t)$ . Finally note that, **Case A** is limited to solutions  $l_i A_i(t-1) \leq A_i(t) \leq \beta_{\text{toss}} \sigma_i g_i + l_i A_i(t-1)$ . **Case B** can lead to solutions where  $A_i(t) < l_i A_i(t-1)$ , for which  $P_i(t) = d_i$ . Moreover, if we have  $P(t) < d_i$  and  $\tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t) > v_i(t)$ , it follows that  $A_i(t) < l_i A_i(t-1)$ .

## C.2 Abatement function for final energy reduction

The abatement function for final energy reduction differs from those for primary energy substitution in terms of the signs. We have the following form:

$$F(t) = - \min \left( \tilde{a}_{\text{fe}} \tilde{P}_{\text{fe}}(t)^{\tilde{b}_{\text{fe}}} + l_{\text{fe}} \Delta F(t-1) - \hat{F}(t), v_{\text{fe}}(t) \right). \quad (44)$$

Here,  $\tilde{a}_{\text{fe}} \leq 0$  and  $v_{\text{fe}}(t)$  is the minimum allowable amount of  $F_i(t)$ . Using the definitions  $a_{\text{fe}} := |\tilde{a}_{\text{fe}}|^{-1/\tilde{b}_{\text{fe}}}$ ,  $b_{\text{fe}} := 1/\tilde{b}_{\text{fe}}$ ,  $g_{\text{fe}} := \left( \frac{u_{\text{fe}} - d_{\text{fe}}}{a_{\text{fe}}} \right)^{1/b_{\text{fe}}}$ , and  $\Delta F(t) = \frac{\eta_{\text{toss}}}{\beta_{\text{toss}}} A_{\text{fe}}(t)$ , we can link Eq. 44 to the marginal cost function 7, following the steps of Section C.1.

## C.3 Abatement functions for industry and AFOLU sectors

The abatement functions for Industry and AFOLU sectors are defined as:

$$A_j(t) = \min \left( \tilde{a}_j \tilde{P}_j(t)^{\tilde{b}_j} + l_j A_j(t-1), v_j(t) \right),$$

where  $\tilde{P}_j(t) := \min(u_j, P(t)) - \min(d_j, P(t))$  and  $u_j \geq d_j$ . As before, using the definitions  $\tilde{a}_j := a_j^{-1/b_j}$ ,  $\tilde{b}_j := 1/b_j$ , and  $g_j := \tilde{a}_j(u_j - d_j)^{\tilde{b}_j}$ , we can link this abatement function, to the marginal cost function in Eq 8 and its associated constraints.

## C.4 Abatement functions for carbon capture

The abatement function for carbon capture is defined as:

$$S_k(t) = \min \left( \tilde{a}_k \tilde{P}_k(t)^{\tilde{b}_k} + l_k A_k(t-1) + \hat{S}_k(t), v_k(t) \right),$$

where  $\tilde{P}_k(t) := \min(u_k, P(t)) - \min(d_k, P(t))$  and  $u_k \geq d_k$ . As before, using  $\tilde{a}_k := a_k^{-1/b_k}$ ,  $\tilde{b}_k := 1/b_k$ ,  $\delta_k := d_k$ , and  $g_k := \tilde{a}_k(u_k - d_k)^{\tilde{b}_k}$ , we can link the abatement function to Eq. 9 and its associated constraints.

# ANNEX 2

Co-author statements

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I, Dr. Artem Baklanov, certify that Johannes Bednar completed the majority of the work in the journal articles and working papers below, which form part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).
- J. Bednar, A. Baklanov, J. Macinante, The carbon removal obligation: Updated analytical model and scenario analysis. IIASA Working Paper WP-23-001 (2023); <https://pure.iiasa.ac.at/id/eprint/18572/>.
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).
- J. Bednar, A. Baklanov, A Reduced-Complexity Model of Process-Based IAMs. IIASA Working Paper WP-25-001(2025); <https://pure.iiasa.ac.at/id/eprint/20834/>.
- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

Signature:

A handwritten signature in purple ink, appearing to read 'Baklanov A.', is written over a horizontal line.

Date:

14.10.25

Sincerely,

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I, Dr. Fabian Wagner, certify that Johannes Bednar completed the majority of the work in the journal articles below, which form part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).

Signature:

A handwritten signature in blue ink, appearing to read 'F. Wagner', with a long horizontal flourish extending to the right.

Date: 20 October 2025

Sincerely,

Fabian Wagner

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I, Prof. Jim W. Hall, certify that Johannes Bednar completed the majority of the work in the journal articles below, which form part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).
- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

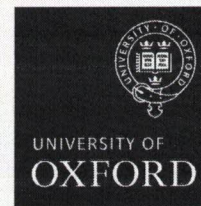
A handwritten signature in black ink that reads 'JW Hall'. The signature is written in a cursive style with a large, looping initial 'J'.

Signature:

Date: 15 October 2025

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I, Dr. Justin Macinante, certify that Johannes Bednar completed the majority of the work in the journal articles and working papers below, which form part of his DPhil thesis:

- J. Bednar, A. Baklanov, J. Macinante, The carbon removal obligation: Updated analytical model and scenario analysis. IIASA Working Paper WP-23-001 (2023); <https://pure.iiasa.ac.at/id/eprint/18572/>.
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).
- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

Signature:

A handwritten signature in black ink, appearing to read 'Justin Macinante', written over a large, circular scribble.

Date:

15 October 2025

Sincerely,

JUSTIN MACINANTE

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I, Dr. Marcus Thomson, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).

Signature:

A handwritten signature in black ink, appearing to be 'M. Thomson', written over a light blue horizontal line.

Date:

Sincerely,

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I, Prof. Michael Obersteiner, certify that Johannes Bednar completed the majority of the work in the journal articles below, which form part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).
- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

Signature:

A handwritten signature in blue ink, appearing to be 'M. Obersteiner', written over a faint, light blue oval-shaped background.

Date: Oct 21, 2025

Sincerely,

Michael Obersteiner

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I, Prof. Myles Allen, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).

A handwritten signature in black ink, appearing to read 'M. Allen', is written above a long, horizontal, slightly curved line that serves as a signature underline.

Signature:

Date: 14<sup>th</sup> October 2025

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I, Dr. Navraj Singh Ghaleigh, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).

Signature: 

Date:

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I, Dr. Oliver Geden, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).

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A handwritten signature in blue ink, appearing to be 'O. Geden', written over a horizontal line.

Date:

21 OCT, 2025

Sincerely,

OLIVER GEDEN

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I, Dr. Thomas Gasser, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

Signature:

A handwritten signature in black ink, appearing to read 'Thomas Gasser', written over a light blue horizontal line.

Date: 14 Oct 2025

Sincerely,

# ANNEX 3

Extended Data Figures and Tables  
for Chapter 3

**Extended Data Table 1 | Net and gross emission removal in illustrative pathways from the IPCC's Special Report on global warming of 1.5°C**

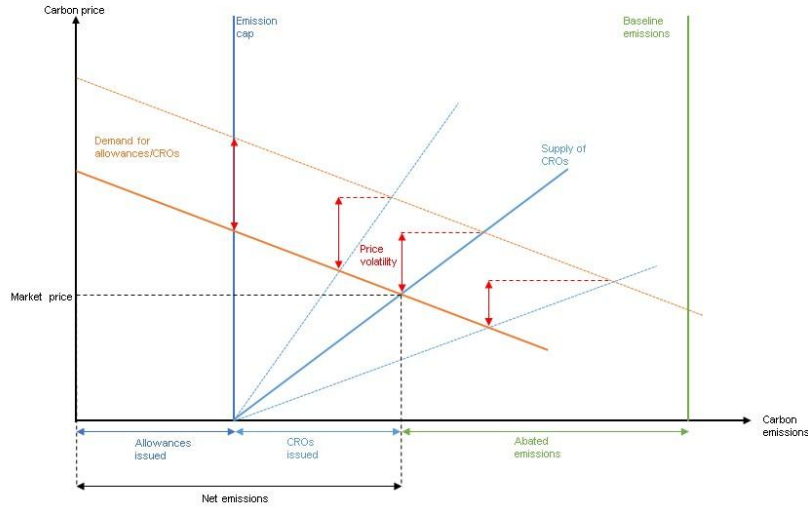
Net and gross emission removal including bioenergy with carbon capture and storage (BECCS) and Agriculture, Forestry and Other Land Use (AFOLU). To compute emission removal in term of years of current emissions we used a net emission value of 11.73 GtC in 2019. Data were retrieved from the scenario database hosted by IIASA and available at: <https://data.ene.iiasa.ac.at/iamc-1.5c-explorer>.

SR1.5 illustrative pathway	Net CO <sub>2</sub> removal	Gross CO <sub>2</sub> removal	Net CO <sub>2</sub> removal	Gross CO <sub>2</sub> removal
	(GtC)		(years of 2019 net emissions)	
P1_MESSAGEix-GLOBIOM 1.0_LowEnergyDemand	25.6	52.1	2.2	4.4
P2_AIM/CGE 2.0_SSP1-19	45.3	109.1	3.9	9.3
P3_MESSAGE-GLOBIOM 1.0_SSP2-19	102.8	169.4	8.8	14.4
P4_REMIND-MAgPIE 1.5_SSP5-19	211.8	326.4	18.1	27.8

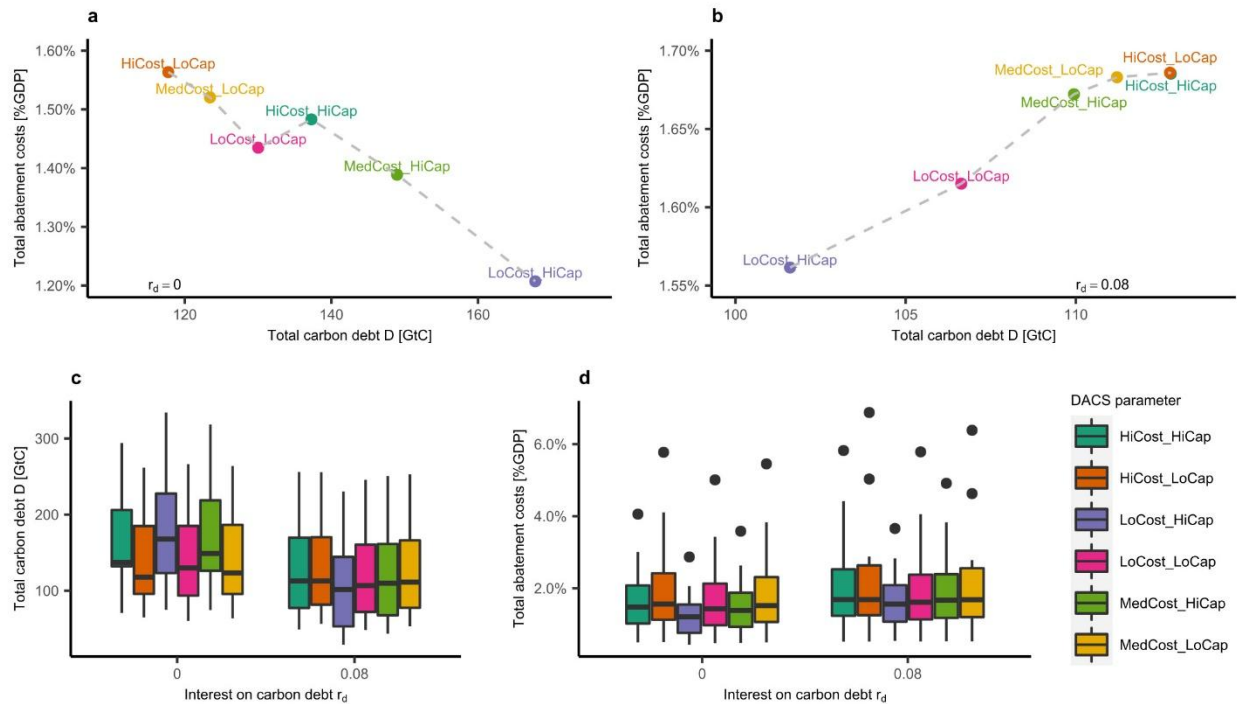
**Extended Data Table 2 | Combinations of models and SSPs used to calibrate the model in this study**

13 combinations of models and SSPs for which RCP1.9 results are available in the SSP scenario database. The RCP2.6 scenarios presented in the Results are composed of these 13 configurations of our model combined with six rates of interest on carbon debt ( $r_d = 0, 0.005, 0.1, 0.2, 0.4, 0.8$ ), resulting in 78 scenarios. The RCP1.9 scenarios are composed of the same 78 model configurations combined with 6 marginal abatement cost curves for direct air capture and storage resulting in 468 scenarios.

Model	SSP1	SSP2	SSP4	SSP5
WITCH-GLOBIOM	X		X	
REMIND-MAgPIE	X	X		X
MESSAGE-GLOBIOM	X	X		
IMAGE	X			
GCAM4	X	X		X
AIM/CGE	X	X		

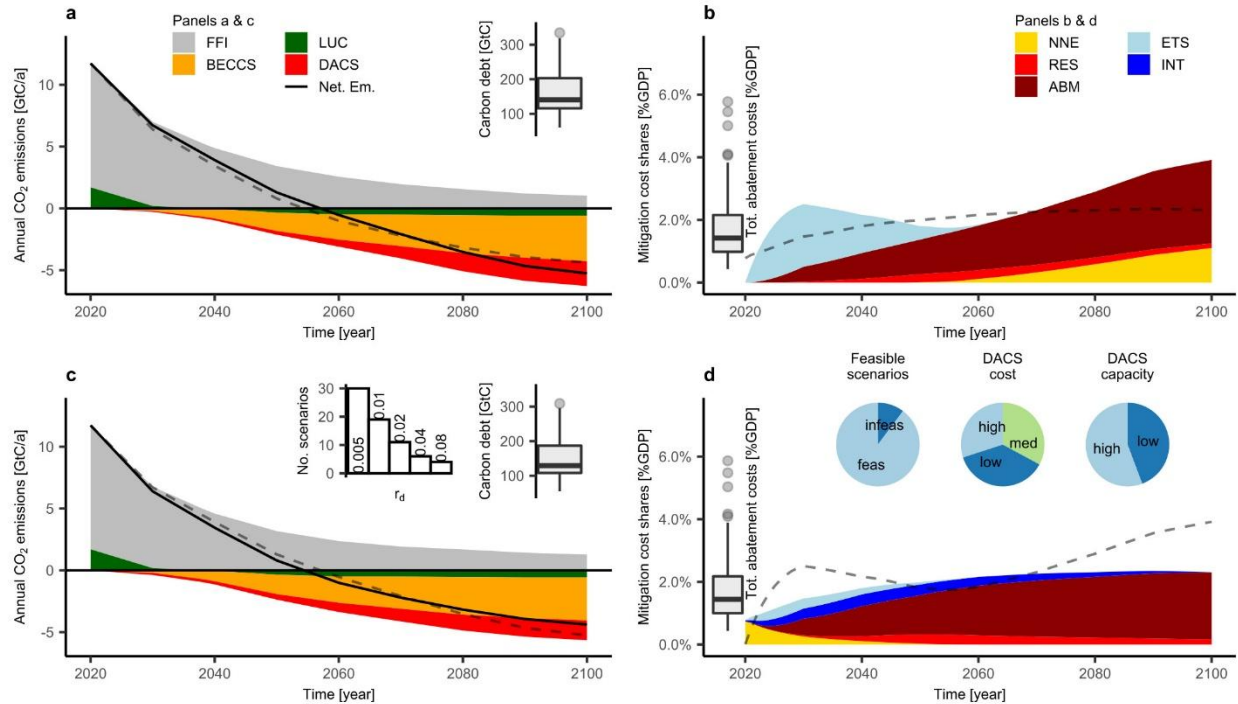


**Extended Data Figure 1 | Schematic supply of emission allowances and Carbon Removal Obligations (CROs) at a fixed point in time.** The supply of allowances is completely inelastic (emission cap), whereas the supply elasticity of CROs is determined by discounted future abatement costs, which increase as the demand for CROs increases, as well as interest costs, which can be controlled by managing authorities and financial institutions (dashed blue CRO supply curves). If CROs are traded on a market, they clear at the same price as allowances and thereby reduce the price of allowances. The larger the elasticity of the CRO supply curve, the lower the potential for price volatility (red arrows), as, e.g., induced by a demand shock (dashed orange line). The sum of allowances and CROs issued equals net emissions. Abated emissions equal the difference between baseline emissions (green) and net emissions and are comprised of emission reductions and/or carbon removal.

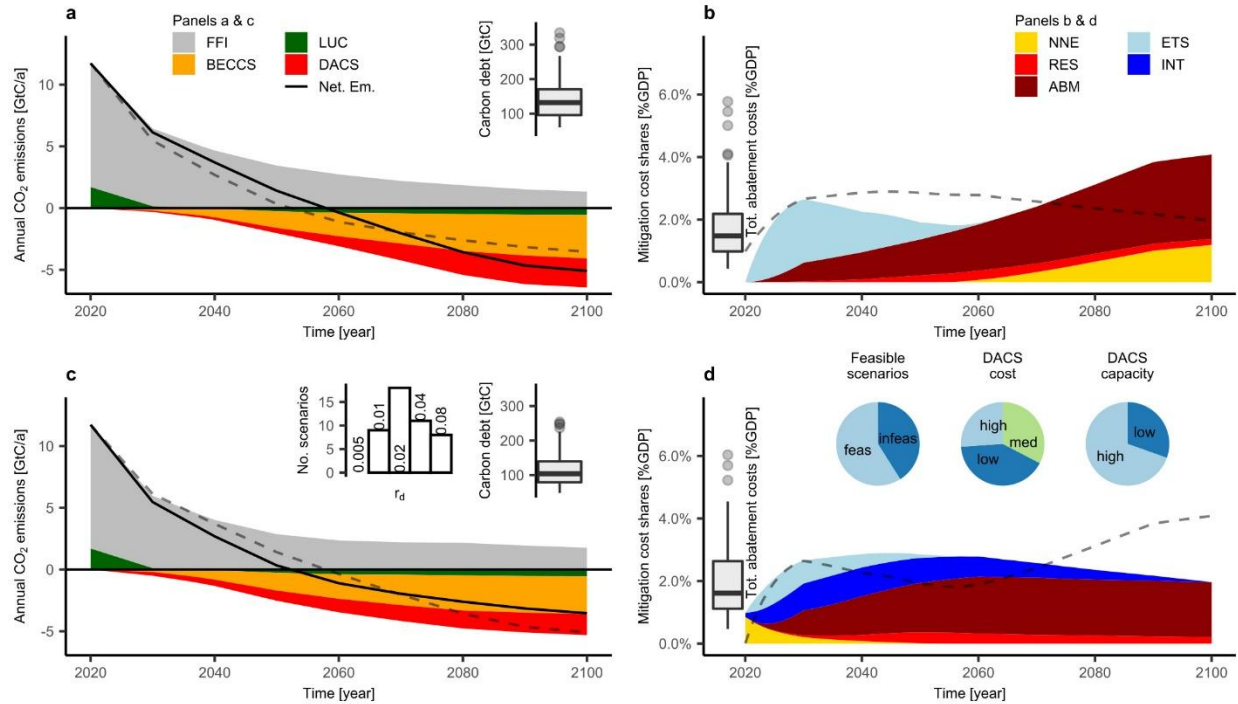


**Extended Data Figure 2 | 1.5°C (RCP1.9) scenarios abatement costs and carbon debt for six different marginal abatement cost (MAC) curves of direct air capture and storage (DACs) and interest rates on carbon debt  $r_d = 0$  and  $r_d = 0.08$ .** For a definition of  $D$  refer to the Methods; abatement costs are discounted and expressed as GDP percentage. Abatement costs are exclusive of interest costs. For each rate  $r_d$ , 78 scenarios (13 scenarios as for the RCP2.6 analysis times 6 DACS parameters) are grouped by DACS costs (low to high, i.e. "LoCost", "MedCost", "HiCost") and DACS capacity limits (10% and 30% of baseline emissions, i.e. "LoCap" and "HiCap"). **Panels a & b:** Median abatement costs as function of median carbon debt  $D$  for

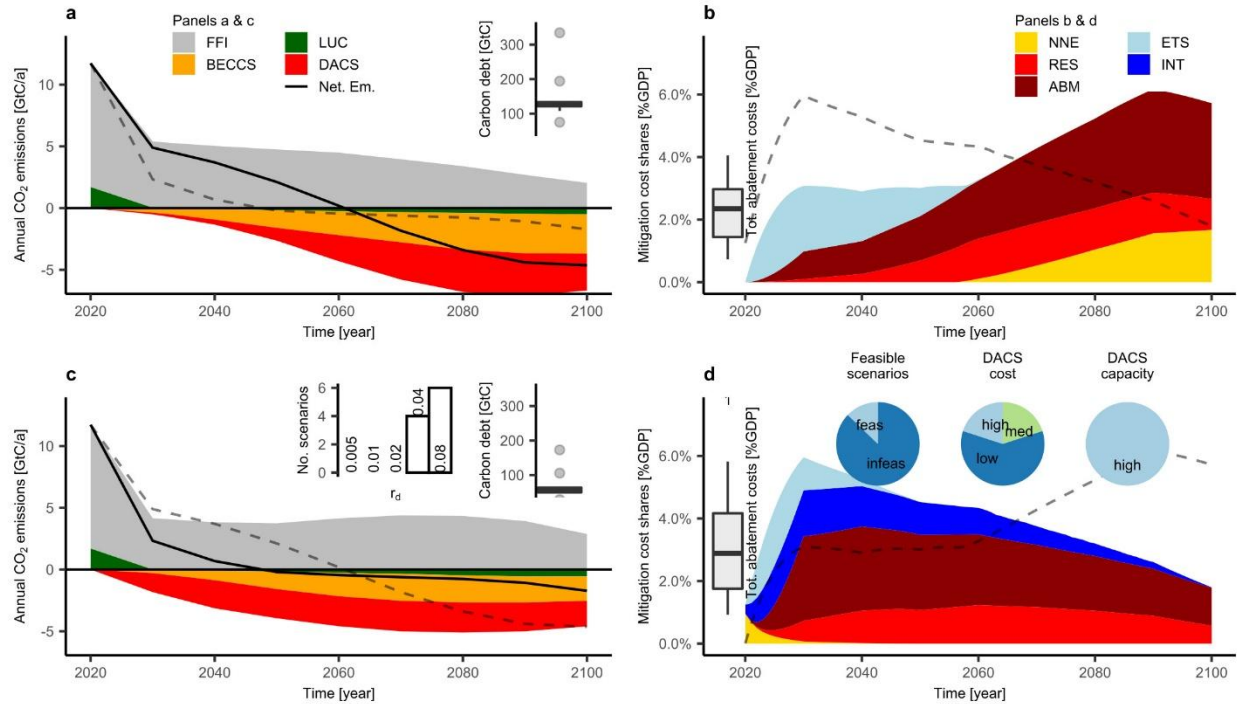
$r_d = 0$  (panel a) and  $r_d = 0.08$  (panel b). For  $r_d = 0$  we observe an inverse relation between the level of carbon debt and abatement costs; and the capacity limit is a stronger determinant of abatement costs than DACS deployment costs. This “discounting effect” is reversed when  $r_d = 0.08$  and high levels of  $D$  are penalized. In this case, lower abatement costs are realized by lower carbon debt (and vice versa). For both rates  $r_d$  “LoCost\_HiCap” DACS scenarios are characterized by the lowest abatement costs, however, at very different levels of  $D$ . When interest is invoked DACS deployments costs become an increasingly important determinant of total abatement costs. **Panels c & d: Distribution of total carbon debt  $D$  (panel c) and abatement costs (panel d) for the median values shown in panels a & b.** Boxes indicate the 25-75% interquartile ranges around medians (bold solid line), whiskers indicate min to max ranges, black dots mark outliers.



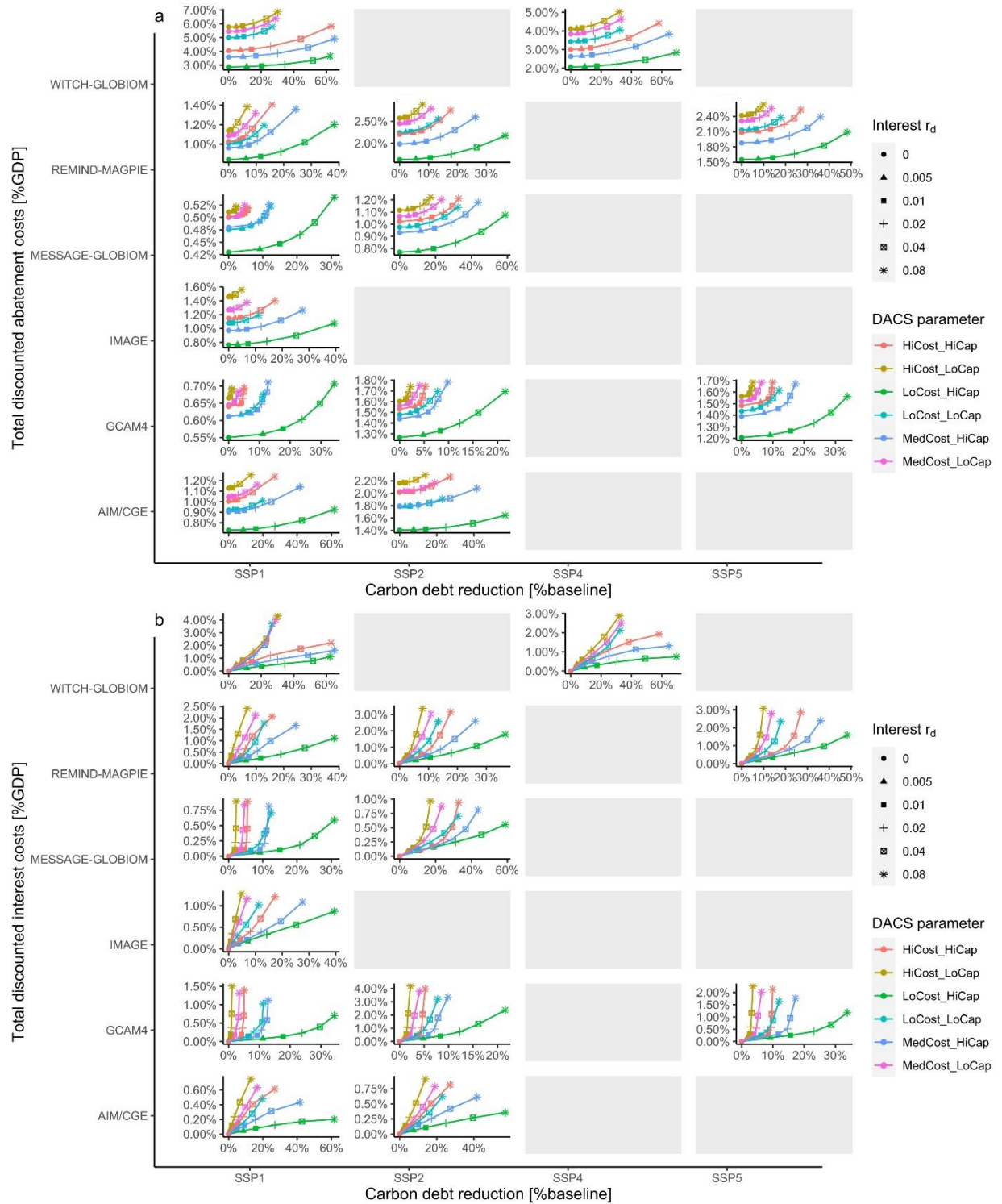
**Extended Data Figure 3 | 1.5°C (RCP1.9) pathways under a conventional ETS (panels a and b) compared to a CRO-ETS (panels c and d).** The underlying set of scenarios was filtered for those scenarios that achieve at least a 5% reduction of total carbon debt compared to their baselines (see Methods). **Panels a and c:** Geometric median net emissions (solid line) and gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS), land use change (LUC) and direct air capture and storage (DACs). Net emissions from panel a are also displayed in panel c (dashed line) and vice-versa. Total carbon debt  $D$  is shown as box-and-whiskers plot. Boxes indicate the 25-75% interquartile range around median values (bold line), whiskers indicate min to max ranges, points mark the outliers. **Panels b and d:** Annual mitigation costs as GDP percentage, including the share of average abatement costs attributed to emission reductions (ABM), to compensation of residual emissions by CDR (RES) and to net negative emissions (NNE) as well as expenditures for allowances (ETS) and interest costs (INT). Total mitigation costs (i.e., ABM+RES+NNE+ETS+INT) from panel d are also displayed in panel b (dashed line) and vice-versa. Box-and-whiskers plots show total discounted abatement costs (i.e., ABM+RES+NNE) as GDP percentage, the number above the chart indicates out-of-range outliers. Pie charts in panel d summarize properties of the underlying set of scenarios (see Methods). The distribution of  $r_d$  in CRO-ETS scenarios is depicted in panel c.



**Extended Data Figure 4 | 1.5°C (RCP1.9) pathways under a conventional ETS (panels a and b) compared to a CRO-ETS (panels c and d).** The underlying set of scenarios was filtered for those scenarios that achieve at least a 15% reduction of total carbon debt compared to their baselines (see Methods). **Panels a and c:** Geometric median net emissions (solid line) and gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS), land use change (LUC) and direct air capture and storage (DACs). Net emissions from panel a are also displayed in panel c (dashed line) and vice-versa. Total carbon debt  $D$  is shown as box-and-whiskers plot. Boxes indicate the 25-75% interquartile range around median values (bold line), whiskers indicate the min to max ranges, points mark the outliers. **Panels b and d:** Annual mitigation costs as GDP percentage, including the share of average abatement costs attributed to emission reductions (ABM), to compensation of residual emissions by CDR (RES) and to net negative emissions (NNE) as well as expenditures for allowances (ETS) and interest costs (INT). Total mitigation costs (i.e., ABM+RES+NNE+ETS+INT) from panel d are also displayed in panel b (dashed line) and vice-versa. Box-and-whiskers plots show total discounted abatement costs (i.e., ABM+RES+NNE) as GDP percentage, the number above the chart indicates out-of-range outliers. Pie charts in panel d summarize properties of the underlying set of scenarios (see Methods). The distribution of  $r_d$  in CRO-ETS scenarios is depicted in panel c.

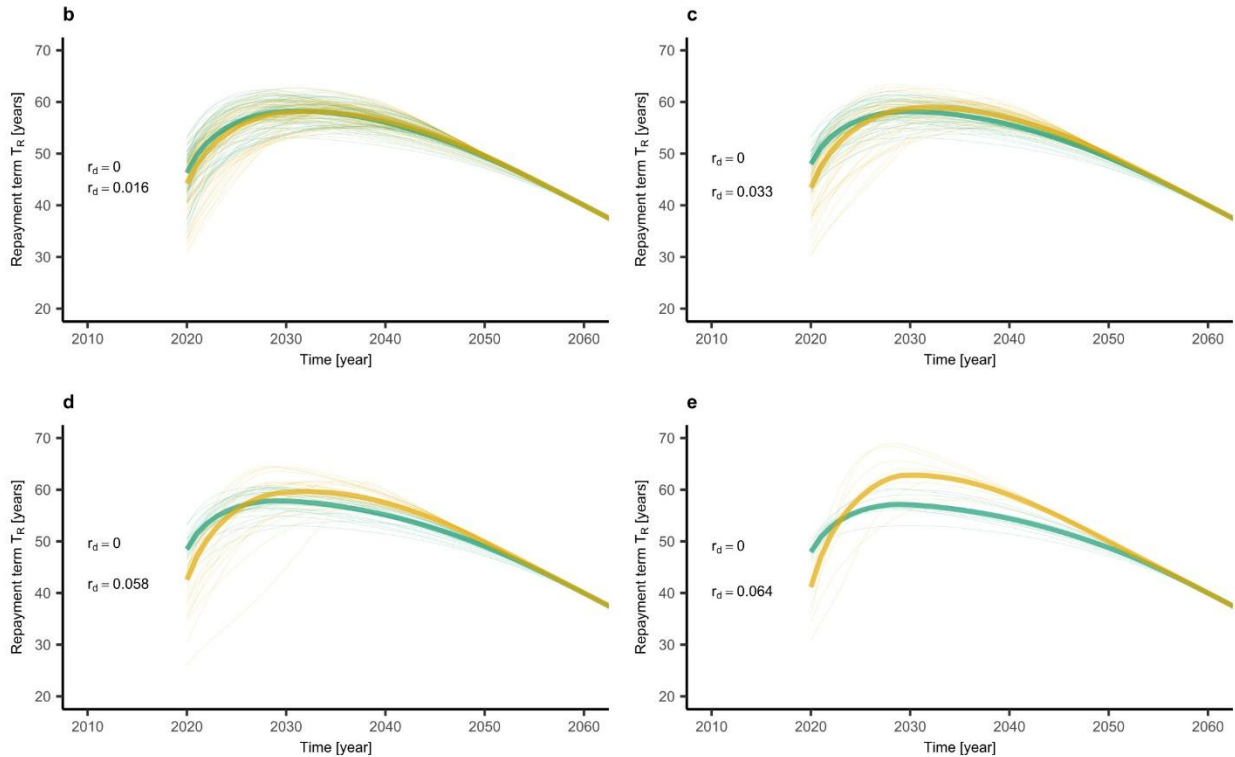
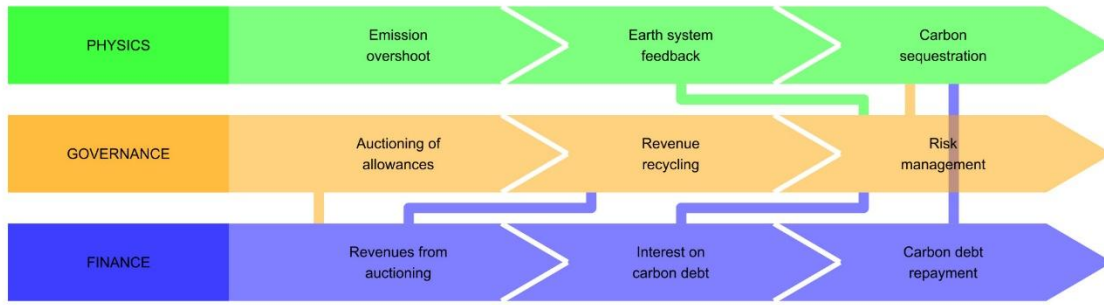


**Extended Data Figure 5 | 1.5°C (RCP1.9) pathways under a conventional ETS (panels a and b) compared to a CRO-ETS (panels c and d).** The underlying set of scenarios was filtered for those scenarios that achieve at least a 45% reduction of total carbon debt compared to their baselines (see Methods). **Panels a and c:** Geometric median net emissions (solid line) and gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS), land use change (LUC) and direct air capture and storage (DACs). Net emissions from panel a are also displayed in panel c (dashed line) and vice-versa. Total carbon debt  $D$  is shown as box-and-whiskers plot. Boxes indicate the 25-75% interquartile range around median values (bold line), whiskers indicate the min to max ranges, points mark the outliers. **Panels b and d:** Annual mitigation costs as GDP percentage, including the share of average abatement costs attributed to emission reductions (ABM), to compensation of residual emissions by CDR (RES) and to net negative emissions (NNE) as well as expenditures for allowances (ETS) and interest costs (INT). Total mitigation costs (i.e., ABM+RES+NNE+ETS+INT) from panel d are also displayed in panel b (dashed line) and vice-versa. Box-and-whiskers plots show total discounted abatement costs (i.e., ABM+RES+NNE) as GDP percentage, the number above the chart indicates out-of-range outliers. Pie charts in panel d summarize properties of the underlying set of scenarios (see Methods). The distribution of  $r_d$  in CRO-ETS scenarios is depicted in panel c.

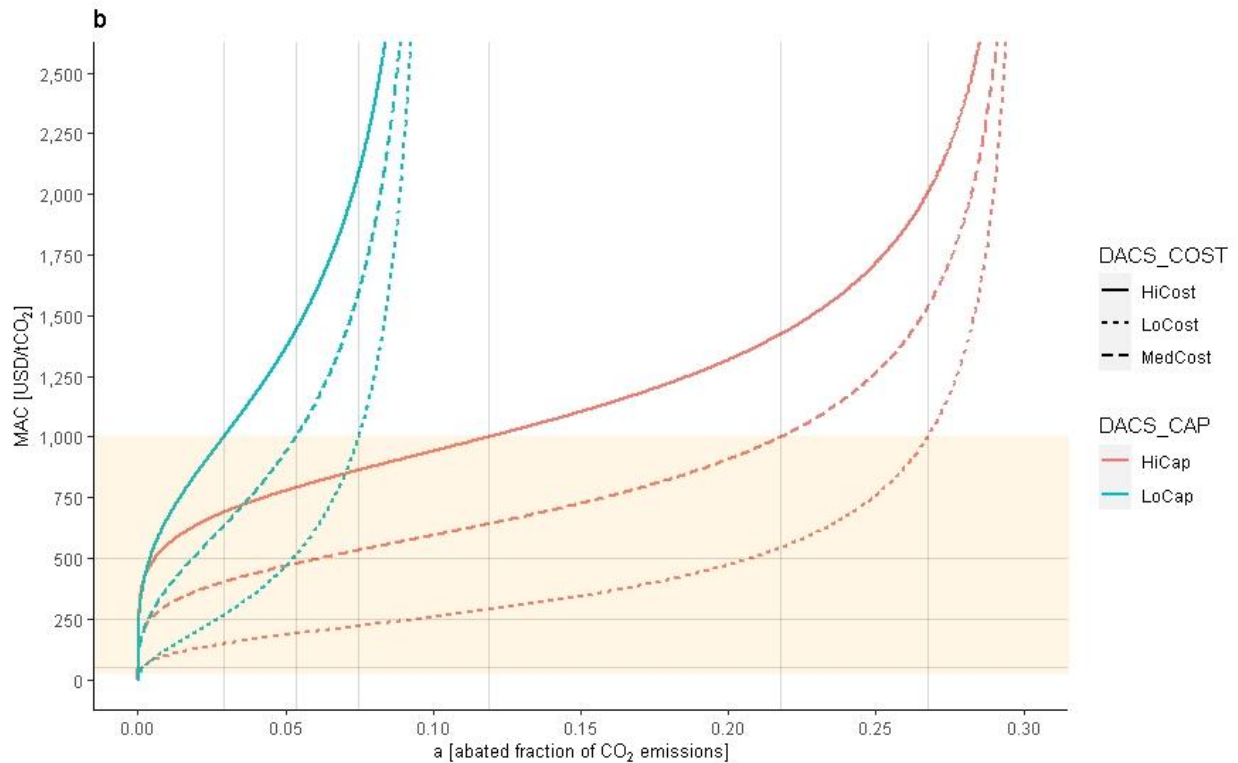
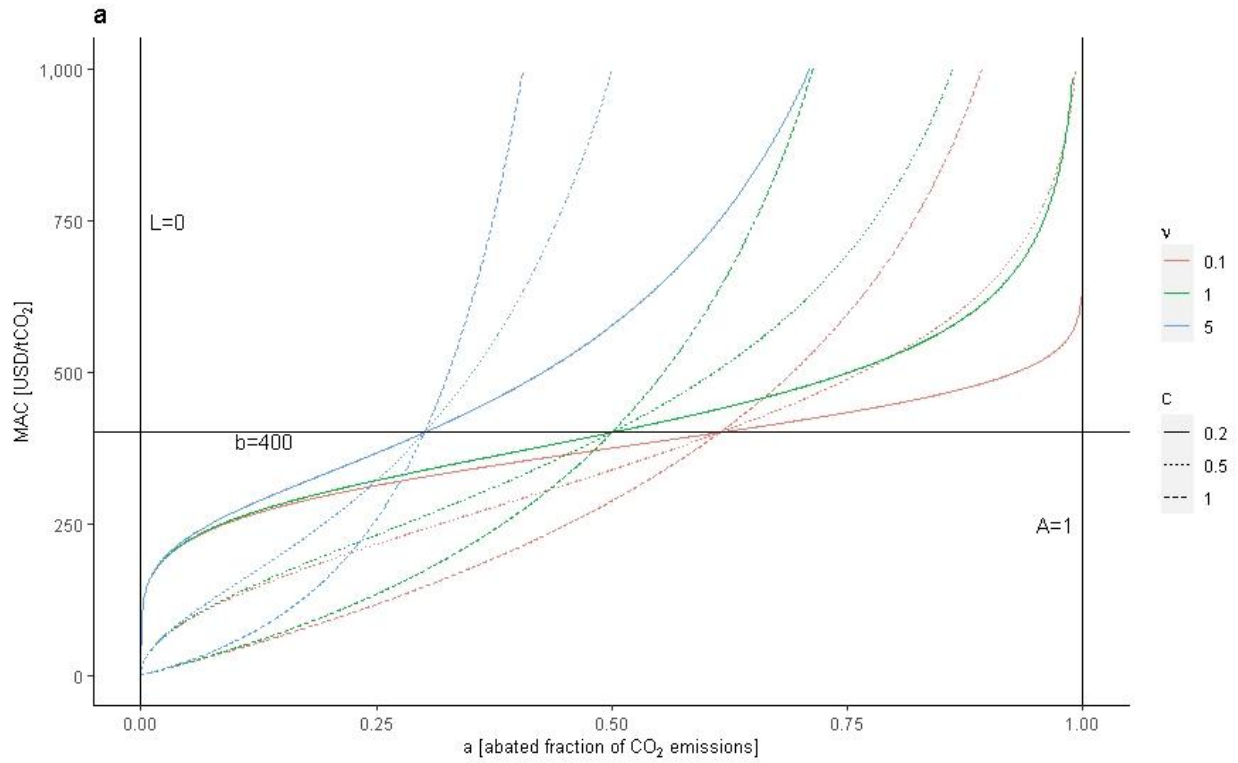


**Extended Data Figure 6 | 1.5°C (RCP1.9) scenarios' abatement costs (panel a) and interest costs (panel b) as function of percentage carbon debt reduction compared to the baseline scenario, i.e., where  $r_d = 0$ , for all 468 RCP1.9 scenarios, grouped by the carbon debt interest rate ( $r_d$ ) and cost and capacity parameters of direct air capture and storage (DACs). DACS cost parameters range from low to high, i.e., "LoCost", "MedCost", "HiCost"; capacity limits include 10% and 30% of baseline emissions, i.e., "LoCap" and "HiCap". **Panel a:** Total discounted abatement costs excluding interest costs (i.e., ABM + RES + NNE as in Figure 4 and Extended Data Figure 7-9). **Panel b:** Total discounted interest costs (i.e. INT as in Figure 4 and Extended Data Figures 7-9).**

a



**Extended Data Figure 7 | Schematic overview and illustrative repayment terms of RCP1.9 scenarios. Panel a:** Schematic overview of the CRO-ETS. The physical overshoot of a cumulative emission target, potentially amplified by outgassing of CO<sub>2</sub> from the Earth's stocks, subsequently necessitates carbon sequestration for returning to the target. For accrued carbon debt CROs are issued, obliging emitters to compensate for a tonne of CO<sub>2</sub> before a specified maturity, e.g., by physically removing atmospheric CO<sub>2</sub> or by acquiring an adequate quantity of allowances in the future. Similar to financial debt, CROs require debtors to pay interest to hedge physical and financial risks associated with carbon debt. Three earmarked financial resources are created under a CRO-ETS (1) Revenues from auctioning allowances are recycled into the economy to the benefit of society. (2) Revenues from interest on carbon debt are targeted at managing risks, i.e., by enabling additional carbon sequestration when Earth system risks (e.g., permafrost thaw) and financial risks (e.g., default risk of debtors) materialize. (3) Funds for repayment of carbon debt are individually managed by debtors. **Panels b-e:** Repayment term function  $T_R(t)$  for the scenarios illustrated in Extended Data Figure 7 (panel b), Extended Data Figure 8 (panel c), Figure 4 (panel d) and Extended Data Figure 9 (panel e). Interest on carbon debt  $r_d$  reflects the mean values of the distributions shown in panel c of these figures. Bold lines indicate geometric median repayment-terms derived from scenarios presented in these figures.  $T_R(t)$  maps the timing of carbon debt accrual to the time of its compensation; see Methods. For instance, in panel c carbon debt accrued in 2020 is compensated approximately 40 years later in scenarios with interest ( $r_d=0.058$ , yellow lines) and roughly 50 years later in scenarios where  $r_d=0$  (turquoise lines). As  $r_d$  is increased, the net zero year moves closer, implying that carbon debt in 2020 is compensated earlier, while in general  $T_R$  extends over longer periods. The increasingly flat net negative emissions profile (when  $r_d$  is increased) implies that  $T_R$  increases more rapidly in the beginning than when  $r_d=0$  because cumulative carbon debt at  $t$  grows faster than cumulative net negative emissions at  $t+T_R(t)$ . The point of inflection indicates where cumulative carbon debt begins to grow more slowly than cumulative net negative emissions compensating that carbon debt. For instance, in panel d (yellow line) cumulative carbon debt from 2030 onwards grows at a slower pace than cumulative net negative emissions approximately 63 years later.



