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ABSTRACT

We analyze how conventional emissions trading schemes (ETS) can be modified by introducing "clean-up certificates" to allow for a phase of net-negative emissions. Clean-up certificates bundle the permission to emit CO2 with the obligation for its removal. We show that demand for such certificates is determined by cost-saving technological progress, the discount rate and the length of the compliance period. Introducing extra clean-up certificates into an existing ETS reduces near-term carbon prices and mitigation efforts. In contrast, substituting ETS allowances with clean-up certificates reduces cumulative emissions without depressing carbon prices or mitigation in the near term. We calibrate our model to the EU ETS and identify reforms where simultaneously (i) ambition levels rise, (ii) climate damages fall, (iii) revenues from carbon prices rise and (iv) carbon prices and aggregate mitigation cost fall. For reducing climate damages, roughly half of the issued clean-up certificates should replace conventional ETS allowances. In the context of the EU ETS, a European Carbon Central Bank could manage the implementation of cleanup certificates and could serve as an enforcement mechanism.

Keywords: carbon removal, carbon pricing, net-negative emissions, carbon debt
JEL Codes: H23, Q48, Q54, Q58

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1. Introduction

As global emissions continue to rise, carbon dioxide removal is becoming an indispensable pillar of climate policy. For limiting global warming to below 2 degrees or even 1.5 degrees Celsius, many mitigation scenarios now consider extensive upscaling of carbon removal. In some models, gross carbon removal amounts to 10-20 Gt CO_2 per year – i.e., around one-quarter to half of current carbon emissions – by the second half of the 21st century (IPCC, 2018). Besides compensating for remaining residual emissions, carbon removal flows could even exceed emission flows and turn net emissions negative for three main reasons: First, because of the slow progress in mitigation and the significant inertia in reducing emissions, net-negative emissions may become mechanically necessary to return to the global temperature target after a period of temperature overshoot (see Fig. 1). Hence, by undoing past emissions, carbon removal makes achieving a climate target possible even after a temporary violation of that target. Second, in a cost-benefit setting with a sufficiently high social cost of carbon, it can be optimal for net emissions to become negative. Recent studies that have updated climate damages upwards (Kotz et al., 2024; Bilal and Känzig, 2024) increase the likelihood of this case. Third, net-negative emissions could be motivated by justice and fairness considerations related to countries' historical responsibility in contributing to global warming. With carbon dioxide removal, countries that started their industrialization early could undo part of their past emissions.

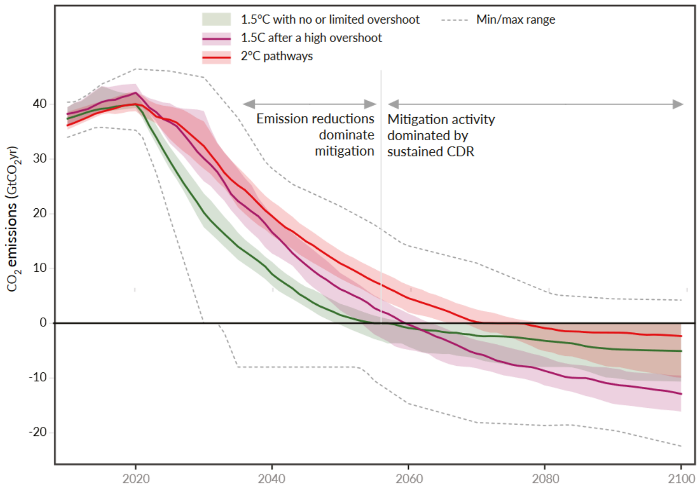

Figure 1: Global net carbon dioxide (CO_2) emissions in scenarios assessed in the Intergovernmental Panel on Climate Change Sixth Assessment Report. Shaded regions show the 5-95th percentile ranges (Smith et al., 2023).

While carbon prices are an effective policy instrument for reducing emissions (see, e.g., Döb--beling-Hildebrandt et al., 2024), incentivizing net-negative emissions via carbon pricing faces two key challenges. First, a carbon tax applied to carbon removal would become a removal subsidy. With an estimated global removal cost of up to two percent of global GDP, financing removal subsidies could put considerable pressure on public funds and therefore face political opposition.[1] As revenues from carbon pricing in a carbon-neutral economy will be low, other sources of finance would need to be accessed. Second, a cap and trade system, such as the EU Emissions Trading System (ETS), can deliver net-zero emissions by allowing the creation of certificates from removed carbon and integrating them in the carbon market. However, without further amendments to the regulation, existing cap-and-trade systems cannot incentivize or finance a later phase of net-negative emissions. This paper addresses these issues.

One way to extend cap-and-trade systems to allow for net-negative emissions could be the inclusion of "carbon debt". In analogy to the carbon budget that indicates the remaining cumulative emissions until mid-century, the cumulative net-negative emissions in the second half of the century represent a debt that needs to be repaid by removing carbon from the atmosphere. While current emission trading systems implement the carbon budget by setting rules for the allocation and the trade of emission allowances, an extension to net-negative emissions requires new rules for the responsibility for carbon debt and ensuring that the debt is paid back.

In this paper, we propose such a set of new rules and investigate how carbon debt can be integrated into an existing ETS by introducing "clean-up certificates". Clean-up certificates bundle the permission to emit CO_2 with an obligation for its removal, thereby shifting the responsibility to clean up emissions via carbon removal to the emitter. In such a system, the number of clean-up certificates corresponds to the amount of carbon debt that can be financed via the ETS.

Our analysis contributes to an emerging literature on carbon debt. Bednar et al. (2021) introduce the mechanism of carbon removal obligations, which links current emissions to carbon debt. The carbon debt enters the balance sheets of the emitters as a liability – similar to financial debt – to banks and central banks. The authors argue that the default risk of carbon debt is addressed by a mark-up on the interest rate paid for carbon debt, thereby relying on the financial sector rather than carbon markets for the implementation. Their numerical simulations show that the interest on carbon debt reduces the reliance on carbon dioxide removal.[2] The idea of linking CO_2 emissions to their removal is also fundamental for carbon takeback obligations (Jenkins et al., 2021, 2023), which require fossil fuel companies to demonstrate removal of a fraction of the associated emissions. To guide the world economy towards net-zero emissions, the fraction converges to 100 percent on a given trajectory. As removal is required before extraction (or import), the takeback obligations do not encompass the concept of carbon debt. In contrast, Lyngfelt et al. (2024) focus on financing CDR in the future, as tight fiscal budgets and lack of international cooperation may otherwise render future CDR infeasible. They suggest requiring emitters to deposit a fee for each unit of emissions that can only be redeemed upon its removal from the atmosphere. Lyngfelt et al. do not determine a necessary minimum value of the fee, arguing instead that when the deposit is invested as part of a public fund, its value eventually increases to a point where it becomes profitable to carry out the removal and redeem the deposit. To incentivize further negative emissions, for example to offset historical emissions, a ratio greater than unity of required removal to emissions could be required from the emitters.

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[1] Assuming annual removal of 10-20 $GtCO_2$ in the second half of the century at costs of $300/$tCO_2$ (Smith et al., 2023), global CDR expenditures could reach $3-6 trillion annually. With a projected global GDP of $365 trillion in 2075 (average over SSP1–SSP5 scenarios), this represents 0.8-1.6 percent of world GDP.

[2] See Bednar et al. (2023a) for details on the pricing of the premium on carbon debt and Bednar et al. (2023b) for details on the implementation.

