Operationalizing the net negative carbon economy

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The remaining carbon budget for limiting global warming to 1.5°C will likely be exhausted within this decade[1,2]. Carbon debt[3] generated thereafter will need to be compensated by net negative emissions[4]. However, economic policy instruments to guarantee potentially very costly net carbon-dioxide removal (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[5]. 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_2 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.

Introduction

Delivering on the many national and corporate net-zero emission pledges will likely require gross removal of atmospheric CO_2 on top of conventional emission reductions[6,7]. To achieve the Paris Agreement, global gross CO_2 removals will need to exceed gross residual emissions[4,8] beyond mid-century[1,9]. The resultant net negative emissions compensate carbon debt[3] accrued by CO_2 emissions overshooting the remaining carbon budget[10,11]. 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[1] (Extended Data Table 1). Such large-scale deployment of carbon-dioxide removal (CDR) is controversial mainly for the implied economic and technological risks[12–16] and environmental impacts[17,18]; and because reliance on CDR in mitigation scenarios often goes hand-in-hand with a substantial shift of the mitigation burden to future generations[19].

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[5]. 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_2 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 overshot emissions after the budget's depletion, which has profound implications for the consistent earmarking of accrued revenues from a price on CO_2.

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[20]. 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[21].

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 (ref[9]). 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 an non-renewable resource[22,23], 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 overshot 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 21st century is highly doubtful (ref[5]), 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[24] (Figure 1). For comparison, Norway's large sovereign wealth fund has passed 250% of national GDP[25]. 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[26]. 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[27]. 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.

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[28]. 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_2 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 2) 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[29,30]. 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 overshot, 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 (ref[1]) – 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 (ref[28]). 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[31].

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_2 – 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[2], 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_2 already by 2050, or roughly 7 years[32] of present CO_2 emissions*, according to the 1.5°C-compatible mitigation scenarios LIFE and TECH from the European Commission (COM)[33]. In line with the Union's net zero GHG target for 2050, CO_2 emissions must turn net negative already by 2043[34]. Despite the lack of any adequate mechanism to do so, sectors currently covered by the EU-ETS will therefore need to deliver 50Mt CO_2eq 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[35] will require significant public funding, which is likely to obstruct the implementation of ambitious net-CO_2 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_2 'target' of 26 Gt CO_2** 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[36,37], large energy firms would be incentivized to develop CDR for counterbalancing residual emissions[38]. 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[39]. For CDR suppliers[40,41] 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[42], would likely be under pressure to liberalize intertemporal trade of carbon debt, and thereby establish responsibility for overshot emissions. The EU-wide rollout would therefore be followed by attempts to actively influence regulation globally (e.g., via ‘regulatory export’[43]) and subsequent linkage with other national and regional schemes[44].

**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$_2$*[45].
***2018-2100 period; 1.5-TECH and LIFE scenarios combined,* including net removals.

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[46,47]. 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 3 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 3. 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$_2$ 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”[48]. 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 4 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 22nd century[49]. 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[50–52], 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.

Impact on financial flows in time

Figure 4, 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 4d 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 1. Pricing overshot 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 (ref[46]) or from adequately setting intermediate climate targets or constraints on net emissions (ref[20]). However, such measures would individually not resolve the more profound issue of finance of net negative emissions discussed here.

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.

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STRICTLY EMBARGOED UNTIL THURSDAY, 8 JULY 2021 AT 17:00 CENTRAL EUROPEAN TIME (CET) / 16:00 LONDON TIME (BST) / 11:00 US EASTERN TIME