**Extended Data Figure 8 | Marginal abatement cost curves.** Panel a: The functional form of marginal abatement costs,  $MAC(a) = b * \left( \frac{1}{v} * \left( \frac{L-A}{a-A} \right)^v - 1 \right)^c$ , is derived from the inverse generalized logistic function. It is relatively flexible with respect to replicating a wide range of MAC curves derived from the SSP database. Here  $A=1$  and  $L=0$  are upper and lower asymptotes along the y-axis. Crucially,  $MAC(a = A) = \infty$ , therefore  $A$  is a maximum abatement rate built into the MAC curve.  $b$  defines the y-position of the pivot point. The x-position of the pivot point is determined by  $v$ , and for  $v = 1$  it is exactly the middle of the interval  $(L, A)$ ,  $\frac{L+A}{2}$ .  $c$  defines the level of rotation with respect to the pivot point. Panel b: Six stylized MAC curves for

direct air capture and storage (DACS) covering the literature range for costs from 20 to 1000 USD/tCO<sub>2</sub> (orange area). Low-cost MACCs (dotted lines) start at approximately 50 USD/tCO<sub>2</sub> and reach 1000 USD/tCO<sub>2</sub> at abatement rates  $a_{DACS} = 0.07$  (low capacity, blue line) and  $a_{DACS} = 0.27$  (high capacity, red line) equivalent to approximately 3 and 12 GtCO<sub>2</sub>/a at current emission levels, respectively. Medium cost MAC curves (dashed lines) start at 250 USD/tCO<sub>2</sub> and reach 1000 USD/tCO<sub>2</sub> at  $a_{DACS} = 0.05$  (low capacity, blue line) and  $a_{DACS} = 0.22$  (high capacity, red line), i.e. roughly 2 and 10 GtCO<sub>2</sub>/a at current emission levels, respectively. High cost MAC curves (solid lines) start at approximately 500 USD/tCO<sub>2</sub> and reach 1000 USD/tCO<sub>2</sub> at  $a_{DACS} = 0.03$  (low capacity, blue line) and  $a_{DACS} = 0.12$  (high capacity, red line), amounting to roughly 1 and 5 GtCO<sub>2</sub>/a at current emission levels, respectively.

# ANNEX 4

Supplementary Information  
for Chapter 4

# The Carbon Removal Obligation

## Updated analytical model and scenario analysis

Johannes Bednar, Artem Baklanov, Justin Macinante

### Supplementary information

The partial derivative of a function  $f(x_1, \dots, x_n)$  with respect to the variable  $x_i$  is denoted by  $D_i f$ .

**Theorem 1** Consider an *original problem*:

$$\min_{x(\cdot) \in \mathcal{X}} \int_{\tau}^{\theta} f(t, x(t)) dt \quad (1)$$

s.t. some additional constraints on  $x(\cdot)$ . Here  $\mathcal{X}$  denotes the set of all continuous functions  $x(\cdot) : [\tau, \theta] \rightarrow X$ , the set of admissible solutions. We assume that

1.  $X$  is a non-empty convex compact subset of  $\mathbb{R}$  with non-empty interior  $\text{Int } X$ ;
2.  $f$  is continuous in  $[\tau, \theta] \times X$ ;
3. function  $f(t, \cdot)$  is strictly convex on  $X$  and differentiable on  $\text{Int } X$  for all  $t \in [\tau, \theta]$ ;
4.  $D_2 f$ , the derivative of  $f$  w.r.t to the second variable, is continuous in  $[\tau, \theta] \times \text{Int } X$  and has continuous extension to  $[\tau, \theta] \times X$ ;
5. the optimal solution  $x^*(\cdot)$  of (1) exists in the class of continuous functions such that  $x^*(t) \in \text{Int } X \forall t \in [\tau, \theta]$ .

We claim that the same optimal solution holds in the following *modified (constraint-free)* problem:

$$\min_{x(\cdot) \in \mathcal{X}^{pw}} \int_{\tau}^{\theta} [f(t, x(t)) - D_2 f(t, x^*(t))x(t)] dt \quad (2)$$

where  $x^*$  is the optimal solution in the original problem and  $\mathcal{X}^{pw}$  denotes the set of all piece-wise continuous functions  $x(\cdot) : [\tau, \theta] \rightarrow X$ . Note that now additional constraints are omitted and admissible solutions can be piece-wise continuous.

*Proof.*

- From a necessary and sufficient condition for a minimum in an elementary optimal control problem<sup>1</sup>, it follows that any piece-wise continuous function  $\hat{x} : [\tau, \theta] \rightarrow X$  that satisfies

$$\min_{x \in X} f(t, x) - D_2 f(t, x^*(t))x = f(t, \hat{x}(t)) - D_2 f(t, x^*(t))\hat{x}(t) \quad (3)$$

for every point of continuity of  $\hat{x}$  yields the global minimum in the modified problem.

- Note that for any  $t \in [\tau, \theta]$

$$x \mapsto f(t, x) - D_2 f(t, x^*(t))x : X \longrightarrow \mathbb{R} \quad (4)$$

is a strictly convex function defined on convex set  $X$ . Hence, we have two properties: (i) any local minimum is also a global one in  $X$  and (ii) the point of the global minimum is unique.

- By properties (i) and (ii), any stationary point of function (4) that is admissible (belongs to  $X$ ) is the unique solution of the problem in the left-hand side of (3).
- By combining strict convexity and the first-order condition for local extrema, we obtain that for any  $t$ ,  $x^*(t)$  is a unique stationary point of function (4), which is also admissible by the definition since  $x^*(t) \in \text{Int } X$ . Hence,  $x^*$  satisfies property (3):  $\forall t \in [\tau, \theta]$

$$\min_{x \in X} f(t, x) - D_2 f(t, x^*(t))x = f(t, x^*(t)) - D_2 f(t, x^*(t))x^*(t).$$

- Finally,  $x^*$  is the unique solution of (2) in the following sense: any solution of (2) will be equal almost everywhere to  $x^*$  (in the sense of Lebesgue measure). For example, the solutions may differ in a finite number of points but this will not influence the optimal result in (2).  $\square$

Note that Theorem 1 allows a straightforward extension to the case of two variables ( $x_1$  and  $x_2$ ):

**Theorem 2** Consider an *original problem*:

$$\min_{x_1(t), x_2(t) \in X} \int_{\tau}^{\theta} f(t, x_1(t), x_2(t)) dt \quad (5)$$

s.t. some additional constraints on  $x_1, x_2$ . Here  $\mathcal{X}$  denotes the set of all continuous functions  $x(\cdot) : [\tau, \theta] \rightarrow X$  such that  $x(t) \in X$ . We assume that

1.  $X$  is non-empty convex compact subset of  $\mathbb{R}$  with non-empty interior;
2.  $f$  is continuous in  $[\tau, \theta] \times X \times X$ ;

<sup>1</sup>see p.160 in Alekseev V.M., Tikhomirov V.M., Fomin S.V. *Optimal Control*. Springer Science + Business Media, New York (1987)

3.  $f(t, \cdot, \cdot)$  is strictly convex on  $X \times X$  and differentiable on  $\text{Int } X \times \text{Int } X$  for all  $t \in [\tau, \theta]$ ;
4.  $D_2 f, D_3 f$  are continuous in  $[\tau, \theta] \times \text{Int } X \times \text{Int } X$  and have continuous extensions to  $[\tau, \theta] \times X \times X$ ;
5. the optimal solution  $x_1^*(\cdot), x_2^*(\cdot)$  of (5) exists in the class of continuous functions such that  $x_1^*(\cdot), x_2^*(\cdot) \in \text{Int } X \forall t \in [\tau, \theta]$ .

We claim that the same optimal solution holds in the following *modified (constraint-free) problem*:

$$\min_{x_1, x_2 \in \mathcal{X}^{pw}} \int_{\tau}^{\theta} [f(t, x_1(t), x_2(t)) - x_1(t) D_2 f(t, x_1^*(t), x_2^*(t)) - x_2(t) D_3 f(t, x_1^*(t), x_2^*(t))] dt \quad (6)$$

where  $x^*$  is the optimal solution in the original problem and  $\mathcal{X}^{pw}$  denotes the set of all piece-wise continuous functions  $x(\cdot) : [\tau, \theta] \rightarrow X$  such that  $x(t) \in X$ . Note that now additional constraints are omitted and admissible solutions can be piece-wise continuous.

**How we use Theorem 2.** In the paper, we deal with the problem

$$\min_{\alpha, \mu} \int_{T_0}^T f_c(t, \alpha(t), \mu(t)) e^{-R(t-T_0)} dt, \quad (7)$$

s.t. the additional scenario-specific constraints. For applying Theorem 2, we need to transform variables  $\alpha(t)$  and  $\mu(t)$  such that their ranges of possible values do not depend on time, i.e., we will introduce normalised versions of this variables with the constant range.

First, let us recall the definitions of cost functions:

$$f_c(t, \alpha(t), \mu(t)) = E(t) \left( \int_0^{\alpha(t)} f_{\alpha}(t, a) da + \int_0^{\mu(t)} f_{\mu}(t, a) da \right)$$

$$f_i(t, a) = Q_i(t) \left( \frac{a}{U_i(t) - a} \right)^{C_i}, C_i > 0, i = \alpha, \mu,$$

where  $Q_i, U_i : [T_0, T] \rightarrow (0, \infty)$  are given continuous functions.

Second, by using the following transformations for variables

$$\tilde{\alpha}(t) = \frac{\alpha(t)}{U_{\alpha}(t)}, \tilde{\mu}(t) = \frac{\mu(t)}{U_{\mu}(t)}, \quad (8)$$

we modify the cost functions:

$$\tilde{f}_i(t, a) = Q_i(t) \left( \frac{a}{1 - a} \right)^{C_i}, i = \alpha, \mu;$$

$$\tilde{f}_c(t, \tilde{\alpha}(t), \tilde{\mu}(t)) = E(t) \left( U_{\alpha}(t) \int_0^{\tilde{\alpha}(t)} \tilde{f}_{\alpha}(t, a) da + U_{\mu}(t) \int_0^{\tilde{\mu}(t)} \tilde{f}_{\mu}(t, a) da \right).$$

The relationship between functions is quite straightforward:

$$\tilde{f}_c(t, \tilde{\alpha}(t), \tilde{\mu}(t)) = f_c(t, \tilde{\alpha}(t)U_\alpha(t), \tilde{\mu}(t)U_\mu(t));$$

$$\tilde{f}_i(t, a) = f_i(t, aU_i(t)), i = \alpha, \mu.$$

Note that tilde sign ( $\tilde{\phantom{x}}$ ) indicates that the object operates with transformed variables.

Third, we specify Theorem 2 for our case:

$$f(\hat{t}, \hat{x}_1, \hat{x}_2) = \tilde{f}_c(\hat{t}, \hat{x}_1, \hat{x}_2)e^{-R(\hat{t}-T_0)}; x_1 = \tilde{\alpha}, x_2 = \tilde{\mu}, \tau = T_0, \theta = T.$$

We assume that  $X = [\epsilon, 1 - \epsilon]$ , where  $\epsilon > 0$  is small enough to not influence the optimal solution. Given the form of the function of total costs, the existence of optimal solutions is sufficient for such  $\epsilon$  to be well defined. Hence the normalised abatement rate at instant  $t$  can be in the range  $[\epsilon, 1 - \epsilon]$ . Introduction of such  $\epsilon$  is also a standard practice in numerical optimisation.

Then

$$D_2 f(t, \tilde{\alpha}, \tilde{\mu}) = e^{-R(t-T_0)} D_2 \tilde{f}_c(t, \tilde{\alpha}, \tilde{\mu}) = e^{-R(t-T_0)} E(t)U_\alpha(t) \tilde{f}_\alpha(t, \tilde{\alpha}),$$

$$D_3 f(t, \tilde{\alpha}, \tilde{\mu}) = e^{-R(t-T_0)} D_3 \tilde{f}_c(t, \tilde{\alpha}, \tilde{\mu}) = e^{-R(t-T_0)} E(t)U_\mu(t) \tilde{f}_\mu(t, \tilde{\mu}).$$

Thus, the original problem is

$$\min_{\tilde{\alpha}(t), \tilde{\mu}(t) \in [\epsilon, 1-\epsilon]} \int_{T_0}^T \tilde{f}_c(t, \tilde{\alpha}(t), \tilde{\mu}(t)) e^{-R(t-T_0)} dt, \quad (9)$$

s.t. the same constraints as in (7) that are accordingly adjusted. Note that solutions of (7) after normalisation (8) are exactly the solutions of (9). This follows from our definitions of all functions with tilde sign<sup>2</sup>. The modified problem for (9), in the context of Theorem 2, is as follows

$$\begin{aligned} \min_{\tilde{\alpha}(t), \tilde{\mu}(t) \in [\epsilon, 1-\epsilon]} \int_{T_0}^T & [\tilde{f}_c(t, \tilde{\alpha}(t), \tilde{\mu}(t)) \\ & - E(t) \tilde{f}_\alpha(t, \tilde{\alpha}^*(t)) U_\alpha(t) \tilde{\alpha}(t) \\ & - E(t) \tilde{f}_\mu(t, \tilde{\mu}^*(t)) U_\mu(t) \tilde{\mu}(t)] e^{-R(t-T_0)} dt \quad (10) \end{aligned}$$

By using (8), we restore our original variables obtaining the equivalent of (10):

$$\begin{aligned} \min_{\substack{\alpha(t) \in [\epsilon U_\alpha(t), (1-\epsilon) U_\alpha(t)], \\ \mu(t) \in [\epsilon U_\mu(t), (1-\epsilon) U_\mu(t)]}} \int_{T_0}^T & [f_c(t, \alpha(t), \mu(t)) \\ & - E(t) f_\alpha(t, \alpha^*(t)) \alpha(t) \\ & - E(t) f_\mu(t, \mu^*(t)) \mu(t)] e^{-R(t-T_0)} dt \quad (11) \end{aligned}$$

<sup>2</sup>We thank Mikhail Gomoyunov for hinting us to use the elegant transformation instead of proving Theorem 2 for a more general case.

Recall that  $e(t) = E(t)(1 - \alpha(t))$  and  $r(t) = E(t)\mu(t)$ . Since  $P_\alpha(t) = f_\alpha(t, \alpha^*(t))$ ,  $P_\mu(t) = f_\mu(t, \mu^*(t))$ , we have that (11) takes the form

$$\begin{aligned} \min_{\substack{\alpha(t) \in [\epsilon U_\alpha(t), (1-\epsilon)U_\alpha(t)], \\ \mu(t) \in [\epsilon U_\mu(t), (1-\epsilon)U_\mu(t)]}} \int_{T_0}^T [f_c(t, \alpha(t), \mu(t)) \\ + P_\alpha(t) \underbrace{E(t)(1 - \alpha(t))}_{e(t)} \\ - P_\mu(t) \underbrace{E(t)\mu(t)}_{r(t)} - \Delta(t)] e^{-R(t-T_0)} dt \quad (12) \end{aligned}$$

where  $\Delta(t) = P_\alpha(t)E(t)$  does not depend on  $\alpha, \mu$  hence can be omitted since we aim only for optimal  $\alpha, \mu$ . In this sense, problem (12) is equivalent to the following problem

$$\min_{\alpha, \mu} \int_{T_0}^T [f_c(t, \alpha(t), \mu(t)) + P_\alpha(t)e(t) - P_\mu(t)r(t)] e^{-R(t-T_0)} dt. \quad (13)$$

Finally, we conclude that (13) is indeed solved by optimal  $\alpha^*, \mu^*$  of (7); this result was used in the main text.

**Remark:** Theorem 2 requires for  $\tilde{f}_c(t, \cdot, \cdot)e^{-R(t-T_0)}$ , in particular, to have continuous partial derivatives and to be strictly convex in  $[\epsilon, 1 - \epsilon] \times [\epsilon, 1 - \epsilon]$  for any  $t \in [T_0, T]$ . Note that the multiplier  $e^{-R(t-T_0)}$  does not play an important role since it is a positive constant for any instant  $t$ , so we focus only on  $\tilde{f}_c(t, \cdot, \cdot)$ . The costs are defined such that for a fixed  $t \in [T_0, T]$ , instantaneous cost function  $\tilde{f}_c(t, \cdot, \cdot)$  is twice continuously differentiable in  $[\epsilon, 1 - \epsilon] \times [\epsilon, 1 - \epsilon]$ , which implies continuous differentiability. This allows us to consider the Hessian matrix for  $\tilde{f}_c(t, \cdot, \cdot)$  being a function of two variables:

$$\mathbf{H}(\tilde{\alpha}, \tilde{\mu}) = \begin{pmatrix} E(t)U_\alpha(t) D_2 \tilde{f}_\alpha(t, \tilde{\alpha}) & 0 \\ 0 & E(t)U_\mu(t) D_2 \tilde{f}_\mu(t, \tilde{\mu}) \end{pmatrix}.$$

For  $\tilde{\alpha}, \tilde{\mu} \in [\epsilon, 1 - \epsilon]$ , this matrix is positive definite since  $E(t)U_i(t) > 0$ ,  $i = \alpha, \mu$ , and both derivatives are positive. Hence, this implies strict convexity of  $\tilde{f}_c(t, \cdot, \cdot)$ .

# ANNEX 5

Supplementary Information  
for Chapter 5

## Supplementary Information

### 1. Comparison between Original and Updated Proposals

In this supplementary information (SI) document, we use the term 'Original Proposal' to refer to the policy framework proposed by Bednar et al. (2021). In contrast, the 'Updated Proposal,' which is described in the main article, represents our revised approach.

The Original Proposal aimed to incentivize net carbon removals or net negative CO<sub>2</sub> emissions in order to address the carbon budget overshoot. It considered carbon debt as the result of net CO<sub>2</sub> emissions exceeding a 'temporally distributed instantaneous' (TDI) carbon budget, as explained in section 2 of this SI. The compensation for this carbon debt relied on net negative CO<sub>2</sub> emissions. Concurrently, the Original Proposal suggested incorporating carbon dioxide removal (CDR) activities, aimed at offsetting residual emissions (see Figure 1a in the main article for an explanation of the terminology), through an emissions trading scheme (ETS) alongside the main CRO mechanisms. This integration of the CDR market into both the ETS and the CRO framework was referred to as the 'CRO-ETS,' as illustrated in Figure S1e.

In contrast, the Updated Proposal in the main article considers carbon debt as the result of gross CO<sub>2</sub> emissions, which is then compensated for by gross removals over time. Carbon debt can be defined either as gross emissions occurring after depleting the remaining cumulative (RC) carbon budget (Figure S1a) or as gross emissions contemporaneously exceeding a pathway reflecting a TDI carbon budget (Figure S1c), as discussed in more detail in section 2. This adjustment to the principal CRO mechanism has significant implications:

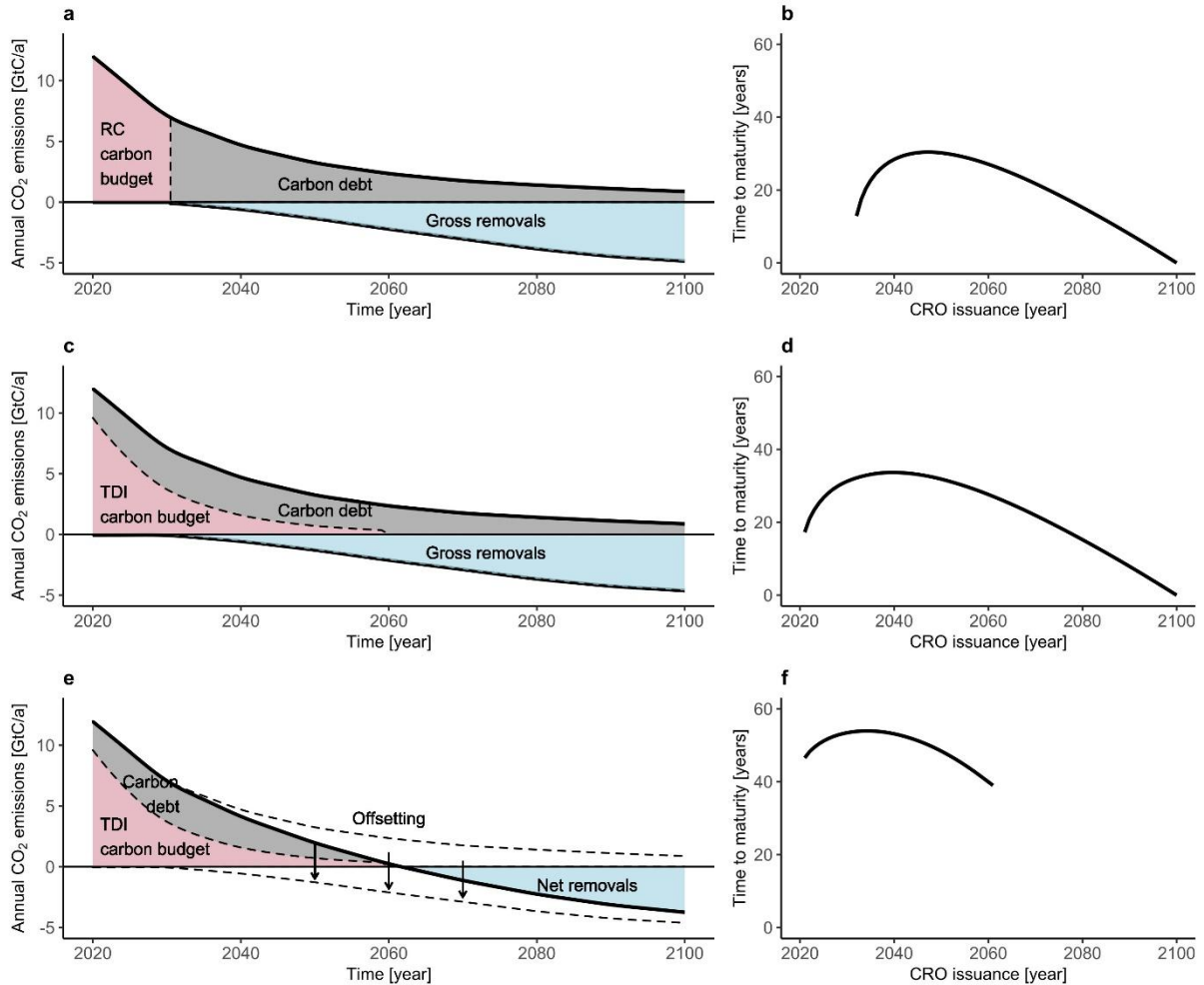
- i. By extending its scope from net to gross emissions, CROs are no longer restricted to financing net removals only. CROs now address CDR in general, regardless of entering the realm of net negative emissions. CROs aim to promote early uptake and innovation of CDR while managing the associated risks of CDR-based mitigation strategies.
- ii. The CDR market is disentangled from conventional carbon pricing, reducing the regulatory burden implied by the Original Proposal significantly.
- iii. A separate market for CDR allows for the possibility of diverging price levels between CDR and ERs, potentially influenced by different technological learning rates, as discussed in the main article. This divergence in price levels forms the basis for setting separate targets for ERs and CDR.
- iv. Unlike the Original Proposal, the separation of the CDR market from the ETS means that CROs and emission allowances are not fungible, as detailed in section 2.
- v. The CRO pricing instrument in the Updated Proposal adjusts price levels separately for ERs and CDR, impacting gross emissions and removals rather than net (negative) emissions. This is a departure from the Original Proposal, which aimed to control the net CO<sub>2</sub> emissions path in the CRO-ETS.
- vi. Maturities under the Updated Proposal, calculated based on gross emissions and removals, are significantly shorter compared to the Original Proposal. As gross removals typically ramp up before net removals, CRO holders can terminate their obligations earlier. For a

comparison, refer to panels b and d of Figure S1, illustrating the repayment term structures under the Updated Proposal, and panel f, reflecting the Original Proposal.

An extended comparison between elements of the Original and Updated Proposals is provided in Table S1.

*Table S1. Similarities and differences between the Original Proposal and the Updated Proposal.*

<b>Element</b>	<b>Original Proposal</b>	<b>Updated Proposal</b>
Carbon budget	There are two options for implementing carbon budgets into the CRO framework: Either (1) emissions following in time the date of depletion of the remaining cumulative (RC) carbon budget, or (2) emissions contemporaneously overshooting a temporally distributed instantaneous (TDI) carbon budget are considered carbon debt. The TDI carbon budget in sum equals the RC carbon budget.	
Carbon debt generation	Generated by net emissions overshooting the RC or TDI carbon budget.	Generated by gross emissions overshooting the RC or TDI carbon budget.
Carbon debt compensation	Compensated by net removals.	Compensated by gross removals (total CDR).
Role of conventional carbon pricing (ETS, carbon tax)	Charge a price for depleting the carbon budget. Required for offsetting of emissions with removals to achieve net zero transition and offsetting of residual emissions after net zero.	Charge a price for depleting the carbon budget. Ceases to exist when the RC carbon budget gets depleted, or when the TDI carbon budget becomes zero.
CDR market integration.	CDR market integration into conventional carbon pricing scheme and CRO framework. CROs can be discharged against emission allowances.	CDR market integration only into CRO framework. 'Removal units' are non-fungible with emission allowances.
Additionality	Credits generated by additionality principle are excluded from conventional pricing and CRO framework.	
Price of ERs	Established in ETS, equals CDR price, adjusted by CRO pricing.	After phase-out of conventional pricing only as shadow price induced by principal CRO mechanism and adjusted by CRO pricing.
Price of CDR	Established on CDR market integrated into ETS, equals ER price, adjusted by CRO pricing.	Established on CDR market. CDR market price depends on the amount of CROs (demand) and the marginal costs of removal units (supply). Demand for CROs adjusted by CRO pricing, which thus impacts on CDR price.
CRO pricing	Adjusts the single price path of ERs and CDR, thus, has an impact on the path of net emissions/removals.	Adjusts the separate prices of ERs and CDR, thus, has an impact on the paths of gross emissions and gross removals.
Target setting	Target setting is limited to net emissions/removals due to the single price path of ERs and CDR.	Separate targets for ERs and CDR can be achieved by inducing adequate price signals for ERs and CDR.
CRO maturities	Maturities reflect time horizon between net emissions and net removals, resulting in rather long maturities.	Maturities reflect time horizon between gross emissions and gross removals, resulting in much shorter maturities



**Figure S1: Panel a, c, e:** Elements characterizing different versions of the CRO policy framework. **Panels: b, d, e:** Repayment term structures showing the time to maturity in years as a function of the date of CRO issuance for the profiles shown in panels a, c, e. For an analytical definition see Bednar, Baklanov, and Macinante (2023). **Panel a:** Elements characterizing the CRO framework of the Updated Proposal as discussed in the main article of this Supplementary Information document. Carbon debt is generated by gross emissions once the remaining cumulative (RC) carbon budget has been depleted, here around 2030. Carbon debt is compensated intertemporally by gross removals. **Panel c:** Elements of the CRO framework according to the Updated Proposal given a temporally distributed instantaneous (TDI) carbon budget. The cumulative sum of the TDI carbon budget equals the RC carbon budget. Carbon debt is generated by gross emissions exceeding the TDI carbon budget (pink area). Carbon debt is compensated intertemporally by gross removals. In case a conventional carbon pricing scheme, like an emissions trading scheme (ETS) is operating in parallel to the CRO framework, the conventional pricing scheme is bound to the TDI carbon budget (pink). **Panel e:** Elements of the CRO-ETS according to the Original Proposal (Bednar et al. 2021). Carbon debt is generated by net emissions exceeding the TDI carbon budget (pink area). Carbon debt is intertemporally compensated by net removals. The emission caps over time of the linked ETS equal the TDI carbon budget. CDR integration into the ETS is required for contemporaneously offsetting gross emissions minus net emissions (blank part of gross emissions) with gross removals minus net removals (blank part of gross removals).

## 2. Transition scenarios for implementing the CRO framework with a positive RC carbon budget

In the main article, we make the assumption that gross emissions are equivalent to carbon debt, indicating the operationalization of the CRO framework upon depleting the RC carbon budget (see Figure S1a). Existing carbon pricing arrangements would cease to exist with the initialization of the CRO framework, for instance, the EU-ETS would require earlier retirement than currently anticipated. Here, we present two scenarios for implementing the CRO framework *before* the RC carbon budget is exhausted (see Figure S1c). It is assumed that economies derive benefits from fully utilizing the RC

carbon budget, hence, its depletion needs to be coordinated with the operation of the CRO framework:

**Scenario 1:** In this scenario, there is no carbon pricing scheme in place. The depletion of a regional RC carbon budget is projected to occur several decades into the future. The duration of depletion depends on the size of the RC carbon budget, which can be influenced by burden sharing arrangements (e.g., developing nations with limited responsibility for climate change have a relatively larger carbon budget than industrial nations) or the stringency of the climate target (a 2°C climate goal implies a larger RC carbon budget than 1.5°C). While an overshoot of the carbon budget is likely in this scenario, it is not certain. There is a political will to initiate efforts for CDR. The CRO framework is chosen as the preferred policy tool, regardless of the necessity for net carbon removals, due to its advantages in promoting CDR uptake and innovation through a standalone CDR market. Several integration options for the RC carbon budget are available:

#### Option 1: Sector-by-Sector Integration

Sectors are progressively integrated into the CRO framework while the remaining sectors are allowed to emit without paying for their emissions. This gradual integration leads to the depletion of the RC carbon budget over time, ensuring all sectors are integrated into the CRO framework when the carbon budget is fully depleted.

#### Option 2: Increasing Emissions-to-Carbon Debt Ratio

All sectors are integrated into the CRO framework, with the ratio of gross emissions to carbon debt gradually increasing. Initially, one tonne of gross CO<sub>2</sub> emissions may result in 0.5 tonnes of carbon debt, requiring the emitter to remove 0.5 tonnes of CO<sub>2</sub> in the future. Over time, this ratio is increased until it reaches one, indicating the depletion of the carbon budget.

**Scenario 2:** In this scenario, an ETS is already in operation, and the depletion of the regional RC carbon budget is estimated to occur within approximately a decade based on current emissions. It is highly likely that gross CO<sub>2</sub> emissions will surpass the RC carbon budget. The transition involves aligning emissions allowed under the ETS with the RC carbon budget, which would necessitate significant reductions in future allowances. Simultaneously, the CRO framework is gradually introduced alongside the ETS, and demand for the CDR market solely comes from CROs. The transition options are as follows:

#### Option 1: Sector-by-Sector Transition

Sectors are progressively transferred from the ETS to the CRO framework. Taking into account sector-specific marginal abatement costs, it is anticipated that the ETS price does not converge with the marginal costs associated with a CRO (i.e., the CRO Premium plus discounted future CDR price).

#### Option 2: Hybrid Approach

Emitters are mandated to cover a fraction of their gross CO<sub>2</sub> emissions with allowances under the ETS, while the remaining emissions are considered carbon debt and addressed through CROs. Over time, the ratio of CROs to allowances increases until it reaches one, indicating the depletion of the RC carbon budget and the discontinuation of the ETS.

#### Option 3: Emitter Choice

Emitters are granted flexibility to choose between obtaining allowances or acquiring CROs, providing a range of compliance options tailored to individual circumstances and promoting participation in both the ETS and the CRO framework.

Integrating the depletion of the RC carbon budget into the CRO framework or operating an ETS in parallel for that purpose (or a carbon tax, following a similar approach as described in Scenario 2) necessitates the definition of a TDI carbon budget, as shown in Figure S1c. The RC carbon budget is reflected by summing up the TDI carbon budget over time. Hence, the amount of carbon debt generated at each point in time is determined by gross emissions that exceed the TDI carbon budget at each point in time. The TDI carbon budget is needed for determining the time varying Emissions-to-Carbon Debt Ratio (Scenario 1) and for setting emission caps over time in an ETS (Scenario 2).

To ensure a smooth parallel operation between an ETS and a CRO framework, several considerations need to be addressed. Firstly, there might be a moral hazard associated with the continued issuance of allowances to emitters once the carbon budget has been depleted. It is crucial that the sum of emission caps over time accurately reflects the RC carbon budget, rather than simply continuing with the existing and scheduled caps.

During the gradual phase-out of the existing ETS sufficient notice to participant emitters should be provided to unwind their forward positions and utilize any remaining ETS allowances. It is anticipated that such a transitional period would run for a period of several years, while ETS allowances are typically surrendered on an annual basis. Hence, depending on the profile of the particular ETS in question, the transition period needs to be set to minimize any impacts resulting from the transition.

Furthermore, it is important to exclude credits generated through ERs or emission avoidance based on the principle of additionality from both the ETS and the CRO framework. This exclusion is vital to prevent double counting and maintain environmental integrity, ensuring accurate price signals and facilitating the achievement of climate targets set by the global RC carbon budget.

Moreover, it is crucial to note that in parallel operation, CROs and emission allowances are not fungible. If an ETS is still operational when a CRO reaches maturity, it would not be possible to discharge a CRO using an allowance. Allowing such trade would lead to convergence between the CDR market price and the ETS price, undermining the pricing mechanism of the CRO framework, which aims to incentivize separate price paths for ERs and CDR, as discussed in the main article.

### 3. Implementation

Interaction of public and private sector actors in implementation of the proposed CRO policy framework, as discussed at section 3.3 of the main article, is elaborated in Table S2 in terms of the particular element of the proposal and the actors' respective roles.

*Table S2: public sector and private sector roles and their interaction*

Element	Primary roles	Instrument or mechanism	Detail
Emissions = carbon debt	Government	Legislation	Created by primary legislation, establishes concept of carbon debt as financial debt.
Scheduled categories of emitters must measure emissions, report, have audited	Government/regulatory body/registry/carbon accounting and auditing bodies	Legislation/regulation/accounting and auditing rules	Part of new primary legislation; and amended corporate financial reporting regime.

Audited emissions included in emitters' accounts/balance sheet	Government/accounting bodies	Legislation/regulation	Rules to set out how emissions should be included in accounts as carbon debt/CROs.
Carbon debt formalised as a legal instrument in the form of Carbon Removal Obligation (CRO)	Government	Legislation	CRO instruments created by primary legislation to represent carbon debt in accounts of emitters; CRO legislatively defined as financial instrument; CRO measured in tonnes CO <sub>2</sub> ; CRO subject to a CRO Premium (i.e., interest).
Central bank mandate to implement government economic policy clarified to include carbon debt management in the economy	Government/central bank	Legislation/administrative action	Central bank given responsibility and the tools to manage carbon debt in the economy going forward.
CROs issued by commercial banks to emitter-customers; commercial banks must hold reserve accounts with central bank, on balance of which base rate interest (a CRO Base Premium) paid, hypothecated to future funding	Central bank	Legislation/central bank regulation	Commercial banks must ensure that sufficient CROs issued each year to cover emitter-customer annual carbon debt liability; Commercial banks run CRO reserve accounts with central bank, pay base rate interest (CRO Base Premium) on CRO balance held in reserve account (thus a function of how much their customer base is emitting at any point in time).
Commercial banks establish CRO accounts for their emitter-customers (at CRO Commercial Premium set in accordance with normal financial risk assessment but also climate risk assessment) (CRO Commercial Premium possibly subject to control by government policy or %	Commercial banks	Legislation/regulation/commercial banks' T&Cs for business customers. Commercial banks will need to hedge risk of defaulting customers.	Emitter-customers have obligation to show CROs in balance sheet commensurate with emissions; pay CRO Commercial Premium to commercial bank until CROs removed from balance sheet by retiring removal units. Commercial banks liable to central bank for defaulting customers.

also hypothecated to future funding)			
CRO repayment in standard-based removal units.	Government/national or international standards bodies	Legislation/regulation, including adoption of national or international standard for bundling CDR projects, standard-based removal units generated by projects that meet standard	Removal units generated by CDR projects; Removal units legislatively defined as financial instrument and also as a 'property right', in a legal sense; Removal units measured in tonnes CO <sub>2</sub> .
Emitter-customers of banks buy standard-based removal units in the market and cancel them to acquit CRO liabilities	CDR trading market platform, market participants, especially holders of CROs, project management companies selling standard-based removal units)	Trading rules, financial markets regulation. Potential for distributed ledger trading platform, with settlement in CBDC would enhance central bank carbon debt management capacity. Application of DLT would enable the provenance of removal units to be traced throughout their existence from issuance by the project to retirement, irrespective of how much they are traded (thus operates to prevent double counting, fraud, etc.)	Normal trading market; purchase/cancellation of standard-based removal units by emitter-customer reflected in adjustment to CROs in balance sheet; CRO Price payment by emitter-customer to CRO issuer bank, and by bank on its account with central bank reduced to reflect reduction in CRO liability on balance sheet.

As noted in section 3.4 of the main article, subject to resolution of some preliminary elements, the legal framework to implement the CRO policy proposal might comprise a package of three instruments: an enactment of primary legislation; development of a national (or international) standard; and secondary legislation (a regulation) to adopt the standard and implement the primary legislation. Details of these three instruments are set out in the following sections.

### Primary legislation

Thus, assuming a date, or time period, can be pinpointed when the global RC carbon budget, for the chosen temperature target, is determined to be expended and from which date (or period) emissions = carbon debt, the primary legislation might include elements set out in Table S3.

Table S3: Provisions in primary legislation

Element	Detail
➤ Legal framework overview	
➤ Legal framework objective	
➤ Introduce concept of carbon debt into law	
➤ Establish the related legal obligations, instruments and mechanisms to give effect to the legislative objective	
➤ set out roles and responsibilities of various parties	

<ul style="list-style-type: none"> <li>➤ provide for parties/entities to which obligations apply to be prescribed by regulation</li> </ul>	
<ul style="list-style-type: none"> <li>➤ related matters, including</li> </ul>	<ul style="list-style-type: none"> <li>➤ expanded monitoring, reporting and verification (MRV) – carbon removal obligations (CROs) might be based on scope 1 emissions only, but reporting obligations might include scope 1, 2 and 3 emissions;</li> <li>➤ provide for service providers in MRV to be certified and achieve specific skill, capacity, integrity levels;<sup>1</sup></li> <li>➤ that legal entities in prescribed categories must (a) report emissions; (b) hold CROs in respect of reported scope 1 emissions; (c) pay CRO Commercial Premium; and (d) disclose CRO holdings in their financial reporting and balance sheet;</li> <li>➤ that commercial banks (a) be authorized to issue CROs to customers that have obligations to hold CROs in respect of their reported emissions; (b) must each set up a CRO reserve account with the central bank; and (c) pay CRO Base Premium;</li> <li>➤ carbon debt is extinguished by CRO holders acquiring and retiring removal units; in the event that the CRO holder becomes insolvent without extinguishing their carbon debt, that obligation defaults to the commercial bank that issued the CROs;</li> <li>➤ removal units are generated and issued by CDR projects, in accordance with the Standard;</li> <li>➤ to generate and issue standard-based removal units, CDR projects must be accredited as satisfying the Standard; and</li> <li>➤ the project management company would be required to carry responsibility to ensure viability of the storage arrangements long-term, and this might be subject to formal legal ability to lift the corporate veil (that is, liability being passed through to company officers and/or shareholders in the event of fraud or mismanagement).</li> </ul>

### Standard

The purpose of the standard (“Standard”) would be to define minimum criteria for CDR projects and specify outcomes that the projects should achieve in order to be able to generate standard-based removal units. The mechanism put forward for implementation is proposed as one illustration of how it might proceed, rather than as the only one. All the same, it is noted that there is much activity in the EU, UK and other governments examining the introduction of such standards, as well as in standards organizations (BSI) and in the VCM (see ICVCM and also Climate Impact Exchange, Singapore (CIX)). As such, while the ultimate form of any such standard is yet to be determined, it seems reasonable to assume that a standard-based approach should form part of the proposed mechanism.

<sup>1</sup> European Securities and Markets Authority (ESMA) regulation of credit reference agencies (CRAs) provides one model for this.

The objectives would be to: ensure uniformity and consistency of outcomes across all projects; to identify risks and shortcomings of individual methods, in order to facilitate high integrity removal units; to apply an agreed taxonomy covering all CDR methods; and to ensure appropriate governance and high-level oversight and management of CDR project development within the jurisdiction (e.g., to avoid inappropriate application of resources; to avoid imbalances in land uses and/or CDR methods; ensure distribution of CDR projects conforms to objectives of local and national planning policies and laws).

Elements that the Standard might relate to: a minimum set of criteria for constituting the CDR project; minimum criteria for the outcomes the project would need to achieve; criteria addressing long-term management of the project; and elements addressing governance requirements. Table 4 sets out illustrations of what those elements might include.

Table 4S: Illustrations of minimum criteria elements of the Standard

Element	Minimum criteria
<ul style="list-style-type: none"> <li>➤ Elements addressing a baseline for how a project might be constituted</li> </ul>	<ul style="list-style-type: none"> <li>➤ Agreed scientific/technical community taxonomy: for example, The Royal Society; or other taxonomies proposed in the academic literature;</li> <li>➤ project lifetime say, at least [100] years (depends on definition of ‘permanence’);</li> </ul>
<ul style="list-style-type: none"> <li>➤ Elements addressing a baseline for the outcomes the project might achieve</li> </ul>	<ul style="list-style-type: none"> <li>➤ requirement that removals must all be real, permanent (as defined), verified;</li> <li>➤ project must be able to guarantee a minimum volume of removals over its lifetime at a more or less consistent rate;</li> <li>➤ Storage must be for say, at least [100] years, but this also depends on the accepted definition of ‘permanence’;</li> <li>➤ co-benefits (such as environmental, social, biodiversity-related, nature-enhancing) must be measured and reported annually;</li> <li>➤ prescribed actions for minimizing negative impacts (externalities, such as through conflicting land use issues).</li> </ul>
<ul style="list-style-type: none"> <li>➤ Elements addressing long-term management</li> </ul>	<ul style="list-style-type: none"> <li>➤ Operational management – must be planned; funded; annually audited;</li> <li>➤ Risk management – risks identified; management planned; funded; annually audited;</li> </ul>
<ul style="list-style-type: none"> <li>➤ Elements addressing governance</li> </ul>	<ul style="list-style-type: none"> <li>➤ MRV baseline, disclosure and transparency requirements (noting that MRV will vary according to the CDR method, so standard can only set out generic requirements unless each method addressed individually)</li> </ul>

Additionally, it is expected that the Standard would indicate: how the number of removal units that a project might issue would be calculated; set out delivery risk management requirements; set out any other risk management requirements; and indicate requirements pertaining to formation and management of the project. Table S5 sets out examples indicating what might be included in these requirements.

Table S5: Examples of further criteria required by the Standard

Further criteria	Detail
➤ Issuance of outcomes (standard-based removal units)	Formula to determine how many standard-based removal units result from the project, based on removal and storage criteria, possibly other factors needing to be included.
➤ Delivery risk management	Requirements might include: <ul style="list-style-type: none"> <li>➤ physical – % of removal units held as reserve buffer</li> <li>➤ financial - insurance</li> </ul>
➤ Other business and commercial risk management	Requirements might include: <ul style="list-style-type: none"> <li>➤ physical – % of removal units held as reserve buffer</li> <li>➤ financial - insurance</li> </ul>
➤ Project company formation and management	Requirements might include: <ul style="list-style-type: none"> <li>➤ individual CDR project developers need to form a legal structure (e.g. management company) which will be governed by the terms of the agreement reached between the developers of the project;</li> <li>➤ management company applies for certification under the Standard in order to be able to issue standard-based removal units;</li> <li>➤ application sets out how the project satisfies all the requirements of the Standard;</li> <li>➤ how the standard-based removal units are split between the project participants will be a matter for agreement between them in forming the project.</li> </ul>

### Secondary legislation

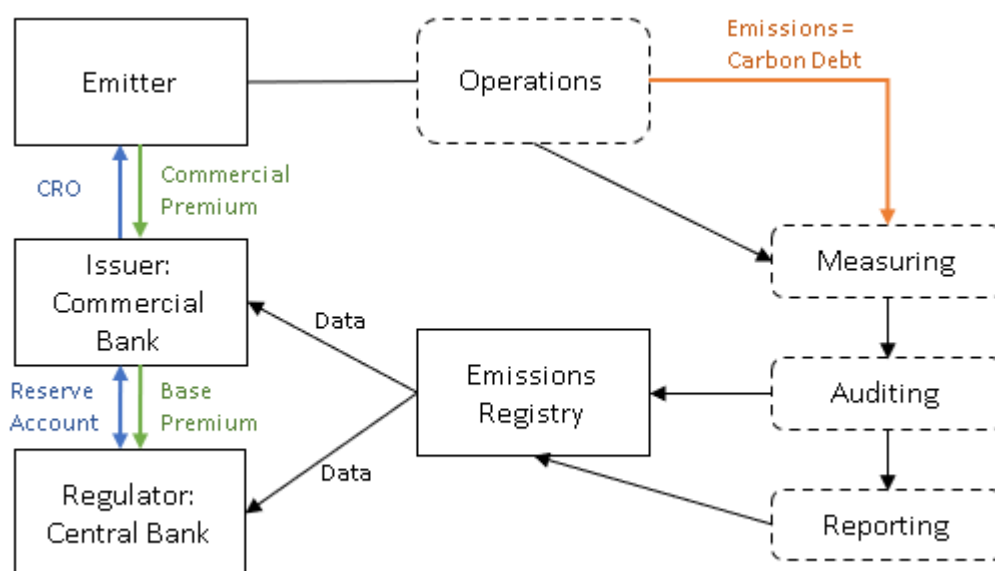
The regulation would implement and give effect to the primary legislation, including by adopting the Standard; prescribing categories of emitter entities whose emissions = carbon debt, represented by CROs that must be disclosed in their financial accounts; setting out operative elements of CROs; and defining concepts such as ‘permanence’ and ‘co-benefits’.

The regulation could elaborate the meaning given to a standard-based removal unit constituting a property right, that is, that the project that issues the removal unit has an obligation to maintain the storage for the specified period, and that this obligation is enforceable not just by the administrator

of the scheme for issuing removal units, but also by the party that acquires the unit. If the unit is cancelled, the party cancelling the unit would have a continuing right to enforce the obligation for the length of storage time associated with that removal unit. It might provide also that rights attaching to the removal unit would be distinct from any rights in the land or infrastructure associated with the project, or any other off-take from the project (biomass, energy, timber, etc.). The regulation could also prescribe minimum management measures (physical and financial) for storage, e.g., including against leakage risk/saturation risk/reversal risk – for instance, insurance or buffers for losses.

While these legislative instruments may be expressed only to become operational at a future date when the global RC carbon budget will be expended, it is both feasible and essential they are put in place expeditiously, ready for such future activation. Doing so would provide clarity and certainty to investors and other stakeholders, helping to incentivize the scaling up of the CDR sector. In the case of the Standard, steps to develop and promulgate it as soon as practicable would provide direction and guidance to future market participants.