The idea of ensuring removal by demanding a deposit that is redeemable and tradable is similar to carbon shares in Lemoine (2020). Lemoine proposes a carbon stock tax that emitters pay as a rental charge for storing carbon in the atmosphere until the time when they remove the CO_2 from the atmosphere. The incentive to remove emissions is impaired when firms can forego the rental charge in case of bankruptcy. To address this moral hazard, Lemoine introduces upfront payment via a bond that is redeemable upon removal, and tradable carbon shares that financialize the liability. Rickels et al. (2021) analyze the integration of negative emissions into a cap and trade system like the EU ETS, highlighting both legal and economic challenges. They point out that full integration of carbon removal increases efficiency, whereas imposing quantity constraints on removals reduces the efficiency of carbon markets. However, constraints may be necessary, as large-scale substitution of abatement by removal could reduce political feasibility and public acceptance.[3] Consequently, Rickels et al. (2021) propose separation of the markets for emission reductions and carbon removal. This separation allows for incentivizing carbon dioxide removal without interfering with the existing EU ETS. An intermediary could connect the two markets by buying removal credits and selling them into the ETS (at a lower price). Furthermore, Rickels et al. (2022) suggest that the intermediary could build a strategic reserve by banking removal credits, which could be used to cushion price spikes in the ETS. In sum, the incentives for technological learning in both technologies are maintained by managing the prices for removal and abatement separately.

In contrast to the existing literature, we explore options for the integration of carbon dioxide removal in an existing ETS that allow for a temporary overshoot of the carbon budget and a phase of net-negative emissions. Additionally, we show how the trade-off between “mitigation deterrence” and economic flexibility can directly be controlled by the regulator. These two features allow to improve the dynamic efficiency of emissions trading schemes while simultaneously safeguarding against the environmental concerns of crowding out mitigation. Using an analytically tractable, dynamic model of an emissions trading scheme, we model the introduction of clean-up certificates, carbon debt, and collateral requirements. We derive closed-form solutions and fully characterize the equilibrium paths of net emissions and the price of emission permits. We calculate the price of clean-up certificates and identify the length of different characteristic phases (transition to net zero, net zero, and net negative). We find that the demand for clean-up certificates is driven by the anticipated technological progress in abatement and removal, the discount rate and the length of the compliance period. In particular, without (sufficient) cost-savings in CDR materializing over time, there is no market for clean-up certificates.

We show that clean-up certificates can be introduced without deterring mitigation efforts if emission permits of an equal amount are retired. Since the number of emission permits remains the same, neither net emissions nor carbon prices are affected in the near-term. Simultaneously, associating carbon debt with existing emission permits reduces cumulative emissions below the

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[3] As surveyed by Burke and Gambhir (2022), the underlying worry is that integrating carbon dioxide removal in compliance markets deters mitigation efforts. This mitigation deterrence may occur due to two reasons. First, there is uncertainty about removal capacities and cost, making future removal an imperfect substitute for near-term mitigation. Similarly, lack of additionality, non-permanence of storage or moral hazard may cause planned net-negative emissions never to materialize. Second, integrating carbon removal may reduce the carbon price in the cap and trade system, thereby impairing the price signal that triggers mitigation and low-carbon investments.

carbon budget, implying a strengthening of the ambition of the ETS. Implicitly, the net-negative emissions are financed by forgone revenues from permit auctioning, as the clean-up certificates sell at a lower price than regular emission permits. In contrast, introducing clean-up certificates in addition to the carbon budget of an existing ETS exerts downward pressure on the carbon price, and mitigation efforts are deterred. The carbon budget is temporarily overshot, and cumulative emissions only return to the original target at the end of the compliance period. In this case, the net-negative emissions induced by clean-up certificates are not additional to the carbon budget. However, the regulator may also choose the extent to which this "clean-up" is additional: a share of carbon debt could be attached to existing emission permits to create additional net-negative emissions, while the remainder could be issued as newly created clean-up certificates that will crowd-out mitigation and reduce abatement cost. In this way, the regulator can choose the trade-off between dynamic efficiency and environmental integrity.

We numerically illustrate these results by calibrating our model to the EU ETS and show the implications for net emission pathways, carbon prices, and fiscal revenues when clean-up certificates are used to increase ambition levels or to reduce the carbon price. We identify a trade-off for choosing the share of clean-up certificates that replace permits in the ETS: a higher share brings down climate change damages, but increases compliance costs and reduces the revenues from auctioning emission permits and clean-up certificates. However, we find that given sufficient technological progress, there exists a set of clean-up policies that reduce cumulative climate damages while simultaneously increasing fiscal revenues and lowering carbon prices and mitigation costs.

Finally, we discuss institutional aspects that are relevant to ensure a functioning market for clean-up certificates. When financial intermediaries cannot overcome liability problems and default risks due to long time horizons and large uncertainties, a public institution might step in. It would charge the carbon debt to buyers of clean-up certificates and take the risk to finance the future carbon removals. This latter property makes it a lender of last resort for carbon debt – a 'carbon central bank'. Similarly, time inconsistency problems that are inherent to the management of carbon budgets can be reduced by delegation to an independent institution. In the context of the EU ETS, a European Carbon Central Bank could address both issues.

The remainder of the paper is structured as follows: Section 2 presents the model and the characterization of net emissions and carbon prices in closed form. In Section 3, we present the model calibration to the case of the EU ETS and discuss the results. In Section 4, we discuss institutional challenges for the governance of clean-up certificates. We conclude in Section 5.

2. The model

2.1. The Social Planner model

We analyze an economy where net-emissions $Q(t)$ accumulate without decay in the atmospheric carbon stock $X(t)$ and where the initial atmospheric carbon stock is normalized to zero $X(0) = 0$. Consider a conventional approach of climate policy represented by a limit to cumulative

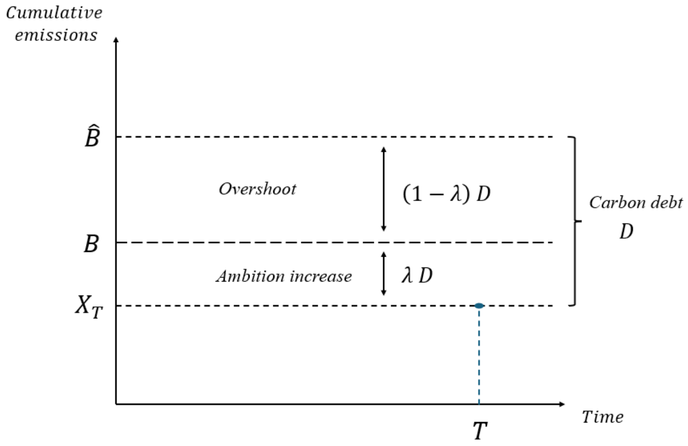

Figure 2: Relation of the budget B, the long-term target X_T, the overshoot cap $\hat{B}$ and the carbon debt D. The fraction λ of carbon debt is issued to increase the ambition of the long-term target.

emissions – a carbon budget B – that cannot be exceeded at any time such that $X(t) \leq B$. Let a social planner minimize discounted abatement cost that are consistent with that target until the end of the planning horizon T. Assume further, for simplicity, that T is sufficiently large so that the economy reaches net-zero before T under the conventional carbon budget approach, and that after T, the economy will continue to operate with zero net emissions.

Against this backdrop, we consider a modification of the carbon budget approach as visualized in Figure 2. The original cumulative budget B is replaced by a so-called 'overshoot budget' $\hat{B} \geq B$ that may be equal or larger than the original budget. Additionally, the social planner considers a long-term target X_T on cumulative emissions with $X(T) \leq X_T$ that has to be met at time T but can be exceeded for $t < T$. When $X_T < B$, the cumulative emissions will be lower at time T than in the conventional carbon budget case. However, relaxing the original budget to $\hat{B}$ may imply that temporarily, cumulative emissions, and thus, global warming becomes higher compared to the conventional carbon budget approach.