Figures

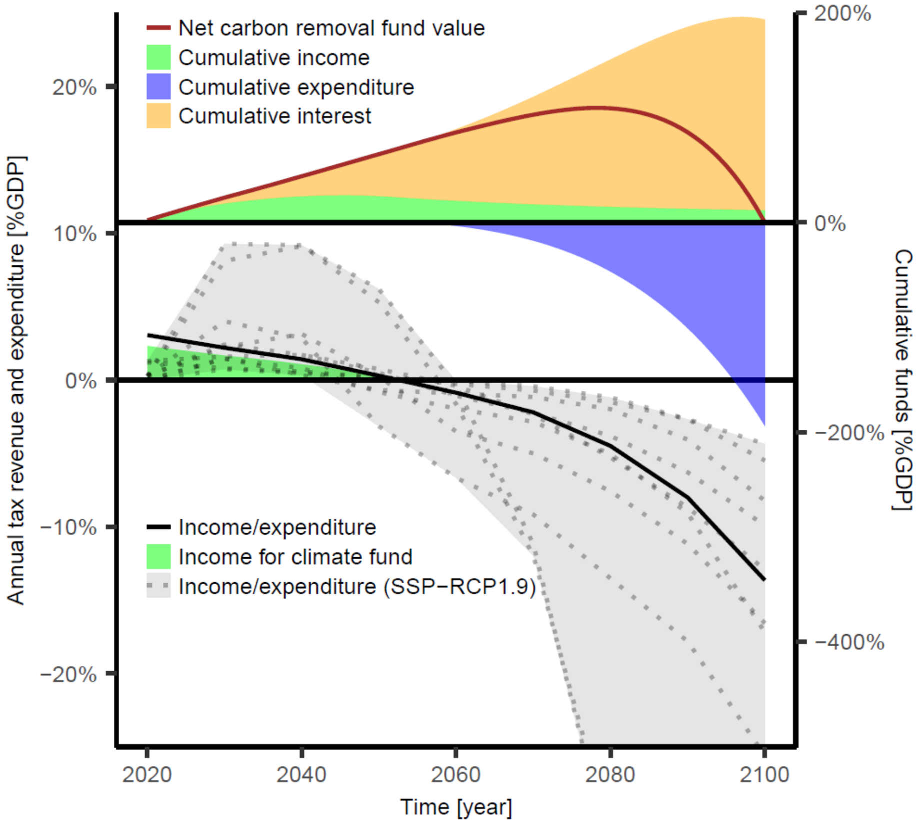

Figure 1: Idealized global tax scheme with net carbon removal fund. Lower figure (left hand side axis): Public income and expenditure from a tax on net emissions expressed as GDP percentage. Hotelling-compatible (exponential) carbon prices from SSP-RCP1.9 scenarios are multiplied by net emissions and 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 ϕ =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 ϕ. **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.