### Mechanism for issuing CROs



*Figure S2. Mechanism for issuing carbon removal obligations (CROs) in relation to carbon debt: Legislation/regulation provides that prescribed categories of legal entities ('emitters') must reflect emissions as carbon debt on their balance sheet; Emissions (carbon debt) measured/reported/audited as it would be under an emission trading scheme (ETS), however, reporting is via financial accounts, as emitter must hold a CRO (legal instrument reflecting carbon debt in accounts) in respect of each tonne CO<sub>2</sub> emitted per annum; Commercial banks issue CROs to their emitter-customers, just as they would in a deposit account when lending to a customer. Thus, emitters must hold CRO accounts in respect of their annual emissions/carbon debt; Commercial banks charge interest (a 'CRO Commercial Premium') on CROs in the account; Role of central bank: CRO issuance initiated by each commercial bank, but commercial bank must hold reserve account with central bank, on which it pays interest (a 'CRO Base Premium').*

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- Bednar, Johannes, Michael Obersteiner, Artem Baklanov, Marcus Thomson, Fabian Wagner, Oliver Geden, Myles Allen, and Jim W. Hall. 2021. "Operationalizing the Net-Negative Carbon Economy." *Nature* 596 (7872): 377–83. <https://doi.org/10.1038/s41586-021-03723-9>.

# ANNEX 6

Supplementary Figures and Tables  
for Chapter 6

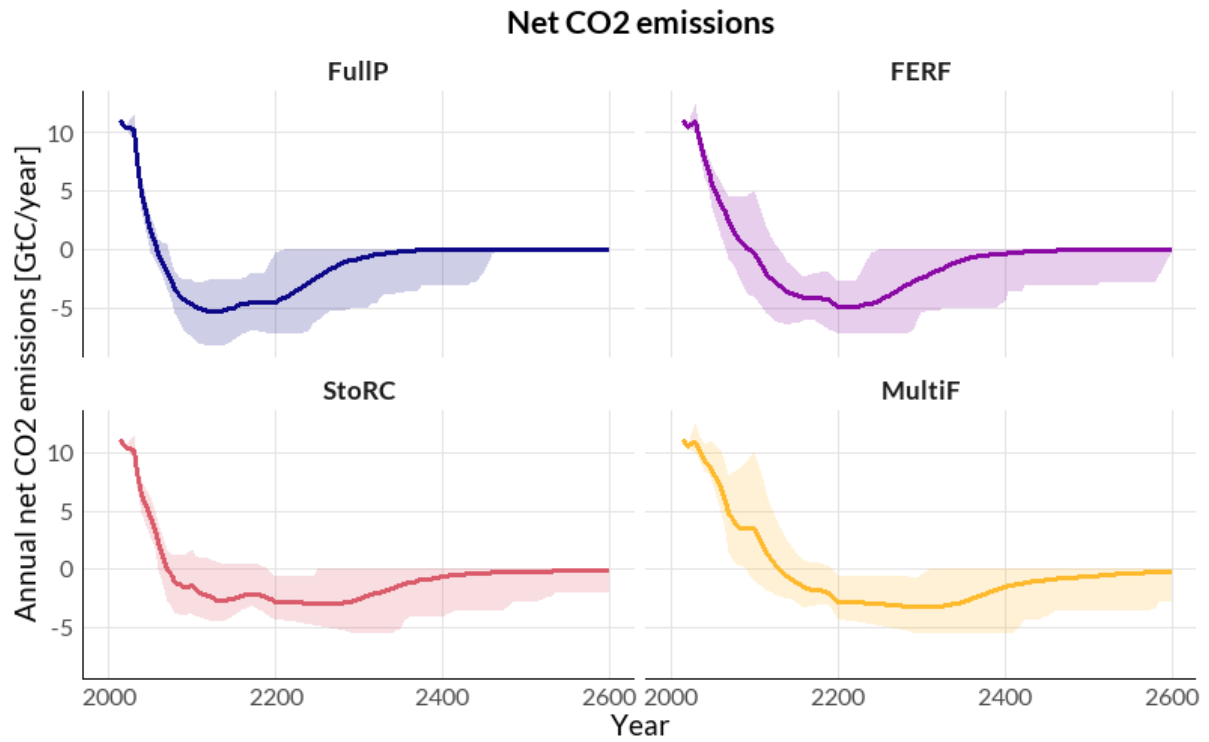


Figure S1. Modeled global net CO<sub>2</sub> emission pathways assuming stabilization of time-lagged impacts. Scenarios are conditioned on the requirement that both sea-level rise and permafrost thaw are stabilized. In most cases, stabilizing one of these metrics implies the other is already on a gradual declining trajectory. Solid lines show the ensemble mean net CO<sub>2</sub> emissions for each scenario, with shaded bands representing the full range (minimum to maximum) across the ensemble.

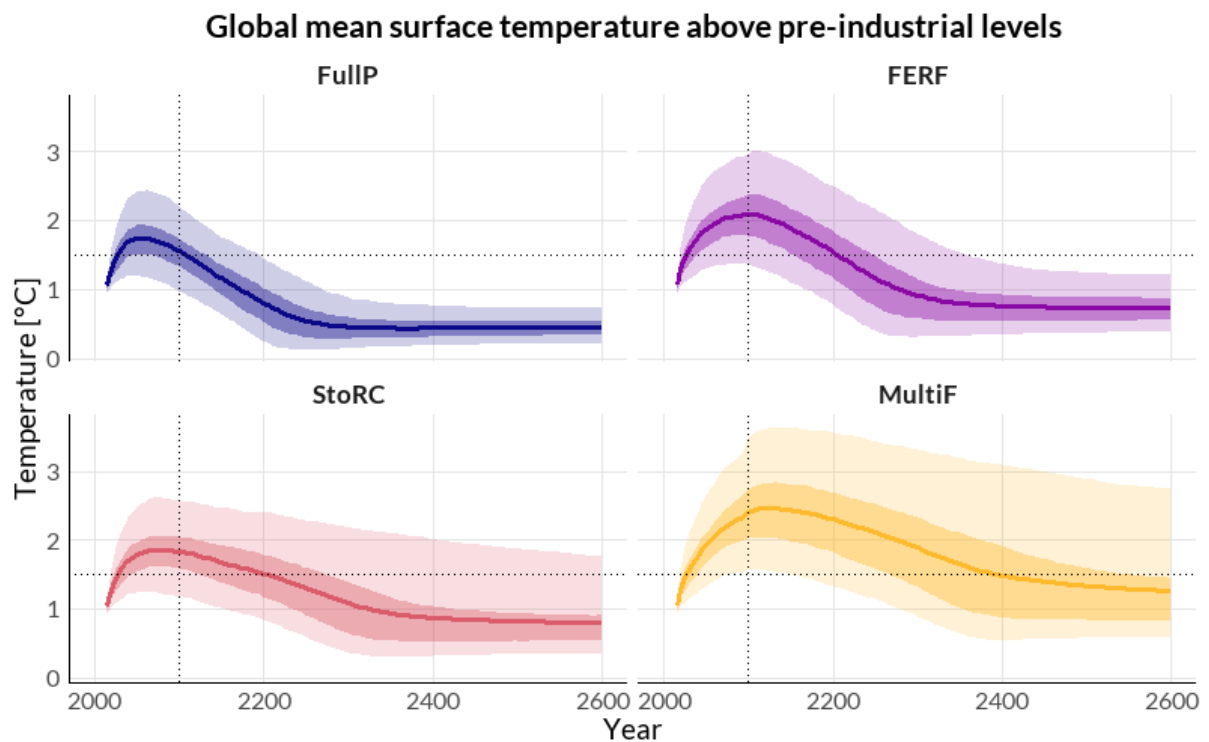


Figure S2. Modeled global mean surface temperature increase above pre-industrial levels. Scenarios are conditioned on the requirement that both sea-level rise and permafrost thaw are stabilized. In most cases, stabilizing one of these metrics implies the other is already on a gradual declining trajectory. Mean temperature trajectories are shown for each scenario (colored lines), with shaded bands indicating uncertainty ranges across the ensemble: the darker band shows the interquartile range (25th–75th percentile), and the lighter band shows the 5th–95th percentile range. The dashed vertical line marks the year 2100 (end-of-century reference), and the dotted horizontal line indicates the 1.5 °C global temperature limit under the Paris Agreement.

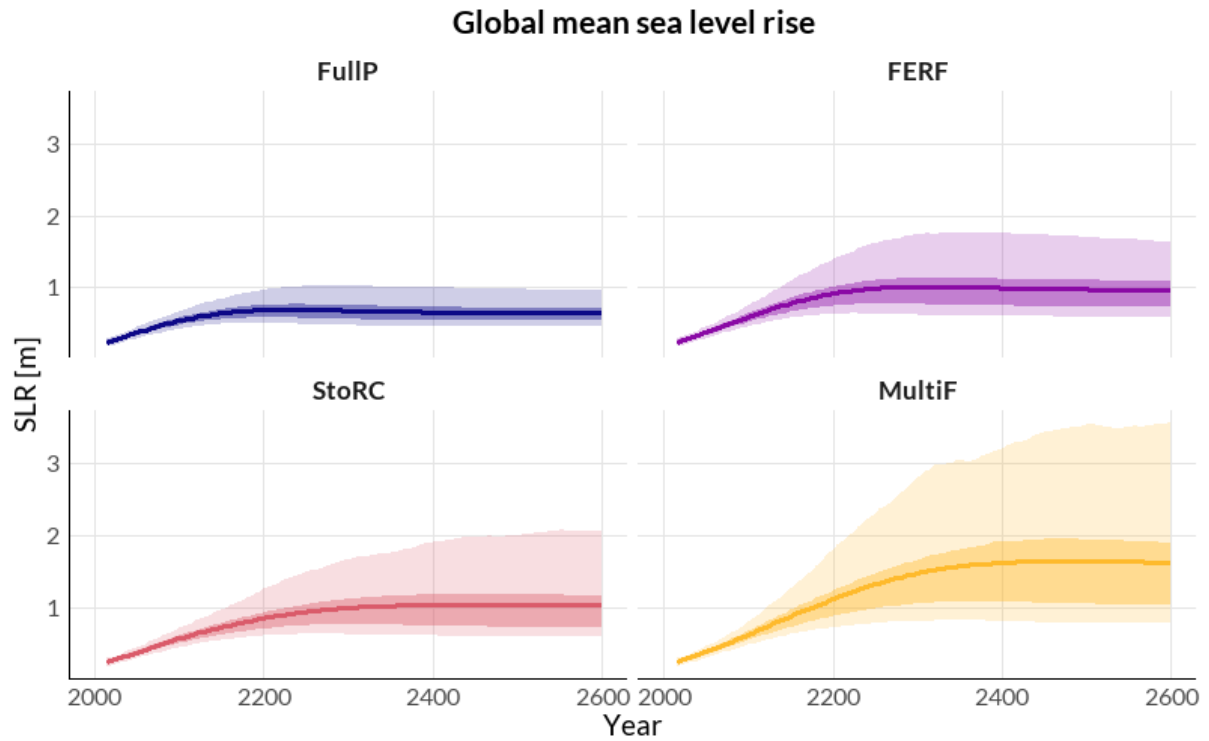


Figure S3. Projected global mean sea level rise (SLR). Scenarios are conditioned on the requirement that both sea-level rise and permafrost thaw are stabilized. In most cases, stabilizing one of these metrics implies the other is already on a gradual declining trajectory. Mean SLR trajectories are shown for each scenario (colored lines), with shaded bands indicating uncertainty ranges across the ensemble: the darker band shows the interquartile range (25th–75th percentile), and the lighter band shows the 5th–95th percentile range.

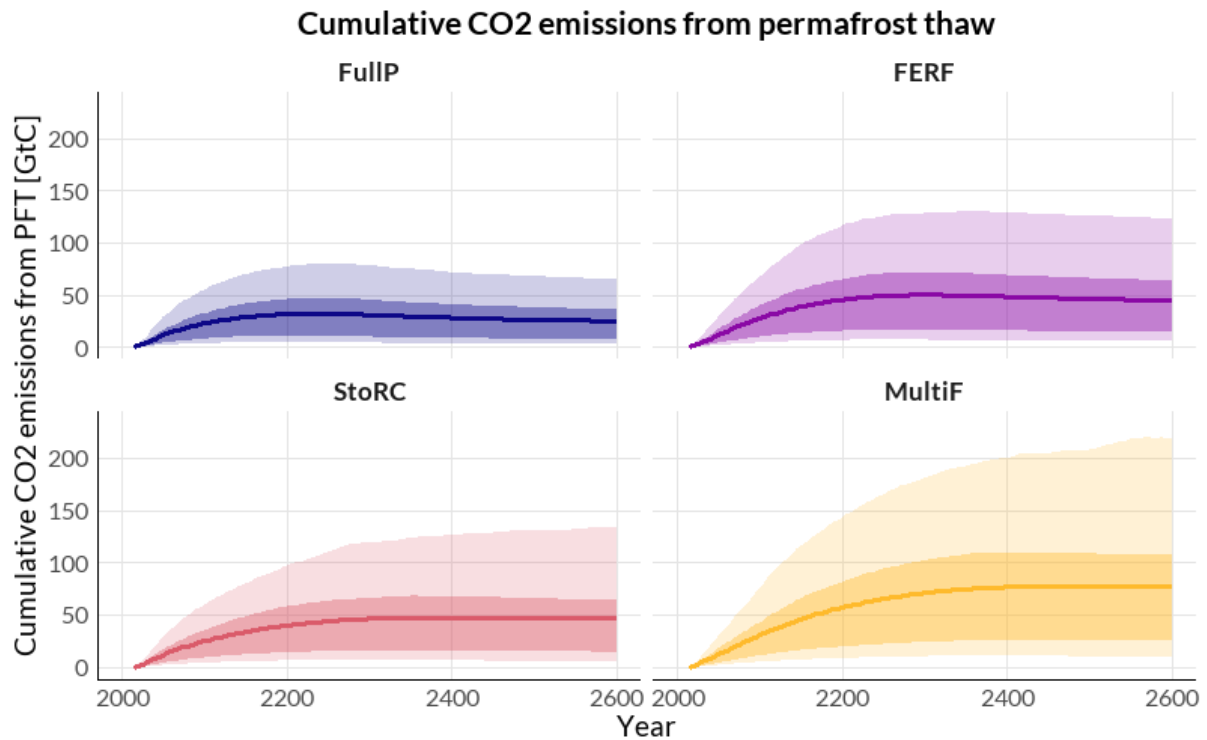


Figure S4. Projected global cumulative CO<sub>2</sub> emissions from permafrost thaw (PFT). Scenarios are conditioned on the requirement that both sea-level rise and permafrost thaw are stabilized. In most cases, stabilizing one of these metrics implies the other is already on a gradual declining trajectory. Mean cumulative emission trajectories are shown for each scenario (colored lines), with shaded bands indicating uncertainty ranges across the ensemble: the darker band shows the interquartile range (25th–75th percentile), and the lighter band shows the 5th–95th percentile range.

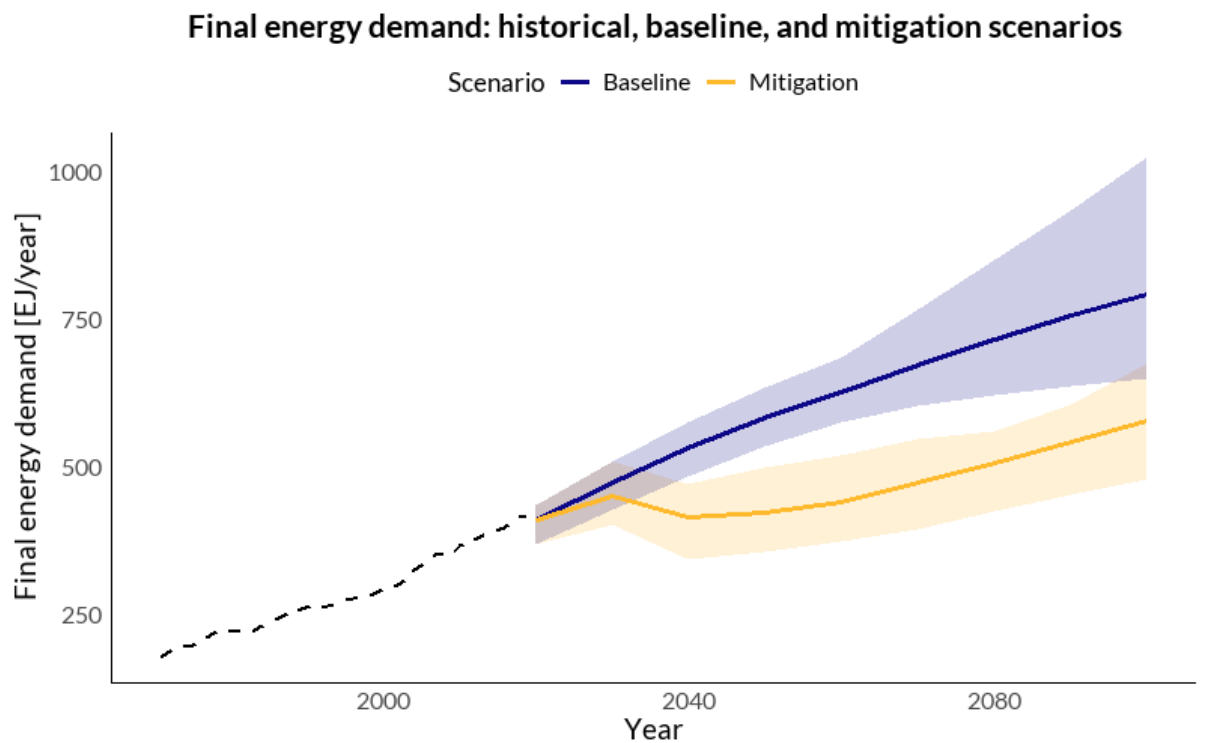


Figure S5. Annual final energy demand is shown as the mean (solid line) and full range (shaded area) across all trajectories in the Full Portfolio (FullIP) scenario, alongside the corresponding baseline pathways and the historical

trend (black dashed line). Scenarios with reduced progress in lowering the economy's final energy intensity are assumed to follow the baseline trajectories, which broadly extend the historical trend of rising energy demand.

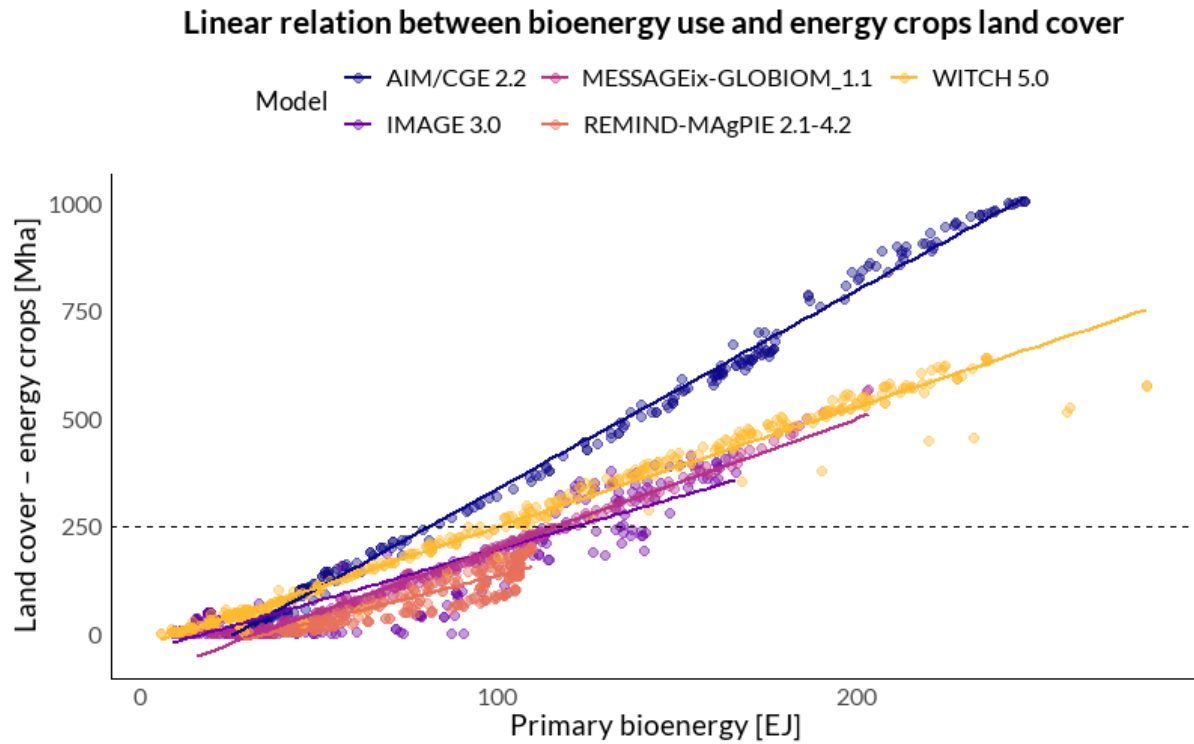


Figure S6. Linear relationship between primary bioenergy use and land cover for energy crops across dp-IAMs. The dashed horizontal line indicates a 250 Mha upper limit on land area allocated to energy crops. Using this threshold, we estimate an upper bound on annual primary bioenergy supply for each dp-IAM derived parameter set: AIM/CGE 2.2 (81 EJ), GEM-E3\_V2021 (100 EJ), IMAGE 3.0 (121 EJ), MESSAGEix-GLOBIOM\_1.1 (116 EJ), TIAM-ECN 1.1 (100 EJ), REMIND-MAgPIE 2.1-4.2 (154 EJ), and WITCH 5.0 (100 EJ). For TIAM-ECN 1.1 and GEM-E3\_V2021, no land cover data were available and the bioenergy limit was directly set to 100 EJ/year.

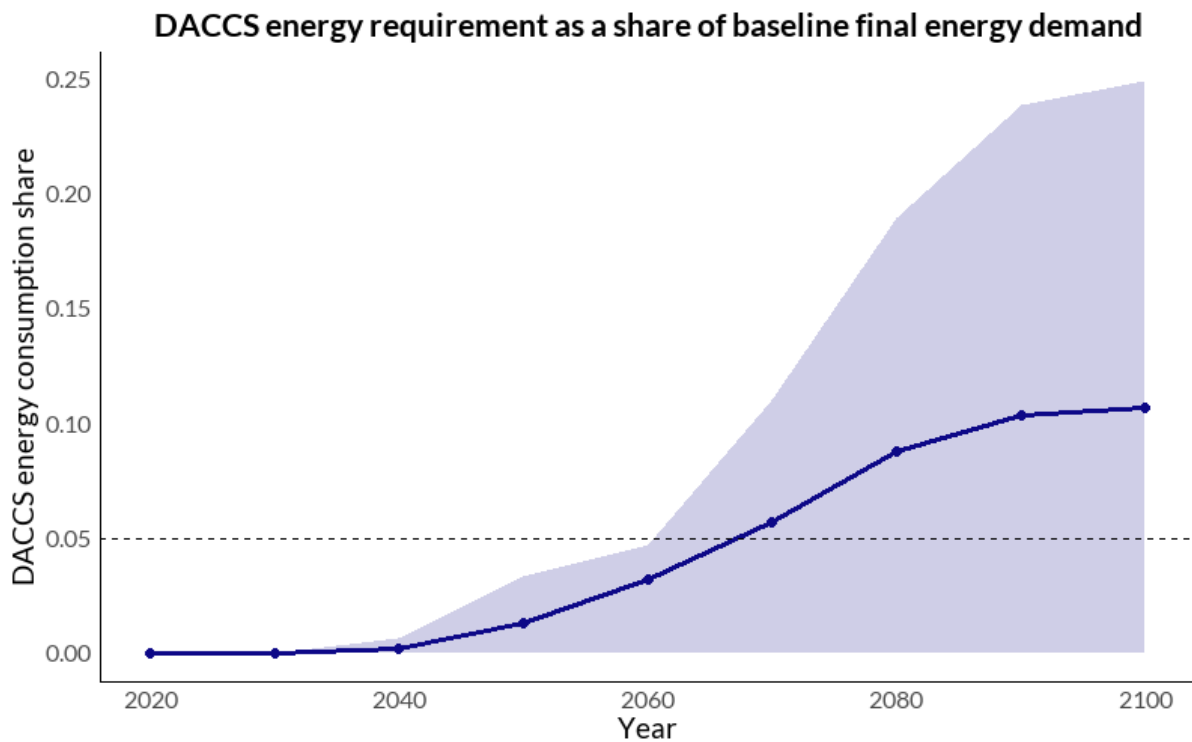


Figure S7. Mean and range (min to max) of DACCS energy consumption as a share of total baseline final energy demand across all 14 trajectories of the Full Portfolio (FullP) scenario. The dashed horizontal line represents the upper bound on allowable DACCS energy use as a fraction of final energy demand.

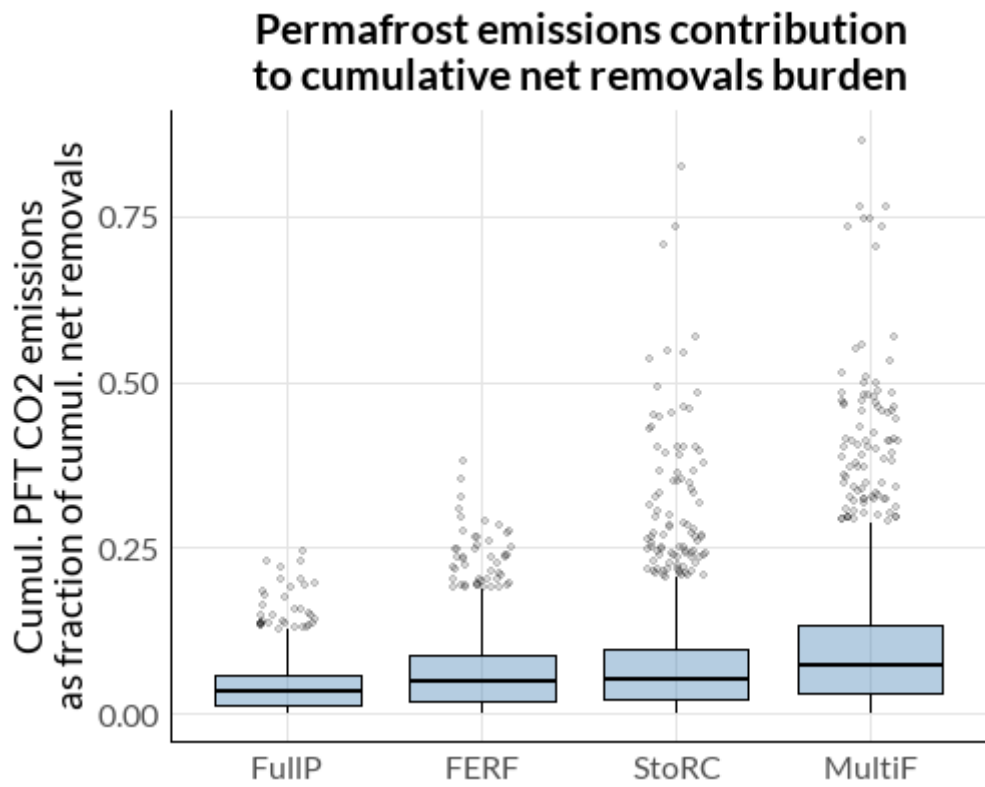


Figure S8. Distribution of cumulative CO<sub>2</sub> emissions from permafrost thaw (PFT) as a fraction of cumulative net CO<sub>2</sub> removals for each scenario. Distributions are illustrated as box-and-whisker plots, where the box represents the interquartile range (25th–75th percentile), the horizontal line indicates the median, and the whiskers extend to the most extreme values within 1.5 times the interquartile range.

**Table S1: Description of stylized constraints that are combined in different configurations to generate the mitigation scenarios.** Each row represents a different scenario, and each column corresponds to a specific constraint. The constraints are as follows: final energy demand follows baseline scenario assumptions and does not respond to a carbon price; the land area allocated to bioenergy is limited to a maximum of 250 million hectares; final energy consumption by DACCS is capped at 5% of total baseline final energy demand; and the annual growth rate of geological CO<sub>2</sub> storage capacity is capped at 15%, starting from 110 MtCO<sub>2</sub> per year in 2030. This storage constraint hence applies to CCS, BECCS, and DACCS technologies.

<b>Scenario</b>	<b>Narrative Summary</b>	<b>Final Energy Demand</b>	<b>Bioenergy</b>	<b>DACCS</b>	<b>Geological CO<sub>2</sub> Storage</b>
<b>FullIP</b>	Full mitigation portfolio available. Represents idealized dp-IAM assumptions.	Carbon price–driven reduction as in dp-IAMs	Unconstrained	Unconstrained	Unconstrained
<b>FERF</b>	Final energy reduction failure, e.g., due to new energy consumers or rebound effects.	Follows dp-IAM baseline assumptions	Unconstrained	Unconstrained	Unconstrained
<b>StoRC</b>	Storage and removals constrained: limits on BECCS, DACCS, and storage scale-up.	Carbon price–driven reduction as in dp-IAMs	250 Mha limit for energy crops	DACCS energy consumption ≤ 5% of baseline final energy	Growth capped at 15%/yr starting at 110 MtCO <sub>2</sub> /yr in 2030.
<b>MultiF</b>	Multiple constraints, combining FERG and StoRC assumptions.	Follows dp-IAM baseline assumptions	250 Mha limit for energy crops	DACCS energy consumption ≤ 5% of baseline final energy	Growth capped at 15%/yr starting at 110 MtCO <sub>2</sub> /yr in 2030.

# ANNEX 1

A Reduced-Complexity Model of Process-  
Based IAMs

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## **Abstract**

This working document presents the development and calibration of abatement cost functions for a reduced-complexity integrated assessment model (IAM). A total of ten cost functions, partially linked to one another, are developed and calibrated based on complex process-based IAMs. This design allows the reduced-complexity model to replicate scenarios produced by more detailed IAMs while running significantly faster. The improved computational efficiency enables the exploration scenarios based on multiple parameter sets, each representing a complex IAM, to provide a robust representation of technological uncertainty.

The final model is versatile, functioning either as an optimization tool (e.g., for cost minimization under a temperature target or welfare maximization when linked to a Ramsey growth model like DICE) or as a simulation tool that takes a carbon price path as input. It is important to note that this document focuses solely on the cost functions, which form the model's core, as well as some exploratory model extensions. Other components, such as climate or economic modules, can be easily linked using existing models.

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# 1 Model description

## 1.1 Model variables and index sets

In this model, various variables are indexed by specific categories to represent different aspects of energy use, emissions, and costs. Below, we define each variable along with its respective index set. A summary of the model is provided in ANNEX B.

### 1.1.1 Primary energy $W_i$

Represents the quantity of primary energy. The index  $i$  belongs to the set of primary energy types  $\mathcal{I} = \{\text{foss}, \text{nbr}, \text{bio}, \text{nuc}, \text{trad}\}$ , where:

- $W_{\text{foss}}$ : Primary energy from fossil fuels
- $W_{\text{nbr}}$ : Primary energy from non-biomass renewables
- $W_{\text{bio}}$ : Primary energy from biomass
- $W_{\text{nuc}}$ : Primary energy from nuclear
- $W_{\text{trad}}$ : Primary energy from traditional biomass

### 1.1.2 Final energy $F$

Represents the quantity of final energy and encompasses all end-use energy types without differentiation. Abatement in final energy is denoted by the index  $fe$ .

### 1.1.3 Other emitting sectors

Emitting sectors other than the energy sector include the industrial and Agriculture, Forestry, and Other Land Use (AFOLU) sectors, which are represented by the set  $\mathcal{N} = \{\text{ind}, \text{afolu}\}$ .

### 1.1.4 Emissions $E_j$

Represents emissions associated with different sectors. The index  $j$  belongs to the set  $\mathcal{J} = \mathcal{N} \cup \{\text{ener}\}$ , where:

- $E_{\text{ener}}$ : Pre-capture emissions from the energy system (i.e., emissions are aggregated as if no carbon capture were present)
- $E_{\text{ind}}$ : Pre-capture industrial process emissions (e.g., cement, steel)
- $E_{\text{afolu}}$ : Net emissions from AFOLU

### 1.1.5 Carbon capture $S_k$

Represents the amount of emissions captured and stored from the atmosphere and point sources, like fossil carbon capture and storage (CCS). The index  $k$  is associated with different capture and storage options, defined by the set  $\mathcal{K} = \{s\_foss, s\_bio, s\_ind, s\_dac\}$ , where:

- $S_{s\_foss}$ : Carbon capture via fossil CCS
- $S_{s\_bio}$ : Removals via bioenergy with CCS (BECCS)
- $S_{s\_ind}$ : Carbon capture via industry CCS
- $S_{s\_dac}$ : Removals via direct air CCS (DACCS)

### 1.1.6 Absolute abatement $A_m$

Represents reductions in emissions or increase of carbon capture compared to a baseline (but not expressed as fraction of baseline emissions). The index  $m$  belongs to the expanded set  $\mathcal{M} = \mathcal{I} \cup \mathcal{N} \cup \mathcal{K} \cup \{fe\}$ , where we have abatement through: emission reductions from primary energy substitution, industry and AFOLU emission reductions, carbon capture, as well as emission reductions from reducing final energy demand.

### 1.1.7 Marginal costs $P_m$ and total costs $C_m$

Represent the marginal and total cost associated with each type of emission reduction or carbon capture, respectively. The index  $m$  is the same as for  $A_m$  and uses the set  $\mathcal{M}$ .

## 1.2 Model parameters

### 1.2.1 Carbon intensity of fossil fuels $\beta_{foss}$

We define  $\beta_{foss}$  as the carbon intensity of fossil fuels. A simplifying assumption is made that  $\beta_{foss}$  is constant, although in reality it varies depending on the fossil fuel mix. This mix may differ especially between baseline and mitigation scenarios.

### 1.2.2 Conversion efficiencies $\eta_i$

Conversion efficiencies  $\eta_i$ , where  $0 < \eta_i < 1$ , represent the efficiency with which primary energy is converted into final energy. These parameters capture technological and systemic losses during the conversion process (e.g., electricity generation or refining). We assume these efficiencies remain constant, even as energy end-use patterns change. The index  $i$  is defined as in Section 1.1.1.

### 1.2.3 Fossil fuel substitution efficiencies $\sigma_i$

The fossil fuel substitution efficiency  $\sigma_i$  is defined as the ratio of the conversion efficiency of energy type  $i$  to that of fossil fuels:

$$\sigma_i := \frac{\eta_i}{\eta_{foss}}$$

This parameter allows comparisons of how efficiently alternative energy sources substitute for fossil fuels in delivering final energy.

### 1.3 Basic model structure

Net carbon emissions from the energy, industry, and AFOLU sectors are calculated as follows:

$$E_{\text{net}}(t) = \sum_{j \in \{\text{ener, ind, afolu}\}} E_j(t) - \sum_{k \in \{\text{s.foss, s.bio, s.ind, s.dac}\}} S_k(t),$$

where  $E_{\text{net}}(t)$  represents net emissions, and  $E_j(t)$  denotes emissions from different sectors (see Section 1.1.4). The term  $S_k(t)$  represents carbon capture from point sources or the atmosphere, as introduced in Section 1.1.5.

Pre-capture emissions from the energy sector,  $E_{\text{ener}}(t)$ , are calculated based on the primary fossil energy consumption  $W_{\text{foss}}(t)$  and the carbon intensity of fossil fuels,  $\beta_{\text{foss}}$  (see Section 1.2.1):

$$E_{\text{ener}}(t) = \beta_{\text{foss}} W_{\text{foss}}(t).$$

Final energy  $F(t)$  is defined as a linear function of the primary energy sources, weighted by their respective conversion efficiencies  $\eta_i$ , as defined in Section 1.2.2

$$F(t) = \sum_{i \in \{\text{foss, nuc, bio, trad, nbr}\}} \eta_i W_i(t).$$

From this relationship, the primary fossil energy consumption  $W_{\text{foss}}(t)$  can be expressed as:

$$W_{\text{foss}}(t) = \frac{1}{\eta_{\text{foss}}} \left( F(t) - \sum_{i \in \{\text{nuc, bio, trad, nbr}\}} \eta_i W_i(t) \right). \quad (1)$$

### 1.4 Baseline and mitigation scenarios

To distinguish between elements from the baseline and mitigation scenarios, we introduce a hat notation. For instance,  $\hat{W}_{\text{foss}}(t)$  represents the fossil primary energy in the baseline scenario. Initially, model variables are fixed to their baseline values, such that:

$$W_i(t_0) := \hat{W}_i(t_0) \quad \text{and} \quad F(t_0) := \hat{F}(t_0).$$

The same applies to carbon capture, so that:

$$S_k(t_0) := \hat{S}_k(t_0).$$

For internal consistency, the initial value of fossil primary energy,  $W_{\text{foss}}(t_0)$ , is calculated using Eq. (1).

## 1.5 Energy sector abatement

It is assumed that abatement can occur through reducing final energy  $F(t)$ , for example through increased efficiency or reduced demand, compared to a baseline; or by increasing other sources of zero-carbon primary energy  $W_i(t)$ , where  $i \in \{\text{nuc}, \text{bio}, \text{nbr}\}$ , compared to a baseline, thus substituting  $W_{\text{foss}}(t)$ . In this section, cost functions for reducing  $F(t)$  and increasing  $W_i(t)$  are introduced. Traditional biomass,  $W_{\text{trad}}(t)$ , does not represent a valid substitute for fossil fuels. It is phased-out in virtually all mitigation scenarios, with minor differences between individual scenario pathways. Moreover, the impact of carbon pricing on  $W_{\text{trad}}(t)$  is not obvious, hence, it is assumed that  $W_{\text{trad}}(t) := \hat{W}_{\text{trad}}(t)$ .

We define abatement,  $A(t)$ , compared to the baseline scenario as:

$$A(t) := \beta_{\text{foss}} \left( \hat{W}_{\text{foss}}(t) - W_{\text{foss}}(t) \right). \quad (2)$$

We define  $\Delta W_i(t) := \hat{W}_i(t) - W_i(t)$  and  $\Delta F(t) := \hat{F}(t) - F(t)$ . Because  $W_{\text{trad}}(t) := \hat{W}_{\text{trad}}(t)$ ,  $\Delta W_{\text{trad}}(t) = 0$ . From (1), it follows that:

$$\Delta W_{\text{foss}}(t) = \frac{\Delta F(t)}{\eta_{\text{foss}}} - \frac{\sum_{i \in \{\text{nuc}, \text{bio}, \text{nbr}\}} \eta_i \Delta W_i(t)}{\eta_{\text{foss}}}.$$

Furthermore, combining with 2,

$$A(t) = \beta_{\text{foss}} \left( \frac{\Delta F(t)}{\eta_{\text{foss}}} - \frac{\sum_{i \in \{\text{nuc}, \text{bio}, \text{nbr}\}} \eta_i \Delta W_i(t)}{\eta_{\text{foss}}} \right).$$

Using fossil fuel substitution efficiencies  $\sigma_i := \frac{\eta_i}{\eta_{\text{foss}}}$  (see Section 1.2.3), abatement can be attributed to different sources:

$$A_{\text{fe}}(t) := \frac{\beta_{\text{foss}} \Delta F(t)}{\eta_{\text{foss}}},$$

$$A_i(t) := -\beta_{\text{foss}} \sigma_i \Delta W_i(t), \quad i \in \{\text{nuc}, \text{bio}, \text{nbr}\}. \quad (3)$$

### 1.5.1 Cost functions for primary energy substitution

In an optimization setting, the model's objective function typically incorporates the total cost function – either directly, in the case of cost minimization, or indirectly through a utility function in an economic growth framework (e.g., welfare maximization in the DICE model). Here, we introduce such cost functions. Roughly speaking, we explain how a feasible path of  $W_i(\cdot)$  (equivalently,  $A_i(\cdot)$ ) produces paths of marginal costs  $P_i(\cdot)$ , and total costs  $C_i(\cdot)$ . In contrast, in ANNEX C we show how based on a carbon price path,  $P(\cdot)$  we can compute  $A_i(\cdot)$ ,  $P_i(\cdot)$  and  $C_i(\cdot)$ , a process used for the calibration of the model, and running the model in a simulation setting, rather than optimization.

Marginal abatement costs,  $P_i(t)$ , that capture the complex process of substituting fossil fuels with alternative primary energy sources are defined as (recall that  $\Delta W_i < 0$ ):

$$P_i(t) = \begin{cases} a_i(-\Delta W_i(t) + l_i \Delta W_i(t-1))^{b_i} + d_i, & \text{for } \Delta W_i(t) \leq l_i \Delta W_i(t-1) \\ d_i, & \text{for } \Delta W_i(t) > l_i \Delta W_i(t-1) \end{cases}$$

Using the definition for abatement,  $A_i(t) = -\beta_{\text{foss}}\sigma_i\Delta W_i(t)$ , we obtain:

$$P_i(t) = \begin{cases} \frac{a_i}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i} + d_i, & \text{for } A_i(t) \geq l_i A_i(t-1) \\ d_i, & \text{for } A_i(t) < l_i A_i(t-1) \end{cases} \quad (4)$$

The logic of the marginal cost function is as follows: Marginal costs remain constant at the floor level  $d_i$  when  $A_i(t) < l_i A_i(t-1)$ , but follow a power law when  $A_i(t) \geq l_i A_i(t-1)$ . The point at which marginal costs begin to follow a power law depends on previous abatement and the size of the lag parameter,  $l_i$ , where  $0 \leq l_i \leq 1$ , i.e., it is path-dependent. Larger abatement in the beginning leads to future cost functions capable of achieving greater abatement at lower average costs.

Moreover, in an optimization context, the following constraints are imposed:

$$W_i(t) \leq v_i(t), \quad (5)$$

$$A_i(t) \leq \beta_{\text{foss}}\sigma_i g_i + l_i A_i(t-1), \quad (6)$$

where  $v_i(t)$  is the maximum amount of  $W_i(t)$ , as discussed in Section 2.5; and  $g_i$  is a growth parameter further detailed in ANNEX C. Hence, primary energy  $W_i(t)$  cannot exceed  $v_i(t)$ ; and  $g_i$  and  $l_i$  together control the maximum growth of abatement by period.

To obtain total costs from the marginal cost function for the standard case, where  $A_i(t) \geq l_i A_i(t-1)$ , we integrate over abatement from 0 to  $A_i(t)$ . Note that from Eq. 2, it follows that  $A_{i,\min}(t) = 0$  for  $A_i(t) < l_i A_i(t-1)$ , and  $A_{i,\min}(t) = l_i A_i(t-1)$  otherwise:

$$\begin{aligned} C_i(t) &= \int_{A_{i,\min}(t)}^{A_i(t)} \left( \frac{a_i}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (\tilde{A}_i(t) - l_i A_i(t-1))^{b_i} + d_i \right) d\tilde{A}_i \\ &= \int_{l_i A_i(t-1)}^{A_i(t)} \frac{a_i}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (\tilde{A}_i(t) - l_i A_i(t-1))^{b_i} d\tilde{A}_i + \int_0^{A_i(t)} d_i d\tilde{A}_i. \end{aligned}$$

Hence, total costs for abatement from substituting fossil fuels are:

$$C_i(t) = \begin{cases} \frac{a_i}{b_i+1} \left( \frac{1}{(\beta_{\text{foss}}\sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i+1} \right) + d_i A_i(t), & \text{for } A_i(t) \geq l_i A_i(t-1) \\ d_i A_i(t), & \text{for } A_i(t) < l_i A_i(t-1). \end{cases}$$

Structurally, the cost functions derived for other types of abatement are almost identical with the ones introduced here.