In the subsequent analysis, we define the difference between the two targets to be the (maximum) carbon debt $D := \hat{B} - X_T$. The carbon debt measures the maximum amount of overshooting of cumulative emissions compared to the long-term target. In order to link the modified carbon budget with overshooting to the original carbon budget, we define $\lambda := (B - X_T)/D \in [0,1]$. In other words, λ measures to what extent the introduction of the carbon debt D leads to a stricter long-term target than the conventional carbon budget target, as $X_T = B - \lambda D$ (cf. Figure 2). If $\lambda > 0$, allowing for temporary overshooting D units of carbon implies that the long-run target is reduced by λD. For $\lambda = 1$, all permissible overshooting would result in an equivalent reduction of the long-run target X_T; for $\lambda = 0$, overshooting would only increase intertemporal flexibility without affecting the long-term ambition level as $X_T = B$. Any intermediate outcome between these two polar cases can be achieved for $0 < \lambda < 1$. As we will show later, the choice of D allows for increasing intertemporal flexibility, reducing abatement cost, while the choice of λ

will increase the long-term ambition level. Hence, both parameters reflect the trade-off between cost-efficiency and environmental integrity.

The costs of emissions abatement and emissions removal are captured by the cost function $f(Q)$ of net emissions $Q(t)$ at time t. In general, $f(Q)$ is the cost of limiting emissions from economic activities to Q. That is, $f(0)$ is the cost of net-zero emissions in a given period, and $f(Q)$ with $Q<0$ gives the cost of achieving $|Q|$ net-negative emissions. Considering net emissions instead of separating abatement and removal implies an efficient balance of the two with equal marginal costs at every point in time where both technologies are used.[4] We allow for technological progress, which enters the cost function as cost saving improvements of the efficiency $A(t)$ in $f(Q)=A(t)a(Q)$, with $a'<0$ and $a''\geq 0$. The cumulative cost, discounted at rate r, are minimized by a social planner subject to the accumulation of carbon in the atmosphere and two constraints on the maximum per-period atmospheric carbon stock $\hat{B}$ and the maximum terminal atmospheric carbon stock X_T, giving:

$$\max_{Q}\int_0^T -\left[A(t)a\left(Q\right)\right]e^{-rt}\mathrm{d}t \tag{1}$$

$$\begin{aligned}
\text{such that}\quad \dot{X} &= Q && && \perp\mu && (2)\\
X(t) &\leq B+(1-\lambda)D && \text{(per-period constraint)} && \perp\gamma && (3)\\
\text{and}\quad X(T) &= B-\lambda D && \text{(transversality condition)} && && (4)
\end{aligned}$$

Note that for $D=0$, the optimization problem collapses to the conventional carbon budget problem. Variables $Q(t)$, $X(t)$, the co-state variable $\mu(t)$ and the Lagrangian multiplier $\gamma(t)$ are all time-dependent. Where possible, we do not indicate time-dependence to keep the equations short and simple. The co-state variable μ is the shadow price of keeping net emissions at Q. The sign of μ will be negative, as an increment in the carbon stock X tightens the remaining budget and therefore has a negative impact on Q in the objective function.[5] The Lagrangian multiplier γ of the per-period constraint is always non-negative and characterizes the stringency of the upper bound on cumulative emissions. The optimal solution is characterized by the following first-order conditions:

$$\mu = A(t)a'(Q) \tag{5}$$

$$\dot{\mu} = r\mu+\gamma \quad \text{or} \quad \hat{\mu} = r+\frac{\gamma}{\mu} \tag{6}$$

That is, the shadow price μ balances with marginal abatement costs. Its growth is driven by

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[4] Consider, for example, removal $R(t)$ and mitigation $M(t)$ as perfect substitutes such that net emissions Q for given baseline emissions $Q_0(t)$ are $Q(t)=Q_0(t)-R(t)-M(t)$. For cost functions $r(R)$ and $m(M)$, cost efficiency at t is then given for $r'(R)=m'(M)$. Without loss of generality, we can therefore proceed with $f(Q)$ as the abatement cost of reducing baseline emissions to the amount of $Q(t)$ net emissions under an efficient use of removal and mitigation.

[5] To see this, rewrite the transversality condition for a point in time t^* along the optimal path as $X(T)=X(t^*)+\int_{t^*}^{T}Q(\tau)d\tau+X_0\leq B$ and rearrange to $\int_{t^*}^{T}Q(\tau)d\tau\leq\bar{X}-X_0-X(t^*)$ to see that an increase in $X(t^*)$ negatively affects Q for $t>t^*$.

discount rate r and the stringency of the per-period constraint.

2.2. Implementation by emissions trading with clean-up certificates

As we abstract from market distortions, the solution can be implemented as a market equilibrium in a modified emissions trading scheme with two types of tradable emission permits.[6] First, a *conventional emission permit* that corresponds to a standard emission allowance gives the holder the right to emit one unit of carbon. The amount of these permits corresponds to the target in the terminal period X_T. The full integration of carbon removals in the emissions trading scheme as modeled by the net abatement technology $f(Q)$ implies further that conventional permits can be created by removal firms. These permits are, however, net-neutral for emissions in any time step as the created removals will be exactly offset by additional emissions. The second type of permits are *clean-up certificates* that bundle emission permits with an obligation to remove the associated ton of carbon until T. Hence, a holder of a clean-up certificate has the right to emit one unit of carbon but must remove it until T. The number of clean-up certificates corresponds to the amount of carbon debt D, which provides a clear intuition: using a clean-up certificate constitutes a form of debt due to the removal costs associated with the clean-up obligation.

This interpretation can be applied to the case of a policy reform, where an existing conventional ETS without carbon debt ($D = 0$) is modified by introducing carbon debt D with the additionality parameter λ. In particular, $\lambda \in [0,1]$ indicates the degree of additionality of carbon removals introduced to the system: If $\lambda > 0$, some conventional emission permits of the carbon budget are replaced with clean-up certificates and lead to additional net-negative emissions, while the share $(1-\lambda)$ of clean-up certificates are newly created permits that lead to an overshooting of the original carbon budget. For $\lambda = 1$, all clean-up certificates replace conventional certificates. The introduction of the carbon debt then translates to an increase in the ambition level of the long-term climate target. In contrast, for $\lambda = 0$, clean-up certificates introduce additional intertemporal flexibility without increasing the ambition level of the long-term climate target.

The price for emitting one ton of carbon in the emissions trading scheme is $(-\mu)$ (see Appendix A). Due to the no-arbitrage condition, the price of the clean-up certificate must equal the price of the conventional emission permit minus the discounted removal costs. We will give the exact expression for this price below in Section 2.5.

As the social planner problem can be translated into an equivalent emissions trading scheme as outlined above, we focus mainly on the planner's problem in the remainder of the article for analytical exposition. We provide, however, the corresponding interpretations of shadow prices and quantities within an emissions trading scheme. We discuss other ways of implementing the social planner model as well as further institutional aspects in Section. 4.

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[6] See Appendix A for the formal derivation of the emissions trading scheme.