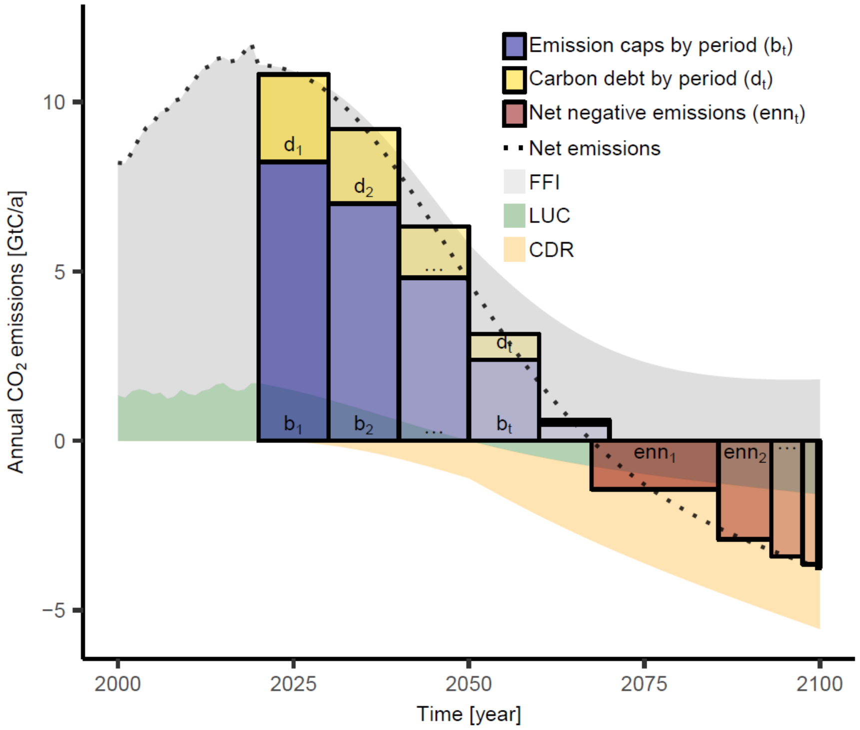

Figure 2: Idealized emission trading system (ETS) with intertemporal trade of carbon debt. Illustrative 2°C pathway with gross carbon emissions from fossil fuels and industry (FFI), land use change (LUC), and non-specified sources of carbon-dioxide removal (CDR) including the schematic architecture of 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 ref[53].

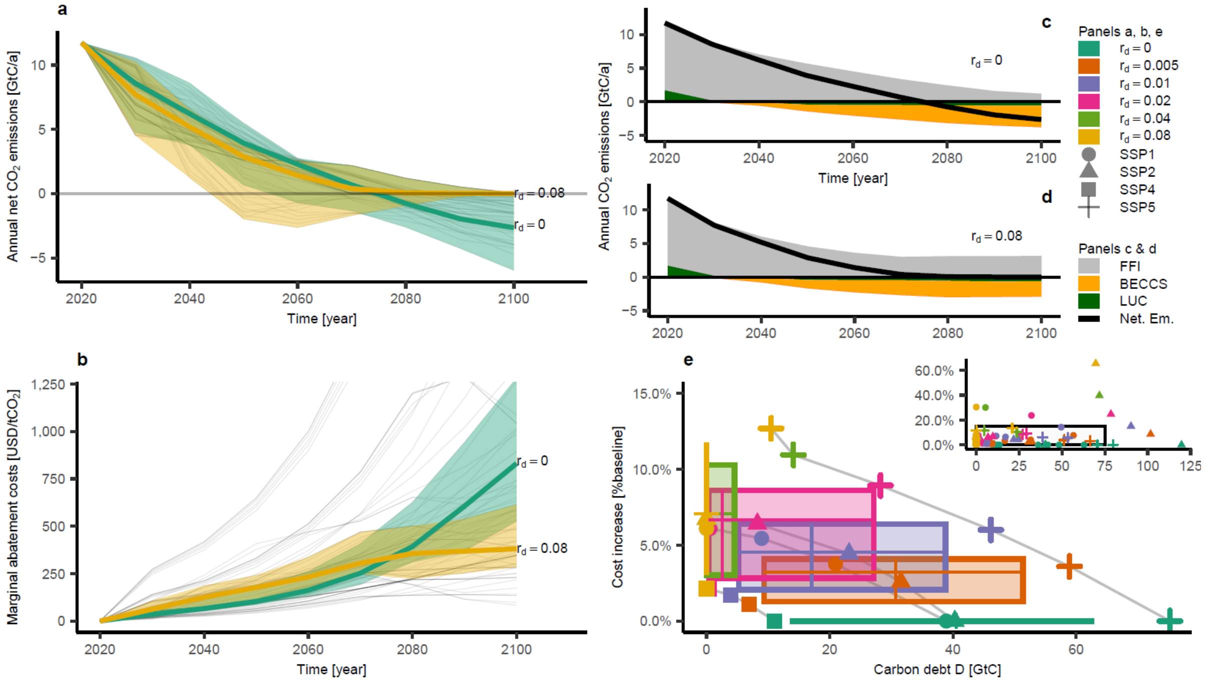

Figure 3: 2°C (RCP2.6) mitigation scenarios for a range of interest rates on carbon debt. Panel a: Net CO$_2$ emissions of all scenarios with r_d = 0 (turquoise) and r_d = 0.08 (yellow), including geometric median paths (bold solid lines) and min to max ranges (shaded areas). **Panel b:** Marginal abatement 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).