## 1.5.2 Cost functions for final energy reduction

For final energy, the objective is to decrease energy use, as opposed to increasing a substitute for fossil fuels in the case of primary energy. Hence, the cost function differs from those for primary energy substitution in terms of the signs. Marginal costs for reducing final energy are defined as:

$$F_{\text{fe}}(t) = \begin{cases} a_{\text{fe}} \left( \frac{\eta_{\text{to}}}{\beta_{\text{to}}} \right)^{b_{\text{fe}}} (A_{\text{fe}}(t) - l_{\text{fe}} A_{\text{fe}}(t-1))^{b_{\text{fe}}} + d_{\text{fe}}, & \text{for } A_{\text{fe}}(t) \geq l_{\text{fe}} A_{\text{fe}}(t-1) \\ d_{\text{fe}}, & \text{for } A_{\text{fe}}(t) < l_{\text{fe}} A_{\text{fe}}(t-1) \end{cases} \quad (7)$$

Moreover, in an optimization context, the following constraints are imposed:

$$F(t) \geq v_{\text{fe}}(t),$$

$$A_{\text{fe}}(t) \leq \frac{\beta_{\text{to}}}{\eta_{\text{to}}} g_{\text{fe}} + l_{\text{fe}} A_{\text{fe}}(t-1).$$

Here,  $v_{\text{fe}}(t)$  is the minimum allowable amount of  $F_i(t)$ , as discussed in Section 2.5; and  $g_{\text{fe}}$  is a growth parameter, further explained in ANNEX C. As for primary energy substitution, to obtain total costs from the marginal cost function, we integrate over abatement:

$$C_{\text{fe}}(t) = \int_{A_{\text{fe}, \min}(t)}^{A_{\text{fe}}(t)} \left( a_{\text{fe}} \left( \frac{\eta_{\text{to}}}{\beta_{\text{to}}} \right)^{b_{\text{fe}}} (\tilde{A}_{\text{fe}}(t) - l_{\text{fe}} A_{\text{fe}}(t-1))^{b_{\text{fe}}} + d_{\text{fe}} \right) d\tilde{A}_{\text{fe}}.$$

Hence, the total costs are:

$$C_{\text{fe}}(t) = \begin{cases} \frac{a_{\text{fe}}}{b_{\text{fe}}+1} \left( \frac{\eta_{\text{to}}}{\beta_{\text{to}}} \right)^{b_{\text{fe}}} (A_{\text{fe}}(t) - l_{\text{fe}} A_{\text{fe}}(t-1))^{b_{\text{fe}}+1} + d_{\text{fe}} A_{\text{fe}}(t), & \text{for } A_{\text{fe}}(t) \geq l_{\text{fe}} A_{\text{fe}}(t-1) \\ d_{\text{fe}} A_{\text{fe}}(t), & \text{for } A_{\text{fe}}(t) < l_{\text{fe}} A_{\text{fe}}(t-1). \end{cases}$$

## 1.6 Industry and AFOLU sector abatement

Emissions from the industry and AFOLU sectors, as in Section 1.1.4, are denoted by  $E_j(t)$ , where  $j \in \mathcal{N} = \{\text{ind}, \text{afolu}\}$ . Abatement with respect to a baseline is given as  $A_j(t) := \hat{E}_j(t) - E_j(t)$ . We define marginal abatement costs in these sectors as:

$$P_j(t) = \begin{cases} a_j (A_j(t) - l_j A_j(t-1))^{b_j} + d_j, & \text{for } A_j(t) \geq l_j A_j(t-1) \\ d_j, & \text{for } A_j(t) < l_j A_j(t-1). \end{cases} \quad (8)$$

and impose the following constraints for optimization:

$$A_j(t) \leq v_j(t),$$

$$A_j(t) \leq g_j + l_j A_j(t-1).$$

Here,  $v_j$  represents the maximum allowable abatement in the industry and AFOLU sectors, further detailed in Section 2.5; and  $g_j$  is a growth parameter discussed in ANNEX C. As before, a total cost function can be derived by integrating over abatement:

$$C_j(t) = \begin{cases} \frac{a_j}{b_j+1} (A_j(t) - l_j A_j(t-1))^{b_j+1} + d_j A_j(t), & \text{for } A_j(t) \geq l_j A_j(t-1) \\ d_j A_j(t), & \text{for } A_j(t) < l_j A_j(t-1). \end{cases}$$

## 1.7 Carbon capture

Carbon capture, denoted by  $S_k(t)$  as introduced in Section 1.1.5, leads to abatement with respect to a baseline, represented by  $A_k(t) := S_k(t) - \hat{S}_k(t)$ . Because captured CO<sub>2</sub> cannot exceed the CO<sub>2</sub> produced during fossil fuel combustion, biofuel use, or industrial processes, we cap the amount of  $S_k(t)$  for  $k \in \{\text{s\_foss}, \text{s\_bio}, \text{s\_ind}\}$  as follows:

$$\begin{aligned} v_{\text{s.foss}}(t) &= f_{\text{s.foss}}^{\text{pot}}(E_{\text{ener}}(t)), \\ v_{\text{s.bio}}(t) &= f_{\text{s.bio}}^{\text{pot}}(W_{\text{bio}}(t)), \\ v_{\text{s.ind}}(t) &= f_{\text{s.ind}}^{\text{pot}}(E_{\text{ind}}(t)). \end{aligned}$$

The functions  $f_k^{\text{pot}}$  are explained in Section 2.4. Marginal costs of abatement through carbon capture are defined as:

$$P_k(t) = \begin{cases} a_k (A_k(t) - l_k A_k(t-1))^{b_k} + d_k, & \text{for } A_k(t) \geq l_k A_k(t-1) \\ d_k A_k(t), & \text{for } A_k(t) < l_k A_k(t-1). \end{cases} \quad (9)$$

Moreover, we impose the following constraints:

$$\begin{aligned} S_k(t) &\leq v_k(t), \\ A_k(t) &\leq g_k + l_k A_k(t-1). \end{aligned}$$

The maximum allowable carbon capture quantities,  $v_k$ , for  $k \in \{\text{s.foss}, \text{s.bio}, \text{s.ind}, \text{s.dac}\}$  are discussed in further detail in Section 2.5. The growth parameter,  $g_k$ , is discussed in ANNEX C. Following the same procedure as for primary energy substitution, total costs are computed by integrating over abatement. The total cost expression becomes:

$$C_k(t) = \int_{A_{k,\min}(t)}^{A_k(t)} \left( a (A_k(t) - l_k A_k(t-1))^{b_k} + d_k \right) dA_k,$$

which can be further broken down as:

$$C_k(t) = \int_{l_k A_k(t-1)}^{A_k(t)} a (A_k - l_k A_k(t-1))^{b_k} dA_k + \int_0^{A_k(t)} d_k dA_k.$$

The integration yields:

$$C_k(t) = \begin{cases} \frac{a_k}{b_k+1} (A_k(t) - l_k A_k(t-1))^{b_k+1} + d_k A_k(t), & \text{for } A_k(t) \geq l_k A_k(t-1) \\ d_k A_k(t), & \text{for } A_k(t) < l_k A_k(t-1). \end{cases}$$

## 1.8 Linking carbon price with marginal costs

A general assumption of economic efficiency is expressed as:

$$P_m(t) = P(t) \quad \forall m,$$

meaning that the marginal abatement cost  $P_m(t)$  is equal across all abatement options  $m$ . This reflects the calibration of the model to a unified carbon price, and it is recommended that this condition be upheld if the proposed cost functions are used in an optimization or simulation setting. However, due to the various constraints imposed on abatement, such as Eqs. 5 and 6, there are implied marginal cost caps and floors which vary between abatement options. Therefore, the condition,  $P_m(t) = P(t) \quad \forall m$ , is generally not met by the marginal cost functions introduced in Sections 1.5 through 1.7. In ANNEX C, and more specifically in C.1.1 we illustrate how marginal costs can be kept consistent with a unified carbon price  $P$ .

---

## 2 Model calibration

- **Data source:** We use data from the ENGAGE model intercomparison, available in the AR6 database. The scenarios are based on the socioeconomic pathway of SSP2.
- **Data structure:** The dataset is organized by model, scenario, and year. Different near-term policy assumptions, as well as overshoot and non-overshoot scenarios for the same carbon budget, are present. However, for calibration purposes, these distinctions are not considered.
- **Parameter sets:** A parameter set is calibrated for each complex IAM included in the dataset.
- **Component Calibration:** Each component, such as cost functions, is calibrated individually rather than optimizing parameters for the entire model simultaneously.
- **Notation:** Throughout this document, lowercase letters refer to variables from the dataset, while uppercase letters denote modeled variables used in the equations.
- **Abatement notation:** To prevent confusion with the cost function coefficients, abatement from the dataset is denoted by  $x_m(t)$ , defined as:

$$x_m(t) = \hat{e}_m(t) - e_m(t),$$

where  $\hat{e}_m(t)$  and  $e_m(t)$  represent baseline and mitigation scenario emissions from the dataset, respectively.

### 2.1 Data preparation and polishing

The following steps are applied prior to calibration to ensure consistent and meaningful data:

- **Scenario filtering:** We exclude
  - COVID-related scenarios, identified by “COV” in the scenario name,
  - Sensitivity analysis scenarios, identified by “NDCp”,
  - Scenarios with non-standard discount rates, identified by “DR”,
  - All scenarios from the COFFEE 1.1 and POLES ENGAGE IAMs due to data gaps and inconsistencies that could not be reliably corrected.
- **IAM-specific adjustments:**
  - For **GEM-E3\_V2021**, Carbon Sequestration|CCS|Biomass is missing from the AR6 database. We instead retrieve Primary Energy|Biomass|Modern|w/ CCS from the ENGAGE-native database and infer biomass sequestration using assumed capture efficiencies.
  - For **IMAGE 3.0** AFOLU emissions increase in mitigation scenarios compared to the baseline, which is incompatible with the defined cost functions. AFOLU emissions are therefore set to an average path of mitigation scenarios. Costs are assumed to be zero. The scenario EN\_INDCi2030\_1400f is removed because the reported carbon price is 0.

- For **WITCH 5.0**, we observe inconsistencies in CO<sub>2</sub> emissions in relation to fossil energy consumption. To correct this:
  - \* We add `Emissions|CO2|Industrial Processes` to `Emissions|CO2|Energy` and set industrial emissions to zero.
  - \* This adjustment ensures that pre-capture emissions (i.e., energy emissions plus captured emissions) remain non-negative in regional data and consistent with primary fossil energy use.
- We harmonize `Primary Energy|Biomass|Traditional` across scenarios by replacing scenario-specific trajectories with the median trajectory for each IAM across all scenarios. Traditional biomass is phased-out in all scenarios.
- **DACCS Energy Correction:** DACCS is only available in scenarios from the models WITCH 5.0 and REMIND-MAGPIE 2.1-4.2. The reported final and primary energy uses includes the energy consumed by DACCS. To avoid overestimating the energy actually used for economic activities, we correct final and primary energy by removing the share attributable to DACCS.

DACCS energy demand per tonne of CO<sub>2</sub> is assumed to be 6.9 GJ heat and 1.55 GJ electricity in WITCH 5.0, and 10 GJ heat and 2 GJ electricity in REMIND-MAGPIE 2.1-4.2, based on literature ([Realmonde et al. \[2019\]](#)) and model documentation ([PIK Potsdam Institute for Climate Impact Research](#)). From scenario data we infer that the energy carriers used to supply this demand differ: in WITCH 5.0, heat is assumed to be primarily provided by natural gas (80%, vs. 20% from hydrogen), whereas in REMIND-MAGPIE 2.1-4.2, it comes almost entirely from hydrogen (95%, vs. 5% from natural gas), which is itself produced from electricity and fossil fuels. Electricity for DACCS, including electricity used indirectly for hydrogen production, is assumed to come fully from NBRs in both IAMs, which is consistent with the high renewable shares observed in their DACCS-intensive scenarios.

The source shares for hydrogen (electricity vs. fossil) and the efficiencies of various conversion processes are either assumed or inferred directly from the scenario data. This allows us to attribute DACCS energy demand back to primary energy carriers.

We then correct both final energy (by subtracting the total DACCS energy demand) and primary energy (by subtracting the upstream energy used to supply DACCS heat and electricity). For WITCH 5.0, an additional correction is made to the accounting of fossil fuels with and without CCS, since gas used for DACCS appears to be reported inconsistently across those categories. We resolve this by reallocating gas energy and adjusting reported fossil CCS capture accordingly.

## 2.2 Carbon intensity

For the calibration of the carbon intensity of fossil fuels  $\beta_{\text{fossil}}$ , we use a simple linear regression model of the form:

$$e_{\text{ener}}(t) \sim \beta_{\text{fossil}} w_{\text{fossil}}(t)$$

where  $e_{\text{ener}}(t)$  denotes pre-capture emissions from the energy sector, and  $w_{\text{fossil}}(t)$  represents primary energy consumption from fossil fuels. The results for each IAM are summarized in Table 1.

Model	$\beta_{\text{foss}}$
AIM/CGE 2.2	68
GEM-E3_V2021	61
IMAGE 3.0	69
MESSAGEix-GLOBIOM_1.1	70
TIAM-ECN 1.1	65
REMIND-MAgPIE 2.1-4.2	70
WITCH 5.0	67

Table 1: Estimated carbon intensity of fossil fuels ( $\beta_{\text{foss}}$ ) in MtCO<sub>2</sub>/EJ for various IAMs

## 2.3 Energy conversion

We estimate the energy conversion efficiencies between primary energy,  $w_i(t)$ , and final energy,  $f(t)$ , with a linear regression model of the form:

$$f(t) \sim \sum_{i \in \{\text{foss}, \text{nuc}, \text{bio}, \text{trad}, \text{nbr}\}} \eta_i w_i(t).$$

However, estimating these conversion efficiencies individually for each IAM is challenging due to the high degree of multicollinearity between the primary energy sources. To overcome this, we employ a two-stage calibration approach:

### 2.3.1 Initial calibration using data from all IAMs

In the first stage, we combine data from all IAMs. This significantly reduces collinearity among the primary energy sources, with variance inflation factors (VIF) values below 5, indicating moderate but acceptable multicollinearity.

In this stage, we use a Bayesian linear regression approach to estimate the coefficients  $\eta_i$  for each primary energy source,  $w_i$ .

We assign uninformative priors (uniform distribution between 0 and 1) to most coefficients. The exception is nuclear energy, where we impose a prior between 0.7 and 0.9 due to its significantly smaller scale in scenarios compared to other energy sources, making the estimate unreliable. Moreover, for traditional biomass,  $w_{\text{trad}}$ , we follow the convention that primary and final energy are the same, fixing the parameter  $\eta_{\text{trad}}$  to 1 through the prior.

### 2.3.2 IAM-specific calibration using informative priors

In the second stage, we perform the calibration for each IAM separately. To address multicollinearity issues that arise when fitting the model to individual IAM data, we use informative priors based on the results from the first stage. The expected values (means) of the coefficients  $\eta_i$  from the initial calibration are used as the means of normal distributions as priors, with a narrow standard deviation of 0.01. This ensures that the estimates for each IAM remain consistent with the global calibration while allowing for model-specific variation. We keep the prior for nuclear energy uniform between 0.7 and 0.9.

Model	$\eta_{\text{bio}}$	$\eta_{\text{nbr}}$	$\eta_{\text{nuc}}$	$\eta_{\text{foss}}$
AIM/CGE 2.2	$0.53 \pm 0.01$	$0.78 \pm 0.01$	$0.82 \pm 0.05$	$0.68 \pm 0$
GEM-E3_V2021	$0.56 \pm 0.01$	$0.81 \pm 0.01$	$0.79 \pm 0.06$	$0.75 \pm 0$
IMAGE 3.0	$0.53 \pm 0.01$	$0.80 \pm 0.01$	$0.74 \pm 0.03$	$0.73 \pm 0$
MESSAGEix-GLOBIOM_1.1	$0.52 \pm 0.01$	$0.88 \pm 0.01$	$0.83 \pm 0.03$	$0.78 \pm 0$
TIAM-ECN 1.1	$0.53 \pm 0.01$	$0.80 \pm 0.01$	$0.82 \pm 0.05$	$0.74 \pm 0.01$
REMIND-MAgPIE 2.1-4.2	$0.53 \pm 0.01$	$0.76 \pm 0$	$0.83 \pm 0.05$	$0.78 \pm 0$
WITCH 5.0	$0.43 \pm 0.01$	$0.79 \pm 0.01$	$0.74 \pm 0.04$	$0.66 \pm 0$

Table 2: Estimated energy conversion efficiencies ( $\eta$ ) for various IAMs.

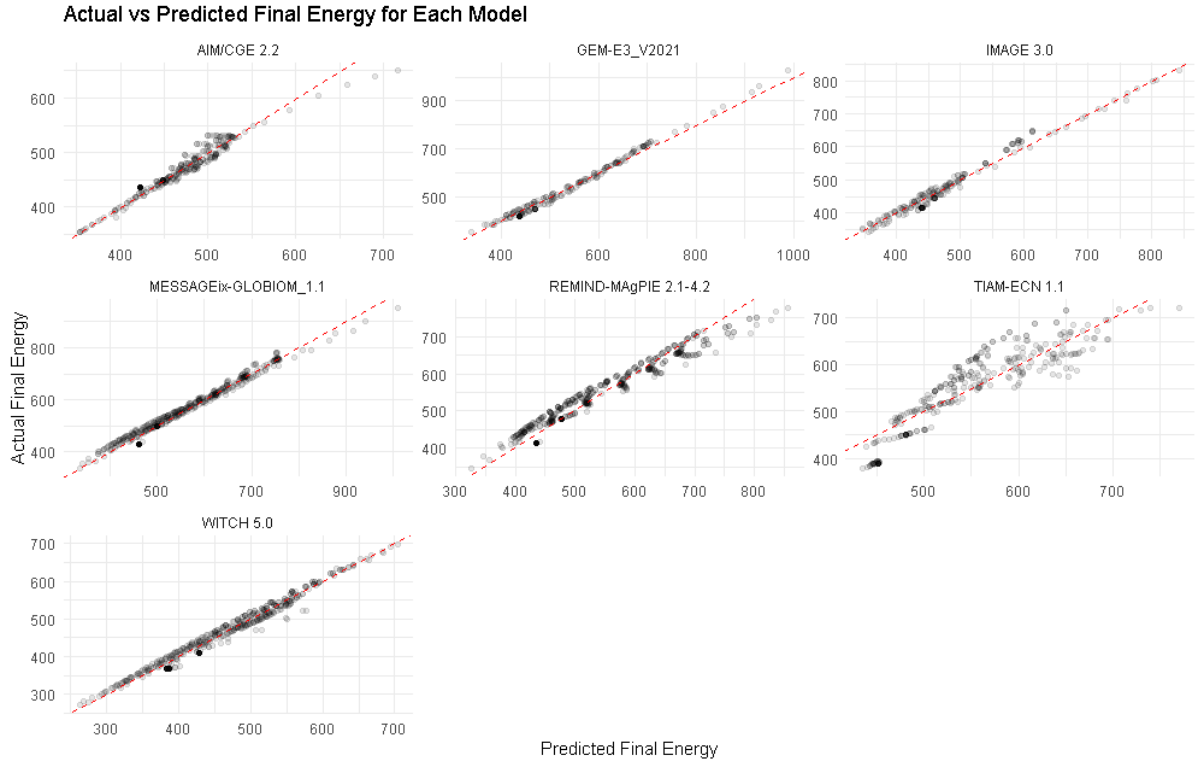


Figure 1: Actual vs. predicted final energy using energy conversion efficiencies ( $\eta$ ) Table 2

### 2.3.3 Results

The energy conversion efficiencies for each IAM are shown in Table 2. Actual versus predicted final energy is shown for each IAM in Figure 1.

The fossil fuel substitution efficiencies, denoted as  $\sigma_i := \frac{\eta_i}{\eta_{\text{foss}}}$ , are presented in Table 3. These efficiencies measure how effectively different energy sources can substitute for fossil fuels in terms of energy conversion.

## 2.4 Carbon capture potentials

We compute the potentials for bioenergy CCS and industry CCS by analyzing the maximum ratio of carbon captured to the corresponding primary energy or emissions in the dataset. The maximum ratios obtained for each IAM are summarized in Table 4.

Fossil CCS is modeled differently due to several factors. Unlike bioenergy, which increases with stricter climate policies, fossil fuel use generally declines, leading to the temporary deployment of fossil CCS

Model	$\sigma_{\text{bio}}$	$\sigma_{\text{nbr}}$	$\sigma_{\text{nuc}}$
AIM/CGE 2.2	$0.78 \pm 0.01$	$1.16 \pm 0.01$	$1.21 \pm 0.08$
GEM-E3 <sub>V</sub> 2021	$0.75 \pm 0.01$	$1.09 \pm 0.01$	$1.06 \pm 0.08$
IMAGE 3.0	$0.72 \pm 0.01$	$1.09 \pm 0.01$	$1.00 \pm 0.04$
MESSAGEix-GLOBIOM <sub>1.1</sub>	$0.67 \pm 0.01$	$1.12 \pm 0.01$	$1.06 \pm 0.04$
TIAM-ECN 1.1	$0.72 \pm 0.01$	$1.08 \pm 0.01$	$1.11 \pm 0.08$
REMIND-MAGPIE 2.1-4.2	$0.68 \pm 0.01$	$0.97 \pm 0.01$	$1.06 \pm 0.07$
WITCH 5.0	$0.65 \pm 0.01$	$1.20 \pm 0.01$	$1.12 \pm 0.06$

Table 3: Fossil fuel substitution efficiencies  $\sigma_i := \frac{\eta_i}{\eta_{\text{foss}}}$  for various IAMs.

in many scenarios until fossil point sources are phased out. Additionally, bioenergy is mostly used for BECCS, creating a clear link between bioenergy consumption and carbon capture, while fossil fuel end-uses are more diverse, making it harder to directly relate fossil fuel use to CCS potential. Although similar issues might arise with industrial emissions, fossil CCS is significantly larger in scale, allowing for a simplified approach to industry CCS.

We compute CCS potentials for each IAM as follows:

#### 2.4.1 Bioenergy CCS potential

We calculate the maximum ratio of carbon captured from bioenergy,  $s_{\text{bio}}$ , to primary bioenergy consumption,  $w_{\text{bio}}$ , over all time steps and over all scenarios for each IAM from the dataset and define bioenergy CCS potential,  $v_{\text{s.bio}}^{\text{pot}}$ , as:

$$v_{\text{s.bio}}^{\text{pot}}(t) = \max\left(\frac{s_{\text{bio}}}{w_{\text{bio}}}\right) W_{\text{bio}}(t)$$

Note,  $W_{\text{bio}}$  refers to the modeled value of bioenergy consumption, while  $w_{\text{bio}}$  is the dataset value of bioenergy consumption.

#### 2.4.2 Industry CCS potential

Similarly, we compute the maximum ratio of industrial CCS,  $s_{\text{ind}}$ , to industrial process emissions,  $e_{\text{ind}}$ , from the dataset and define the industry CCS potential,  $v_{\text{s.ind}}^{\text{pot}}$ , as:

$$v_{\text{s.ind}}^{\text{pot}}(t) = \max\left(\frac{s_{\text{ind}}}{e_{\text{ind}}}\right) E_{\text{ind}}(t)$$

Again,  $E_{\text{ind}}$  refers to the modeled value of industrial emissions, while  $e_{\text{ind}}$  is the dataset value of industrial emissions.

#### 2.4.3 Fossil CCS potential

In our empirical approach, the fossil CCS potential,  $v_{\text{s.foss}}^{\text{pot}}$ , is modeled as an increasing piecewise linear function of pre-capture energy system emissions,  $e_{\text{ener}}$ , as exemplified in Figure 2. This function is derived from the left-side increasing portion of the convex hull over the points  $(e_{\text{ener}}, s_{\text{s.foss}})$ . The function is constrained to prevent any positive intercept, ensuring that the CCS potential is zero when  $e_{\text{ener}} = 0$ .

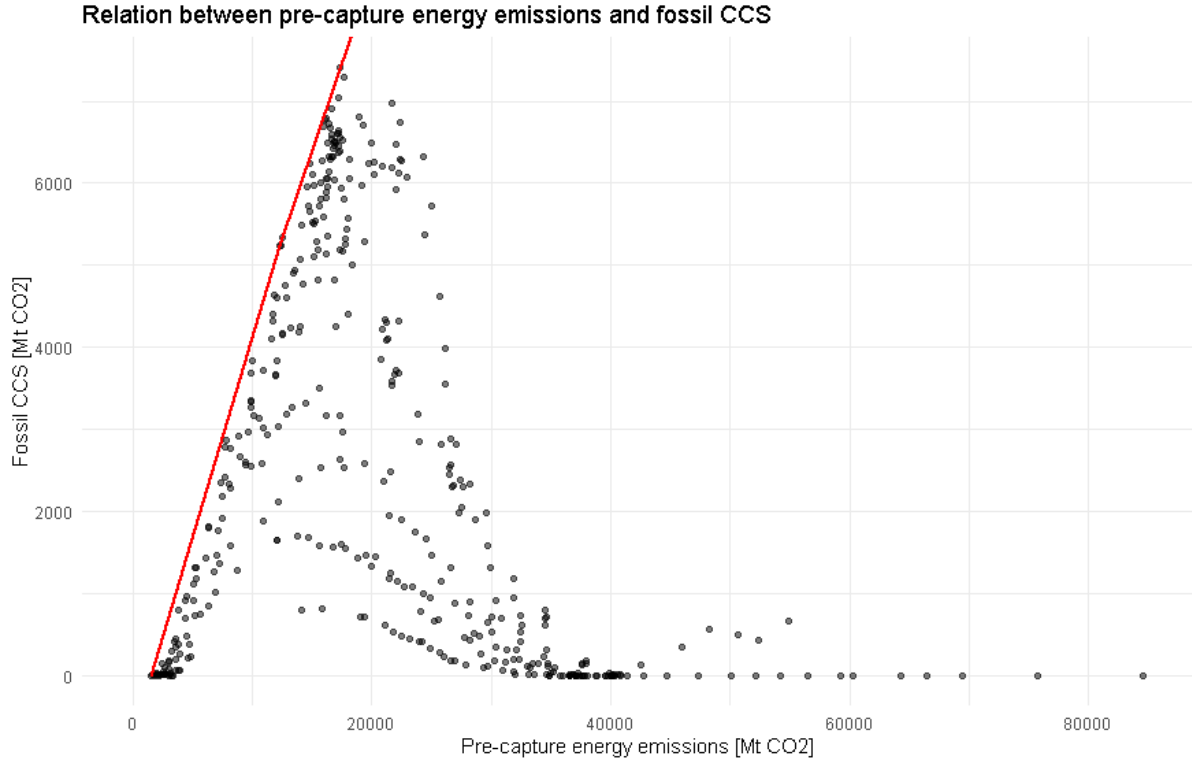


Figure 2: Red line is the fossil CCS potential for MESSAGEix-GLOBIOM 1.1

<b>Model</b>	$\max \left( \frac{s_{\text{bio}}}{w_{\text{bio}}} \right)$	$\max \left( \frac{s_{\text{ind}}}{e_{\text{ind}}} \right)$
AIM/CGE 2.2	63.5	0.359
GEM-E3_V2021	33.7	0
IMAGE 3.0	86.1	0.968
MESSAGEix-GLOBIOM_1.1	56.8	0.531
REMIND-MAgPIE 2.1-4.2	49.7	0.756
TIAM-ECN 1.1	66.0	0
WITCH 5.0	44.9	NA

Table 4: Maximum capture ratios for bioenergy with CCS and industry CCS from the dataset. A value of 0 indicates that there is no industry CCS in the data, while NA indicates that there are no industry emissions in the data. These ratios are used to calculate carbon capture potentials,  $v_{s_{\text{bio}}}^{\text{pot}}$  and  $v_{s_{\text{ind}}}^{\text{pot}}$ , based on modeled values of  $W_{\text{bio}}$  and  $E_{\text{ind}}$ .

## 2.5 Variable bounds

In this section, we define the variable bounds, denoted by  $v_m(t)$ , which are calculated as the maximum (or minimum) reported values within each time step, across all scenarios and for each IAM of the dataset. These bounds serve to constrain the potential range of key variables, ensuring that their modeled values remain within plausible limits over time. For instance, see the variable bounds for primary bioenergy in Figure 3. Note that the bounds for carbon capture are based on the potentials outlined in the previous section, hence, they depend on model variables.

The following relationships are used to determine the bounds for each time step  $t$ :

For primary energy, the bounds at each time step are:

$$v_i(t) = \max(w_i(t)), \quad i \in \{\text{nbr, bio, nuc}\},$$

For carbon capture, the bounds at each time step are:

$$v_k(t) = \min\left(\max(s_k(t), v_k^{\text{pot}}(t)), v_{\text{s\_dac}}(t)\right), \quad k \in \{\text{s\_bio, s\_foss, s\_ind}\},$$
$$v_{\text{s\_dac}}(t) = \max(s_{\text{s\_dac}}(t))$$

For abatement in the AFOLU and industry sectors, the bounds at each time step are:

$$v_{\text{ind}}(t) = \max(a_{\text{ind}}(t)),$$
$$v_{\text{afolu}}(t) = \max(a_{\text{afolu}}(t)).$$

Finally, for final energy, the bound at each time step is:

$$v_{\text{fe}}(t) = \min(f(t)).$$

## 2.6 Model validation

### 2.6.1 Energy and emissions

Table 5 reports the root mean square error (RMSE) and coefficient of determination ( $R^2$ ) for each parameter set (IAM), measuring the goodness of fit between modeled and reported net emissions under the reported carbon price scenarios.

Reported versus modeled values for primary energy, final energy, and emissions across all available abatement options are presented in Figures 9 through 15 in Appendix A for each parameter set (IAM) individually. The resulting net emissions pathway, derived from the combination of all model components, is also shown.

### 2.6.2 Average costs

Abatement costs are generally not explicitly reported for mitigation scenarios, and the calibration of cost functions in this model targets energy or emissions quantities rather than costs directly. To ensure

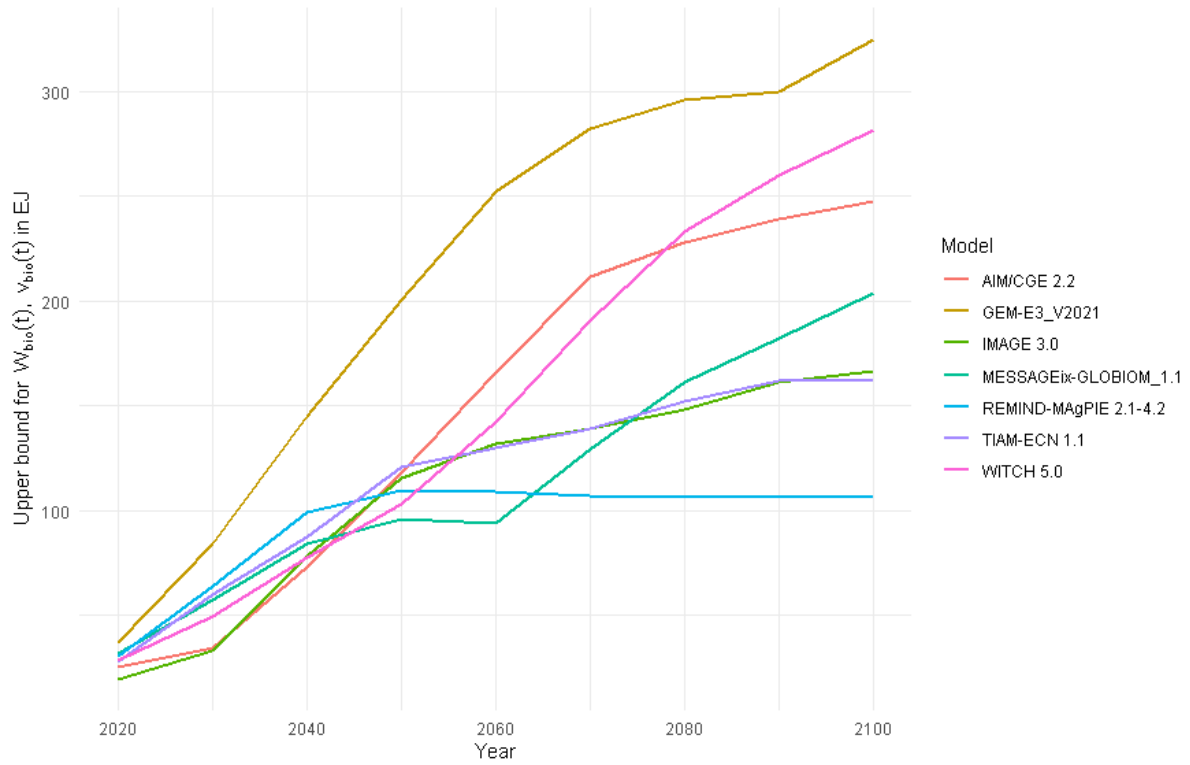


Figure 3: Upper variable bound for  $W_{\text{bio}}(t)$ .

Model	RMSE [GtCO <sub>2</sub> ]	R <sup>2</sup>
AIM/CGE 2.2	2.53	0.978
GEM-E3_V2021	2.67	0.974
IMAGE 3.0	3.89	0.951
MESSAGEix-GLOBIOM_1.1	5.11	0.926
TIAM-ECN 1.1	4.49	0.935
REMIND-MAgPIE 2.1-4.2	4.77	0.914
WITCH 5.0	2.31	0.977

Table 5: Goodness-of-fit metrics from comparing all reported scenario time series with modeled pathways for each IAM. RMSE and  $R^2$  values assess how well modeled net emissions match reported data under different carbon price scenarios, as illustrated in Figures 9 through 15.

consistency with external cost estimates, we impose soft lower bounds on the average cost of each abatement option. If the median of modeled average costs across scenarios for a given abatement option falls below its respective bound, a penalty is applied during calibration.

These bounds are median values estimated through visual interpretation of Figure SPM.7 in IPCC [2022]. However, two important limitations should be acknowledged. First, the categorization of abatement options in the IPCC figure does not align precisely with those used in our model. This mismatch is particularly evident in the treatment of final energy demand reductions, for which no meaningful bound could be derived. Second, the figure reports only cost ranges, and median values are not explicitly provided. The estimated medians, which serve as soft cost floors during calibration, are summarized in Table 6. The modeled average cost distributions are illustrated in Figure 4.

Abatement option	Est. Median	Low	High
Non-biomass Renewables	0	0	100
Nuclear	35	0	200
Bioenergy	80	20	200
AFOLU	50	0	200
Industry	35	0	200
CCS–Fossil	80	50	200
CCS–Bio	80	50	200
CCS–Industry	150	100	200

Table 6: Estimated median average costs in USD/tCO<sub>2</sub> for abatement options used in the model. A penalty is applied during calibration if the median modeled abatement cost falls below the estimated median. The lower and upper bounds represent the estimated ranges derived from IPCC AR6 WGIII Figure SPM.7.

Additionally, modeled total average abatement costs are compared against the reported consumption loss per ton of abated CO<sub>2</sub>, where available. While consumption loss is generally considered a reasonable proxy for abatement costs, this relationship does not hold for AIM/CGE 2.2, where reported consumption loss frequently exceeds the carbon price. In simpler economic models such as DICE, this would imply that average costs exceed marginal costs, a conceptually inconsistent outcome. The discrepancy may reflect model-specific assumptions or dynamics not fully reflected here. This comparison is illustrated in Figure 16 in Appendix A.

## 2.7 Non-CO<sub>2</sub> radiative forcing

We estimate non-CO<sub>2</sub> radiative forcing  $r_{\text{nonCO}_2}(t)$  from fossil primary energy  $w_{\text{foss}}(t)$  via

$$r_{\text{nonCO}_2}(t) = \exp(\kappa + \gamma_1 w_{\text{foss}}(t) + \gamma_2 w_{\text{foss}}(t)^\rho).$$

Parameters are estimated per IAM and across all IAMs to inform parameter sets where no non-CO<sub>2</sub> radiative forcing was reported. The relationship  $w_{\text{foss}}(t)$  vs.  $r_{\text{nonCO}_2}(t)$  is shown in Figure 5. Model skill is shown in Figure 6, comparing reported and predicted  $r_{\text{nonCO}_2}(t)$ .

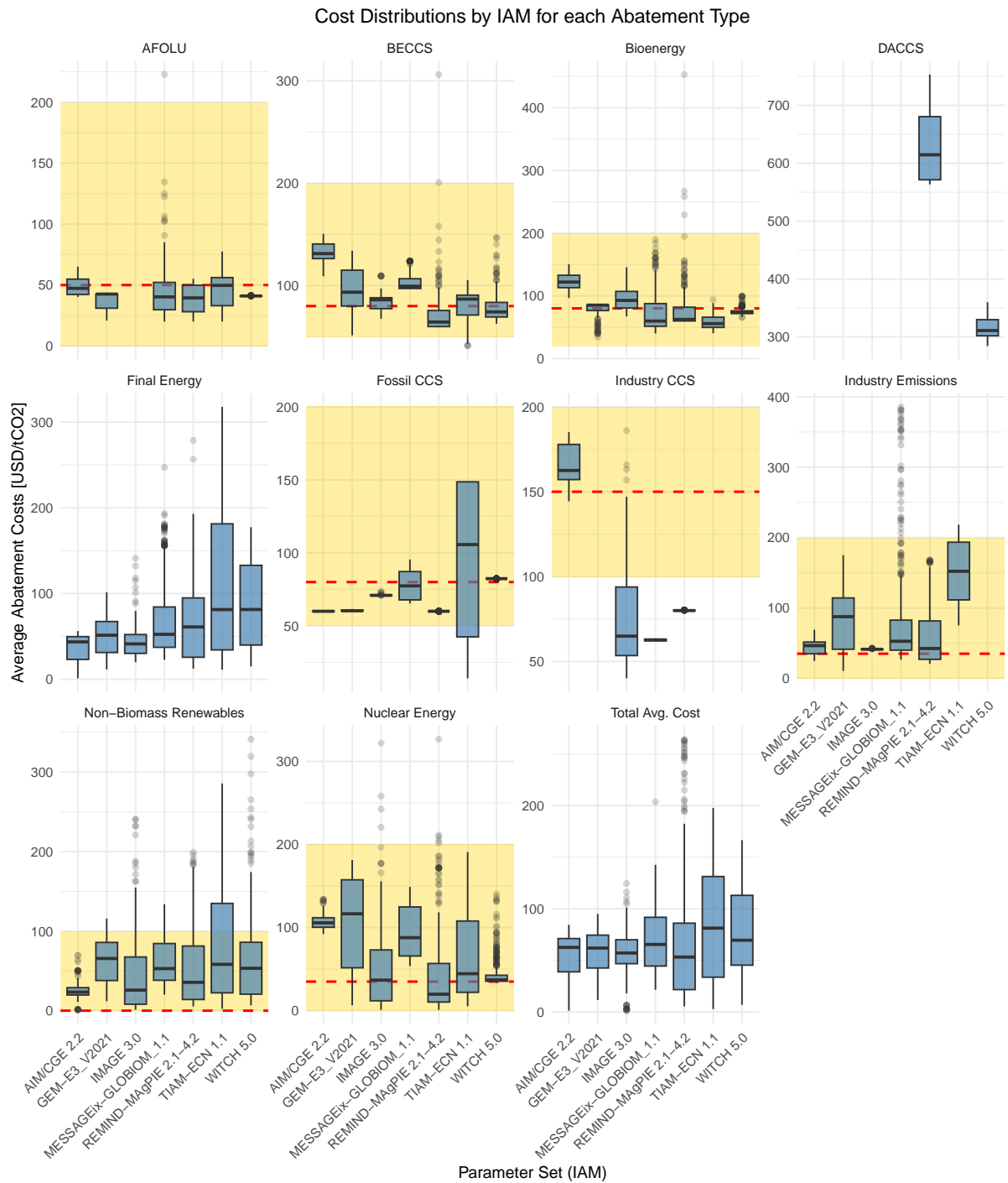


Figure 4: Distribution of average abatement costs by parameter set (IAM) across abatement types. Boxplots represent the interquartile range, median, and outliers of modeled cost estimates for each abatement option and IAM. Shaded yellow ribbons indicate the cost ranges, while the dashed line shows the soft lower cost bound as listed in Table 6. Panels are scaled individually for readability. This visualization supports the evaluation of whether models stay within plausible cost corridors for different abatement options.

## Data and exponential model

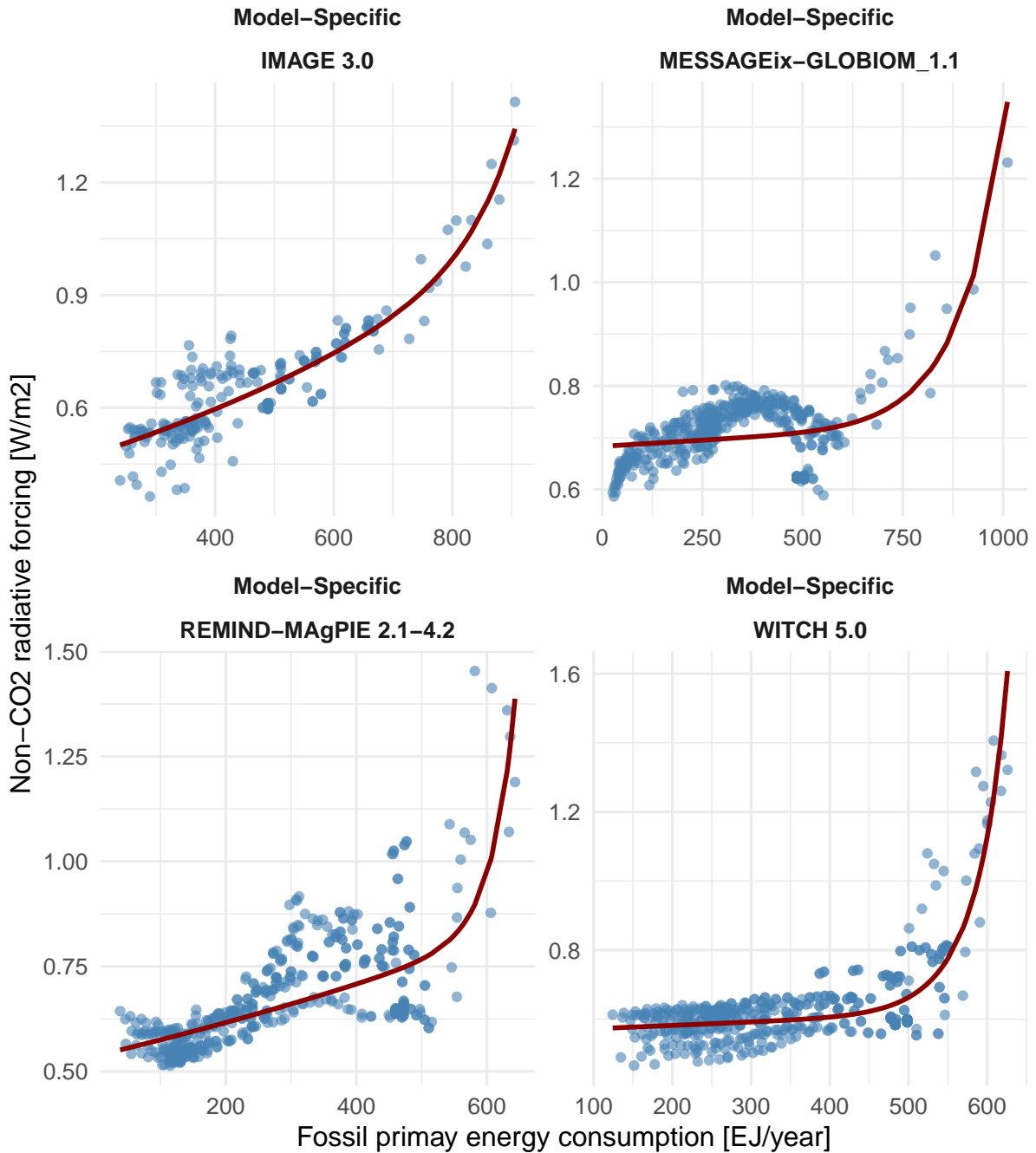


Figure 5: Relationship between fossil primary energy consumption  $w_{\text{foss}}(t)$  and non-CO<sub>2</sub> radiative forcing  $r_{\text{nonCO}_2}(t)$  with fitted exponential model.

## Observed vs. predicted non-CO<sub>2</sub> radiative forcing

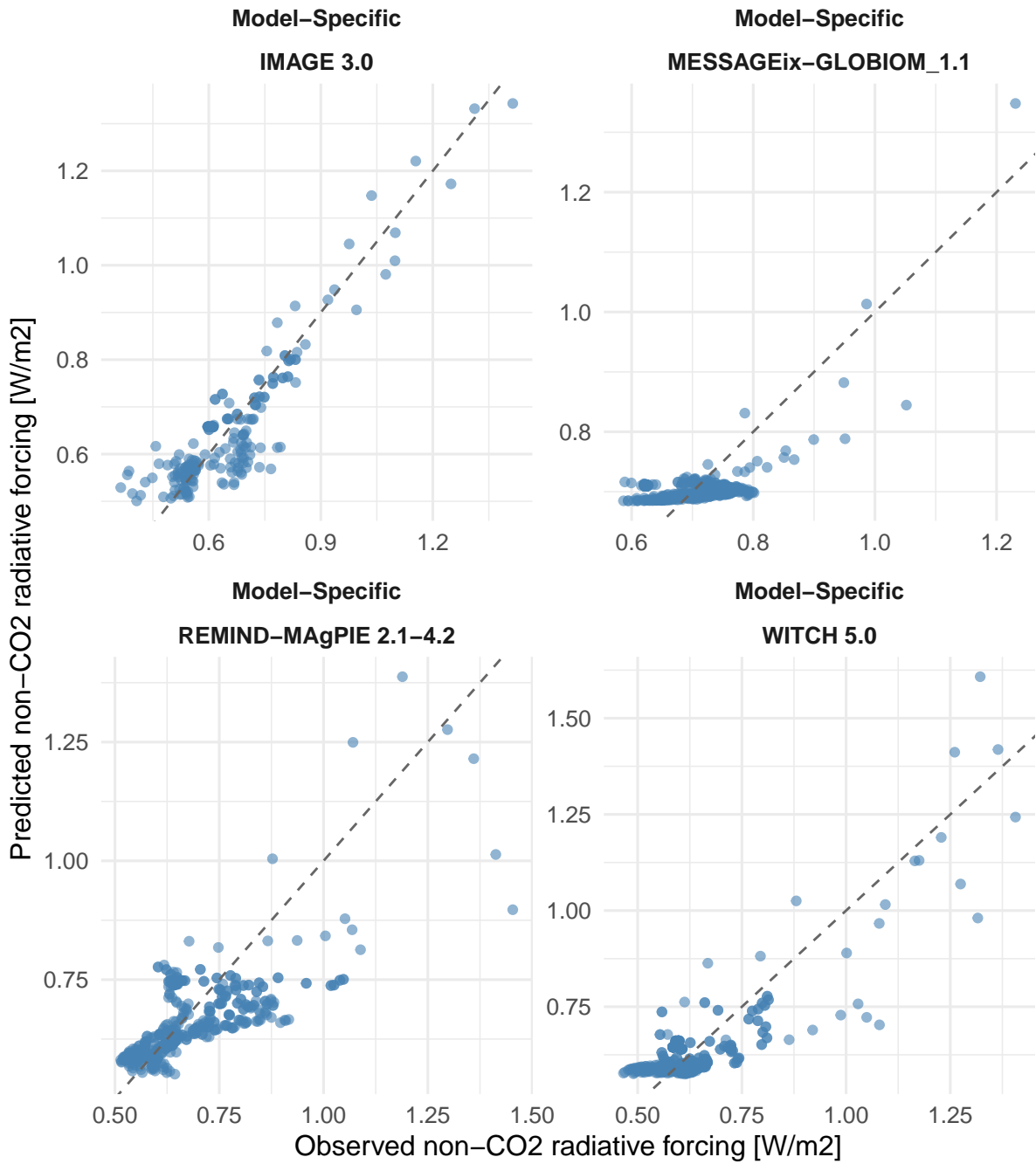


Figure 6: Observed versus predicted non-CO<sub>2</sub> radiative forcing  $r_{\text{nonCO}_2}(t)$  for individual IAMs.