2.3. Net emission pathways

Taking the time derivative of (5) and dividing by the original equation yields

$$\hat{\mu} = g + \frac{a''}{a'}\dot{Q} \tag{7}$$

where $\hat{\mu} := \frac{\dot{\mu}}{\mu}$ is the rate of change of the shadow price and $g := \frac{\dot{A}}{A}$ is the autonomous rate of change of marginal abatement cost,[7] which, combined with (6), can be solved for $\dot{Q}$:

$$\dot{Q} = \left((r-g) + \frac{\gamma}{\mu}\right)\frac{a'}{a''} \tag{8}$$

At this point we make specific assumptions about the cost function $f(Q)$. For the variable cost we assume an exponential function $a(Q) = e^{-\alpha Q}$, that is, we assume that the costs of reducing emissions increase at a constant relative rate, α. The choice of the exponential function simultaneously implies that marginal costs (of mitigation and removal) increase a constant relative rate, $a''/a' = \alpha$. Furthermore, for the autonomous technological efficiency $A(t)$, we assume a constant rate of technological change $-g$. With these assumptions, equation (8) can be rewritten as

$$\dot{Q} = -\left((r-g) + \frac{\gamma}{\mu}\right)\frac{1}{\alpha} \tag{9}$$

Together, the differential equations (6) and (9) characterize the dynamics of any efficient solution.

2.4. Reference case: No carbon debt

As a reference scenario, we consider the case of no carbon debt, that is, $D = 0$. The per-period constraint (3) and the transversality condition (4) simplify to $X(t) \leq B$ for all t. The assumptions of no carbon debt and no permit borrowing are in line with the current implementation of the EU ETS. When the remaining carbon budget is still positive, $B > 0$, the economy transitions to net-zero emissions in a first phase, followed by a second phase with continued net-zero emissions.

Phase 1: Transition to net-zero emissions Starting at $B > X(0) = 0$ the per-period constraint (4) is not binding, and we have $\gamma = 0$ such that (9) simplifies to

$$\dot{Q} = -\frac{(r-g)}{\alpha} \tag{10}$$

That is, net-emissions decrease at a constant rate at a pace that increases with the rates of dis-

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[7] We refer to $-g$ as the rate of technological progress, but it also encompasses broader structural changes, for example, demand changes.

counting (r) and cost-reducing technological progress ($-g$) as long as $r > g$, which we assume to be the case.[8] Hence, we can express net-emissions at time t as

$$Q(t) = Q_0 - \frac{(r-g)}{\alpha}t \tag{11}$$

The time T_1^{NCD} at which the budget is exhausted (in the no carbon debt (NCD) case) is found by integrating over (11) such that $B = X(T_1^{\mathrm{NCD}}) = \int_0^{T_1^{\mathrm{NCD}}} Q(t)dt$. With $Q(T_1^{\mathrm{NCD}}) = 0$ in (11), we can then solve for Q_0

$$T_1^{\mathrm{NCD}} = \sqrt{\frac{2\alpha B}{r-g}} \tag{12}$$

$$Q_0 = \sqrt{\frac{2(r-g)B}{\alpha}} \tag{13}$$

Finally, plugging (13) into (5) yields an expression for the initial shadow price μ_0, which grows at the constant rate r due to (6). Together with (11), (12) and (13), this describes the transition to net-zero emissions.

$$\mu_0 = -\alpha A_0 e^{-\sqrt{2\alpha(r-g)B}} \tag{14}$$

$$\mu(t) = \mu_0 e^{rt},\ t \leq T_1^{\mathrm{NCD}} \tag{15}$$

The exponential increase with the discount rate in time in (15) is standard Hotelling dynamics. Furthermore, we observe in (14) that the initial carbon price μ_0 is decreasing in the level of the cap B and in the rate of technological progress $-g$.

Phase 2: Net-zero emissions Once the budget is exhausted and the per-period constraint (3) binds, we have $(\gamma > 0)$. As net-emissions must remain zero until the end of the time horizon, we know from equation (9) that

$$\frac{\gamma}{\mu} = g - r \tag{16}$$

Together with equation (6) this implies that the shadow price for emissions decreases at the rate of technological progress. For (16) to hold, this must also be true for γ.

$$\hat{\mu} = \hat{\gamma} = g \tag{17}$$

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[8] If $r > g$, the costs of abatement grow at a lower rate than the discount rate. This seems to be a plausible case, as many abatement and carbon removal technologies still have significant potential for cost reductions, implying even $g < 0$.

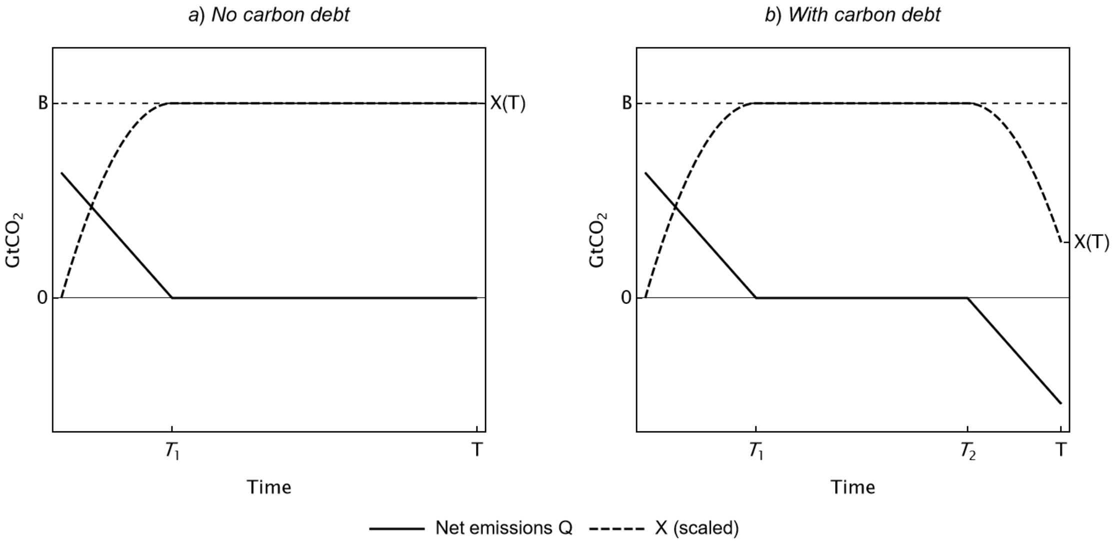

Figure 3: Illustration of the carbon dynamics: the carbon stock (dashed lines) and flow (solid lines) for the cases of no carbon debt (a), carbon debt with increased ambition (b).

As $\mu(T_1^{\text{NCD}})$ is known and g and r are exogenous, equation (16) also pins down the level of γ.

$$\mu(t) = \mu(T_1)e^{g(t-T_1^{\text{NCD}})} = -\alpha A_0 e^{gt} \tag{18}$$

$$\gamma(t) = (g-r)\mu(t) = (r-g)\alpha A_0 e^{gt} \tag{19}$$

In summary, net emissions and carbon prices in the case of no carbon debt are given by

$$Q(t) = \begin{cases} Q_0 - \frac{(r-g)}{\alpha}t, & \text{if } t \le T_1^{\text{NCD}} \\ 0, & \text{if } T_1^{\text{NCD}} < t \le T \end{cases} \tag{20}$$

$$\mu(t) = \begin{cases} \left(-\alpha A_0 e^{-\sqrt{2\alpha(r-g)B}}\right)e^{rt}, & \text{if } t \le T_1^{\text{NCD}} \\ -\alpha A_0 e^{gt}, & \text{if } T_1^{\text{NCD}} < t \le T \end{cases} \tag{21}$$

The left panel of Fig. 3 illustrates the emission dynamics. The case of a carbon budget without carbon debt is the well-known case of standard ETS with partial temporal flexibility, that is, with free banking of permits but no borrowing. As in the seminal resource extraction model in Hotelling (1931), the permit price grows with the discount rate until the emission permits are exhausted. Once the carbon budget is reached, the permit price remains at the marginal costs of maintaining net-zero emissions by abating or removing emissions. As net emissions are constant (and zero), marginal costs in this phase change only with technological progress $-g$.