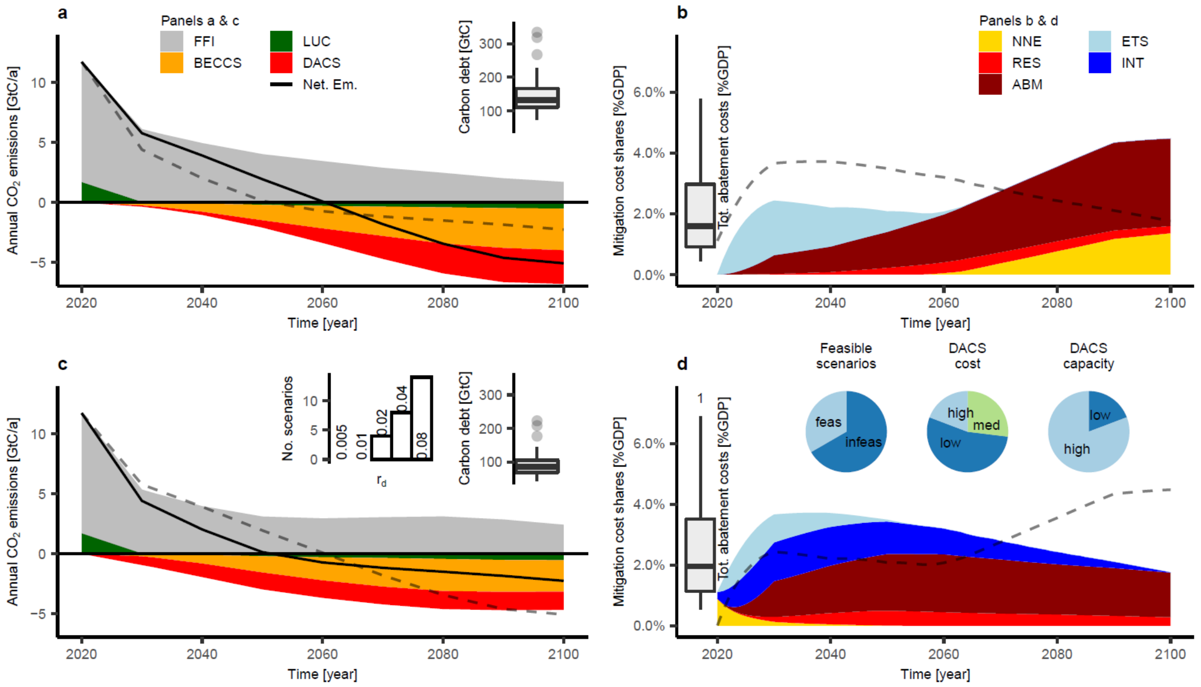

Figure 4: 1.5°C (RCP1.9) pathways under a conventional ETS (panels a and b) compared to a CRO-ETS (panels c and d). Panels a and c: Geometric median net emissions (solid line) and gross emissions from fossil fuels and industry (FFI), bioenergy with carbon capture and storage (BECCS), land use change (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.

Methods

Basic analytical setup

Emission reductions induced by a CRO-ETS are quantified using a Hotelling-type optimization problem (see ref[46] 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:

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

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:

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

subject to:

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

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:

$$c_{tot}\big(t, a(t)\big) = E_{base}(t) * \int_{0}^{a(t)} MAC(t, \tilde{a})\, d\tilde{a}. \qquad [4]$$

Assume that under an idealized CRO-ETS a constant fraction 1-ϕ 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 ϕ is defined as the ratio of cumulative net negative emissions e_{NN} to cumulative net positive emissions e_{NP}:

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

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

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

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

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

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

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

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

Consequently, we can write ϕ as:

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

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

Instead of exogenously imposing ETS emission caps, ϕ 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_2:

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

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:

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

and instantaneous interest payments are obtained by multiplication of the quantity of CO_2 for which CROs have been issued ($d = \phi * e_{NP}$) 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:

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

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

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

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

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

Mitigation cost discounting

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

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

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_2 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.