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## 3 Exploratory model modifications

This section outlines a set of exploratory modifications to the calibrated model, aimed at extending its applicability beyond the scope of reported scenario data.

### 3.1 Integration of DACCS into all parameter sets

DACCS is incorporated as an abatement option into all model parameter sets, including those in which it was not originally reported. We use a lower-cost parameter set from WITCH 5.0 and a higher-cost parameter set from REMIND-MAGPIE 2.1-4.2 (see Figure 4). Each of these DACCS configurations is combined with the parameter set for all other abatement types from each IAM, resulting in a total of 14 model parameter sets (2 DACCS variants × 7 IAMs).

### 3.2 Extension of time horizon

The model's temporal scope is extended beyond 2100 to explore the long-term implications of mitigation strategies beyond the typical reporting window of IAMs. The key points of this extrapolation include:

- For consistency, the full range of abatement types is extrapolated beyond 2100. However, not all components continue to be modeled as functions of the carbon price, as they are before 2100.
- Fossil fuel emissions follow a predefined linear phase-out trajectory and are no longer price-responsive after 2100.
- Fossil fuel emissions serve as the basis for fossil CCS deployment, which continues to be determined by the carbon price, as in the pre-2100 period.
- Bioenergy and nuclear energy remain functions of the carbon price. Their deployment remains capped at the maximum levels observed between 2020 and 2100 in scenarios. Extrapolation requires an extension of baseline assumptions.
- Bioenergy serves as the basis for BECCS deployment, which continues to be determined by the carbon price.
- NBRs are assumed to meet the residual energy demand not covered by other sources, justified by their vast physical potential. NBRs are thus no functions of the carbon price post-2100.
- The baseline energy supply is extrapolated under the assumption that the fractional (i.e., relative) energy mix, such as the share of bioenergy in total primary energy, remains constant beyond 2100 at its 2100 level. This requires projecting total energy demand forward.
- Energy demand is extrapolated using a DICE-like approach in which energy demand is inferred from economic output, which itself is driven by exogenous projections of population and factor productivity growth.
- DACCS remains modeled as a function of the carbon price beyond 2100. However, the upper bound from the 2020–2100 period is imposed to reflect limits on deployment potential.

- The AFOLU sector, which typically acts as a net carbon sink before 2100 in most scenarios, is gradually phased toward net-zero emissions in the post-2100 period.
- Although long-term extrapolations inherently involve large uncertainty, several factors limit the spread between post-2100 trajectories:
  - Long-term net emissions are guided by residual fossil fuel emissions, as well as CDR.
  - Fossil fuel emissions follow a fixed phase-out path, independent of economic or policy assumptions. Bioenergy deployment, as basis for BECCS, is bounded by sustainability constraints commonly embedded in IAMs. In ambitious mitigation scenarios, these bounds are typically hit already before 2100. As a result, uncertainties in future GDP or energy demand affect only the timing at which upper limits of bioenergy are reached. Similarly, DACCS upper bounds from the 2020-2100 periods are maintained.
  - In other words, under a sufficiently high carbon price, such as one following a Hotelling-rule growth path, scenarios tend to converge toward similar long-run net-negative emissions trajectories.
- Modeled abatement costs are only credible for the period until 2100.

### 3.2.1 Extrapolation of population and economic output

We use a discrete-time Solow-style growth model to simulate economic output and capital accumulation with a fixed savings rate in the post-2100 period. This, in turn, is used to determine future energy demand. The model's production function, with output  $Y(t)$ , population  $L(t)$ , total factor productivity (TFP)  $\alpha(t)$  and capital elasticity  $\gamma$  is given by:

$$Y(t) = \alpha(t)L(t)^{1-\gamma}K(t)^\gamma$$

**Population extension for SSP2** Population trajectories are extended by blending the reported IAM-specific population projection for 2100,  $L(2100)$ , with an extended SSP2 population pathway,  $L_{SSP2}(t)$ , that runs to 2300. The scaling ratio

$$r_L = \frac{L(2100)}{L_{SSP2}(2100)}$$

is applied with a linearly decaying weight

$$w(t) = \frac{2300 - t}{200}$$

to yield

$$L(t) = L_{SSP2}(t) \cdot r_L^{w(t)}, \quad t > 2100.$$

This approach ensures asymptotically converging to the extended SSP2 trajectory by 2300.

The  $L_{SSP2}$  pathway was obtained from IIASA's POPJUS program. The series until 2100 follows the updated SSP population scenario in [K.C. et al. \[2024\]](#). For the extension to 2300, the same assumptions as to 2100 were maintained, with the exception that the fertility rate converges to 1.75 children per woman by the year 2200 for all countries, and the maximum life expectancy is set at 105 years for both sexes.

**Extrapolation of economic output** We first infer  $\alpha(t)$  by rearranging the production function using scenario data for output and population:

$$\alpha(t) = \frac{Y(t)}{L(t)^{1-\gamma}K(t)^\gamma}$$

Investment is derived from reported output and consumption,  $C(t)$ :

$$I(t) = Y(t) - C(t)$$

Capital then evolves according to the standard discrete-time capital accumulation equation, with capital depreciation  $\delta$ :

$$K(t+1) = (1 - \delta\Delta t)K(t) + \Delta t \cdot I(t)$$

We initialize capital in the first time step at 210 trillion USD (2010), based on data from the Penn World Table version 10.01 [Feenstra et al. \[2015\]](#).

We compute TFP  $\alpha(t)$  for capital elasticity  $\gamma = 0.35$ , as in [Leimbach et al. \[2017\]](#) for SSP2, and capital depreciation  $\delta = 0.1$ , as in [Barrage and Nordhaus \[2024\]](#). An exponential function is then fitted to the resulting TFP trajectories:

$$\alpha(t) = Ae^{bt}$$

To account for declining productivity growth post-2100, the estimated growth rate  $b$  is adjusted using an exponential decay:

$$b(t) = b \cdot e^{-\lambda(t-2100)}$$

TFP is then extrapolated recursively, following the logic of DICE 2023 ([Barrage and Nordhaus \[2024\]](#)), where the decline rate is set to  $\lambda = 0.0075$ :

$$\alpha(t) = \alpha(t-1) \cdot e^{b(t)}$$

The savings rate, defined as  $s(t) = \frac{I(t)}{Y(t)}$ , is assumed to converge linearly from its 2100 baseline scenario value to a fixed level of  $s = 0.20$  by 2200 after which it remains constant. This reflects a moderate, ‘middle-of-the-road’ investment level consistent with the SSP design principle of convergence to medium capital intensities. Using the Solow growth model, the savings rate, and the extrapolated TFP trajectories, we generate a set of economic growth pathways, presented in Figure 7.

### 3.2.2 Abatement post 2100

For all abatement options other than NBRs, cost functions and imposed upper bounds on abatement, as introduced in Section 2.5, are assumed to remain valid beyond 2100, and their baselines are accordingly extended. NBRs are expected to grow beyond any values observed in scenarios up to 2100 and are therefore determined using a different logic (see Section 3.2.3).

**Extrapolation of baselines** Extrapolation of baseline scenarios is required for all abatement options other than NBRs,. We begin by extending the baseline for total primary energy. Let  $\hat{W}(t)$  denote total primary energy consumption of baseline scenarios and  $Y(t)$  economic output as described in

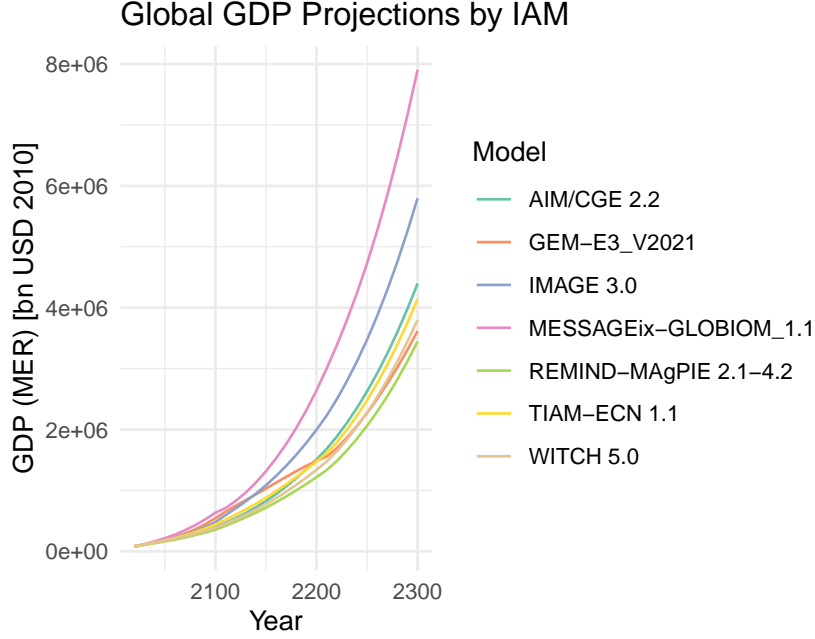


Figure 7: Extrapolated global GDP trajectories by IAM, in billion 2010 USD.

Section 3.2.1. We define the primary energy intensity

$$\phi(t) = \frac{\hat{W}(t)}{Y(t)}$$

using reported values for  $\hat{W}(t)$  and  $Y(t)$  over 2020–2100. We apply a hyperbolic decay function to extend primary energy intensity beyond 2100:

$$\phi(t) = \frac{\phi(2100)}{1 + \left( -\frac{\dot{\phi}(2100)}{\phi(2100)} \right) \cdot (t - 2100)},$$

where  $\dot{\phi}(2100)$  denotes the derivative at  $t = 2100$ . Combining the extended  $\phi(t)$ , as illustrated for all IAMs in Figure 8, with  $Y(t)$  yields the extended total primary energy path  $\hat{W}(t)$  up to 2300.

Primary nuclear and bioenergy shares of  $\hat{W}(t)$  are held constant at 2100 levels, implying proportional growth of  $\hat{W}_{\text{bio}}$  and  $\hat{W}_{\text{nucl}}$  with  $\hat{W}$  after 2100 until any predefined upper bounds (see Section 2.5) are reached.

Other baselines are extended as follows: Similar to energy intensity, industrial emissions intensity is extrapolated by fitting a log-linear relationship over 2020–2100, i.e.  $\log \frac{\hat{E}_{\text{ind}}(t)}{Y(t)} \sim t$ . AFOLU emissions are extended by first estimating a linear trend in emissions for the period after 2050, and then applying a logistic scaling factor  $(1 + \exp(0.1(t - 2150)))^{-1}$  to that trend, such that net (negative) AFOLU emissions smoothly transition towards net zero with an inflection point at 2150. Like industry emissions intensity, traditional biomass use,  $W_{\text{trad}}$ , is extrapolated using a log-linear fit. For industry CCS,  $\hat{S}_{\text{s.ind}}$ , and BECCS,  $\hat{S}_{\text{s.bio}}$ , the share relative to the baseline activity,  $\hat{E}_{\text{ind}}$  and  $\hat{W}_{\text{bio}}$ , respectively, is held constant at its 2100 value, subject to any applicable upper bounds. CCS on fossil fuels ( $\hat{S}_{\text{s.fossil}}$ ) is phased out after 2100 with the expectation that fossil fuels are being phased out (see Section 3.2.3). Note, however, that only few baseline scenarios feature CCS, and none of them feature DACCS. Final energy is extrapolated as  $\hat{F}(t) = \eta_{\text{tot}} \hat{W}(t)$ , where  $\eta_{\text{tot}}$  is the total final-to-primary energy conversion efficiency in 2100.

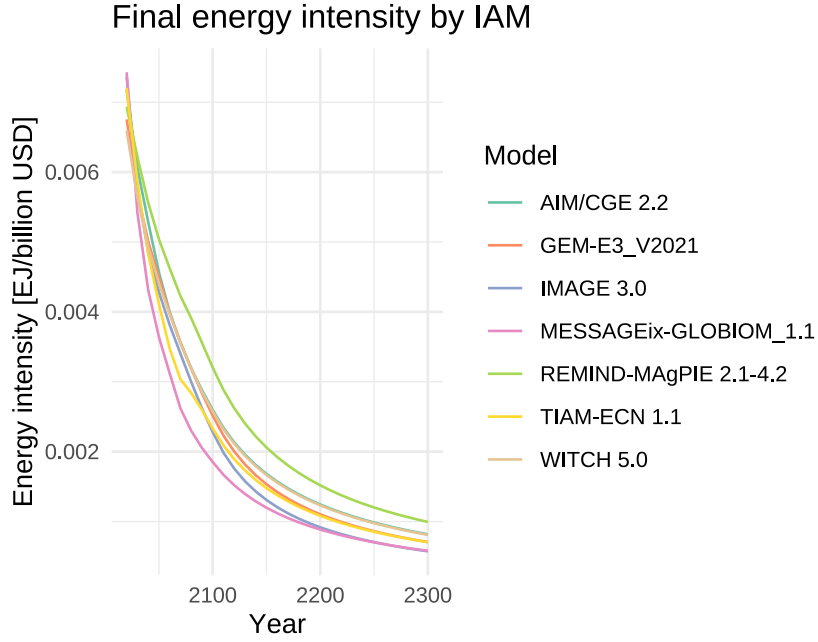


Figure 8: Extrapolated final energy intensity by IAM, in EJ / billion 2010 USD.

For ultra long-term projections beyond 2300, it is assumed that a steady state of net negative emissions will be achieved. That is, abatement options will operate at their maximum capacity. To hold net negative emissions at a constant level, baselines are fixed at their 2300 value after this date.

### 3.2.3 Extrapolation of primary energy

We define a linear phase-out of fossil primary energy  $W_{\text{foss}}(t)$ , starting from its value at time  $t_0 = 2100$ , denoted as  $W_{\text{foss}}(t_0)$ , and decreasing to zero by a specified end year. The phase-out proceeds at a constant rate and is expressed as:

$$W_{\text{foss}}(t) = \max \left( W_{\text{foss}}(t_0) \cdot \left( 1 - \frac{t - t_0}{t_{\text{end}} - t_0} \right), 0 \right)$$

where  $t \geq t_0$ . The formulation ensures that fossil energy use declines linearly to zero by the final year and remains zero thereafter.

Nuclear and bioenergy pathways are determined by using the marginal abatement cost functions under a specified carbon price path. As long as the imposed carbon price remains high enough, abatement via these options continues to grow until an upper bound is reached.

NBRs are assumed to fill the remaining energy demand not met by fossil fuels, bioenergy, or nuclear. The NBR contribution is calculated as the residual required to satisfy final energy demand, adjusted for conversion efficiencies:

$$W_{\text{nbr}}(t) = \frac{1}{\eta_{\text{nbr}}} \left[ F(t) - \sum_{i \in \{\text{bio}, \text{nuc}, \text{foss}, \text{trad}\}} \eta_i W_i(t) \right]$$

This approach is justified by the vast physical potential of renewable energy sources such as wind and solar, which are not assumed to be capacity-limited in this long-term extrapolation.

The fossil fuel phase-out trajectory, modulated by potential use of fossil CCS, effectively determines the gross emissions path. If fossil energy use is already low by 2100 (in a high-ambition scenario), it is likely that bioenergy and nuclear options have reached their maximum levels, implying that continued increases in energy demand will be met almost entirely by expanding NBR deployment. In this case, NBRs are already substantial in 2100 and continue to grow approximately in line with final energy demand, which itself depends on economic growth. In contrast, if fossil fuel use remains high in 2100 (a lower-ambition scenario), bioenergy and nuclear may still have room to grow post-2100, partially offsetting the reduction in fossil energy. However, NBRs will also have to expand more aggressively to fill the gap, yet starting from a lower level in 2100.

## References

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## **A Additional Figures**

### Model Validation for AIM/CGE 2.2

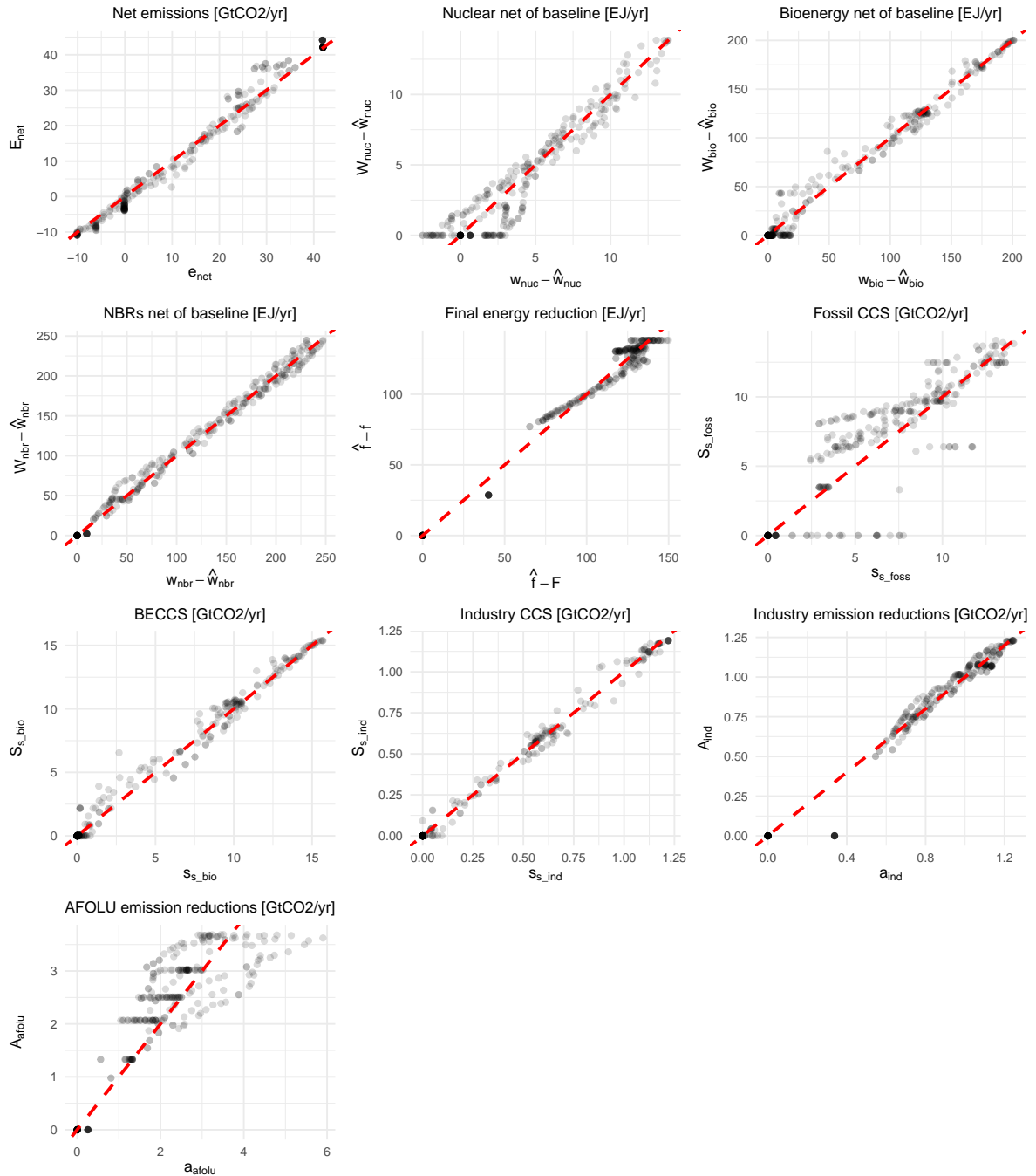


Figure 9: Model Validation for the AIM/CGE 2.2 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for GEM-E3\_V2021

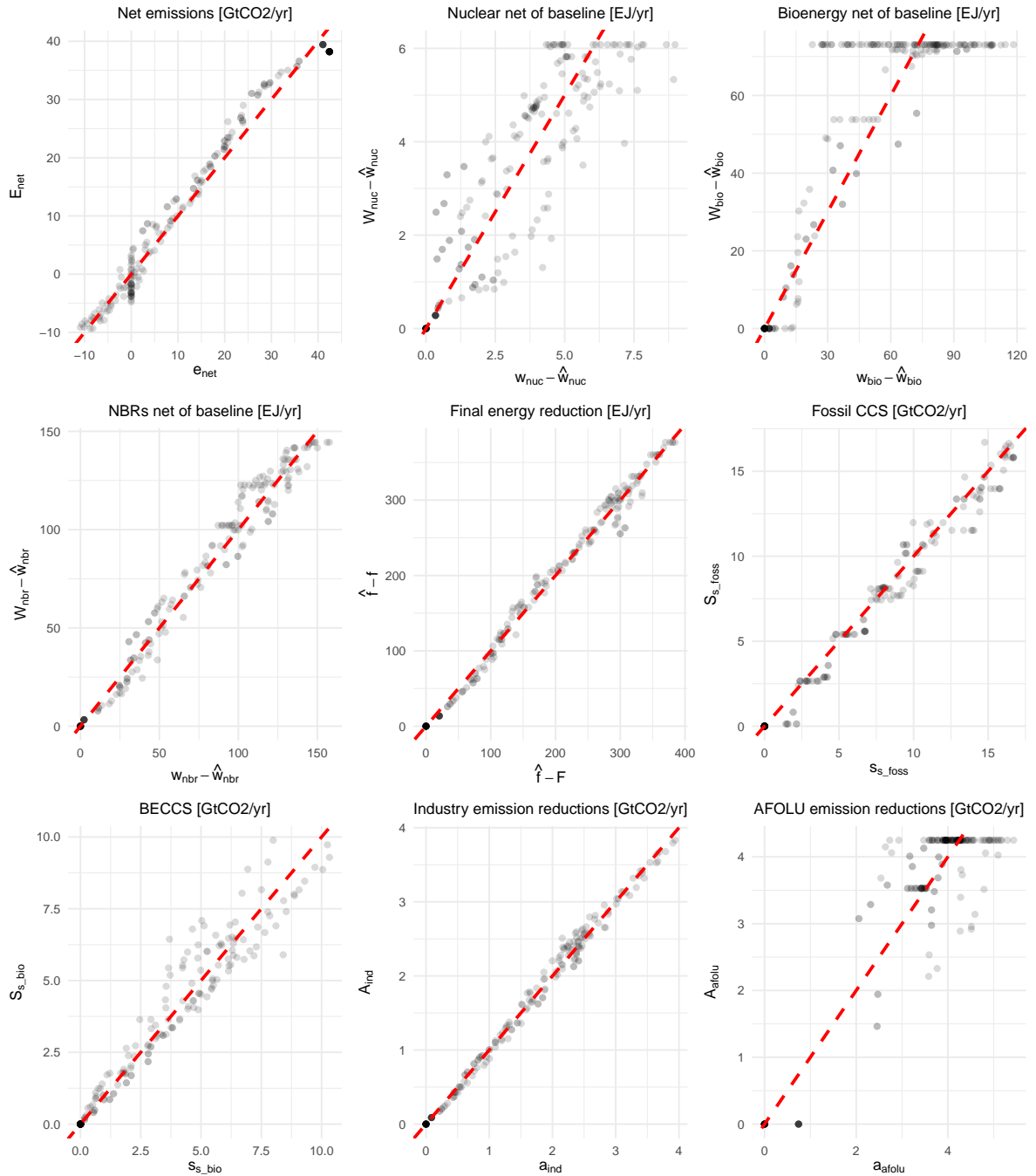


Figure 10: Model Validation for the GEM-E3 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for IMAGE 3.0

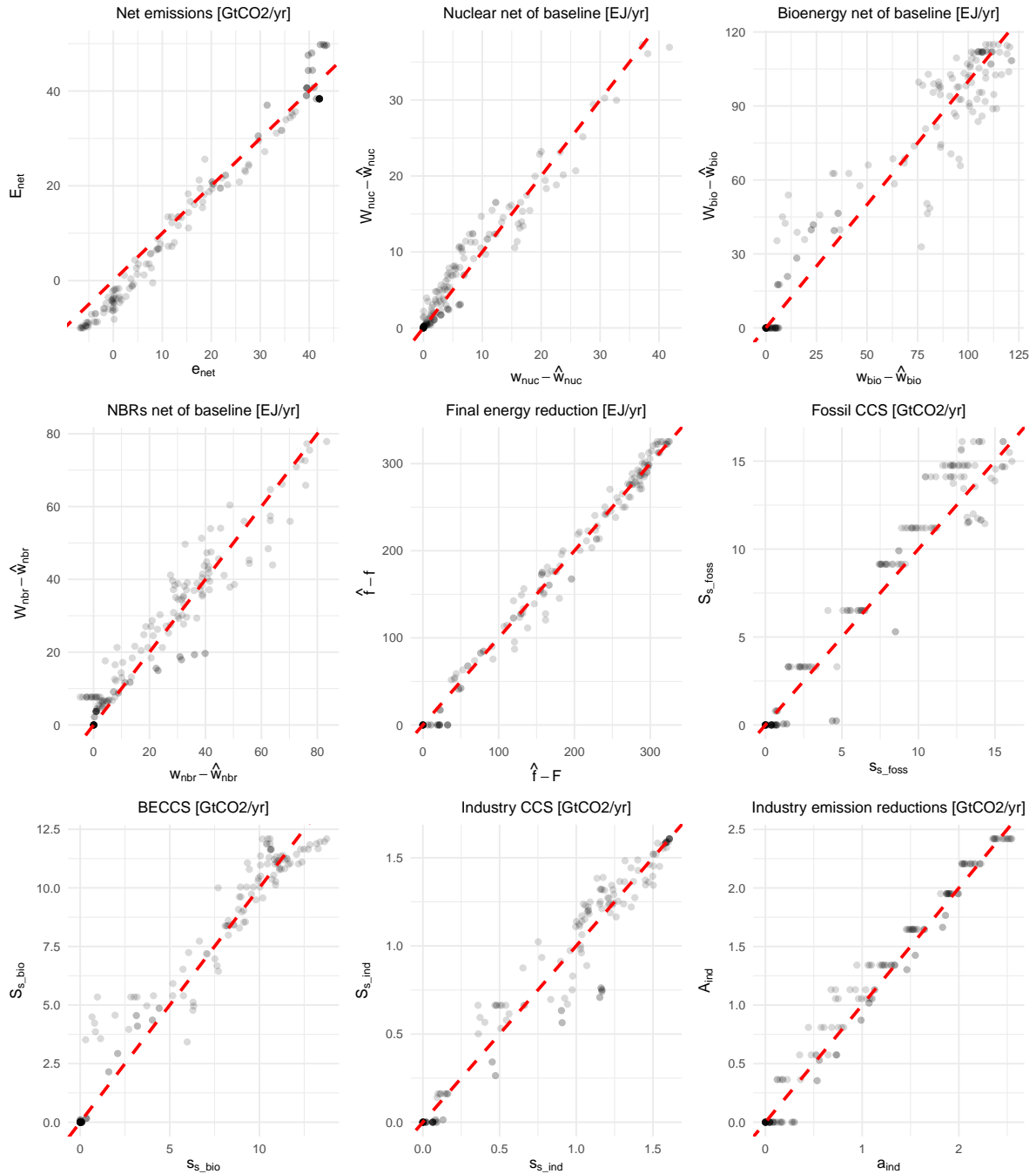


Figure 11: Model Validation for the IMAGE 3.0 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for MESSAGEix-GLOBIOM\_1.1

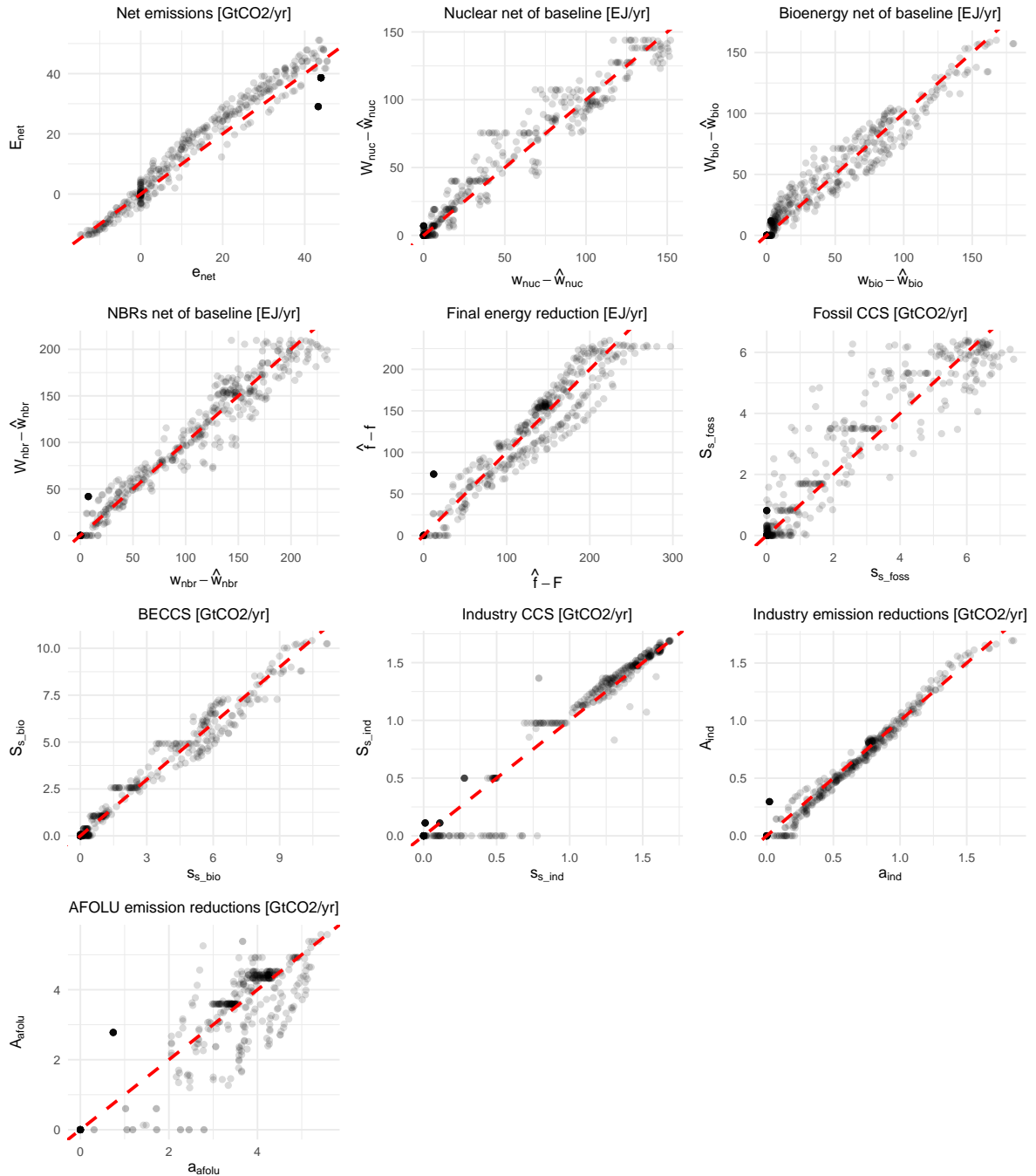


Figure 12: Model Validation for the MESSAGEix-GLOBIOM 1.1 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for REMIND-MAgPIE 2.1-4.2

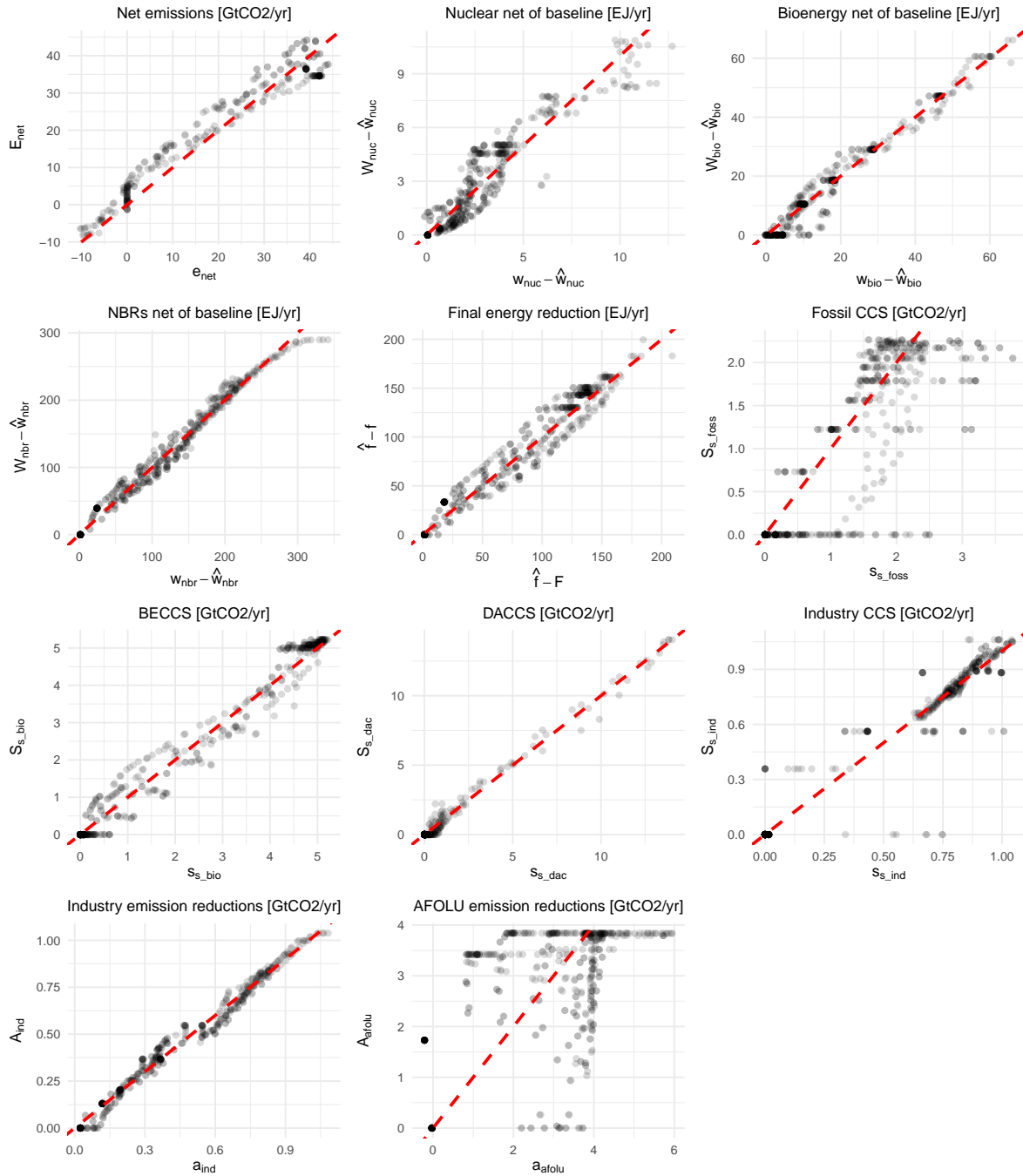


Figure 13: Model Validation for the REMIND-MAgPIE 2.1-4.2 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for TIAM-ECN 1.1

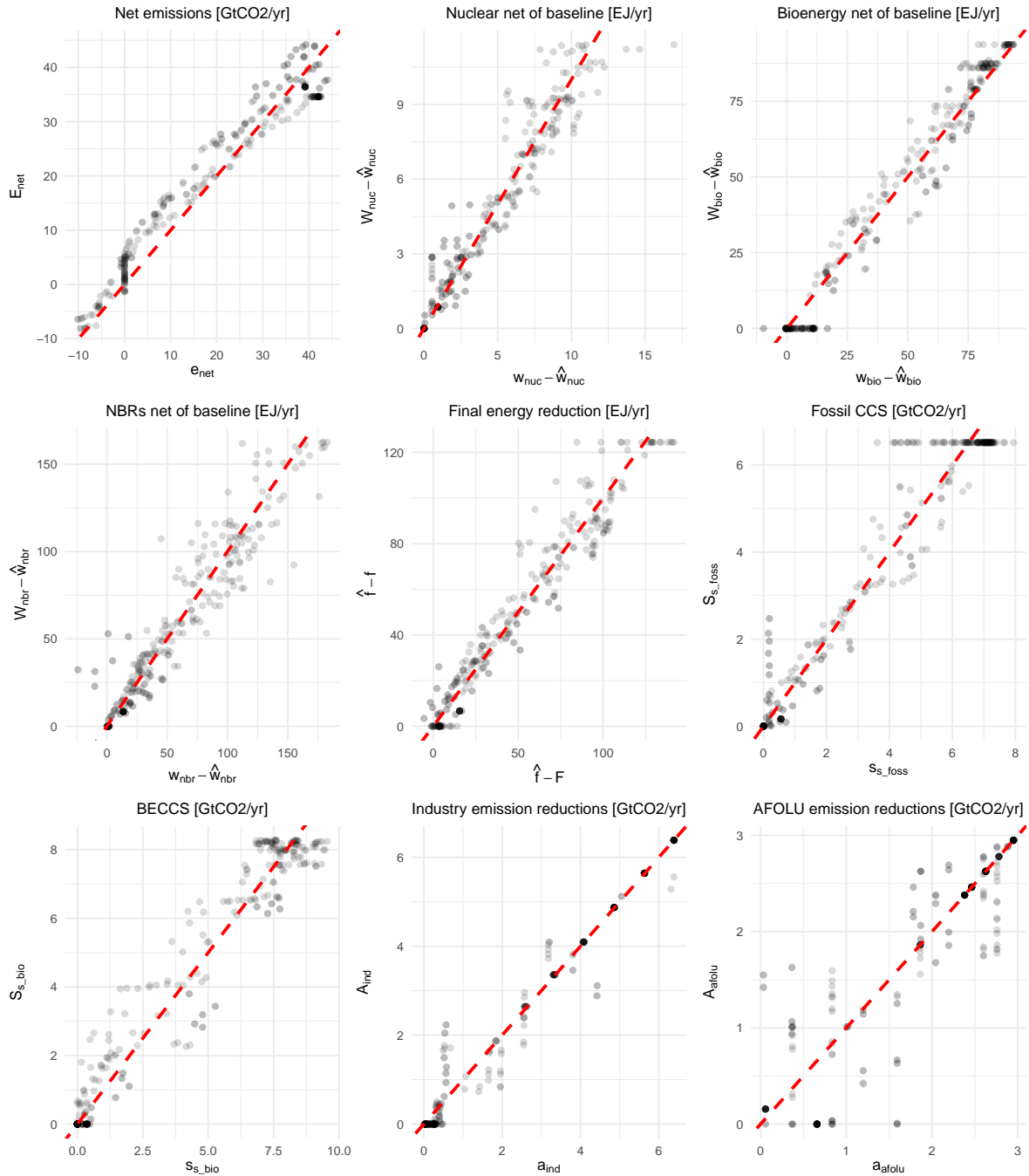


Figure 14: Model Validation for the TIAM-ECN 1.1 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

### Model Validation for WITCH 5.0

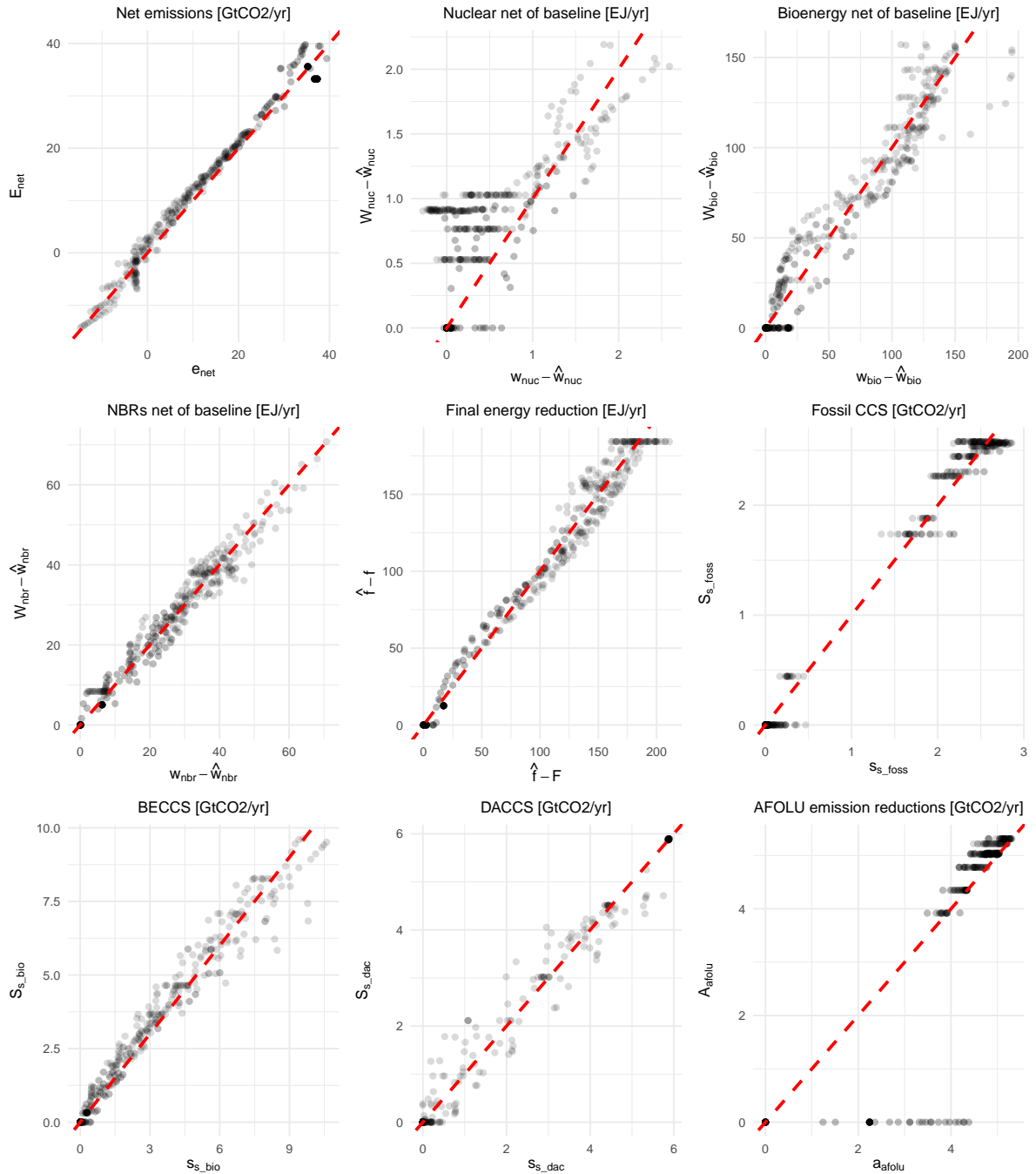


Figure 15: Model Validation for the WITCH 5.0 IAM. Panels displaying emissions and removals (Net Emissions, Fossil CCS, BECCS, DACCS, Industry CCS, Industry Emission Reductions, AFOLU Emission Reductions) are presented in GtCO<sub>2</sub>/yr, while panels showing energy figures (Nuclear, Bioenergy, NBRs, Final Energy) are in EJ/yr.

## Comparison of average abatement costs with consumption loss per tCO<sub>2</sub>

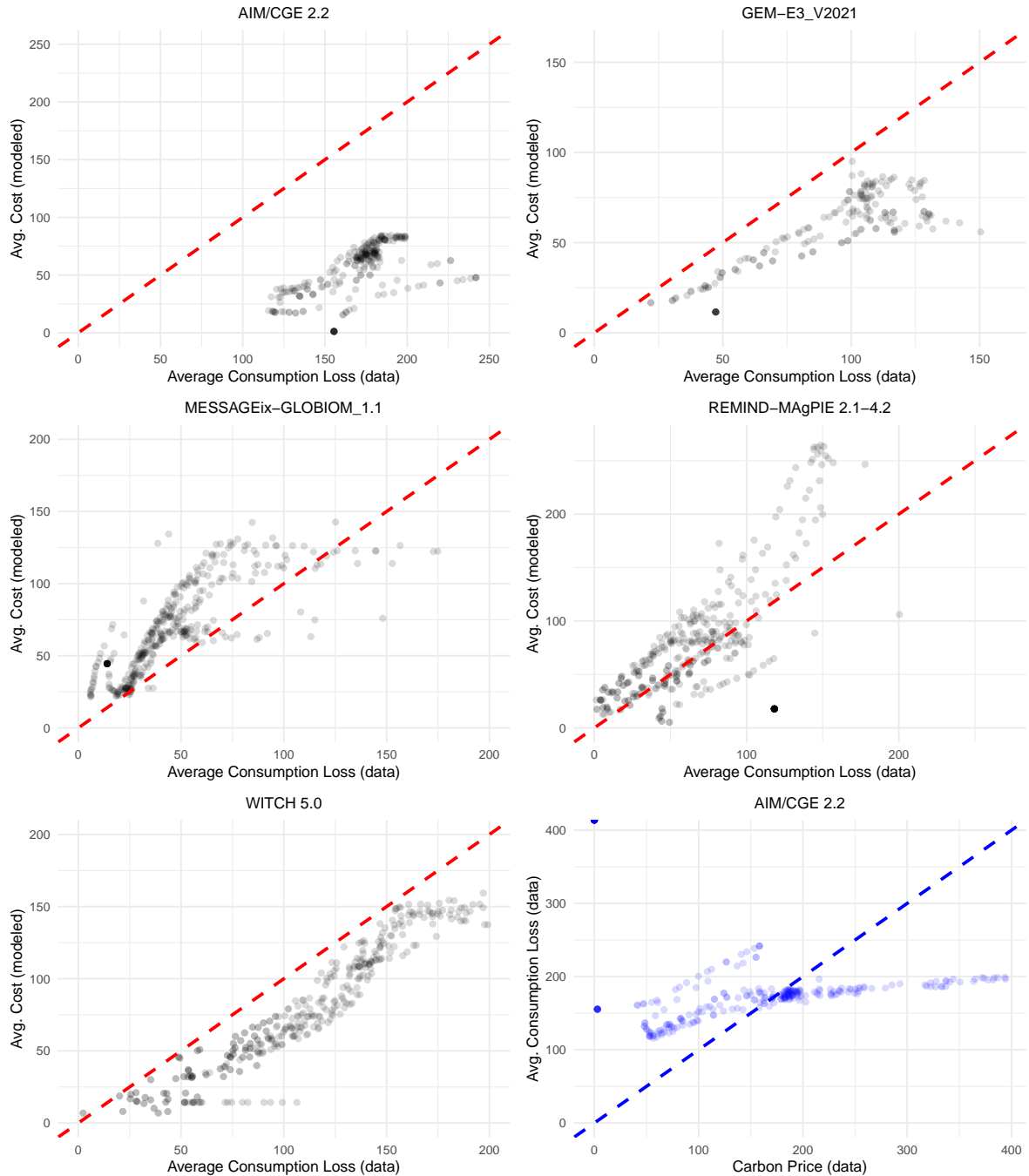


Figure 16: Reported consumption loss per tCO<sub>2</sub> versus modeled total average abatement costs. No consumption loss data are available for IMAGE 3.0 and TIAM-ECN 1.1. For AIM/CGE 2.2, reported consumption loss is also plotted against reported carbon prices (bottom right). If carbon prices represent marginal abatement costs and consumption loss per tCO<sub>2</sub> approximates average costs, then consumption loss should not exceed the carbon price. However, this condition is frequently violated for AIM/CGE 2.2, suggesting that consumption loss may not be a reliable proxy for average abatement costs in this case, which could explain the observed deviation from modeled estimates (top left).