To implement this solution in a permit trade system with banking but without borrowing, the regulator could, for example, issue all B emission permits at time $t = 0$. The firm would bank permits and use them until T_1^{NCD}. The permits would be traded at the price $p_X(t) = -\mu(t)$,

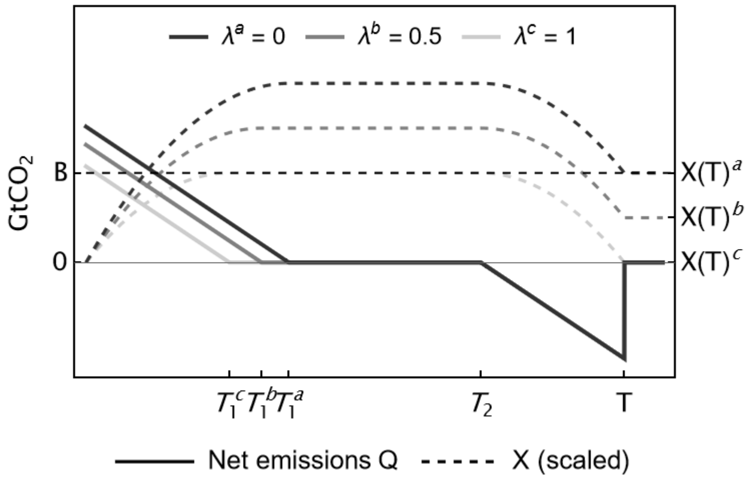

Figure 4: Net-emissions and cumulative emissions over time for a given amount of carbon debt ($D = B$). Depending on the policy parameter λ, carbon debt can lead to *a)* clean-up of a temporary overshoot of the budget ($\lambda = 0$), *c)* lower long-term cumulative emissions due to additional clean-up ($\lambda = 1$), or *b)* a mix of the two ($0 < \lambda < 1$).

although net permit trade of the representative firm would be zero (cf. model of the firm in Appendix A).

2.5. Carbon debt

Whether carbon debt $D > 0$, introduced by the regulator, affects the per-period constraint (3) or the transversality condition (4) depends on the choice of λ. The policy parameter λ governs the extent to which clean-up is additional to the budget B. If carbon debt is attached to existing certificates ($\lambda > 0$), the long-term target in the transversality condition $X(T) = B - \lambda D$ reflects an increase in ambition due to carbon debt. If, alternatively, carbon debt is issued by creating new emission permits ($\lambda < 1$), the per-period constraint is relaxed and the budget will be overshot up to $\hat{B} = B + (1 - \lambda)D > B$.

In the following, we first derive the net-emissions and carbon price pathways for the general case of $\lambda \in [0, 1]$ and then discuss the implications of different degrees of additionality.

Phase 1: Transition to net-zero emissions As before, we have $\gamma = 0$ until the per-period constraint is not reached, and net-emissions are

$$Q(t) = Q_0 + \frac{(g - r)}{\alpha} t \tag{22}$$

Following the same steps as in Section 2.4 we find T_1^{CD} where X hits the upper bound $\hat{B}$ in the case with carbon debt (CD superscript). Using β, the relative size of carbon debt with respect to the original target B, that is $D = \beta B$ with $\beta > 0$, we can rewrite T_1^{CD} in terms of T_1^{NCD} of the no carbon debt case.

$$T_1^{\text{CD}} = \sqrt{\frac{2\alpha\hat{B}}{r-g}} = T_1^{\text{NCD}}\sqrt{1-\lambda\beta+\beta} \tag{23}$$

Hence, introducing carbon debt ($\beta > 0$) that is not fully additional ($\lambda < 1$) moves the point of net-zero emissions further into the future. Plugging (12) into (22) shows that Q_0 is increased by the same factor.

$$Q_0 = \sqrt{\frac{2(r-g)\hat{B}}{\alpha}} = Q_0^{\text{NCD}}\sqrt{1-\lambda\beta+\beta} \tag{24}$$

Finally, we combine (24) with (5) to derive the initial level of the shadow price μ_0, and by virtue of (6) we obtain $\mu(t)$.

$$\mu_0 = -\alpha A_0 e^{-\sqrt{2\alpha(r-g)\hat{B}}} = \mu_0^{\text{NCD}} e^{\sqrt{2\alpha(r-g)B}\left(1-\sqrt{1-\lambda\beta+\beta}\right)} \tag{25}$$

$$\mu(t) = \mu_0 e^{rt},\ t \leq T_1^{\text{CD}} \tag{26}$$

Together with (22), (23) and (24), this describes the transition to net-zero emissions as a function of the exogenous variables in the model. Figure 4 illustrates how a lower degree of additionality of clean-up λ implies higher initial net-emissions Q_0 and a later time T_1^{CD} of reaching net-zero.

Moreover, equation (25) shows that the initial carbon price falls as the level of carbon debt β increases or the degree of additionality λ decreases. Consequently, introducing carbon debt without full additionality of clean-up leads to mitigation deterrence. Contrary, in case of full additionality ($\lambda = 1$), the initial net-emissions Q_0, the time of net-zero T_1^{CD} and the initial carbon price μ_0 are exactly equal to the case of no carbon debt. Hence, the introduction of carbon debt with $\lambda = 1$ translates into an increase in ambition via net-negative emissions without mitigation deterrence or stranded assets in mitigation.

Phase 2: Net-zero emissions Once the per-period constraint is reached, we have $\gamma > 0$ and, more specifically, the dynamics of $\gamma(t)$ and $\mu(t)$ from equation (6) and (9) during the net-zero emissions phase are

$$\frac{\gamma}{\mu} = g - r \tag{27}$$

$$\hat{\mu} = \hat{\gamma} = g \tag{28}$$

Thus, γ and μ converge to zero at the rate of technological progress.

$$\mu(t) = \mu(T_1^{\text{CD}})e^{g(t-T_1^{\text{CD}})} = -\alpha A_0 e^{gt}, \qquad T_1^{\text{CD}} \leq t \leq T_2^{\text{CD}} \tag{29}$$

Emissions remain at net-zero from T_1^{CD} to the end of the net-zero phase, T_2^{CD}. The latter is determined by the optimal duration of the clean-up phase, which we consider next.

Phase 3: Net-negative emissions During the clean-up phase, the carbon debt D needs to be settled by net-negative emissions. With the beginning of the clean-up phase, the per-period constraint is no longer binding and the associated multiplier γ falls back to zero. The change in net-emissions $\dot{Q}$ and their level $Q(t)$ thus evolve as in the first phase, that is, Q is falling linearly, starting at $Q(T_2^{\text{CD}}) = 0$. For $t \geq T_2^{\text{CD}}$ net emissions are given by

$$Q(t) = -\frac{(r-g)}{\alpha}(t - T_2^{\text{CD}}) \tag{30}$$

To find the time at which the clean-up phase begins, we set the cumulative net-emissions ΔQ from time T_2^{CD} to T equal to the carbon debt D.

$$\Delta Q = \int_{T_2^{\text{CD}}}^{T} Q(t)dt = \frac{(g-r)(T - T_2^{\text{CD}})^2}{2\alpha} = -D \tag{31}$$

Solving for T_2^{CD} yields

$$T_2^{\text{CD}} = T - \sqrt{\frac{2\alpha\beta B}{r-g}} = T - \sqrt{\beta}T_1^{\text{NCD}} \tag{32}$$

Unsurprisingly, the higher the relative carbon debt β, the longer the clean-up phase. Similarly, we observe that the longer the time horizon the later the beginning of the clean-up phase, because discounting and technological progress reduce the cost when removal is delayed. This finding suggests that clean-up policies may suffer from time inconsistency, and we discuss institutional implications for ensuring commitment in Section 4. Furthermore, Figure 4 illustrates that for a given level of carbon debt, the timing and duration of the clean-up phase depends on the amount of carbon debt β but not on its allocation λ.