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.

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.

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[24,54]. 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[53] (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 ref[53].

We fit the inverse of the generalized logistic function[55] 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):

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

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

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

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[22,23]. 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[56]. 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[57], 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_2 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.

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[16], making it more independently scalable. However, capital and energy requirements are uncertain and potentially enormous. Costs range between 20 and 1000 USD/tCO_2[16,18,58–60], and potentials for CDR range from 0.5-5 $GtCO_2$/a in 2050 to 15-40 $GtCO_2$/a in 2100[18], however, these potentials are mainly constrained by cost considerations rather than biophysical limits[61]. 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]:

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

and change total costs in [4] to:

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

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

$$MAC\big(t, a(t)\big) = MAC_{DACS}\big(a_{DACS}(t)\big). \qquad [\ 21\ ]$$

To obtain a detailed technology downscaling of sources and sinks of CO_2 (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 withing the same IAM/SSP configuration and the same year) and add DACS after the interpolation.

1.5°C scenarios for Figure 4

For Figure 4 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 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 4. 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 SI1.3 and numerically in SI1.4., abatement and interest costs are illustrated in Extended Data Figure 6 for all scenarios.

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[62], 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.

Software and solver

The model is solved using the CONOPT solver in GAMS v26.1. CONOPT is based on the Generalized Reduced Gradient (GRG) algorithm, one of the most robust and commonly applied methods for solving models with highly nonlinear objective functions or constraints[63].

Data availability

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Code availability

The source code of the numerical model used for generating the data used in this study is available at https://github.com/jobednar/CROmodel.

The numerical model was calibrated using scenarios from the SSP scenario database hosted by IIASA and available at https://tntcat.iiasa.ac.at/SspDb/.

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Statements

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Author Contribution

Michael Obersteiner, Fabian Wagner, Marcus Thomson and Johannes Bednar have equally contributed to identifying the knowledge gaps and main ideas of this article, as well as sharpening the field of interest. Johannes Bednar acted as lead author and was primarily involved in formalizing and quantifying the ideas of the article, as well as in drafting of the main article and development of analytical and numerical methods. Jim Hall and Michael Obersteiner have supervised the development of the article from the first draft throughout the review process. Jim Hall, Oliver Geden, Myles Allen, Fabian Wagner and Marcus Thomson contributed to the work's framing, conception and design, as well as to the interpretation of results. Artem Baklanov provided quality control of methods and result presentation and contributed the mathematical proof of the equations derived in the methods section. Oliver Geden contributed by significantly improving the article's policy relevance, for instance by developing the EU implementation scenario. All authors were equally involved in the revision process and have approved the submitted version of the article.

Competing interest declaration

The authors declare no competing interests.

Additional information

This article contains supplementary information.

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Extended Data Legends

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.

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.

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 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 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).

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_2 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_2 before a specified maturity, e.g., by physically removing atmospheric CO_2 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 ear-marked 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, $MAC(a) = b * \left(\frac{1}{v} * \left(\left(\frac{L-A}{a-A}\right)^{v} - 1\right)\right)^{c}$, 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, $MAC(a = A) = inf$, 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_2 (orange area). Low-cost MACCs (dotted lines) start at approximately 50 USD/tCO_2 and reach 1000 USD/tCO_2 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 $GtCO_2$/a at current emission levels, respectively. Medium cost MAC curves (dashed lines) start at 250 USD/tCO_2 and reach 1000 USD/tCO_2 at a_{DACS} = 0.05 (low capacity, blue line) and a_{DACS} = 0.22 (high capacity, red line), i.e. roughly 2 and 10 $GtCO_2$/a at current emission levels, respectively. High cost MAC curves (solid lines) start at approximately 500 USD/tCO_2 and reach 1000 USD/tCO_2 at a_{DACS} = 0.03 (low capacity, blue line) and a_{DACS} = 0.12 (high capacity, red line), amounting to roughly 1 and 5 $GtCO_2$/a at current emission levels, respectively.