## B Model overview

Symbol	Elements	Meaning
$\mathcal{I}$	{foss, nbr, bio, nuc, trad}	Primary energy types: fossil, non-biomass renewables, biomass, nuclear, traditional biomass
$\mathcal{N}$	{ind, afolu}	Sectors: industry, AFOLU (Agriculture, Forestry, and Other Land Use)
$\mathcal{J}$	$\mathcal{N} \cup \{\text{ener}\}$	Sectors: energy, industry, AFOLU
$\mathcal{K}$	{s.foss, s.bio, s.ind, s.dac}	Carbon capture types: fossil CCS, BECCS, industry CCS, DACCS
$\mathcal{M}$	$\mathcal{I} \cup \mathcal{N} \cup \mathcal{K} \cup \{\text{fe}\}$	Abatement options: primary energy types, industry, AFOLU, capture types, final energy reduction

Table 7: Index sets used in the model: symbols, elements, and meanings.

Symbol	Explanation	Units
$W_i$	Primary energy of type $i, i \in \mathcal{I}$	EJ/yr
$W_{\text{foss}}$	Primary energy from fossil fuels	EJ/yr
$W_{\text{nbr}}$	Primary energy from non-biomass renewables	EJ/yr
$W_{\text{bio}}$	Primary energy from biomass	EJ/yr
$W_{\text{nuc}}$	Primary energy from nuclear	EJ/yr
$W_{\text{trad}}$	Primary energy from traditional biomass	EJ/yr
$F$	Final energy	EJ/yr
$E_{\text{net}}$	Net emissions (all sectors)	GtCO <sub>2</sub> /yr
$E_j$	Pre-capture emissions from sector $j, j \in \mathcal{J}$	GtCO <sub>2</sub> /yr
$E_{\text{ener}}$	Pre-capture emissions from energy system	GtCO <sub>2</sub> /yr
$E_{\text{ind}}$	Pre-capture industrial process emissions	GtCO <sub>2</sub> /yr
$E_{\text{afolu}}$	Net emissions from AFOLU	GtCO <sub>2</sub> /yr
$S_k$	Carbon captured/stored via option $k$	GtCO <sub>2</sub> /yr
$S_{\text{s.foss}}$	Capture via fossil CCS	GtCO <sub>2</sub> /yr
$S_{\text{s.bio}}$	Removals via BECCS	GtCO <sub>2</sub> /yr
$S_{\text{s.ind}}$	Capture via industry CCS	GtCO <sub>2</sub> /yr
$S_{\text{s.dac}}$	Removals via DACCS	GtCO <sub>2</sub> /yr
$A_{\text{fe}}$	Abatement from reducing final energy	GtCO <sub>2</sub> /yr
$A_i$	Abatement from substituting fossil fuels with primary energy source $i$	GtCO <sub>2</sub> /yr
$\Delta W_i$	Change in primary energy $i$ vs baseline, $i \in \mathcal{I}$	EJ/yr
$\Delta F$	Change in final energy vs baseline	EJ/yr
$v_i(t)$	Upper bound on $W_i(t)$ , $i \in \mathcal{I} \setminus \{\text{foss}\}$	EJ/yr
$v_j(t)$	Upper bound on abatement in sector $j, j \in \mathcal{N}$	GtCO <sub>2</sub> /yr
$v_k(t)$	Upper bound on capture option $k, k \in \mathcal{K}$	GtCO <sub>2</sub> /yr
$v_k^{\text{pot}}(t)$	Technical capture potential of option $k, k \in \mathcal{K} \setminus \{\text{s.dac}\}$	GtCO <sub>2</sub> /yr
$v_{\text{fe}}(t)$	Lower bound on final energy	EJ/yr

Table 8: Model variables with brief explanation and units.

Energy and emission balance:

$$E_{\text{net}}(t) = \sum_{j \in \mathcal{J}} E_j(t) - \sum_{k \in \mathcal{K}} S_k(t); \quad (10)$$

$$E_{\text{ener}}(t) = \beta_{\text{foss}} W_{\text{foss}}(t); \quad (11)$$

$$F(t) = \sum_{i \in \mathcal{I}} \eta_i W_i(t). \quad (12)$$

Symbol	Meaning	Units
$\hat{\cdot}$	hat notation is used to distinguish between elements from the baseline and mitigation scenarios.	
$\hat{W}_i(t)$	Baseline primary energy of type $i, i \in \mathcal{I}$	EJ/yr
$\hat{E}_j(t)$	Baseline pre-capture emissions from sector $j, j \in \mathcal{N}$	GtCO <sub>2</sub> /yr
$\hat{S}_k(t)$	Baseline carbon captured/stored via option $k, k \in \mathcal{K}$	GtCO <sub>2</sub> /yr
$\beta_{\text{foss}}$	Carbon intensity of fossil fuels	GtCO <sub>2</sub> /EJ
$\eta_i$	Conversion efficiency from primary to final energy for type $i, i \in \mathcal{I}$	–
$\sigma_i$	Substitution efficiency of fuel $i$ vs fossil fuels, $i \in \mathcal{I} \setminus \{\text{foss}\}$	–
$d_i, u_i$	Marginal cost floor/ceiling for option $i, i \in \mathcal{I} \setminus \{\text{foss}\}$	USD/tCO <sub>2</sub>
$l_i$	Lag parameter for option $i, i \in \mathcal{I} \setminus \{\text{foss}\}$	–
$a_i, b_i$	Cost function coefficients for option $i, i \in \mathcal{I} \setminus \{\text{foss}\}$	see cost eq.
$g_i$	Growth parameter for max abatement change for option $i, i \in \mathcal{I} \setminus \{\text{foss}\}$	GtCO <sub>2</sub> /yr

Table 9: Model parameters with meanings and units.

Initial conditions and assumptions:

$$W_i(t_0) := \hat{W}_i(t_0), \quad (13)$$

$$F(t_0) := \hat{F}(t_0), \quad (14)$$

$$S_k(t_0) := \hat{S}_k(t_0), \quad (15)$$

$$\Delta W_{\text{trad}}(t) = 0. \quad (16)$$

Abatement:

$$\Delta W_i(t) := \hat{W}_i(t) - W_i(t), \quad i \in \mathcal{I}; \quad (17)$$

$$A(t) := \beta_{\text{foss}} \Delta W_{\text{foss}}(t); \quad (18)$$

$$\sigma_i := \frac{\eta_i}{\eta_{\text{foss}}}, \quad i \in \mathcal{I} \setminus \{\text{foss}\}; \quad (19)$$

$$A_i(t) := -\beta_{\text{foss}} \sigma_i \Delta W_i(t), \quad i \in \mathcal{I} \setminus \{\text{foss}\}; \quad (20)$$

$$\Delta F(t) := \hat{F}(t) - F(t); \quad (21)$$

$$A_{\text{fe}}(t) := \frac{\beta_{\text{foss}} \Delta F(t)}{\eta_{\text{foss}}}; \quad (22)$$

$$A_j(t) := \hat{E}_j(t) - E_j(t), \quad j \in \mathcal{N}; \quad (23)$$

$$A_k(t) := S_k(t) - \hat{S}_k(t), \quad k \in \mathcal{K}. \quad (24)$$

Marginal costs, total costs, and limits for abatement through primary energy substitution:

For  $i \in \mathcal{I} \setminus \{\text{foss}\}$

$$P_i(t) = \begin{cases} \frac{a_i}{(\beta_{\text{foss}} \sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i} + d_i, & \text{if } A_i(t) \geq l_i A_i(t-1) \\ d_i, & \text{if } A_i(t) < l_i A_i(t-1) \end{cases}; \quad (25)$$

$$C_i(t) = \begin{cases} \frac{a_i}{b_i + 1} \left( \frac{1}{(\beta_{\text{foss}} \sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i+1} \right) + d_i A_i(t), & \text{if } A_i(t) \geq l_i A_i(t-1) \\ d_i A_i(t), & \text{if } A_i(t) < l_i A_i(t-1) \end{cases}; \quad (26)$$

$$W_i(t) \leq v_i(t), \quad (27)$$

$$A_i(t) \leq \beta_{\text{foss}} \sigma_i g_i + l_i A_i(t-1). \quad (28)$$

Marginal costs, total costs, and limits for abatement through final energy reduction:

$$P_{\text{fe}}(t) = \begin{cases} a_{\text{fe}} \left( \frac{\eta_{\text{foss}}}{\beta_{\text{foss}}} \right)^{b_{\text{fe}}} (A_{\text{fe}}(t) - l_{\text{fe}} A_{\text{fe}}(t-1))^{b_{\text{fe}}} + d_{\text{fe}}, & \text{if } A_{\text{fe}}(t) \geq l_{\text{fe}} A_{\text{fe}}(t-1); \\ d_{\text{fe}}, & \text{if } A_{\text{fe}}(t) < l_{\text{fe}} A_{\text{fe}}(t-1) \end{cases}; \quad (29)$$

$$C_{\text{fe}}(t) = \begin{cases} \frac{a_{\text{fe}}}{b_{\text{fe}} + 1} \left( \frac{\eta_{\text{foss}}}{\beta_{\text{foss}}} \right)^{b_{\text{fe}}} (A_{\text{fe}}(t) - l_{\text{fe}} A_{\text{fe}}(t-1))^{b_{\text{fe}}+1} + d_{\text{fe}} A_{\text{fe}}(t), & \text{if } A_{\text{fe}}(t) \geq l_{\text{fe}} A_{\text{fe}}(t-1); \\ d_{\text{fe}} A_{\text{fe}}(t), & \text{if } A_{\text{fe}}(t) < l_{\text{fe}} A_{\text{fe}}(t-1) \end{cases}; \quad (30)$$

$$F(t) \geq v_{\text{fe}}(t), \quad (31)$$

$$A_{\text{fe}}(t) \leq \frac{\beta_{\text{foss}}}{\eta_{\text{foss}}} g_{\text{fe}} + l_{\text{fe}} A_{\text{fe}}(t-1). \quad (32)$$

Marginal costs, total costs, and limits for abatement in industry and AFOLU sector:

For  $j \in \mathcal{N}$ ,

$$P_j(t) = \begin{cases} a_j (A_j(t) - l_j A_j(t-1))^{b_j} + d_j, & \text{if } A_j(t) \geq l_j A_j(t-1); \\ d_j, & \text{if } A_j(t) < l_j A_j(t-1) \end{cases}; \quad (33)$$

$$C_j(t) = \begin{cases} \frac{a_j}{b_j + 1} (A_j(t) - l_j A_j(t-1))^{b_j+1} + d_j A_j(t), & \text{if } A_j(t) \geq l_j A_j(t-1); \\ d_j A_j(t), & \text{if } A_j(t) < l_j A_j(t-1) \end{cases}; \quad (34)$$

$$A_j(t) \leq v_j(t), \quad (35)$$

$$A_j(t) \leq g_j + l_j A_j(t-1). \quad (36)$$

Marginal costs, total costs, and limits for carbon capture:

For  $k \in \mathcal{K}$ ,

$$P_k(t) = \begin{cases} a_k (A_k(t) - l_k A_k(t-1))^{b_k} + d_k, & \text{if } A_k(t) \geq l_k A_k(t-1); \\ d_k A_k(t), & \text{if } A_k(t) < l_k A_k(t-1) \end{cases}; \quad (37)$$

$$C_k(t) = \begin{cases} \frac{a_k}{b_k + 1} (A_k(t) - l_k A_k(t-1))^{b_k+1} + d_k A_k(t), & \text{if } A_k(t) \geq l_k A_k(t-1); \\ d_k A_k(t), & \text{if } A_k(t) < l_k A_k(t-1) \end{cases}; \quad (38)$$

$$S_k(t) \leq v_k(t), \quad (39)$$

$$A_k(t) \leq g_k + l_k A_k(t-1). \quad (40)$$

## C Abatement functions

### C.1 Abatement functions for primary energy substitution

The marginal and total cost functions introduced in Sections 1.5 to 1.7 can be used to solve for abatement under a specified objective function in an optimization framework. In contrast, simulation and calibration require functions that directly determine abatement from an exogenous carbon price path  $P(\cdot)$ . Here, we introduce such abatement functions. In essence, we show how a given global carbon price path  $P(\cdot)$  generates a feasible trajectory for  $W_i(\cdot)$ , and thus for  $A_i(\cdot)$ , with the corresponding marginal costs  $P_i(\cdot)$  computed as described in Section C.1.1.

For computing pathways of primary energy sources, we define the following function:

$$W_i(t) = \min \left( \tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t), v_i(t) \right), \quad (41)$$

with

$$\tilde{P}_i(t) := \min(u_i, P(t)) - \min(d_i, P(t)),$$

where  $u_i \geq d_i$ . The parameters  $d_i$  and  $u_i$  denote the marginal cost floor and ceiling, below and above which the imposed carbon price has no effect on abatement. The parameter  $v_i(t)$  specifies the maximum achievable value of  $W_i(t)$  in each period. Recall that  $\Delta W_i(t) = -\frac{A_i(t)}{\beta_{\text{foss}} \sigma_i}$  (see Eq. 3). Moreover, we define the transformations  $\tilde{a}_i := a_i^{-1/b_i}$ ,  $\tilde{b}_i := 1/b_i$ , and  $g_i := \tilde{a}_i(u_i - d_i)^{\tilde{b}_i}$ .

#### Case A

Suppose

$$\tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t) \leq v_i(t).$$

Then,

$$W_i(t) = \tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t).$$

Let us now analyze  $\tilde{P}_i(t)$ .

**Case A.1** – Standard case ( $d_i < P(t) < u_i$ ), hence,  $\tilde{P}_i(t) = P(t) - d_i$ . Substituting yields:

$$W_i(t) - \hat{W}_i(t) + l_i \Delta W_i(t-1) = \tilde{a}_i (P(t) - d_i)^{\tilde{b}_i}.$$

Hence,

$$\left( \tilde{a}_i^{-1} (W_i(t) - \hat{W}_i(t) + l_i \Delta W_i(t-1)) \right)^{1/\tilde{b}_i} = P(t) - d_i,$$

and therefore,

$$P(t) = a_i (W_i(t) - \hat{W}_i(t) + l_i \Delta W_i(t-1))^{b_i} + d_i.$$

Substituting  $A_i(t) = -\beta_{\text{foss}} \sigma_i \Delta W_i(t)$  yields:

$$P(t) = \frac{a_i}{(\beta_{\text{foss}} \sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i} + d_i, \quad (42)$$

Thus, in this carbon price range,  $P_i(t) := P(t)$ .

**Case A.2** – Price ceiling ( $P(t) > u_i$ ) Here,  $\tilde{P}_i(t) = u_i - d_i$ . Inserting into Eq. 41 gives

$$A_i(t) = \beta_{\text{foss}} \sigma_i g_i + l_i A_i(t-1),$$

which represents the maximum feasible per-period growth (compare with Eq. 6). To determine the marginal costs at the maximum growth, we substitute this expression into Eq. 4 and obtain  $P_i(t) = u_i$ .

**Case A.3** – Price floor ( $P(t) < d_i$ ) Here,  $\tilde{P}_i(t) = 0$ . Then, again inserting into Eq. 41 gives

$$A_i(t) = l_i A_i(t-1).$$

This is a lower bound for abatement growth by period. Inserting this into Eq. 4 yields the marginal cost at the lowest possible growth,  $P_i(t) = d_i$ .

**Summary Case A** Given the condition

$$\tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t) \leq v_i(t),$$

we have shown:

- The lowest feasible abatement growth is given by  $A_i(t) = l_i A_i(t-1)$ .
- The largest feasible abatement growth is given by  $A_i(t) = \beta_{\text{foss}} \sigma_i g_i + l_i A_i(t-1)$ .
- Marginal costs satisfy:

$$P_i(t) = \frac{a_i}{(\beta_{\text{foss}} \sigma_i)^{b_i}} (A_i(t) - l_i A_i(t-1))^{b_i} + d_i.$$

So far, we have only considered the upper part of the marginal cost function in Eq 4.

## Case B

Suppose

$$\tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t) > v_i(t).$$

Then,

$$W_i(t) = v_i(t),$$

which reflects Eq. 5, and from which  $A_i(t)$  can be inferred:

$$A_i(t) = \beta_{\text{foss}} \sigma_i (v_i(t) - \hat{W}_i(t)). \quad (43)$$

### C.1.1 Link between carbon price and marginal costs

For **Case A**, we have established a relation between the price path  $P(t)$  and abatement-option-specific marginal costs  $P_i(t)$ :

$$P_i(t) = \begin{cases} P(t), & d_i \leq P(t) \leq u_i, \\ d_i, & P(t) < d_i, \\ u_i, & P(t) > u_i, \end{cases}$$

where  $P(t)$  is the globally imposed carbon price, while  $P_i(t)$  denotes the abatement-option-specific marginal cost. For **Case B**, abatement is trivially derived from Eq. 43, which can be used in Eq. 4 to determine  $P_i(t)$ . In **Case B**  $P_i(t)$  in any case diverges from  $P(t)$ . Finally note that, **Case A** is limited to solutions  $l_i A_i(t-1) \leq A_i(t) \leq \beta_{\text{toss}} \sigma_i g_i + l_i A_i(t-1)$ . **Case B** can lead to solutions where  $A_i(t) < l_i A_i(t-1)$ , for which  $P_i(t) = d_i$ . Moreover, if we have  $P(t) < d_i$  and  $\tilde{a}_i \tilde{P}_i(t)^{\tilde{b}_i} - l_i \Delta W_i(t-1) + \hat{W}_i(t) > v_i(t)$ , it follows that  $A_i(t) < l_i A_i(t-1)$ .

## C.2 Abatement function for final energy reduction

The abatement function for final energy reduction differs from those for primary energy substitution in terms of the signs. We have the following form:

$$F(t) = - \min \left( \tilde{a}_{\text{fe}} \tilde{P}_{\text{fe}}(t)^{\tilde{b}_{\text{fe}}} + l_{\text{fe}} \Delta F(t-1) - \hat{F}(t), v_{\text{fe}}(t) \right). \quad (44)$$

Here,  $\tilde{a}_{\text{fe}} \leq 0$  and  $v_{\text{fe}}(t)$  is the minimum allowable amount of  $F_i(t)$ . Using the definitions  $a_{\text{fe}} := |\tilde{a}_{\text{fe}}|^{-1/\tilde{b}_{\text{fe}}}$ ,  $b_{\text{fe}} := 1/\tilde{b}_{\text{fe}}$ ,  $g_{\text{fe}} := \left( \frac{u_{\text{fe}} - d_{\text{fe}}}{a_{\text{fe}}} \right)^{1/b_{\text{fe}}}$ , and  $\Delta F(t) = \frac{\eta_{\text{toss}}}{\beta_{\text{toss}}} A_{\text{fe}}(t)$ , we can link Eq. 44 to the marginal cost function 7, following the steps of Section C.1.

## C.3 Abatement functions for industry and AFOLU sectors

The abatement functions for Industry and AFOLU sectors are defined as:

$$A_j(t) = \min \left( \tilde{a}_j \tilde{P}_j(t)^{\tilde{b}_j} + l_j A_j(t-1), v_j(t) \right),$$

where  $\tilde{P}_j(t) := \min(u_j, P(t)) - \min(d_j, P(t))$  and  $u_j \geq d_j$ . As before, using the definitions  $\tilde{a}_j := a_j^{-1/b_j}$ ,  $\tilde{b}_j := 1/b_j$ , and  $g_j := \tilde{a}_j (u_j - d_j)^{\tilde{b}_j}$ , we can link this abatement function, to the marginal cost function in Eq 8 and its associated constraints.

## C.4 Abatement functions for carbon capture

The abatement function for carbon capture is defined as:

$$S_k(t) = \min \left( \tilde{a}_k \tilde{P}_k(t)^{\tilde{b}_k} + l_k A_k(t-1) + \hat{S}_k(t), v_k(t) \right),$$

where  $\tilde{P}_k(t) := \min(u_k, P(t)) - \min(d_k, P(t))$  and  $u_k \geq d_k$ . As before, using  $\tilde{a}_k := a_k^{-1/b_k}$ ,  $\tilde{b}_k := 1/b_k$ ,  $\delta_k := d_k$ , and  $g_k := \tilde{a}_k (u_k - d_k)^{\tilde{b}_k}$ , we can link the abatement function to Eq. 9 and its associated constraints.

# ANNEX 2

Co-author statements

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I, Dr. Artem Baklanov, certify that Johannes Bednar completed the majority of the work in the journal articles and working papers below, which form part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).
- J. Bednar, A. Baklanov, J. Macinante, The carbon removal obligation: Updated analytical model and scenario analysis. IIASA Working Paper WP-23-001 (2023); <https://pure.iiasa.ac.at/id/eprint/18572/>.
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).
- J. Bednar, A. Baklanov, A Reduced-Complexity Model of Process-Based IAMs. IIASA Working Paper WP-25-001(2025); <https://pure.iiasa.ac.at/id/eprint/20834/>.
- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

Signature:



Artem Baklanov

Date:

14.10.25

Sincerely,

# Environmental *Change* Institute

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I, Dr. Fabian Wagner, certify that Johannes Bednar completed the majority of the work in the journal articles below, which form part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).

Signature:

A handwritten signature in blue ink, appearing to read 'F. Wagner', with a long horizontal flourish extending to the right.

Date: 20 October 2025

Sincerely,

Fabian Wagner

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I, Prof. Jim W. Hall, certify that Johannes Bednar completed the majority of the work in the journal articles below, which form part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).
- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

A handwritten signature in black ink that reads 'JW Hall'. The signature is written in a cursive style with a large, looping initial 'J'.

Signature:

Date: 15 October 2025

# Environmental Change Institute

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I, Dr. Justin Macinante, certify that Johannes Bednar completed the majority of the work in the journal articles and working papers below, which form part of his DPhil thesis:

- J. Bednar, A. Baklanov, J. Macinante, The carbon removal obligation: Updated analytical model and scenario analysis. IIASA Working Paper WP-23-001 (2023); <https://pure.iiasa.ac.at/id/eprint/18572/>.
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).
- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

Signature:

A handwritten signature in black ink, appearing to read 'Justin Macinante', written over a large, circular scribble.

Date:

15 October 2025

Sincerely,

JUSTIN MACINANTE

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I, Dr. Marcus Thomson, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).

Signature:

A handwritten signature in black ink, appearing to be 'M. Thomson', written over a light blue horizontal line.

Date: 14 October 2025

Sincerely,

Marcus James Thomson, PhD

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I, Prof. Michael Obersteiner, certify that Johannes Bednar completed the majority of the work in the journal articles below, which form part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).
- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).
- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

Signature:

A handwritten signature in blue ink, appearing to be 'M. Obersteiner', written over a faint, light blue circular stamp or watermark.

Date: Oct 21, 2025

Sincerely,

Michael Obersteiner

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I, Prof. Myles Allen, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).

A handwritten signature in black ink, appearing to read 'M. Allen', is written above a long, horizontal, slightly curved line that serves as a signature separator.

Signature:

Date: 14<sup>th</sup> October 2025

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I, Dr. Navraj Singh Ghaleigh, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, J. Macinante, A. Baklanov, J. W. Hall, F. Wagner, N. S. Ghaleigh, M. Obersteiner, Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation. *Clim. Policy* 24, 501–514 (2024).

Signature: 

Date: 19/10/2025

Sincerely,

Navraj Singh Ghaleigh  
n.ghaleigh@ed.ac.uk

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I, Dr. Oliver Geden, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, M. Obersteiner, A. Baklanov, M. Thomson, F. Wagner, O. Geden, M. Allen, J. W. Hall, Operationalizing the net-negative carbon economy. *Nature* 596, 377–383 (2021).

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A handwritten signature in blue ink, appearing to be 'O. Geden', written over a horizontal line.

Date:

21 OCT, 2025

Sincerely,

OLIVER GEDEN

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I, Dr. Thomas Gasser, certify that Johannes Bednar completed the majority of the work in the journal article below, which forms part of his DPhil thesis:

- J. Bednar, A. Baklanov, J. Macinante, J. W. Hall, T. Gasser, M. Obersteiner, Stabilizing time-lagged climate impacts requires net-negative emissions for centuries. *Submitted*.

Signature:

A handwritten signature in black ink, appearing to read 'Thomas Gasser', written over a light blue horizontal line.

Date: 14 Oct 2025

Sincerely,

# ANNEX 3

Extended Data Figures and Tables  
for Chapter 3

**Extended Data Table 1 | Net and gross emission removal in illustrative pathways from the IPCC's Special Report on global warming of 1.5°C**

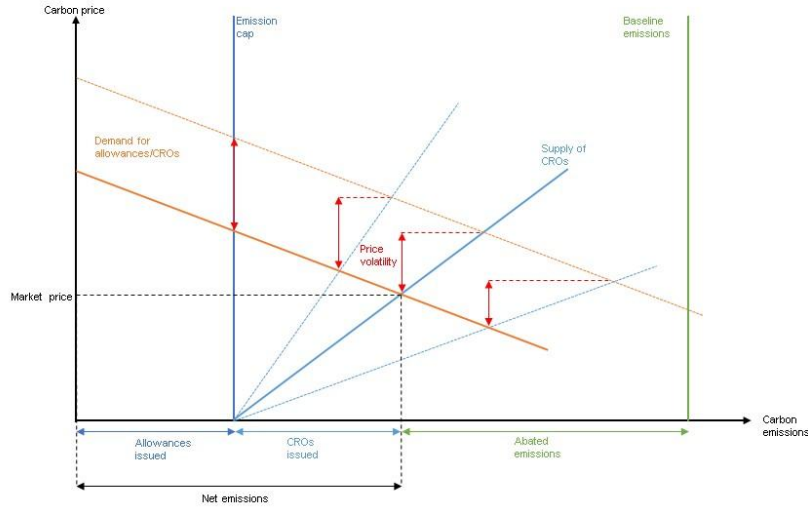
Net and gross emission removal including bioenergy with carbon capture and storage (BECCS) and Agriculture, Forestry and Other Land Use (AFOLU). To compute emission removal in term of years of current emissions we used a net emission value of 11.73 GtC in 2019. Data were retrieved from the scenario database hosted by IIASA and available at: <https://data.ene.iiasa.ac.at/iamc-1.5c-explorer>.

SR1.5 illustrative pathway	Net CO <sub>2</sub> removal	Gross CO <sub>2</sub> removal	Net CO <sub>2</sub> removal	Gross CO <sub>2</sub> removal
	(GtC)		(years of 2019 net emissions)	
P1_MESSAGEix-GLOBIOM 1.0_LowEnergyDemand	25.6	52.1	2.2	4.4
P2_AIM/CGE 2.0_SSP1-19	45.3	109.1	3.9	9.3
P3_MESSAGE-GLOBIOM 1.0_SSP2-19	102.8	169.4	8.8	14.4
P4_REMIND-MAgPIE 1.5_SSP5-19	211.8	326.4	18.1	27.8

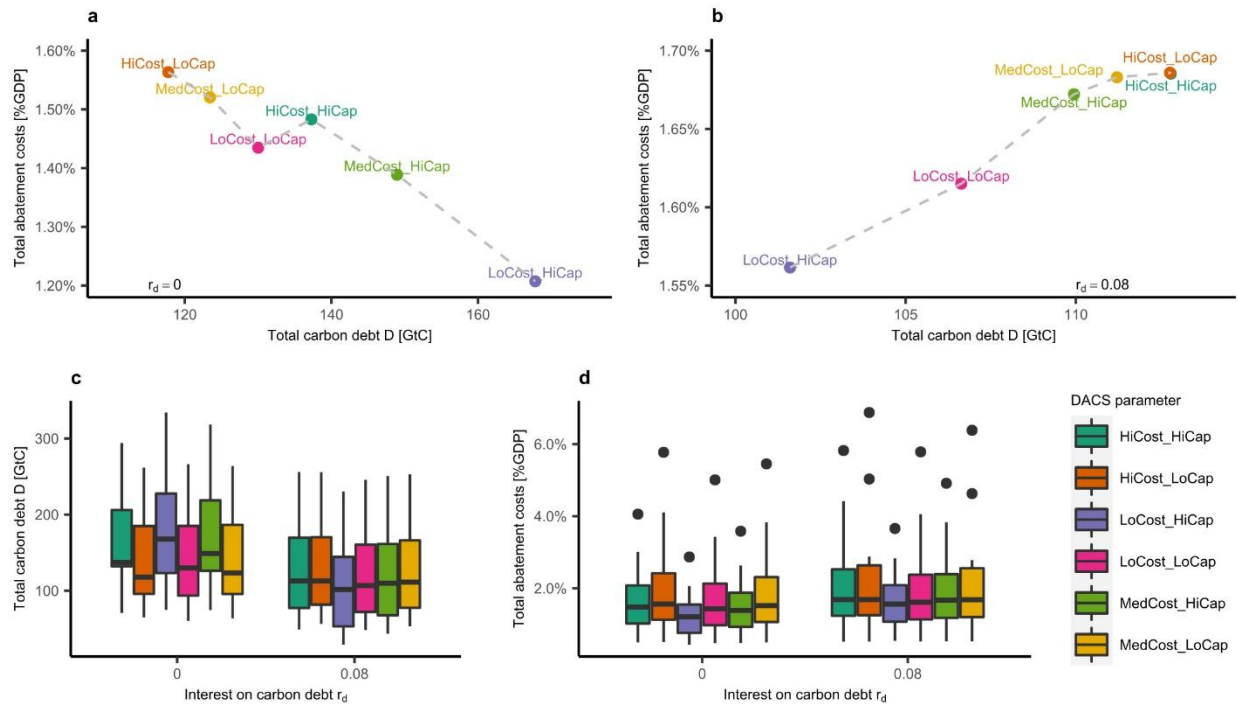
**Extended Data Table 2 | Combinations of models and SSPs used to calibrate the model in this study**

13 combinations of models and SSPs for which RCP1.9 results are available in the SSP scenario database. The RCP2.6 scenarios presented in the Results are composed of these 13 configurations of our model combined with six rates of interest on carbon debt ( $r_d = 0, 0.005, 0.1, 0.2, 0.4, 0.8$ ), resulting in 78 scenarios. The RCP1.9 scenarios are composed of the same 78 model configurations combined with 6 marginal abatement cost curves for direct air capture and storage resulting in 468 scenarios.

Model	SSP1	SSP2	SSP4	SSP5
WITCH-GLOBIOM	X		X	
REMIND-MAgPIE	X	X		X
MESSAGE-GLOBIOM	X	X		
IMAGE	X			
GCAM4	X	X		X
AIM/CGE	X	X		

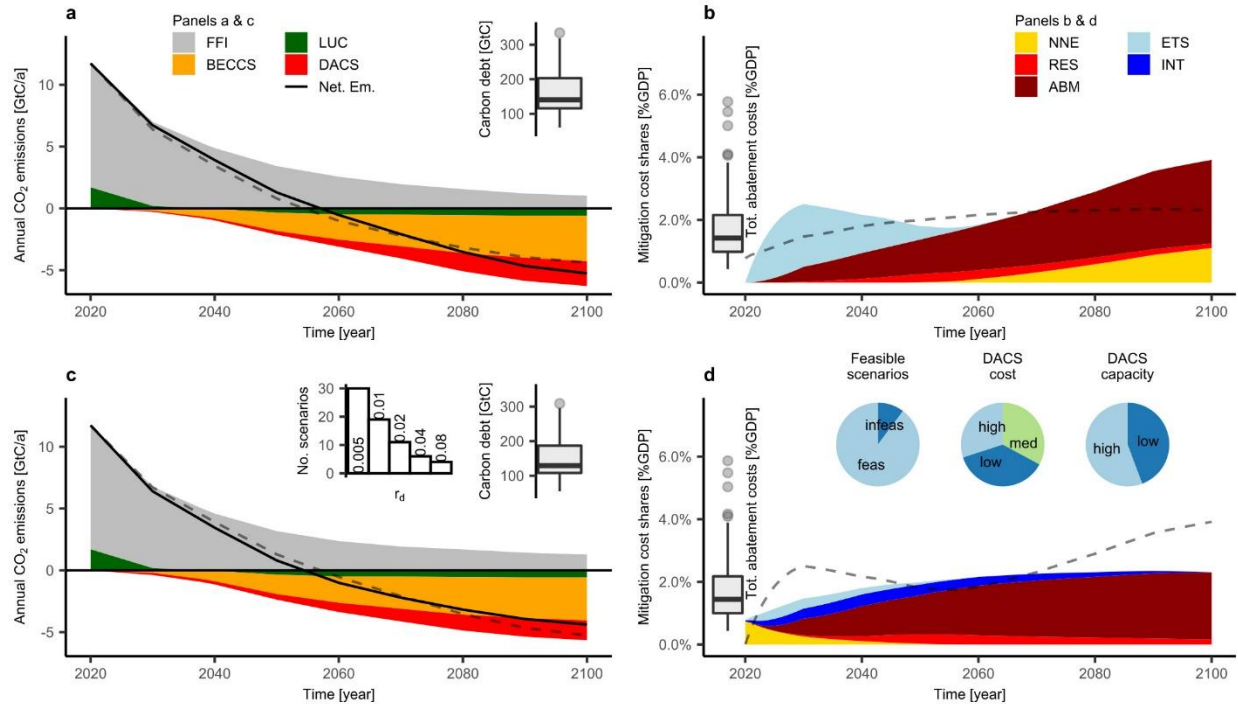


**Extended Data Figure 1 | Schematic supply of emission allowances and Carbon Removal Obligations (CROs) at a fixed point in time.** The supply of allowances is completely inelastic (emission cap), whereas the supply elasticity of CROs is determined by discounted future abatement costs, which increase as the demand for CROs increases, as well as interest costs, which can be controlled by managing authorities and financial institutions (dashed blue CRO supply curves). If CROs are traded on a market, they clear at the same price as allowances and thereby reduce the price of allowances. The larger the elasticity of the CRO supply curve, the lower the potential for price volatility (red arrows), as, e.g., induced by a demand shock (dashed orange line). The sum of allowances and CROs issued equals net emissions. Abated emissions equal the difference between baseline emissions (green) and net emissions and are comprised of emission reductions and/or carbon removal.

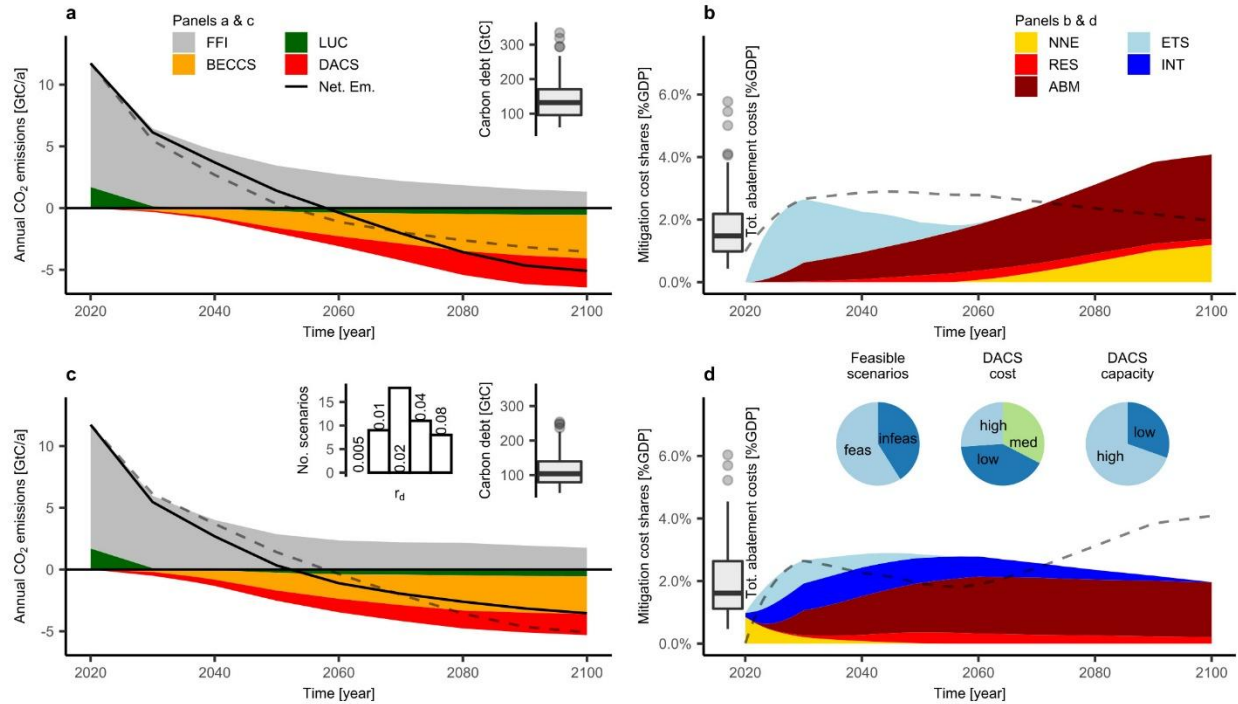


**Extended Data Figure 2 | 1.5°C (RCP1.9) scenarios abatement costs and carbon debt for six different marginal abatement cost (MAC) curves of direct air capture and storage (DACs) and interest rates on carbon debt  $r_d = 0$  and  $r_d = 0.08$ .** For a definition of  $D$  refer to the Methods; abatement costs are discounted and expressed as GDP percentage. Abatement costs are exclusive of interest costs. For each rate  $r_d$ , 78 scenarios (13 scenarios as for the RCP2.6 analysis times 6 DACS parameters) are grouped by DACS costs (low to high, i.e. “LoCost”, “MedCost”, “HiCost”) and DACS capacity limits (10% and 30% of baseline emissions, i.e. “LoCap” and “HiCap”). **Panels a & b:** Median abatement costs as function of median carbon debt  $D$  for

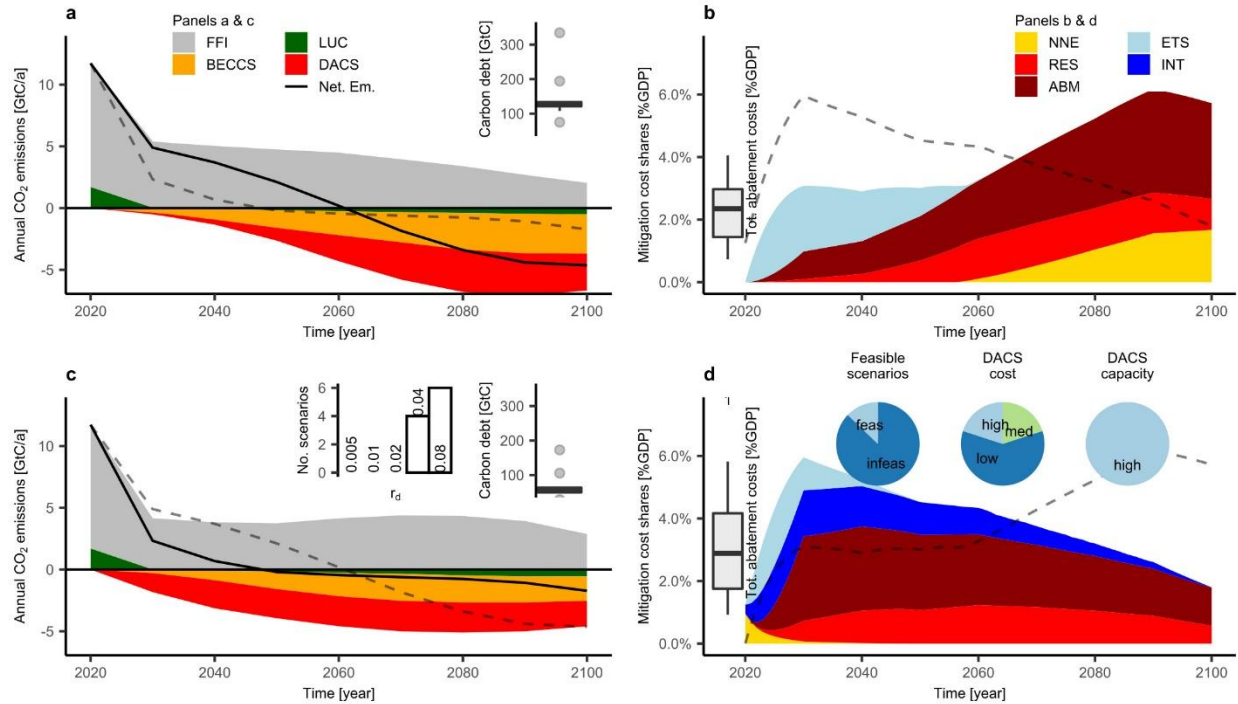
$r_d = 0$  (panel a) and  $r_d = 0.08$  (panel b). For  $r_d = 0$  we observe an inverse relation between the level of carbon debt and abatement costs; and the capacity limit is a stronger determinant of abatement costs than DACS deployment costs. This “discounting effect” is reversed when  $r_d = 0.08$  and high levels of  $D$  are penalized. In this case, lower abatement costs are realized by lower carbon debt (and vice versa). For both rates  $r_d$  “LoCost\_HiCap” DACS scenarios are characterized by the lowest abatement costs, however, at very different levels of  $D$ . When interest is invoked DACS deployments costs become an increasingly important determinant of total abatement costs. **Panels c & d: Distribution of total carbon debt  $D$  (panel c) and abatement costs (panel d) for the median values shown in panels a & b.** Boxes indicate the 25-75% interquartile ranges around medians (bold solid line), whiskers indicate min to max ranges, black dots mark outliers.