Note that the per-period constraint (3) will only bind when there is sufficient time to pay back the carbon debt. The minimum time horizon $\tilde{T}$ such that a given carbon debt budget is exhausted is therefore:

$$\tilde{T} = \left(\sqrt{1 - \lambda\beta + \beta} + \sqrt{\beta}\right) T_1^{\text{NCD}} \tag{33}$$

For shorter time horizons ($T < \tilde{T}$) not all of the available clean-up certificates would be sold. For the remainder of this section we assume that the time horizon is sufficiently long, that is, $T \geq \tilde{T}$. Finally, note that during the clean-up phase, the shadow price of the per-period constraint

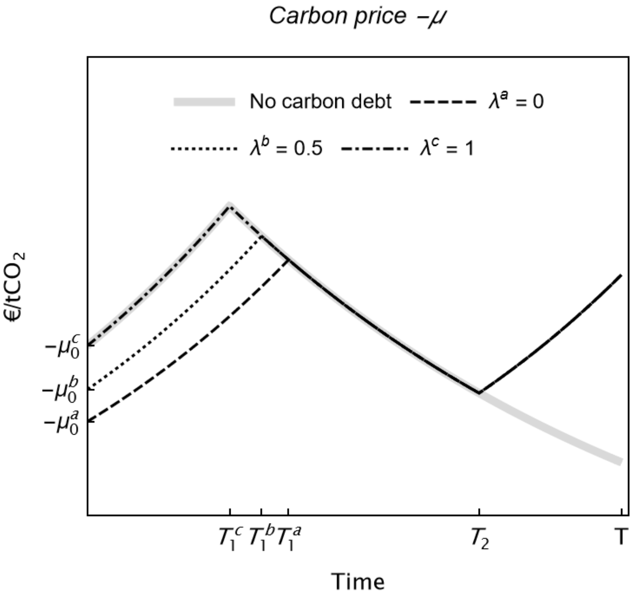

Figure 5: Development of the carbon price in the case of *i)* no carbon debt (solid line), and *ii)* relative carbon debt of $\beta = 1$ with various degrees of additionality (dashed lines). In the case of $\lambda^c = 1$, carbon prices are identical up to the time step T_2 where the clean-up phase begins.

γ is zero, and the shadow price of the emissions cap μ grows with the discount rate.

$$\mu(t) = \mu(T_2)e^{r(t-T_2)} = -\alpha A_0 e^{(g-r)T_2+rt}, \qquad t \geq T_2^{\mathrm{CD}} \tag{34}$$

In summary, net emissions and carbon prices during the three phases of the case of carbon debt are given by

$$Q(t) = \begin{cases} Q_0^{\mathrm{NCD}}\sqrt{1-\lambda\beta+\beta} + \frac{(g-r)}{\alpha}t, & \text{if } t < T_1^{\mathrm{CD}} \\ 0, & \text{if } T_1^{\mathrm{CD}} \leq t < T_2^{\mathrm{CD}} \\ -\frac{(r-g)}{\alpha}\left(t + \sqrt{\beta}T_1^{\mathrm{CD}} - T\right), & \text{if } T_2^{\mathrm{CD}} \leq t \leq T \end{cases} \tag{35}$$

$$\mu(t) = \begin{cases} \mu_0^{\mathrm{NCD}} e^{\sqrt{2\alpha(r-g)B}\left(1-\sqrt{1-\lambda\beta+\beta}\right)+rt}, & \text{if } t < T_1^{\mathrm{CD}} \\ -\alpha A_0 e^{gt}, & \text{if } T_1^{\mathrm{CD}} \leq t < T_2^{\mathrm{CD}} \\ -\alpha A_0 e^{gT_2^{\mathrm{CD}}+r(t-T_2^{\mathrm{CD}})}, & \text{if } T_2^{\mathrm{CD}} \leq t \leq T \end{cases} \tag{36}$$

Figure 5 illustrates the development of the carbon price for a given level of carbon debt and various degrees of additionality. Once again, we observe that carbon prices decrease along the transition to net zero if carbon debt is not fully additional ($\lambda < 1$). However, if carbon debt is solely associated with existing certificates ($\lambda = 1$), the carbon price trajectory is initially identical to the case of no carbon debt. Thus, an increase in ambition and a sustained phase of net-negative emissions can be achieved without increasing short- to medium-term mitigation cost. Only as the economy enters into the clean-up phase the long-term carbon prices exceed the carbon price in the case of no carbon debt.

We can use the permit price equation (36) to determine the price of the carbon debt, i.e. the price of the obligation to remove the carbon later. In an emissions trading scheme, a firm that wants to emit a ton of CO_2 at time $t \leq T_2^{\mathrm{CD}}$ can choose between a conventional permit or a clean-up certificate. As the latter comes with the obligation for later removal in the phase with net-negative emissions, it implies additional costs. If removal occurs at $t' \geq T_2^{CD}$, the discounted costs at time t are $-\mu(t')e^{-r(t'-t)}$ which is equivalent to $-\mu(T_2^{\mathrm{CD}})e^{-r(T_2^{\mathrm{CD}}-t)}$, because the shadow price grows at r after T_2^{CD}. In particular, the present value of the carbon debt at the initial time period, p_0, is then

$$p_0 = -\mu(T_2^{CD})e^{-rT_2^{CD}} \tag{37}$$

Are clean-up certificates an attractive option for firms? The following equation compares their value as an emission permit with the obligation of the carbon debt in present value terms:

$$-\mu_0 - p_0 = \alpha A_0 \left(e^{-(r-g)T + \sqrt{2\alpha(r-g)(\hat{B}-B)}} - e^{-\sqrt{2\alpha(r-g)\hat{B}}} \right) \tag{38}$$

Equation (38) is positive for any $T \geq \tilde{T}$ given by (33). Intuitively, a minimum length of the time horizon is needed for technological progress and discounting, $r-g$, to create sufficient cost-savings in future marginal abatement cost. For shorter time horizons $T < \tilde{T}$, the willingness-to-pay expressed by (38) falls below zero and not all clean-up certificates will be auctioned. Conversely, for $T > \tilde{T}$ the net price for clean-up certificates during the transition to net-zero $t \in [0, T_1^{\mathrm{CD}}]$ is strictly positive, reflecting the scarcity of clean-up certificates. Moreover, by setting carbon debt equal to zero and solving for $(r-g)$, equation (38) reveals the condition on technological progress and the time horizon for any efficient introduction of clean-up certificates.

$$r - g > \frac{2\alpha B}{T^2} \tag{39}$$

If this condition holds, there is a wedge between current and future mitigation cost that can be exploited to finance net-negative emissions via clean-up certificates. We observe that for longer time horizons, less technological progress is required, as there is more time to reduce cost. In contrast, if the remaining budget B is large, faster technological progress is needed to make the clean-up commitment financially viable. Note that the condition in (39) can be reformulated in a condition for the length of the time horizon, that is $T > \sqrt{2\alpha B/(r-g)} = T_1^{NDC}$. Hence, for a given technological progress and budget, the time horizon must be long enough to allow for the cost-efficient transition to net-zero emissions without carbon debt, which we assume to be the case. For a longer time horizon, clean-up certificates could be introduced, while the number of clean-up certificates is constrained by the length of the time horizon given by (33).

3. Numerical illustration

To illustrate quantitative effects, we calibrate the model to EU climate policy consisting of a comprehensive emissions trading scheme covering all sectors from 2030 onwards. We calculate quantitative effects on key model variables and their sensitivity to different degrees of technological progress. Finally, we identify reform options of broad political support where abatement costs fall and ambition levels increase.

3.1. Model calibration

We calibrate our model to fit projections of the carbon price and emissions in a comprehensive (i.e. covering all sectors) EU ETS in the year 2030 (Rickels et al., 2023). We set the end of the time horizon to the year 2100, at the end of which a remaining EU carbon budget of 14 $GtCO_2$, based on ESABCC (2023), needs to be met in the reference scenario. For the case of carbon debt, we start by setting β and λ equal to 1 and assume that 100 percent of the remaining budget can be converted into clean-up certificates. The key parameters of the calibration are summarized in Table 1. Most importantly, we calibrate the model to three different growth rates of marginal abatement and removal cost. The reference scenario is the "middle-of-the-road" scenario of the Shared Socioeconomic Pathways (SSP2, see O'Neill et al. 2014), while the "fast progress" and the "no progress" scenarios assume significantly higher and lower technological progress, respectively. For further details on the calibration refer to Appendix B.

Table 1: Calibration parameters

Symbol	Description	Value	Source
T	length of the time horizon	70 years	assumption
B	1.5°-target GHG budget for the EU	14 $GtCO_2$	ESABCC (2023)
r	discount rate	0.02	WH.GOV (2024)
α	abatement cost parameter	0.453	calibrated to SSP2
g	rate of change in the abatement efficiency	-0.0165	calibrated to SSP2
g^{FP}	"Fast progress" scenario for g	-0.033	assumption: $2 \times g$
g^{NP}	"No progess" scenario for g	0	assumption
Q_0	initial emissions in a comprehensive EU ETS 2030	1501 $MtCO_2$	Rickels et al. (2023)
μ_0	initial carbon price in a comprehensive EU ETS 2030	155 €/tCO_2	Rickels et al. (2023)
A_0	initial value of the abatement efficiency	675.063	calibrated to SSP2
$SCC(t)$	social cost of carbon time series up to 2080		U.S. EPA (2023)

3.2. Results

Using the closed-form solutions derived in Section 2, we plot the net emission pathways and the evolution of the carbon price in Figure 6. Figure 6a shows that without carbon debt and clean-up certificates, net emissions in a comprehensive EU ETS decrease linearly over time and reach

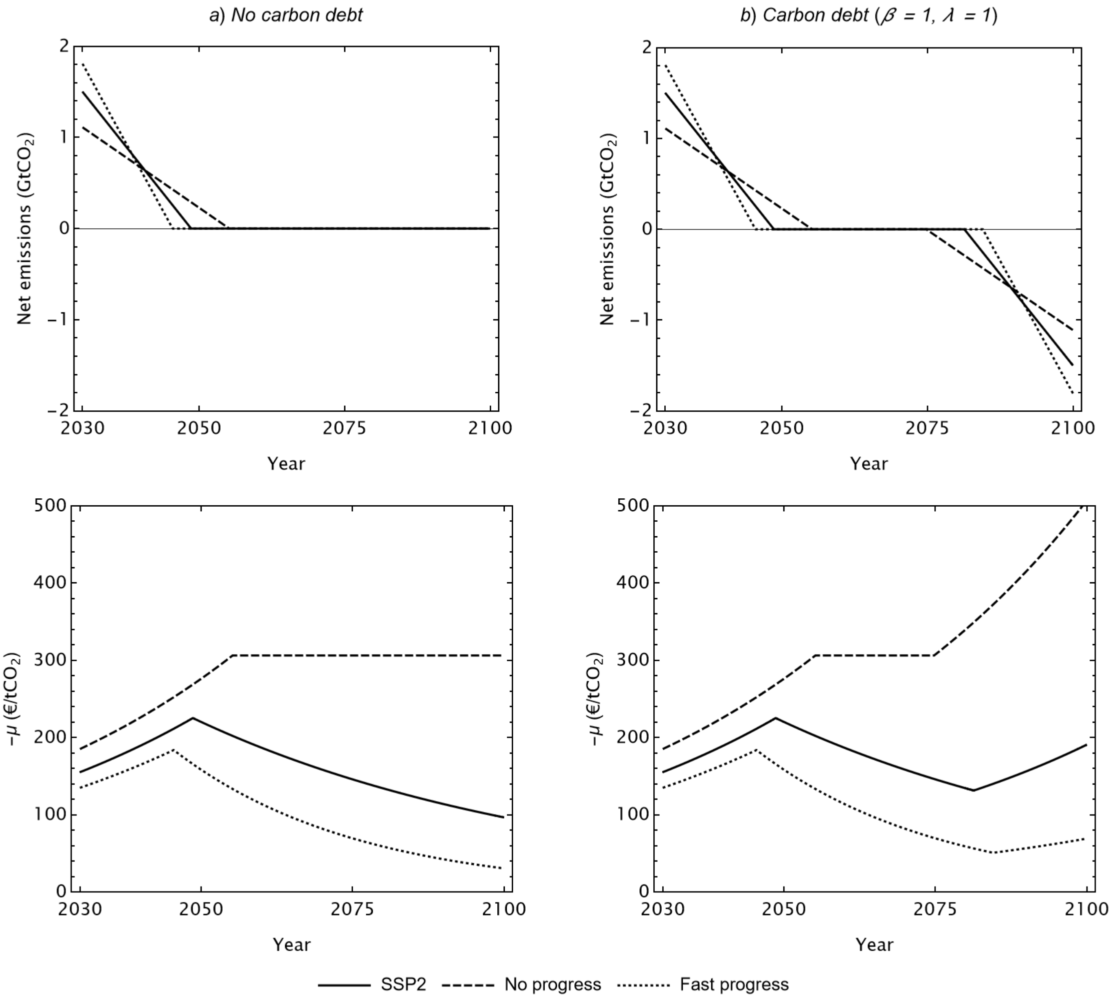

Figure 6: Net-emissions and the carbon price over time in a calibrated comprehensive EU-ETS with and without clean-up certificates that fully replace conventional certificates ($\lambda = 1$). See Table 1 for calibration parameters.

zero around the year 2050. This development is driven by an exponentially increasing carbon price, rising from 155 €/tCO$_2$ in 2030 to approximately 225 €/tCO$_2$ by 2050. In the scenario with fast technological progress, more abatement is shifted into the future, such that net-zero is reached about 3 years earlier. Without technological progress, net-zero is achieved about 6 years later, as it is optimal to distribute the abatement burden over a more extended period.

Figure 6b shows that the introduction of clean-up certificates leads to the same net-emission and carbon price trajectories as in Figure 6a in the short- and medium run. Since in this example all regular certificates are converted into clean-up certificates and no certificates are issued in excess of the budget, the total amount of emission allowances in the market is unchanged. Thus, we do not observe mitigation deterrence or stranded assets in mitigation.