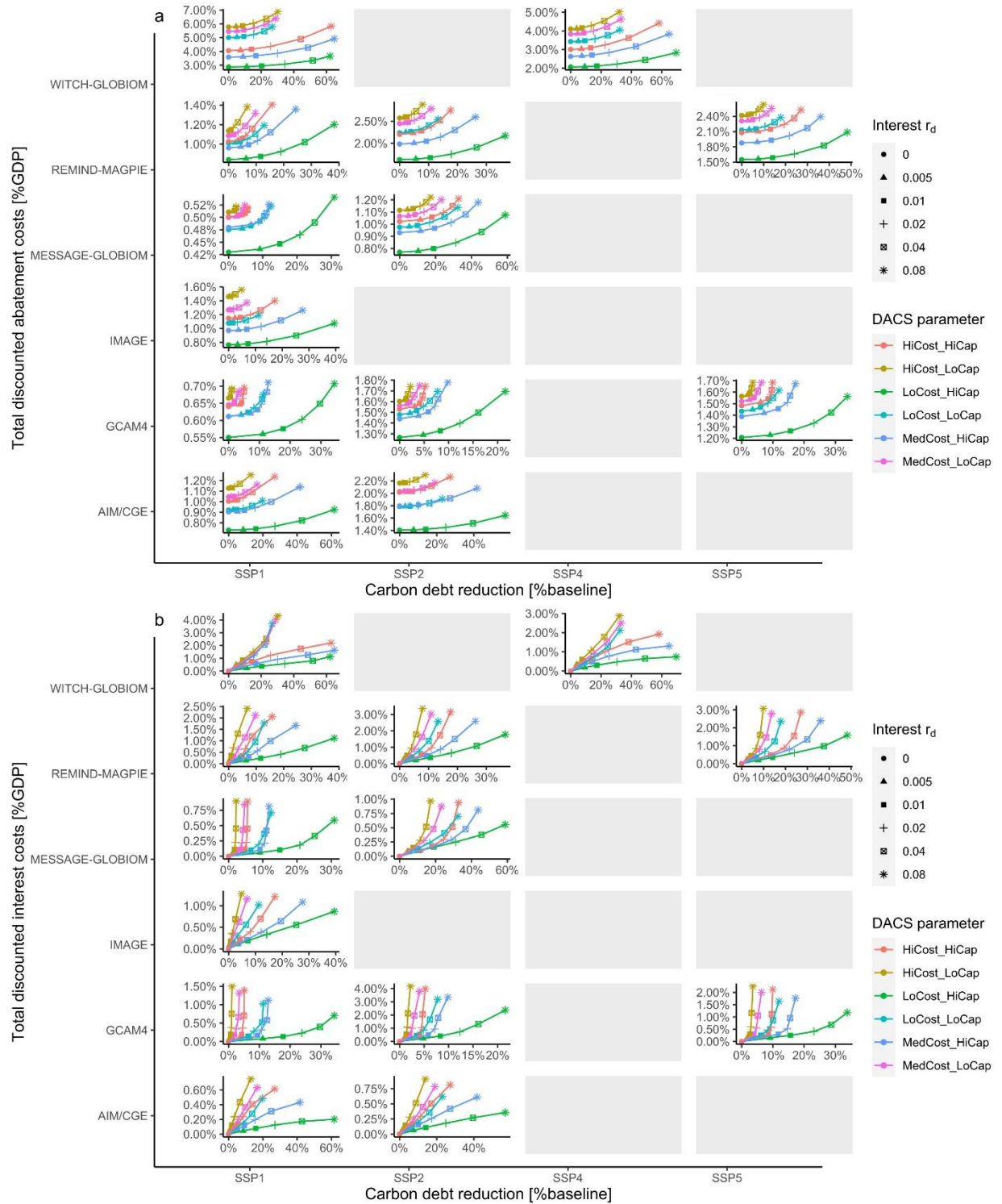
**Extended Data Figure 3 | 1.5°C (RCP1.9) pathways under a conventional ETS (panels a and b) compared to a CRO-ETS (panels c and d).** The underlying set of scenarios was filtered for those scenarios that achieve at least a 5% reduction of total carbon debt compared to their baselines (see Methods). **Panels a and c:** Geometric median net emissions (solid line) and gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS), land use change (LUC) and direct air capture and storage (DACs). Net emissions from panel a are also displayed in panel c (dashed line) and vice-versa. Total carbon debt  $D$  is shown as box-and-whiskers plot. Boxes indicate the 25-75% interquartile range around median values (bold line), whiskers indicate min to max ranges, points mark the outliers. **Panels b and d:** Annual mitigation costs as GDP percentage, including the share of average abatement costs attributed to emission reductions (ABM), to compensation of residual emissions by CDR (RES) and to net negative emissions (NNE) as well as expenditures for allowances (ETS) and interest costs (INT). Total mitigation costs (i.e., ABM+RES+NNE+ETS+INT) from panel d are also displayed in panel b (dashed line) and vice-versa. Box-and-whiskers plots show total discounted abatement costs (i.e., ABM+RES+NNE) as GDP percentage, the number above the chart indicates out-of-range outliers. Pie charts in panel d summarize properties of the underlying set of scenarios (see Methods). The distribution of  $r_d$  in CRO-ETS scenarios is depicted in panel c.



**Extended Data Figure 4 | 1.5°C (RCP1.9) pathways under a conventional ETS (panels a and b) compared to a CRO-ETS (panels c and d).** The underlying set of scenarios was filtered for those scenarios that achieve at least a 15% reduction of total carbon debt compared to their baselines (see Methods). **Panels a and c:** Geometric median net emissions (solid line) and gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS), land use change (LUC) and direct air capture and storage (DACs). Net emissions from panel a are also displayed in panel c (dashed line) and vice-versa. Total carbon debt  $D$  is shown as box-and-whiskers plot. Boxes indicate the 25-75% interquartile range around median values (bold line), whiskers indicate the min to max ranges, points mark the outliers. **Panels b and d:** Annual mitigation costs as GDP percentage, including the share of average abatement costs attributed to emission reductions (ABM), to compensation of residual emissions by CDR (RES) and to net negative emissions (NNE) as well as expenditures for allowances (ETS) and interest costs (INT). Total mitigation costs (i.e., ABM+RES+NNE+ETS+INT) from panel d are also displayed in panel b (dashed line) and vice-versa. Box-and-whiskers plots show total discounted abatement costs (i.e., ABM+RES+NNE) as GDP percentage, the number above the chart indicates out-of-range outliers. Pie charts in panel d summarize properties of the underlying set of scenarios (see Methods). The distribution of  $r_d$  in CRO-ETS scenarios is depicted in panel c.

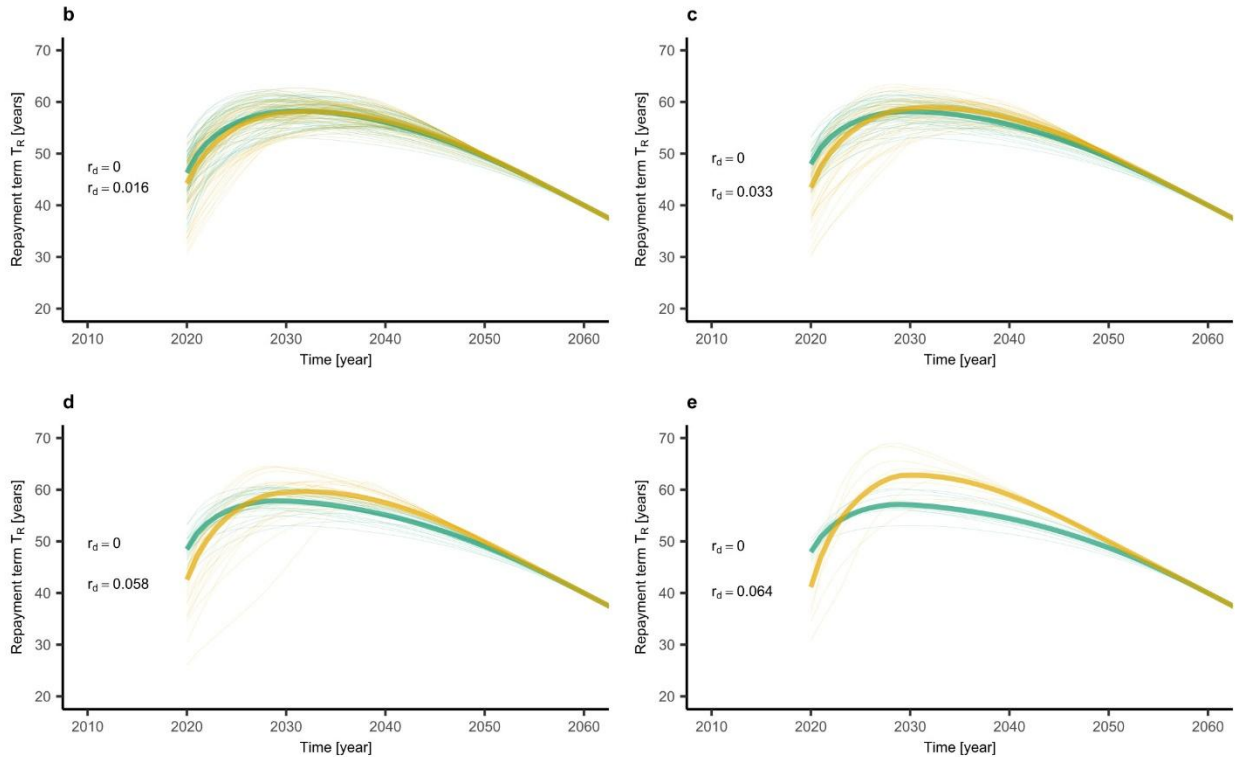
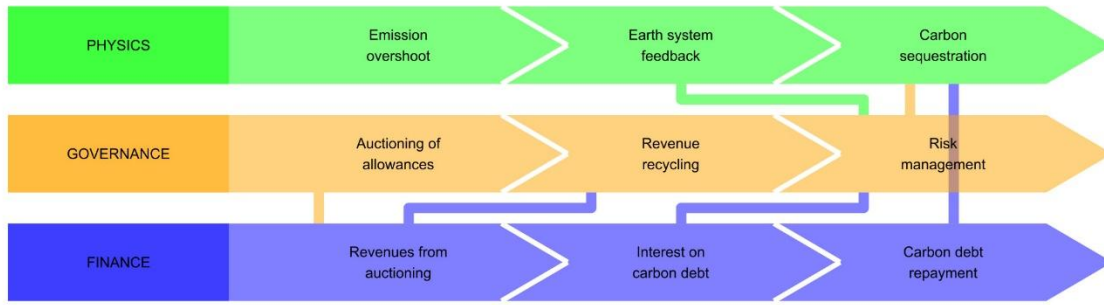


**Extended Data Figure 5 | 1.5°C (RCP1.9) pathways under a conventional ETS (panels a and b) compared to a CRO-ETS (panels c and d).** The underlying set of scenarios was filtered for those scenarios that achieve at least a 45% reduction of total carbon debt compared to their baselines (see Methods). **Panels a and c:** Geometric median net emissions (solid line) and gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS), land use change (LUC) and direct air capture and storage (DACs). Net emissions from panel a are also displayed in panel c (dashed line) and vice-versa. Total carbon debt  $D$  is shown as box-and-whiskers plot. Boxes indicate the 25-75% interquartile range around median values (bold line), whiskers indicate the min to max ranges, points mark the outliers. **Panels b and d:** Annual mitigation costs as GDP percentage, including the share of average abatement costs attributed to emission reductions (ABM), to compensation of residual emissions by CDR (RES) and to net negative emissions (NNE) as well as expenditures for allowances (ETS) and interest costs (INT). Total mitigation costs (i.e., ABM+RES+NNE+ETS+INT) from panel d are also displayed in panel b (dashed line) and vice-versa. Box-and-whiskers plots show total discounted abatement costs (i.e., ABM+RES+NNE) as GDP percentage, the number above the chart indicates out-of-range outliers. Pie charts in panel d summarize properties of the underlying set of scenarios (see Methods). The distribution of  $r_d$  in CRO-ETS scenarios is depicted in panel c.

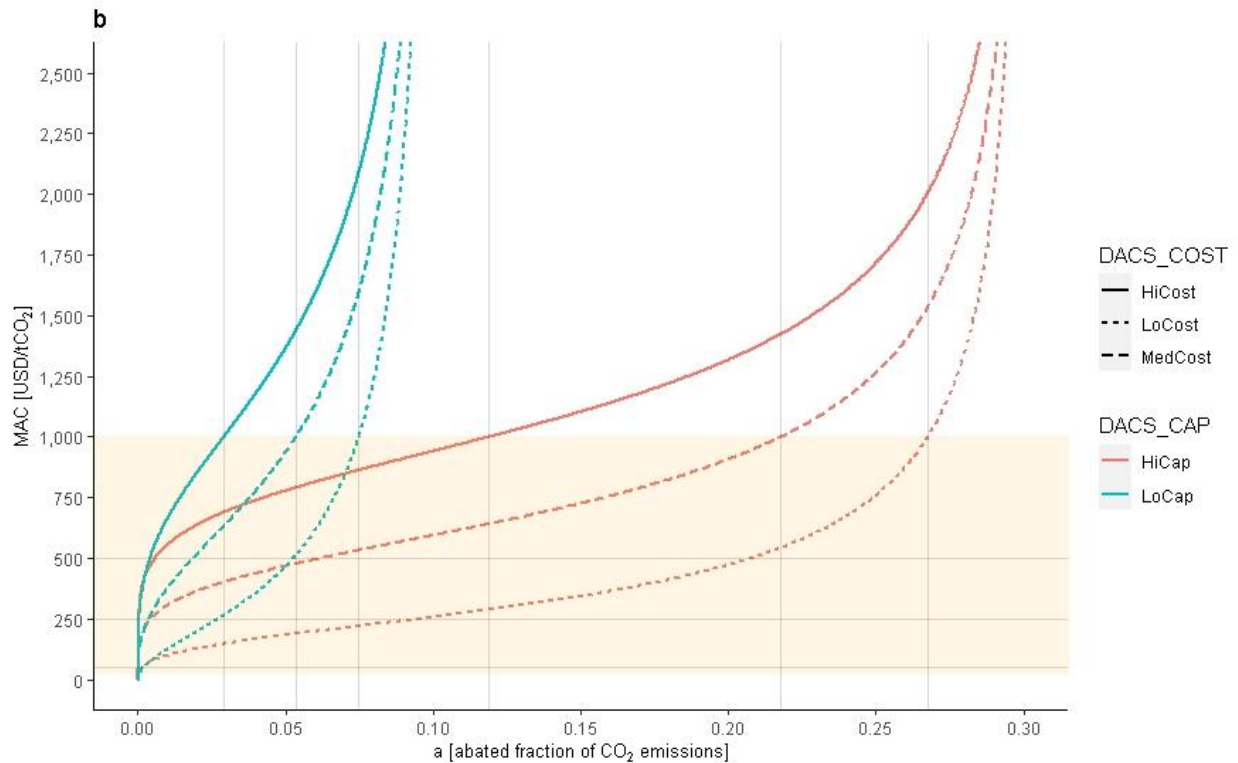
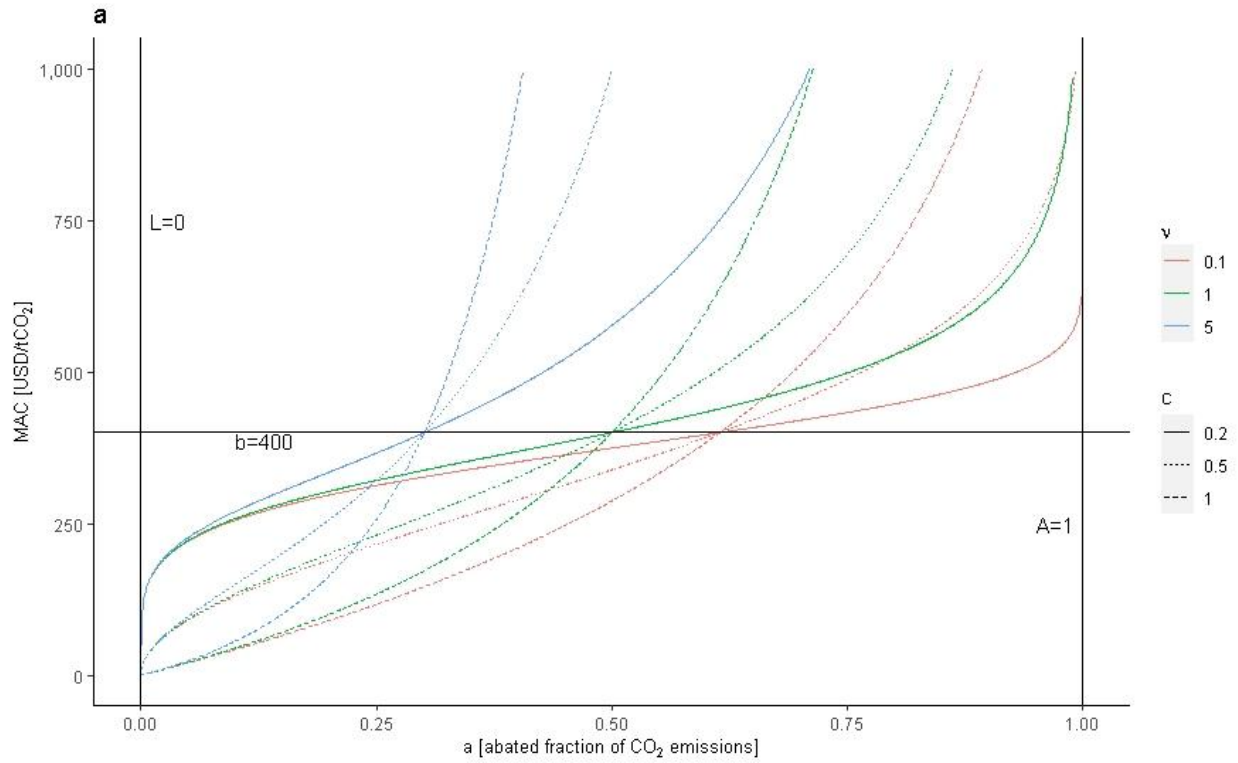


**Extended Data Figure 6 | 1.5°C (RCP1.9) scenarios' abatement costs (panel a) and interest costs (panel b) as function of percentage carbon debt reduction compared to the baseline scenario, i.e., where  $r_d = 0$ , for all 468 RCP1.9 scenarios, grouped by the carbon debt interest rate ( $r_d$ ) and cost and capacity parameters of direct air capture and storage (DACs). DACS cost parameters range from low to high, i.e., "LoCost", "MedCost", "HiCost"; capacity limits include 10% and 30% of baseline emissions, i.e., "LoCap" and "HiCap". **Panel a:** Total discounted abatement costs excluding interest costs (i.e., ABM + RES + NNE as in Figure 4 and Extended Data Figure 7-9). **Panel b:** Total discounted interest costs (i.e. INT as in Figure 4 and Extended Data Figures 7-9).**

**a**



**Extended Data Figure 7 | Schematic overview and illustrative repayment terms of RCP1.9 scenarios. Panel a:** Schematic overview of the CRO-ETS. The physical overshoot of a cumulative emission target, potentially amplified by outgassing of CO<sub>2</sub> from the Earth's stocks, subsequently necessitates carbon sequestration for returning to the target. For accrued carbon debt CROs are issued, obliging emitters to compensate for a tonne of CO<sub>2</sub> before a specified maturity, e.g., by physically removing atmospheric CO<sub>2</sub> or by acquiring an adequate quantity of allowances in the future. Similar to financial debt, CROs require debtors to pay interest to hedge physical and financial risks associated with carbon debt. Three earmarked financial resources are created under a CRO-ETS (1) Revenues from auctioning allowances are recycled into the economy to the benefit of society. (2) Revenues from interest on carbon debt are targeted at managing risks, i.e., by enabling additional carbon sequestration when Earth system risks (e.g., permafrost thaw) and financial risks (e.g., default risk of debtors) materialize. (3) Funds for repayment of carbon debt are individually managed by debtors. **Panels b-e:** Repayment term function  $T_R(t)$  for the scenarios illustrated in Extended Data Figure 7 (panel b), Extended Data Figure 8 (panel c), Figure 4 (panel d) and Extended Data Figure 9 (panel e). Interest on carbon debt  $r_d$  reflects the mean values of the distributions shown in panel c of these figures. Bold lines indicate geometric median repayment-terms derived from scenarios presented in these figures.  $T_R(t)$  maps the timing of carbon debt accrual to the time of its compensation; see Methods. For instance, in panel c carbon debt accrued in 2020 is compensated approximately 40 years later in scenarios with interest ( $r_d=0.058$ , yellow lines) and roughly 50 years later in scenarios where  $r_d=0$  (turquoise lines). As  $r_d$  is increased, the net zero year moves closer, implying that carbon debt in 2020 is compensated earlier, while in general  $T_R$  extends over longer periods. The increasingly flat net negative emissions profile (when  $r_d$  is increased) implies that  $T_R$  increases more rapidly in the beginning than when  $r_d=0$  because cumulative carbon debt at  $t$  grows faster than cumulative net negative emissions at  $t+T_R(t)$ . The point of inflection indicates where cumulative carbon debt begins to grow more slowly than cumulative net negative emissions compensating that carbon debt. For instance, in panel d (yellow line) cumulative carbon debt from 2030 onwards grows at a slower pace than cumulative net negative emissions approximately 63 years later.



**Extended Data Figure 8 | Marginal abatement cost curves.** Panel a: The functional form of marginal abatement costs,  $MAC(a) = b * \left( \frac{1}{v} * \left( \frac{L-A}{a-A} \right)^v - 1 \right)^c$ , is derived from the inverse generalized logistic function. It is relatively flexible with respect to replicating a wide range of MAC curves derived from the SSP database. Here  $A=1$  and  $L=0$  are upper and lower asymptotes along the y-axis. Crucially,  $MAC(a = A) = \text{inf}$ , therefore  $A$  is a maximum abatement rate built into the MAC curve.  $b$  defines the y-position of the pivot point. The x-position of the pivot point is determined by  $v$ , and for  $v = 1$  it is exactly the middle of the interval  $(L, A)$ ,  $\frac{L+A}{2}$ .  $c$  defines the level of rotation with respect to the pivot point. Panel b: Six stylized MAC curves for

direct air capture and storage (DACS) covering the literature range for costs from 20 to 1000 USD/tCO<sub>2</sub> (orange area). Low-cost MACCs (dotted lines) start at approximately 50 USD/tCO<sub>2</sub> and reach 1000 USD/tCO<sub>2</sub> at abatement rates  $a_{DACS} = 0.07$  (low capacity, blue line) and  $a_{DACS} = 0.27$  (high capacity, red line) equivalent to approximately 3 and 12 GtCO<sub>2</sub>/a at current emission levels, respectively. Medium cost MAC curves (dashed lines) start at 250 USD/tCO<sub>2</sub> and reach 1000 USD/tCO<sub>2</sub> at  $a_{DACS} = 0.05$  (low capacity, blue line) and  $a_{DACS} = 0.22$  (high capacity, red line), i.e. roughly 2 and 10 GtCO<sub>2</sub>/a at current emission levels, respectively. High cost MAC curves (solid lines) start at approximately 500 USD/tCO<sub>2</sub> and reach 1000 USD/tCO<sub>2</sub> at  $a_{DACS} = 0.03$  (low capacity, blue line) and  $a_{DACS} = 0.12$  (high capacity, red line), amounting to roughly 1 and 5 GtCO<sub>2</sub>/a at current emission levels, respectively.

# ANNEX 4

Supplementary Information  
for Chapter 4

# The Carbon Removal Obligation

## Updated analytical model and scenario analysis

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### Supplementary information

The partial derivative of a function  $f(x_1, \dots, x_n)$  with respect to the variable  $x_i$  is denoted by  $D_i f$ .

**Theorem 1** Consider an *original problem*:

$$\min_{x(\cdot) \in \mathcal{X}} \int_{\tau}^{\theta} f(t, x(t)) dt \quad (1)$$

s.t. some additional constraints on  $x(\cdot)$ . Here  $\mathcal{X}$  denotes the set of all continuous functions  $x(\cdot) : [\tau, \theta] \rightarrow X$ , the set of admissible solutions. We assume that

1.  $X$  is a non-empty convex compact subset of  $\mathbb{R}$  with non-empty interior  $\text{Int } X$ ;
2.  $f$  is continuous in  $[\tau, \theta] \times X$ ;
3. function  $f(t, \cdot)$  is strictly convex on  $X$  and differentiable on  $\text{Int } X$  for all  $t \in [\tau, \theta]$ ;
4.  $D_2 f$ , the derivative of  $f$  w.r.t to the second variable, is continuous in  $[\tau, \theta] \times \text{Int } X$  and has continuous extension to  $[\tau, \theta] \times X$ ;
5. the optimal solution  $x^*(\cdot)$  of (1) exists in the class of continuous functions such that  $x^*(t) \in \text{Int } X \forall t \in [\tau, \theta]$ .

We claim that the same optimal solution holds in the following *modified (constraint-free)* problem:

$$\min_{x(\cdot) \in \mathcal{X}^{pw}} \int_{\tau}^{\theta} [f(t, x(t)) - D_2 f(t, x^*(t))x(t)] dt \quad (2)$$

where  $x^*$  is the optimal solution in the original problem and  $\mathcal{X}^{pw}$  denotes the set of all piece-wise continuous functions  $x(\cdot) : [\tau, \theta] \rightarrow X$ . Note that now additional constraints are omitted and admissible solutions can be piece-wise continuous.

*Proof.*

- From a necessary and sufficient condition for a minimum in an elementary optimal control problem<sup>1</sup>, it follows that any piece-wise continuous function  $\hat{x} : [\tau, \theta] \rightarrow X$  that satisfies

$$\min_{x \in X} f(t, x) - D_2 f(t, x^*(t))x = f(t, \hat{x}(t)) - D_2 f(t, x^*(t))\hat{x}(t) \quad (3)$$

for every point of continuity of  $\hat{x}$  yields the global minimum in the modified problem.

- Note that for any  $t \in [\tau, \theta]$

$$x \mapsto f(t, x) - D_2 f(t, x^*(t))x : X \longrightarrow \mathbb{R} \quad (4)$$

is a strictly convex function defined on convex set  $X$ . Hence, we have two properties: (i) any local minimum is also a global one in  $X$  and (ii) the point of the global minimum is unique.

- By properties (i) and (ii), any stationary point of function (4) that is admissible (belongs to  $X$ ) is the unique solution of the problem in the left-hand side of (3).
- By combining strict convexity and the first-order condition for local extrema, we obtain that for any  $t$ ,  $x^*(t)$  is a unique stationary point of function (4), which is also admissible by the definition since  $x^*(t) \in \text{Int } X$ . Hence,  $x^*$  satisfies property (3):  $\forall t \in [\tau, \theta]$

$$\min_{x \in X} f(t, x) - D_2 f(t, x^*(t))x = f(t, x^*(t)) - D_2 f(t, x^*(t))x^*(t).$$

- Finally,  $x^*$  is the unique solution of (2) in the following sense: any solution of (2) will be equal almost everywhere to  $x^*$  (in the sense of Lebesgue measure). For example, the solutions may differ in a finite number of points but this will not influence the optimal result in (2).  $\square$

Note that Theorem 1 allows a straightforward extension to the case of two variables ( $x_1$  and  $x_2$ ):

**Theorem 2** Consider an *original problem*:

$$\min_{x_1(t), x_2(t) \in X} \int_{\tau}^{\theta} f(t, x_1(t), x_2(t)) dt \quad (5)$$

s.t. some additional constraints on  $x_1, x_2$ . Here  $\mathcal{X}$  denotes the set of all continuous functions  $x(\cdot) : [\tau, \theta] \rightarrow X$  such that  $x(t) \in X$ . We assume that

1.  $X$  is non-empty convex compact subset of  $\mathbb{R}$  with non-empty interior;
2.  $f$  is continuous in  $[\tau, \theta] \times X \times X$ ;

<sup>1</sup>see p.160 in Alekseev V.M., Tikhomirov V.M., Fomin S.V. *Optimal Control*. Springer Science + Business Media, New York (1987)

3.  $f(t, \cdot, \cdot)$  is strictly convex on  $X \times X$  and differentiable on  $\text{Int } X \times \text{Int } X$  for all  $t \in [\tau, \theta]$ ;
4.  $D_2f, D_3f$  are continuous in  $[\tau, \theta] \times \text{Int } X \times \text{Int } X$  and have continuous extensions to  $[\tau, \theta] \times X \times X$ ;
5. the optimal solution  $x_1^*(\cdot), x_2^*(\cdot)$  of (5) exists in the class of continuous functions such that  $x_1^*(\cdot), x_2^*(\cdot) \in \text{Int } X \forall t \in [\tau, \theta]$ .

We claim that the same optimal solution holds in the following *modified (constraint-free) problem*:

$$\min_{x_1, x_2 \in \mathcal{X}^{pw}} \int_{\tau}^{\theta} [f(t, x_1(t), x_2(t)) - x_1(t) D_2f(t, x_1^*(t), x_2^*(t)) - x_2(t) D_3f(t, x_1^*(t), x_2^*(t))] dt \quad (6)$$

where  $x^*$  is the optimal solution in the original problem and  $\mathcal{X}^{pw}$  denotes the set of all piece-wise continuous functions  $x(\cdot) : [\tau, \theta] \rightarrow X$  such that  $x(t) \in X$ . Note that now additional constraints are omitted and admissible solutions can be piece-wise continuous.

**How we use Theorem 2.** In the paper, we deal with the problem

$$\min_{\alpha, \mu} \int_{T_0}^T f_c(t, \alpha(t), \mu(t)) e^{-R(t-T_0)} dt, \quad (7)$$

s.t. the additional scenario-specific constraints. For applying Theorem 2, we need to transform variables  $\alpha(t)$  and  $\mu(t)$  such that their ranges of possible values do not depend on time, i.e., we will introduce normalised versions of this variables with the constant range.

First, let us recall the definitions of cost functions:

$$f_c(t, \alpha(t), \mu(t)) = E(t) \left( \int_0^{\alpha(t)} f_{\alpha}(t, a) da + \int_0^{\mu(t)} f_{\mu}(t, a) da \right)$$

$$f_i(t, a) = Q_i(t) \left( \frac{a}{U_i(t) - a} \right)^{C_i}, C_i > 0, i = \alpha, \mu,$$

where  $Q_i, U_i : [T_0, T] \rightarrow (0, \infty)$  are given continuous functions.

Second, by using the following transformations for variables

$$\tilde{\alpha}(t) = \frac{\alpha(t)}{U_{\alpha}(t)}, \tilde{\mu}(t) = \frac{\mu(t)}{U_{\mu}(t)}, \quad (8)$$

we modify the cost functions:

$$\tilde{f}_i(t, a) = Q_i(t) \left( \frac{a}{1 - a} \right)^{C_i}, i = \alpha, \mu;$$

$$\tilde{f}_c(t, \tilde{\alpha}(t), \tilde{\mu}(t)) = E(t) \left( U_{\alpha}(t) \int_0^{\tilde{\alpha}(t)} \tilde{f}_{\alpha}(t, a) da + U_{\mu}(t) \int_0^{\tilde{\mu}(t)} \tilde{f}_{\mu}(t, a) da \right).$$

The relationship between functions is quite straightforward:

$$\tilde{f}_c(t, \tilde{\alpha}(t), \tilde{\mu}(t)) = f_c(t, \tilde{\alpha}(t)U_\alpha(t), \tilde{\mu}(t)U_\mu(t));$$

$$\tilde{f}_i(t, a) = f_i(t, aU_i(t)), i = \alpha, \mu.$$

Note that tilde sign ( $\tilde{\phantom{x}}$ ) indicates that the object operates with transformed variables.

Third, we specify Theorem 2 for our case:

$$f(\hat{t}, \hat{x}_1, \hat{x}_2) = \tilde{f}_c(\hat{t}, \hat{x}_1, \hat{x}_2)e^{-R(\hat{t}-T_0)}; x_1 = \tilde{\alpha}, x_2 = \tilde{\mu}, \tau = T_0, \theta = T.$$

We assume that  $X = [\epsilon, 1 - \epsilon]$ , where  $\epsilon > 0$  is small enough to not influence the optimal solution. Given the form of the function of total costs, the existence of optimal solutions is sufficient for such  $\epsilon$  to be well defined. Hence the normalised abatement rate at instant  $t$  can be in the range  $[\epsilon, 1 - \epsilon]$ . Introduction of such  $\epsilon$  is also a standard practice in numerical optimisation.

Then

$$D_2 f(t, \tilde{\alpha}, \tilde{\mu}) = e^{-R(t-T_0)} D_2 \tilde{f}_c(t, \tilde{\alpha}, \tilde{\mu}) = e^{-R(t-T_0)} E(t)U_\alpha(t)\tilde{f}_\alpha(t, \tilde{\alpha}),$$

$$D_3 f(t, \tilde{\alpha}, \tilde{\mu}) = e^{-R(t-T_0)} D_3 \tilde{f}_c(t, \tilde{\alpha}, \tilde{\mu}) = e^{-R(t-T_0)} E(t)U_\mu(t)\tilde{f}_\mu(t, \tilde{\mu}).$$

Thus, the original problem is

$$\min_{\tilde{\alpha}(t), \tilde{\mu}(t) \in [\epsilon, 1-\epsilon]} \int_{T_0}^T \tilde{f}_c(t, \tilde{\alpha}(t), \tilde{\mu}(t))e^{-R(t-T_0)} dt, \quad (9)$$

s.t. the same constraints as in (7) that are accordingly adjusted. Note that solutions of (7) after normalisation (8) are exactly the solutions of (9). This follows from our definitions of all functions with tilde sign<sup>2</sup>. The modified problem for (9), in the context of Theorem 2, is as follows

$$\begin{aligned} \min_{\tilde{\alpha}(t), \tilde{\mu}(t) \in [\epsilon, 1-\epsilon]} \int_{T_0}^T & [\tilde{f}_c(t, \tilde{\alpha}(t), \tilde{\mu}(t)) \\ & - E(t)\tilde{f}_\alpha(t, \tilde{\alpha}^*(t))U_\alpha(t)\tilde{\alpha}(t) \\ & - E(t)\tilde{f}_\mu(t, \tilde{\mu}^*(t))U_\mu(t)\tilde{\mu}(t)]e^{-R(t-T_0)} dt \quad (10) \end{aligned}$$

By using (8), we restore our original variables obtaining the equivalent of (10):

$$\begin{aligned} \min_{\substack{\alpha(t) \in [\epsilon U_\alpha(t), (1-\epsilon)U_\alpha(t)], \\ \mu(t) \in [\epsilon U_\mu(t), (1-\epsilon)U_\mu(t)]}} \int_{T_0}^T & [f_c(t, \alpha(t), \mu(t)) \\ & - E(t)f_\alpha(t, \alpha^*(t))\alpha(t) \\ & - E(t)f_\mu(t, \mu^*(t))\mu(t)]e^{-R(t-T_0)} dt \quad (11) \end{aligned}$$

<sup>2</sup>We thank Mikhail Gomoyunov for hinting us to use the elegant transformation instead of proving Theorem 2 for a more general case.

Recall that  $e(t) = E(t)(1 - \alpha(t))$  and  $r(t) = E(t)\mu(t)$ . Since  $P_\alpha(t) = f_\alpha(t, \alpha^*(t))$ ,  $P_\mu(t) = f_\mu(t, \mu^*(t))$ , we have that (11) takes the form

$$\begin{aligned} \min_{\substack{\alpha(t) \in [\epsilon U_\alpha(t), (1-\epsilon)U_\alpha(t)], \\ \mu(t) \in [\epsilon U_\mu(t), (1-\epsilon)U_\mu(t)]}} \int_{T_0}^T [f_c(t, \alpha(t), \mu(t)) \\ + P_\alpha(t) \underbrace{E(t)(1 - \alpha(t))}_{e(t)} \\ - P_\mu(t) \underbrace{E(t)\mu(t)}_{r(t)} - \Delta(t)] e^{-R(t-T_0)} dt \quad (12) \end{aligned}$$

where  $\Delta(t) = P_\alpha(t)E(t)$  does not depend on  $\alpha, \mu$  hence can be omitted since we aim only for optimal  $\alpha, \mu$ . In this sense, problem (12) is equivalent to the following problem

$$\min_{\alpha, \mu} \int_{T_0}^T [f_c(t, \alpha(t), \mu(t)) + P_\alpha(t)e(t) - P_\mu(t)r(t)] e^{-R(t-T_0)} dt. \quad (13)$$

Finally, we conclude that (13) is indeed solved by optimal  $\alpha^*, \mu^*$  of (7); this result was used in the main text.

**Remark:** Theorem 2 requires for  $\tilde{f}_c(t, \cdot, \cdot)e^{-R(t-T_0)}$ , in particular, to have continuous partial derivatives and to be strictly convex in  $[\epsilon, 1 - \epsilon] \times [\epsilon, 1 - \epsilon]$  for any  $t \in [T_0, T]$ . Note that the multiplier  $e^{-R(t-T_0)}$  does not play an important role since it is a positive constant for any instant  $t$ , so we focus only on  $\tilde{f}_c(t, \cdot, \cdot)$ . The costs are defined such that for a fixed  $t \in [T_0, T]$ , instantaneous cost function  $\tilde{f}_c(t, \cdot, \cdot)$  is twice continuously differentiable in  $[\epsilon, 1 - \epsilon] \times [\epsilon, 1 - \epsilon]$ , which implies continuous differentiability. This allows us to consider the Hessian matrix for  $\tilde{f}_c(t, \cdot, \cdot)$  being a function of two variables:

$$\mathbf{H}(\tilde{\alpha}, \tilde{\mu}) = \begin{pmatrix} E(t)U_\alpha(t)D_2\tilde{f}_\alpha(t, \tilde{\alpha}) & 0 \\ 0 & E(t)U_\mu(t)D_2\tilde{f}_\mu(t, \tilde{\mu}) \end{pmatrix}.$$

For  $\tilde{\alpha}, \tilde{\mu} \in [\epsilon, 1 - \epsilon]$ , this matrix is positive definite since  $E(t)U_i(t) > 0$ ,  $i = \alpha, \mu$ , and both derivatives are positive. Hence, this implies strict convexity of  $\tilde{f}_c(t, \cdot, \cdot)$ .

# ANNEX 5

Supplementary Information  
for Chapter 5

## Supplementary Information

### 1. Comparison between Original and Updated Proposals

In this supplementary information (SI) document, we use the term 'Original Proposal' to refer to the policy framework proposed by Bednar et al. (2021). In contrast, the 'Updated Proposal,' which is described in the main article, represents our revised approach.

The Original Proposal aimed to incentivize net carbon removals or net negative CO<sub>2</sub> emissions in order to address the carbon budget overshoot. It considered carbon debt as the result of net CO<sub>2</sub> emissions exceeding a 'temporally distributed instantaneous' (TDI) carbon budget, as explained in section 2 of this SI. The compensation for this carbon debt relied on net negative CO<sub>2</sub> emissions. Concurrently, the Original Proposal suggested incorporating carbon dioxide removal (CDR) activities, aimed at offsetting residual emissions (see Figure 1a in the main article for an explanation of the terminology), through an emissions trading scheme (ETS) alongside the main CRO mechanisms. This integration of the CDR market into both the ETS and the CRO framework was referred to as the 'CRO-ETS,' as illustrated in Figure S1e.

In contrast, the Updated Proposal in the main article considers carbon debt as the result of gross CO<sub>2</sub> emissions, which is then compensated for by gross removals over time. Carbon debt can be defined either as gross emissions occurring after depleting the remaining cumulative (RC) carbon budget (Figure S1a) or as gross emissions contemporaneously exceeding a pathway reflecting a TDI carbon budget (Figure S1c), as discussed in more detail in section 2. This adjustment to the principal CRO mechanism has significant implications:

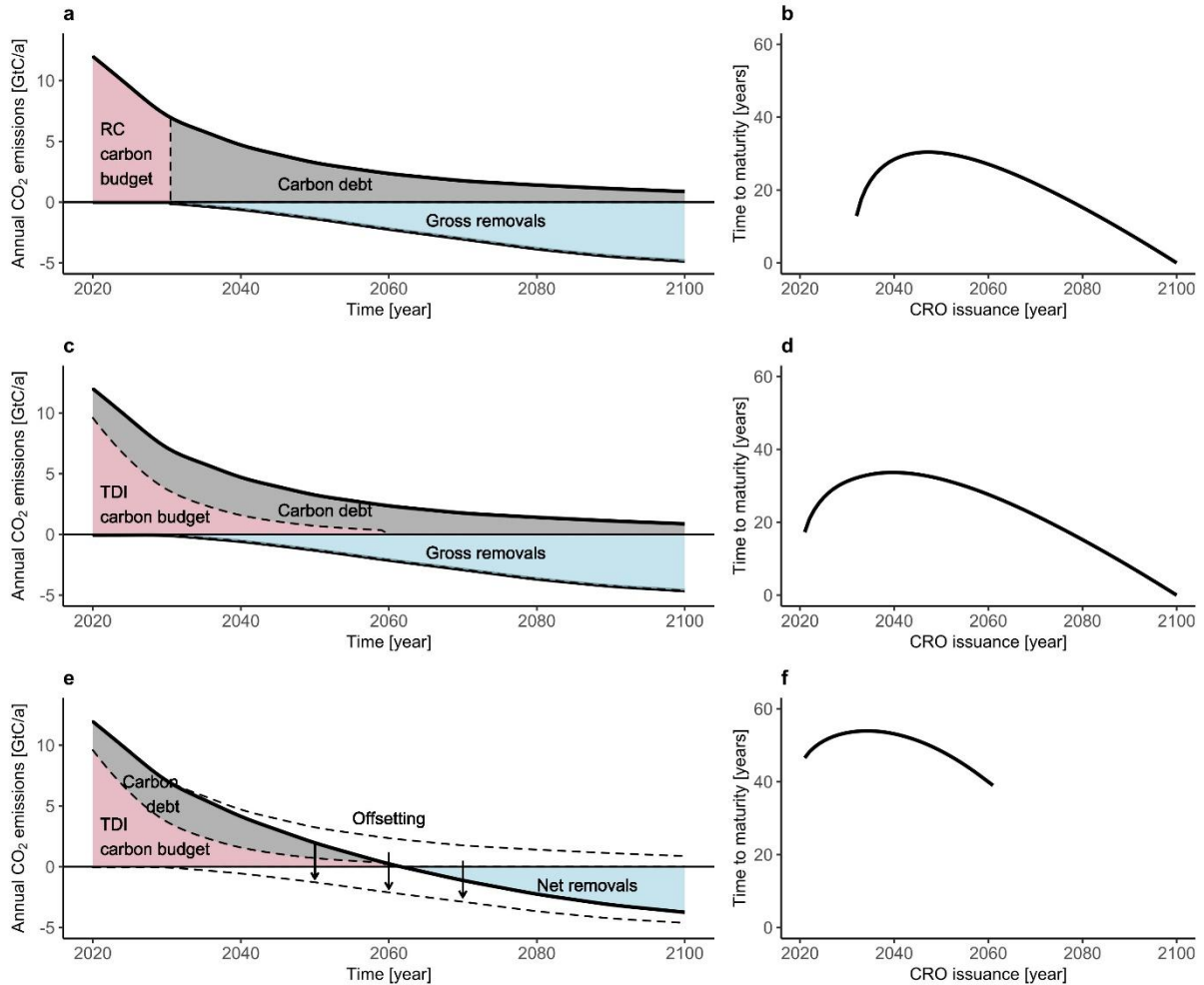
- i. By extending its scope from net to gross emissions, CROs are no longer restricted to financing net removals only. CROs now address CDR in general, regardless of entering the realm of net negative emissions. CROs aim to promote early uptake and innovation of CDR while managing the associated risks of CDR-based mitigation strategies.
- ii. The CDR market is disentangled from conventional carbon pricing, reducing the regulatory burden implied by the Original Proposal significantly.
- iii. A separate market for CDR allows for the possibility of diverging price levels between CDR and ERs, potentially influenced by different technological learning rates, as discussed in the main article. This divergence in price levels forms the basis for setting separate targets for ERs and CDR.
- iv. Unlike the Original Proposal, the separation of the CDR market from the ETS means that CROs and emission allowances are not fungible, as detailed in section 2.
- v. The CRO pricing instrument in the Updated Proposal adjusts price levels separately for ERs and CDR, impacting gross emissions and removals rather than net (negative) emissions. This is a departure from the Original Proposal, which aimed to control the net CO<sub>2</sub> emissions path in the CRO-ETS.
- vi. Maturities under the Updated Proposal, calculated based on gross emissions and removals, are significantly shorter compared to the Original Proposal. As gross removals typically ramp up before net removals, CRO holders can terminate their obligations earlier. For a

comparison, refer to panels b and d of Figure S1, illustrating the repayment term structures under the Updated Proposal, and panel f, reflecting the Original Proposal.

An extended comparison between elements of the Original and Updated Proposals is provided in Table S1.

*Table S1. Similarities and differences between the Original Proposal and the Updated Proposal.*

<b>Element</b>	<b>Original Proposal</b>	<b>Updated Proposal</b>
Carbon budget	There are two options for implementing carbon budgets into the CRO framework: Either (1) emissions following in time the date of depletion of the remaining cumulative (RC) carbon budget, or (2) emissions contemporaneously overshooting a temporally distributed instantaneous (TDI) carbon budget are considered carbon debt. The TDI carbon budget in sum equals the RC carbon budget.	
Carbon debt generation	Generated by net emissions overshooting the RC or TDI carbon budget.	Generated by gross emissions overshooting the RC or TDI carbon budget.
Carbon debt compensation	Compensated by net removals.	Compensated by gross removals (total CDR).
Role of conventional carbon pricing (ETS, carbon tax)	Charge a price for depleting the carbon budget. Required for offsetting of emissions with removals to achieve net zero transition and offsetting of residual emissions after net zero.	Charge a price for depleting the carbon budget. Ceases to exist when the RC carbon budget gets depleted, or when the TDI carbon budget becomes zero.
CDR market integration.	CDR market integration into conventional carbon pricing scheme and CRO framework. CROs can be discharged against emission allowances.	CDR market integration only into CRO framework. 'Removal units' are non-fungible with emission allowances.
Additionality	Credits generated by additionality principle are excluded from conventional pricing and CRO framework.	
Price of ERs	Established in ETS, equals CDR price, adjusted by CRO pricing.	After phase-out of conventional pricing only as shadow price induced by principal CRO mechanism and adjusted by CRO pricing.
Price of CDR	Established on CDR market integrated into ETS, equals ER price, adjusted by CRO pricing.	Established on CDR market. CDR market price depends on the amount of CROs (demand) and the marginal costs of removal units (supply). Demand for CROs adjusted by CRO pricing, which thus impacts on CDR price.
CRO pricing	Adjusts the single price path of ERs and CDR, thus, has an impact on the path of net emissions/removals.	Adjusts the separate prices of ERs and CDR, thus, has an impact on the paths of gross emissions and gross removals.
Target setting	Target setting is limited to net emissions/removals due to the single price path of ERs and CDR.	Separate targets for ERs and CDR can be achieved by inducing adequate price signals for ERs and CDR.
CRO maturities	Maturities reflect time horizon between net emissions and net removals, resulting in rather long maturities.	Maturities reflect time horizon between gross emissions and gross removals, resulting in much shorter maturities



**Figure S1: Panel a, c, e:** Elements characterizing different versions of the CRO policy framework. **Panels: b, d, e:** Repayment term structures showing the time to maturity in years as a function of the date of CRO issuance for the profiles shown in panels a, c, e. For an analytical definition see Bednar, Baklanov, and Macinante (2023). **Panel a:** Elements characterizing the CRO framework of the Updated Proposal as discussed in the main article of this Supplementary Information document. Carbon debt is generated by gross emissions once the remaining cumulative (RC) carbon budget has been depleted, here around 2030. Carbon debt is compensated intertemporally by gross removals. **Panel c:** Elements of the CRO framework according to the Updated Proposal given a temporally distributed instantaneous (TDI) carbon budget. The cumulative sum of the TDI carbon budget equals the RC carbon budget. Carbon debt is generated by gross emissions exceeding the TDI carbon budget (pink area). Carbon debt is compensated intertemporally by gross removals. In case a conventional carbon pricing scheme, like an emissions trading scheme (ETS) is operating in parallel to the CRO framework, the conventional pricing scheme is bound to the TDI carbon budget (pink). **Panel e:** Elements of the CRO-ETS according to the Original Proposal (Bednar et al. 2021). Carbon debt is generated by net emissions exceeding the TDI carbon budget (pink area). Carbon debt is intertemporally compensated by net removals. The emission caps over time of the linked ETS equal the TDI carbon budget. CDR integration into the ETS is required for contemporaneously offsetting gross emissions minus net emissions (blank part of gross emissions) with gross removals minus net removals (blank part of gross removals).

## 2. Transition scenarios for implementing the CRO framework with a positive RC carbon budget

In the main article, we make the assumption that gross emissions are equivalent to carbon debt, indicating the operationalization of the CRO framework upon depleting the RC carbon budget (see Figure S1a). Existing carbon pricing arrangements would cease to exist with the initialization of the CRO framework, for instance, the EU-ETS would require earlier retirement than currently anticipated. Here, we present two scenarios for implementing the CRO framework *before* the RC carbon budget is exhausted (see Figure S1c). It is assumed that economies derive benefits from fully utilizing the RC

carbon budget, hence, its depletion needs to be coordinated with the operation of the CRO framework:

**Scenario 1:** In this scenario, there is no carbon pricing scheme in place. The depletion of a regional RC carbon budget is projected to occur several decades into the future. The duration of depletion depends on the size of the RC carbon budget, which can be influenced by burden sharing arrangements (e.g., developing nations with limited responsibility for climate change have a relatively larger carbon budget than industrial nations) or the stringency of the climate target (a 2°C climate goal implies a larger RC carbon budget than 1.5°C). While an overshoot of the carbon budget is likely in this scenario, it is not certain. There is a political will to initiate efforts for CDR. The CRO framework is chosen as the preferred policy tool, regardless of the necessity for net carbon removals, due to its advantages in promoting CDR uptake and innovation through a standalone CDR market. Several integration options for the RC carbon budget are available:

#### Option 1: Sector-by-Sector Integration

Sectors are progressively integrated into the CRO framework while the remaining sectors are allowed to emit without paying for their emissions. This gradual integration leads to the depletion of the RC carbon budget over time, ensuring all sectors are integrated into the CRO framework when the carbon budget is fully depleted.

#### Option 2: Increasing Emissions-to-Carbon Debt Ratio

All sectors are integrated into the CRO framework, with the ratio of gross emissions to carbon debt gradually increasing. Initially, one tonne of gross CO<sub>2</sub> emissions may result in 0.5 tonnes of carbon debt, requiring the emitter to remove 0.5 tonnes of CO<sub>2</sub> in the future. Over time, this ratio is increased until it reaches one, indicating the depletion of the carbon budget.

**Scenario 2:** In this scenario, an ETS is already in operation, and the depletion of the regional RC carbon budget is estimated to occur within approximately a decade based on current emissions. It is highly likely that gross CO<sub>2</sub> emissions will surpass the RC carbon budget. The transition involves aligning emissions allowed under the ETS with the RC carbon budget, which would necessitate significant reductions in future allowances. Simultaneously, the CRO framework is gradually introduced alongside the ETS, and demand for the CDR market solely comes from CROs. The transition options are as follows:

#### Option 1: Sector-by-Sector Transition

Sectors are progressively transferred from the ETS to the CRO framework. Taking into account sector-specific marginal abatement costs, it is anticipated that the ETS price does not converge with the marginal costs associated with a CRO (i.e., the CRO Premium plus discounted future CDR price).

#### Option 2: Hybrid Approach

Emitters are mandated to cover a fraction of their gross CO<sub>2</sub> emissions with allowances under the ETS, while the remaining emissions are considered carbon debt and addressed through CROs. Over time, the ratio of CROs to allowances increases until it reaches one, indicating the depletion of the RC carbon budget and the discontinuation of the ETS.

#### Option 3: Emitter Choice

Emitters are granted flexibility to choose between obtaining allowances or acquiring CROs, providing a range of compliance options tailored to individual circumstances and promoting participation in both the ETS and the CRO framework.

Integrating the depletion of the RC carbon budget into the CRO framework or operating an ETS in parallel for that purpose (or a carbon tax, following a similar approach as described in Scenario 2) necessitates the definition of a TDI carbon budget, as shown in Figure S1c. The RC carbon budget is reflected by summing up the TDI carbon budget over time. Hence, the amount of carbon debt generated at each point in time is determined by gross emissions that exceed the TDI carbon budget at each point in time. The TDI carbon budget is needed for determining the time varying Emissions-to-Carbon Debt Ratio (Scenario 1) and for setting emission caps over time in an ETS (Scenario 2).

To ensure a smooth parallel operation between an ETS and a CRO framework, several considerations need to be addressed. Firstly, there might be a moral hazard associated with the continued issuance of allowances to emitters once the carbon budget has been depleted. It is crucial that the sum of emission caps over time accurately reflects the RC carbon budget, rather than simply continuing with the existing and scheduled caps.

During the gradual phase-out of the existing ETS sufficient notice to participant emitters should be provided to unwind their forward positions and utilize any remaining ETS allowances. It is anticipated that such a transitional period would run for a period of several years, while ETS allowances are typically surrendered on an annual basis. Hence, depending on the profile of the particular ETS in question, the transition period needs to be set to minimize any impacts resulting from the transition.

Furthermore, it is important to exclude credits generated through ERs or emission avoidance based on the principle of additionality from both the ETS and the CRO framework. This exclusion is vital to prevent double counting and maintain environmental integrity, ensuring accurate price signals and facilitating the achievement of climate targets set by the global RC carbon budget.

Moreover, it is crucial to note that in parallel operation, CROs and emission allowances are not fungible. If an ETS is still operational when a CRO reaches maturity, it would not be possible to discharge a CRO using an allowance. Allowing such trade would lead to convergence between the CDR market price and the ETS price, undermining the pricing mechanism of the CRO framework, which aims to incentivize separate price paths for ERs and CDR, as discussed in the main article.

### 3. Implementation

Interaction of public and private sector actors in implementation of the proposed CRO policy framework, as discussed at section 3.3 of the main article, is elaborated in Table S2 in terms of the particular element of the proposal and the actors' respective roles.

*Table S2: public sector and private sector roles and their interaction*

Element	Primary roles	Instrument or mechanism	Detail
Emissions = carbon debt	Government	Legislation	Created by primary legislation, establishes concept of carbon debt as financial debt.
Scheduled categories of emitters must measure emissions, report, have audited	Government/regulatory body/registry/carbon accounting and auditing bodies	Legislation/regulation/accounting and auditing rules	Part of new primary legislation; and amended corporate financial reporting regime.

Audited emissions included in emitters' accounts/balance sheet	Government/accounting bodies	Legislation/regulation	Rules to set out how emissions should be included in accounts as carbon debt/CROs.
Carbon debt formalised as a legal instrument in the form of Carbon Removal Obligation (CRO)	Government	Legislation	CRO instruments created by primary legislation to represent carbon debt in accounts of emitters; CRO legislatively defined as financial instrument; CRO measured in tonnes CO <sub>2</sub> ; CRO subject to a CRO Premium (i.e., interest).
Central bank mandate to implement government economic policy clarified to include carbon debt management in the economy	Government/central bank	Legislation/administrative action	Central bank given responsibility and the tools to manage carbon debt in the economy going forward.
CROs issued by commercial banks to emitter-customers; commercial banks must hold reserve accounts with central bank, on balance of which base rate interest (a CRO Base Premium) paid, hypothecated to future funding	Central bank	Legislation/central bank regulation	Commercial banks must ensure that sufficient CROs issued each year to cover emitter-customer annual carbon debt liability; Commercial banks run CRO reserve accounts with central bank, pay base rate interest (CRO Base Premium) on CRO balance held in reserve account (thus a function of how much their customer base is emitting at any point in time).
Commercial banks establish CRO accounts for their emitter-customers (at CRO Commercial Premium set in accordance with normal financial risk assessment but also climate risk assessment) (CRO Commercial Premium possibly subject to control by government policy or %	Commercial banks	Legislation/regulation/commercial banks' T&Cs for business customers. Commercial banks will need to hedge risk of defaulting customers.	Emitter-customers have obligation to show CROs in balance sheet commensurate with emissions; pay CRO Commercial Premium to commercial bank until CROs removed from balance sheet by retiring removal units. Commercial banks liable to central bank for defaulting customers.

also hypothecated to future funding)			
CRO repayment in standard-based removal units.	Government/national or international standards bodies	Legislation/regulation, including adoption of national or international standard for bundling CDR projects, standard-based removal units generated by projects that meet standard	Removal units generated by CDR projects; Removal units legislatively defined as financial instrument and also as a 'property right', in a legal sense; Removal units measured in tonnes CO <sub>2</sub> .
Emitter-customers of banks buy standard-based removal units in the market and cancel them to acquit CRO liabilities	CDR trading market platform, market participants, especially holders of CROs, project management companies selling standard-based removal units)	Trading rules, financial markets regulation. Potential for distributed ledger trading platform, with settlement in CBDC would enhance central bank carbon debt management capacity. Application of DLT would enable the provenance of removal units to be traced throughout their existence from issuance by the project to retirement, irrespective of how much they are traded (thus operates to prevent double counting, fraud, etc.)	Normal trading market; purchase/cancellation of standard-based removal units by emitter-customer reflected in adjustment to CROs in balance sheet; CRO Price payment by emitter-customer to CRO issuer bank, and by bank on its account with central bank reduced to reflect reduction in CRO liability on balance sheet.

As noted in section 3.4 of the main article, subject to resolution of some preliminary elements, the legal framework to implement the CRO policy proposal might comprise a package of three instruments: an enactment of primary legislation; development of a national (or international) standard; and secondary legislation (a regulation) to adopt the standard and implement the primary legislation. Details of these three instruments are set out in the following sections.

### Primary legislation

Thus, assuming a date, or time period, can be pinpointed when the global RC carbon budget, for the chosen temperature target, is determined to be expended and from which date (or period) emissions = carbon debt, the primary legislation might include elements set out in Table S3.

Table S3: Provisions in primary legislation

Element	Detail
➤ Legal framework overview	
➤ Legal framework objective	
➤ Introduce concept of carbon debt into law	
➤ Establish the related legal obligations, instruments and mechanisms to give effect to the legislative objective	
➤ set out roles and responsibilities of various parties	

<ul style="list-style-type: none"> <li>➤ provide for parties/entities to which obligations apply to be prescribed by regulation</li> </ul>	
<ul style="list-style-type: none"> <li>➤ related matters, including</li> </ul>	<ul style="list-style-type: none"> <li>➤ expanded monitoring, reporting and verification (MRV) – carbon removal obligations (CROs) might be based on scope 1 emissions only, but reporting obligations might include scope 1, 2 and 3 emissions;</li> <li>➤ provide for service providers in MRV to be certified and achieve specific skill, capacity, integrity levels;<sup>1</sup></li> <li>➤ that legal entities in prescribed categories must (a) report emissions; (b) hold CROs in respect of reported scope 1 emissions; (c) pay CRO Commercial Premium; and (d) disclose CRO holdings in their financial reporting and balance sheet;</li> <li>➤ that commercial banks (a) be authorized to issue CROs to customers that have obligations to hold CROs in respect of their reported emissions; (b) must each set up a CRO reserve account with the central bank; and (c) pay CRO Base Premium;</li> <li>➤ carbon debt is extinguished by CRO holders acquiring and retiring removal units; in the event that the CRO holder becomes insolvent without extinguishing their carbon debt, that obligation defaults to the commercial bank that issued the CROs;</li> <li>➤ removal units are generated and issued by CDR projects, in accordance with the Standard;</li> <li>➤ to generate and issue standard-based removal units, CDR projects must be accredited as satisfying the Standard; and</li> <li>➤ the project management company would be required to carry responsibility to ensure viability of the storage arrangements long-term, and this might be subject to formal legal ability to lift the corporate veil (that is, liability being passed through to company officers and/or shareholders in the event of fraud or mismanagement).</li> </ul>

### Standard

The purpose of the standard (“Standard”) would be to define minimum criteria for CDR projects and specify outcomes that the projects should achieve in order to be able to generate standard-based removal units. The mechanism put forward for implementation is proposed as one illustration of how it might proceed, rather than as the only one. All the same, it is noted that there is much activity in the EU, UK and other governments examining the introduction of such standards, as well as in standards organizations (BSI) and in the VCM (see ICVCM and also Climate Impact Exchange, Singapore (CIX)). As such, while the ultimate form of any such standard is yet to be determined, it seems reasonable to assume that a standard-based approach should form part of the proposed mechanism.

<sup>1</sup> European Securities and Markets Authority (ESMA) regulation of credit reference agencies (CRAs) provides one model for this.

The objectives would be to: ensure uniformity and consistency of outcomes across all projects; to identify risks and shortcomings of individual methods, in order to facilitate high integrity removal units; to apply an agreed taxonomy covering all CDR methods; and to ensure appropriate governance and high-level oversight and management of CDR project development within the jurisdiction (e.g., to avoid inappropriate application of resources; to avoid imbalances in land uses and/or CDR methods; ensure distribution of CDR projects conforms to objectives of local and national planning policies and laws).

Elements that the Standard might relate to: a minimum set of criteria for constituting the CDR project; minimum criteria for the outcomes the project would need to achieve; criteria addressing long-term management of the project; and elements addressing governance requirements. Table 4 sets out illustrations of what those elements might include.

Table 4S: Illustrations of minimum criteria elements of the Standard

Element	Minimum criteria
<ul style="list-style-type: none"> <li>➤ Elements addressing a baseline for how a project might be constituted</li> </ul>	<ul style="list-style-type: none"> <li>➤ Agreed scientific/technical community taxonomy: for example, The Royal Society; or other taxonomies proposed in the academic literature;</li> <li>➤ project lifetime say, at least [100] years (depends on definition of ‘permanence’);</li> </ul>
<ul style="list-style-type: none"> <li>➤ Elements addressing a baseline for the outcomes the project might achieve</li> </ul>	<ul style="list-style-type: none"> <li>➤ requirement that removals must all be real, permanent (as defined), verified;</li> <li>➤ project must be able to guarantee a minimum volume of removals over its lifetime at a more or less consistent rate;</li> <li>➤ Storage must be for say, at least [100] years, but this also depends on the accepted definition of ‘permanence’;</li> <li>➤ co-benefits (such as environmental, social, biodiversity-related, nature-enhancing) must be measured and reported annually;</li> <li>➤ prescribed actions for minimizing negative impacts (externalities, such as through conflicting land use issues).</li> </ul>
<ul style="list-style-type: none"> <li>➤ Elements addressing long-term management</li> </ul>	<ul style="list-style-type: none"> <li>➤ Operational management – must be planned; funded; annually audited;</li> <li>➤ Risk management – risks identified; management planned; funded; annually audited;</li> </ul>
<ul style="list-style-type: none"> <li>➤ Elements addressing governance</li> </ul>	<ul style="list-style-type: none"> <li>➤ MRV baseline, disclosure and transparency requirements (noting that MRV will vary according to the CDR method, so standard can only set out generic requirements unless each method addressed individually)</li> </ul>

Additionally, it is expected that the Standard would indicate: how the number of removal units that a project might issue would be calculated; set out delivery risk management requirements; set out any other risk management requirements; and indicate requirements pertaining to formation and management of the project. Table S5 sets out examples indicating what might be included in these requirements.

Table S5: Examples of further criteria required by the Standard

Further criteria	Detail
➤ Issuance of outcomes (standard-based removal units)	Formula to determine how many standard-based removal units result from the project, based on removal and storage criteria, possibly other factors needing to be included.
➤ Delivery risk management	Requirements might include: <ul style="list-style-type: none"> <li>➤ physical – % of removal units held as reserve buffer</li> <li>➤ financial - insurance</li> </ul>
➤ Other business and commercial risk management	Requirements might include: <ul style="list-style-type: none"> <li>➤ physical – % of removal units held as reserve buffer</li> <li>➤ financial - insurance</li> </ul>
➤ Project company formation and management	Requirements might include: <ul style="list-style-type: none"> <li>➤ individual CDR project developers need to form a legal structure (e.g. management company) which will be governed by the terms of the agreement reached between the developers of the project;</li> <li>➤ management company applies for certification under the Standard in order to be able to issue standard-based removal units;</li> <li>➤ application sets out how the project satisfies all the requirements of the Standard;</li> <li>➤ how the standard-based removal units are split between the project participants will be a matter for agreement between them in forming the project.</li> </ul>

### Secondary legislation

The regulation would implement and give effect to the primary legislation, including by adopting the Standard; prescribing categories of emitter entities whose emissions = carbon debt, represented by CROs that must be disclosed in their financial accounts; setting out operative elements of CROs; and defining concepts such as ‘permanence’ and ‘co-benefits’.

The regulation could elaborate the meaning given to a standard-based removal unit constituting a property right, that is, that the project that issues the removal unit has an obligation to maintain the storage for the specified period, and that this obligation is enforceable not just by the administrator



- Bednar, Johannes, Artem Baklanov, and Justin Macinante. 2023. "The Carbon Removal Obligation: Updated Analytical Model and Scenario Analysis." *IIASA Working Paper WP-23-001* (January). <https://pure.iiasa.ac.at/id/eprint/18572/>.
- Bednar, Johannes, Michael Obersteiner, Artem Baklanov, Marcus Thomson, Fabian Wagner, Oliver Geden, Myles Allen, and Jim W. Hall. 2021. "Operationalizing the Net-Negative Carbon Economy." *Nature* 596 (7872): 377–83. <https://doi.org/10.1038/s41586-021-03723-9>.

# ANNEX 6

Supplementary Figures and Tables  
for Chapter 6

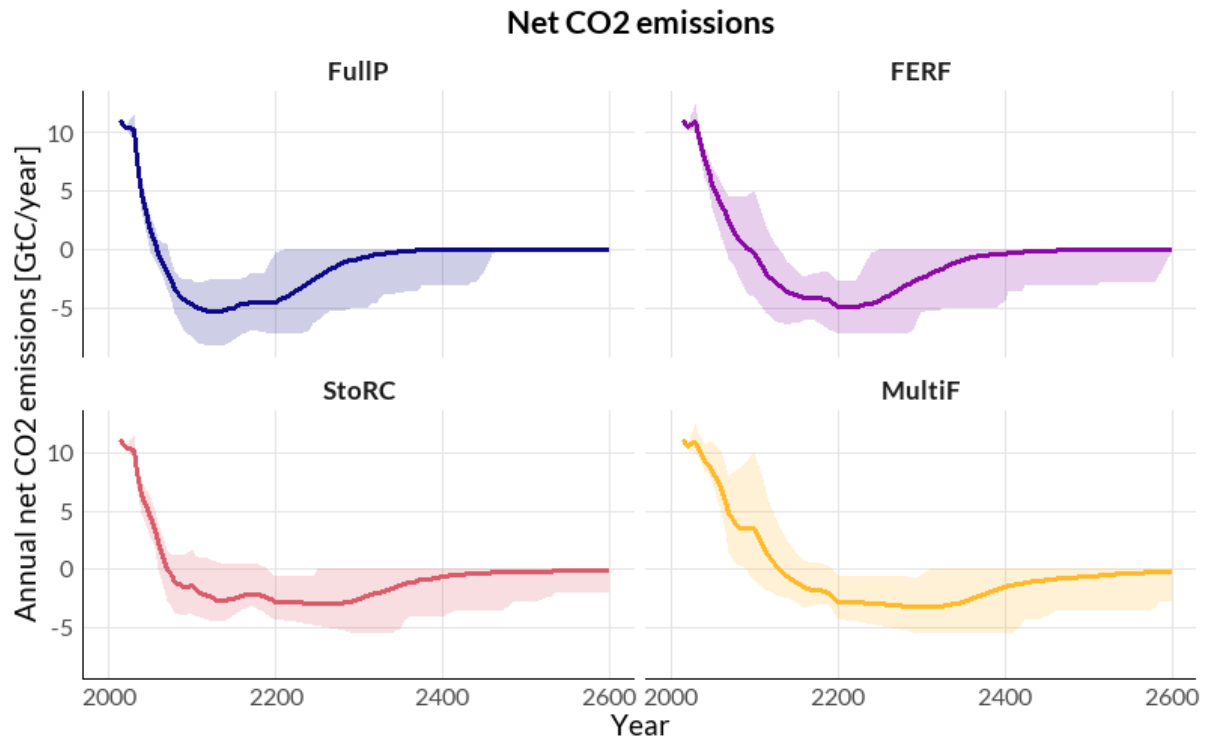


Figure S1. Modeled global net CO<sub>2</sub> emission pathways assuming stabilization of time-lagged impacts. Scenarios are conditioned on the requirement that both sea-level rise and permafrost thaw are stabilized. In most cases, stabilizing one of these metrics implies the other is already on a gradual declining trajectory. Solid lines show the ensemble mean net CO<sub>2</sub> emissions for each scenario, with shaded bands representing the full range (minimum to maximum) across the ensemble.

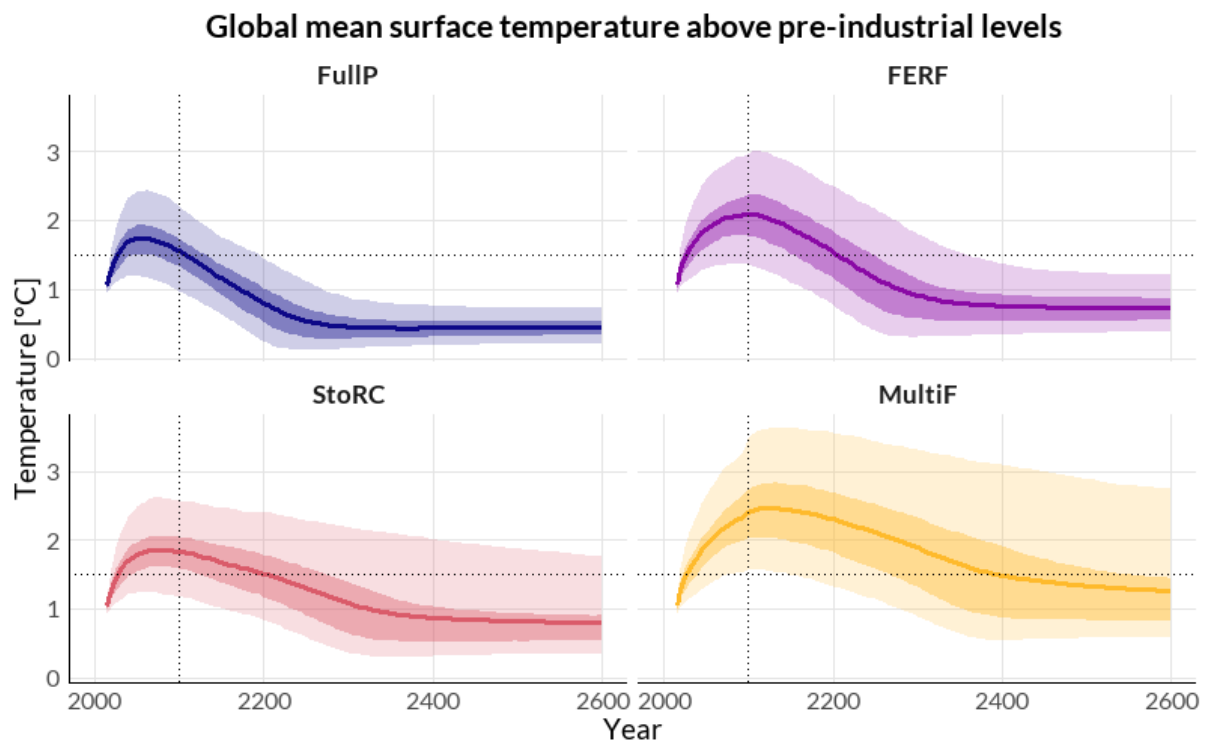


Figure S2. Modeled global mean surface temperature increase above pre-industrial levels. Scenarios are conditioned on the requirement that both sea-level rise and permafrost thaw are stabilized. In most cases, stabilizing one of these metrics implies the other is already on a gradual declining trajectory. Mean temperature trajectories are shown for each scenario (colored lines), with shaded bands indicating uncertainty ranges across the ensemble: the darker band shows the interquartile range (25th–75th percentile), and the lighter band shows the 5th–95th percentile range. The dashed vertical line marks the year 2100 (end-of-century reference), and the dotted horizontal line indicates the 1.5 °C global temperature limit under the Paris Agreement.

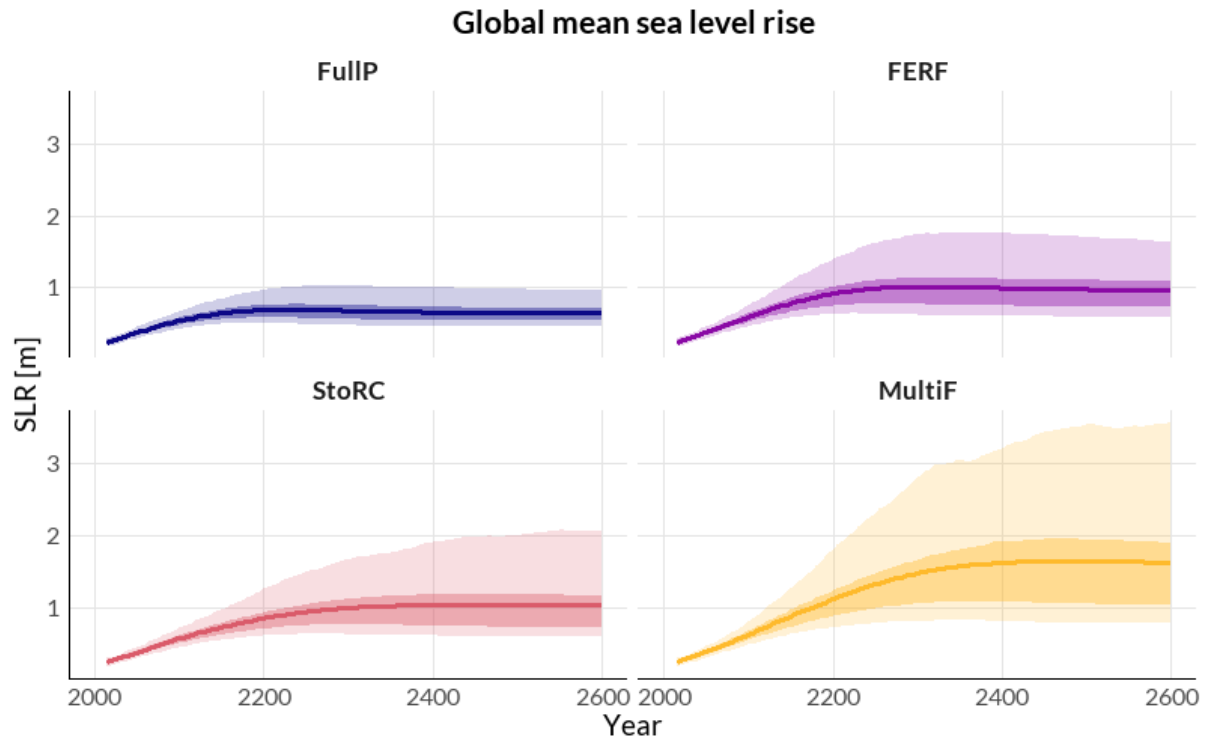


Figure S3. Projected global mean sea level rise (SLR). Scenarios are conditioned on the requirement that both sea-level rise and permafrost thaw are stabilized. In most cases, stabilizing one of these metrics implies the other is already on a gradual declining trajectory. Mean SLR trajectories are shown for each scenario (colored lines), with shaded bands indicating uncertainty ranges across the ensemble: the darker band shows the interquartile range (25th–75th percentile), and the lighter band shows the 5th–95th percentile range.

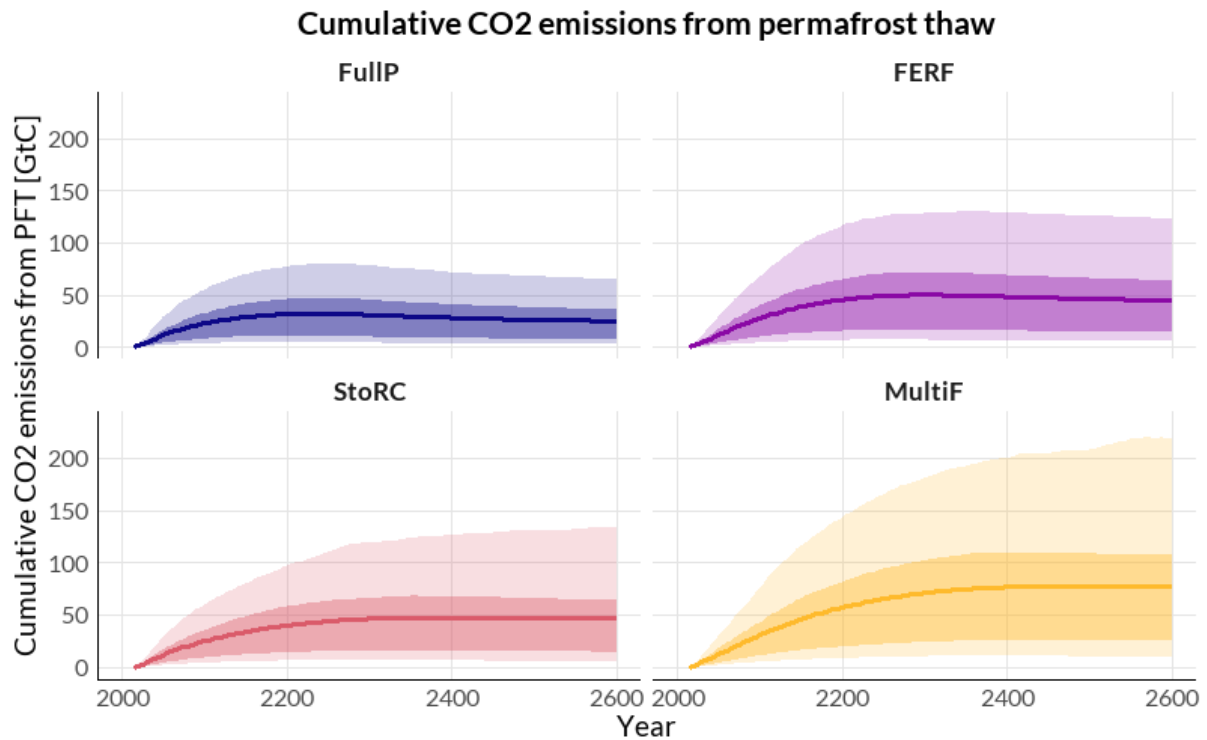


Figure S4. Projected global cumulative CO<sub>2</sub> emissions from permafrost thaw (PFT). Scenarios are conditioned on the requirement that both sea-level rise and permafrost thaw are stabilized. In most cases, stabilizing one of these metrics implies the other is already on a gradual declining trajectory. Mean cumulative emission trajectories are shown for each scenario (colored lines), with shaded bands indicating uncertainty ranges across the ensemble: the darker band shows the interquartile range (25th–75th percentile), and the lighter band shows the 5th–95th percentile range.

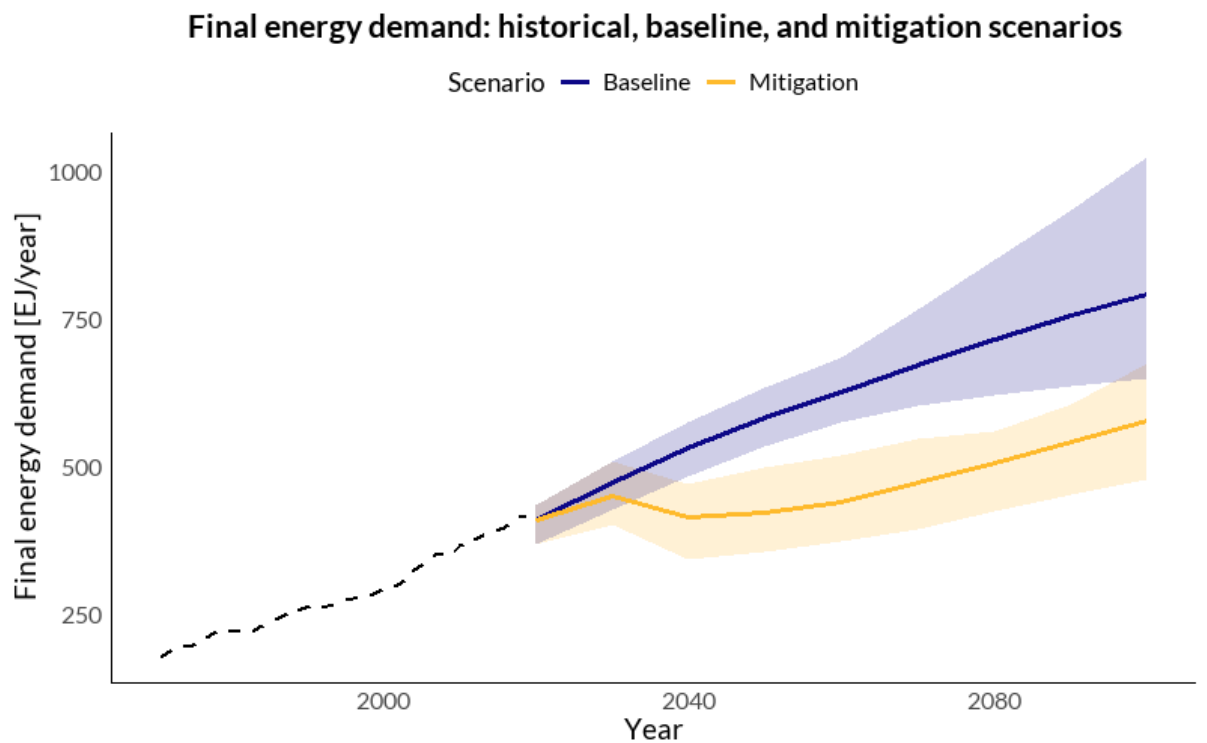


Figure S5. Annual final energy demand is shown as the mean (solid line) and full range (shaded area) across all trajectories in the Full Portfolio (FullIP) scenario, alongside the corresponding baseline pathways and the historical

trend (black dashed line). Scenarios with reduced progress in lowering the economy's final energy intensity are assumed to follow the baseline trajectories, which broadly extend the historical trend of rising energy demand.

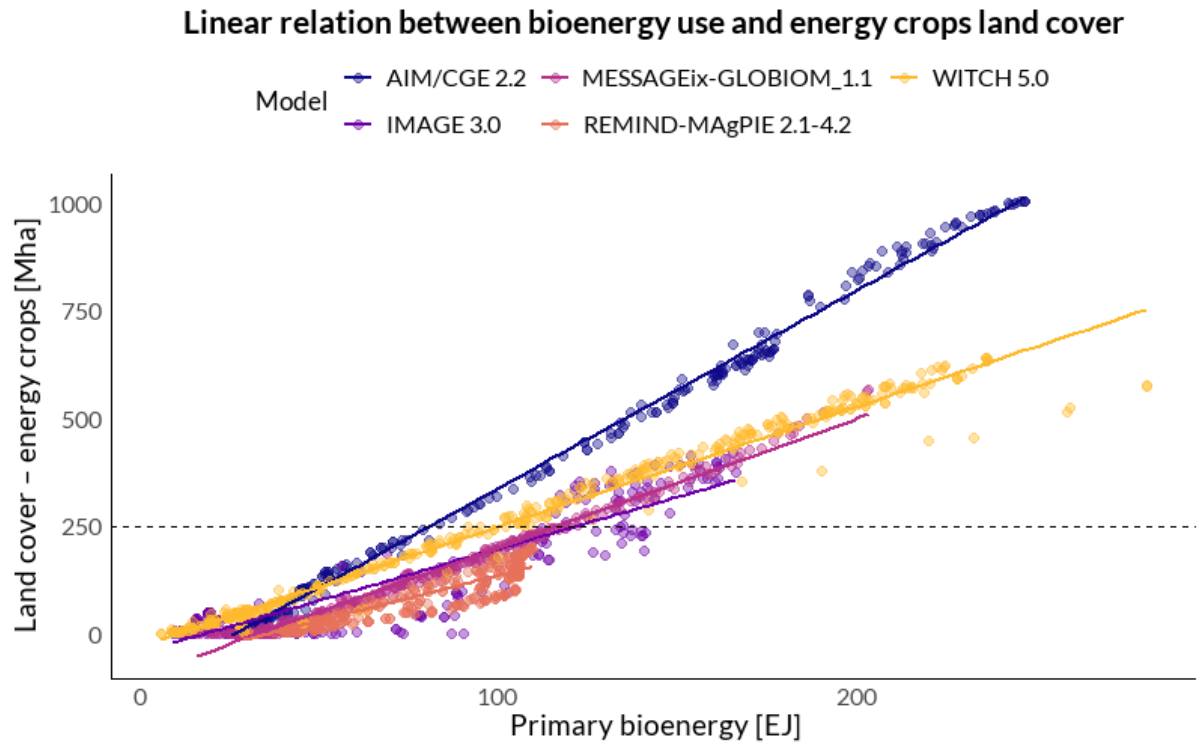


Figure S6. Linear relationship between primary bioenergy use and land cover for energy crops across dp-IAMs. The dashed horizontal line indicates a 250 Mha upper limit on land area allocated to energy crops. Using this threshold, we estimate an upper bound on annual primary bioenergy supply for each dp-IAM derived parameter set: AIM/CGE 2.2 (81 EJ), GEM-E3\_V2021 (100 EJ), IMAGE 3.0 (121 EJ), MESSAGEix-GLOBIOM\_1.1 (116 EJ), TIAM-ECN 1.1 (100 EJ), REMIND-MAgPIE 2.1-4.2 (154 EJ), and WITCH 5.0 (100 EJ). For TIAM-ECN 1.1 and GEM-E3\_V2021, no land cover data were available and the bioenergy limit was directly set to 100 EJ/year.

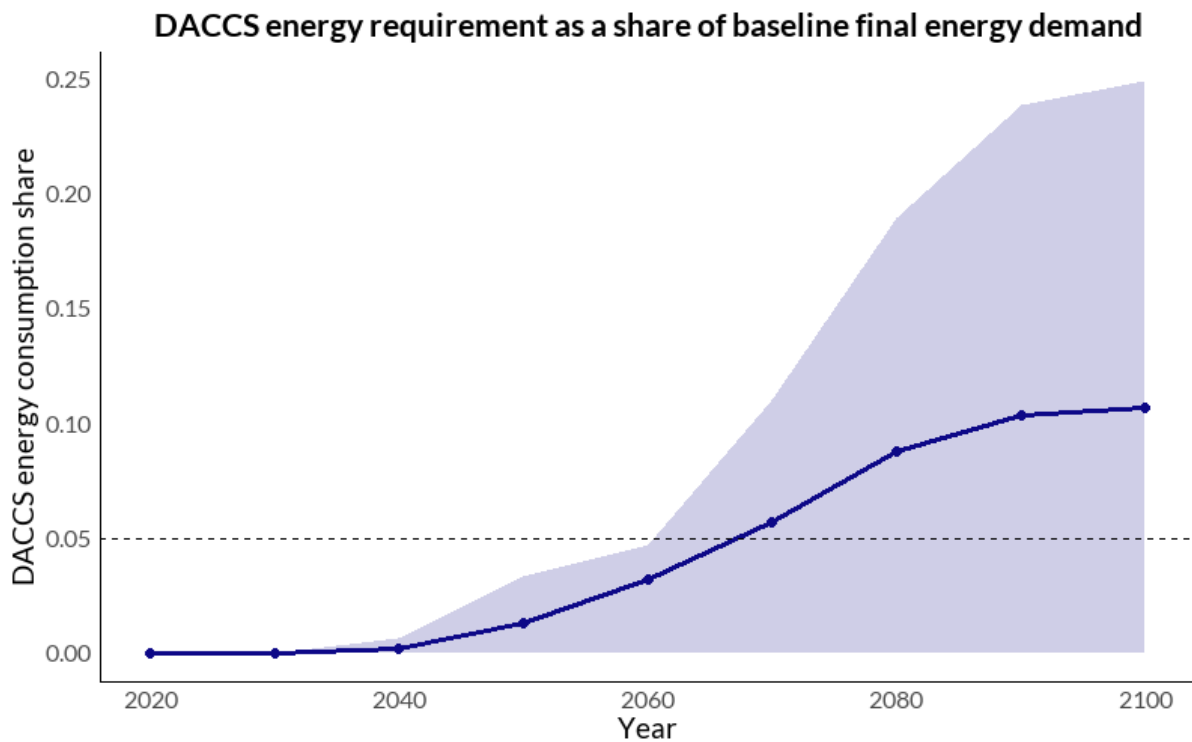


Figure S7. Mean and range (min to max) of DACCS energy consumption as a share of total baseline final energy demand across all 14 trajectories of the Full Portfolio (FullP) scenario. The dashed horizontal line represents the upper bound on allowable DACCS energy use as a fraction of final energy demand.

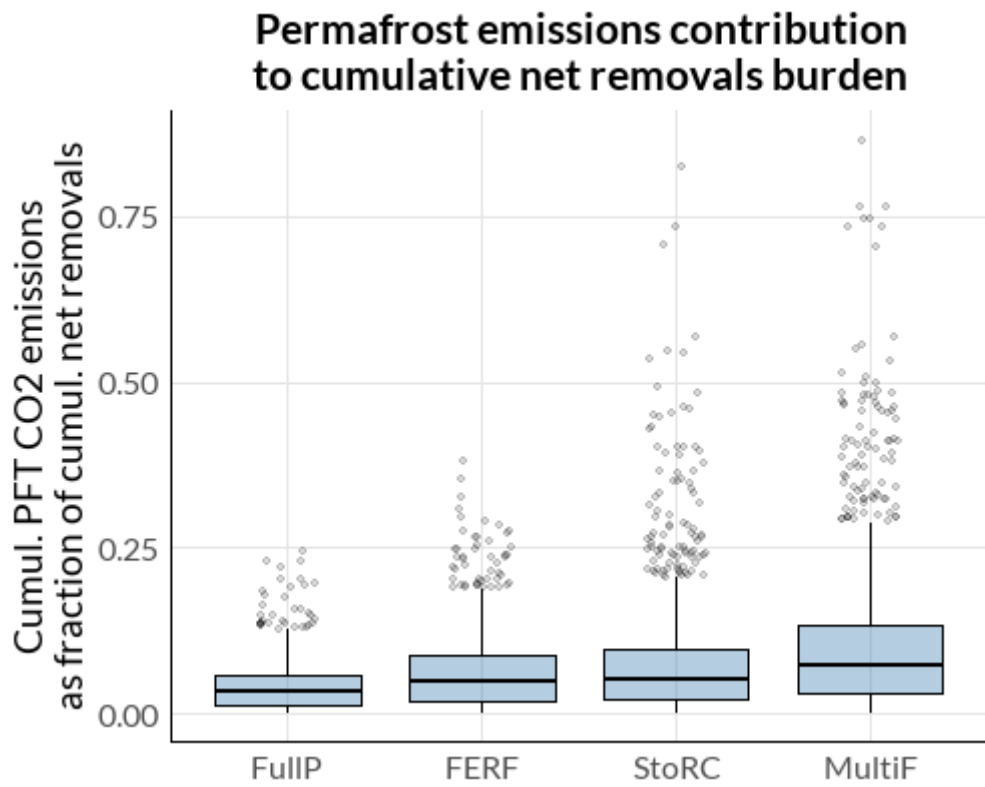


Figure S8. Distribution of cumulative CO<sub>2</sub> emissions from permafrost thaw (PFT) as a fraction of cumulative net CO<sub>2</sub> removals for each scenario. Distributions are illustrated as box-and-whisker plots, where the box represents the interquartile range (25th–75th percentile), the horizontal line indicates the median, and the whiskers extend to the most extreme values within 1.5 times the interquartile range.

**Table S1: Description of stylized constraints that are combined in different configurations to generate the mitigation scenarios.** Each row represents a different scenario, and each column corresponds to a specific constraint. The constraints are as follows: final energy demand follows baseline scenario assumptions and does not respond to a carbon price; the land area allocated to bioenergy is limited to a maximum of 250 million hectares; final energy consumption by DACCS is capped at 5% of total baseline final energy demand; and the annual growth rate of geological CO<sub>2</sub> storage capacity is capped at 15%, starting from 110 MtCO<sub>2</sub> per year in 2030. This storage constraint hence applies to CCS, BECCS, and DACCS technologies.

<b>Scenario</b>	<b>Narrative Summary</b>	<b>Final Energy Demand</b>	<b>Bioenergy</b>	<b>DACCS</b>	<b>Geological CO<sub>2</sub> Storage</b>
<b>FullIP</b>	Full mitigation portfolio available. Represents idealized dp-IAM assumptions.	Carbon price–driven reduction as in dp-IAMs	Unconstrained	Unconstrained	Unconstrained
<b>FERF</b>	Final energy reduction failure, e.g., due to new energy consumers or rebound effects.	Follows dp-IAM baseline assumptions	Unconstrained	Unconstrained	Unconstrained
<b>StoRC</b>	Storage and removals constrained: limits on BECCS, DACCS, and storage scale-up.	Carbon price–driven reduction as in dp-IAMs	250 Mha limit for energy crops	DACCS energy consumption ≤ 5% of baseline final energy	Growth capped at 15%/yr starting at 110 MtCO <sub>2</sub> /yr in 2030.
<b>MultiF</b>	Multiple constraints, combining FERG and StoRC assumptions.	Follows dp-IAM baseline assumptions	250 Mha limit for energy crops	DACCS energy consumption ≤ 5% of baseline final energy	Growth capped at 15%/yr starting at 110 MtCO <sub>2</sub> /yr in 2030.