As the economy enters the net-zero phase, the carbon price decreases due to technological progress in the abatement technology. Approximately by the year 2081, which is 19 years prior to the end of the time horizon, the economy enters the clean-up phase. Net emissions begin to decrease as the carbon price rises. By the end of the time horizon, all carbon debt has been repaid through net-negative emissions. As before, we observe that a change in the rate of technological progress leads to a shift of the burden of mitigation over time. The higher the technological progress, the shorter the transition to net zero and the later the start of the clean-up phase.

Table 2: Price of clean-up certificates as a fraction of the price for regular emission allowances. Degree of additionality λ equal to 1. See Table 1 for calibration parameters.

	Technological progress $-g$		
Clean-up certificates issued	No progress	SSP2	Fast progress
2 GtCO$_2$	0.51	0.81	0.93
7 GtCO$_2$	0.42	0.75	0.90
14 GtCO$_2$	0.32	0.70	0.87

Table 2 shows the price of clean-up certificates as a fraction of the price for regular emission allowances for a set of exemplary parameter values. For a given amount of clean-up certificates, the price increases in technological progress. Intuitively, a stronger cost reduction over time decreases the net present value of removal cost and firms would be willing to pay more for clean-up certificates. Similarly, for a given level of technological progress, the price of clean-up certificates decreases with the amount of clean-up certificates in the market. The intuition is that higher aggregate carbon debt implies higher future removal demand, resulting in a higher net present value of future removal cost. In the example considered above ($\beta = 1$, i.e., carbon debt of 14 GtCO$_2$), the value of the collateral would be between 13 and 68 percent of the carbon price, depending on the rate of technological progress.

Figure 7a illustrates how the introduction of clean-up certificates influences the initial carbon price in the EU ETS. As expected, we observe that the more clean-up certificates are issued in excess of the budget ($\lambda < 1$), the lower the initial carbon price. This effect is stronger the higher the anticipated technological progress. Note again that if clean-up is entirely additional to the budget ($\lambda = 1$), the initial carbon price does not change after the introduction of clean-up

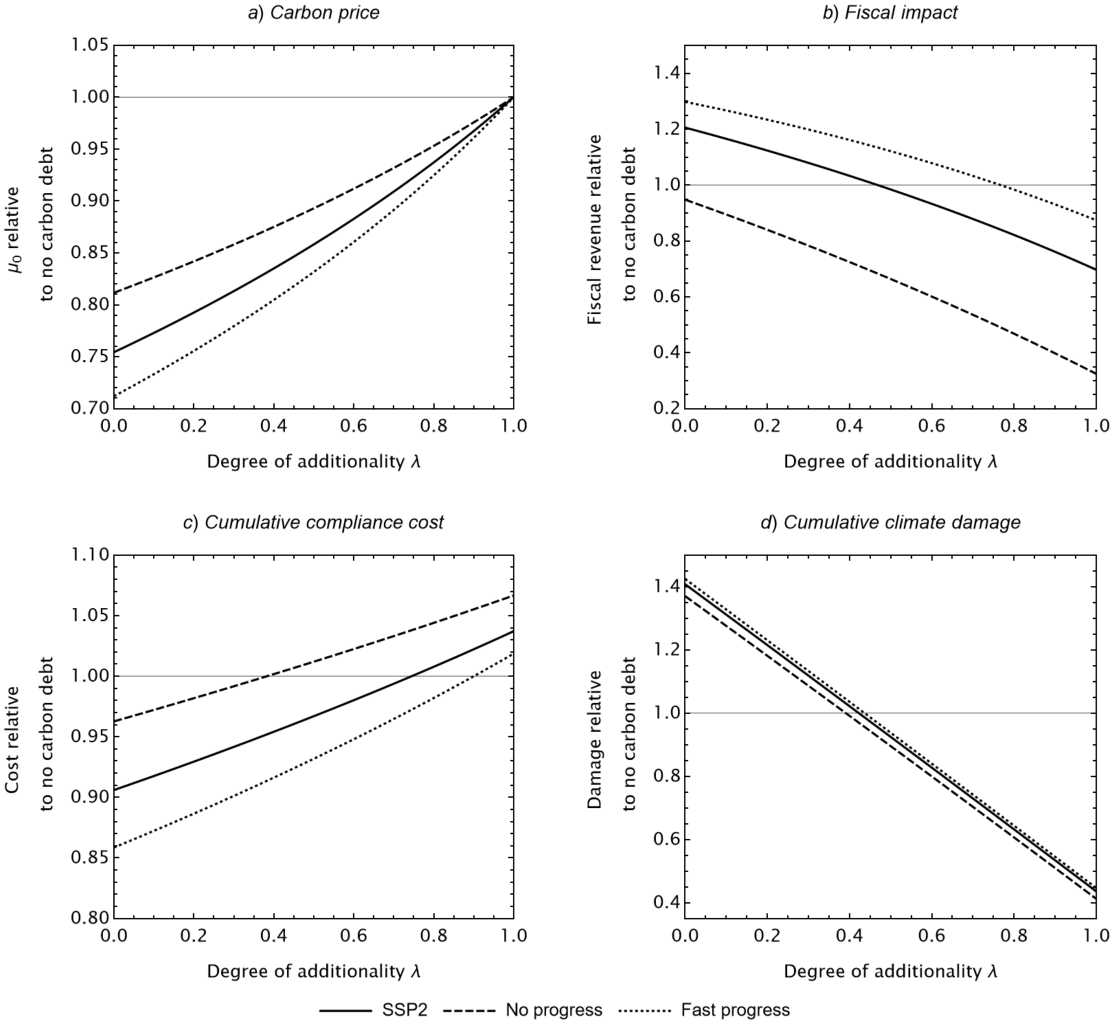

Figure 7: Impact of the introduction of clean-up certificates on the initial carbon price *(a)*, fiscal revenue from permit auctioning *(b)*, cumulative compliance cost *(c)* and cumulative climate damages *(d)* in a calibrated comprehensive EU-ETS, for a given relative carbon debt of $\beta = 1$ (i.e. equal to the initial carbon budget). Impacts are shown relative to the case of no carbon debt and as a function of the degree of additionality λ. If $\lambda = 1$, clean-up certificates replace conventional certificates by 100 percent. See Table 1 for calibration parameters.

certificates.

Figure 7b shows the fiscal revenue from the auctioning of emission allowances and clean-up certificates for various degrees of additionality, relative to the case without carbon debt. In particular, we compute the fiscal impact as follows:

$$\textit{Fiscal impact} = \left(\frac{\mu_0^{CD}\,(B - \lambda D) + (\mu_0^{CD} - p_0^{\mathrm{CD}})D}{\mu_0^{no\;CD}\,B} \right) \tag{40}$$

We see that the fiscal impact is positive for lower degrees of additionality and reaches up to 30 percent in the case of fast technological progress. Hence, the regulator can increase revenues by issuing clean-up certificates in excess of the budget (low λ). However, as the introduction of clean-up certificates decreases the equilibrium price for both regular allowances and for clean-up certificates, the fiscal impact can also be negative in the case of low technological progress. If clean-up certificates are created mostly by attaching carbon debt to existing certificates (high λ), the fiscal revenue decreases because clean-up certificates are auctioned at a lower price than regular emission allowances.

Figure 7c illustrates the impact of introducing clean-up certificates on cumulative compliance cost. To compute this impact, we calculate the cumulative compliance cost with carbon debt relative to the case without carbon debt.

$$\textit{Compliance cost impact} = \left(\frac{\int_0^T \left[A(t)a\left(Q(t)^{CD}\right)\right] e^{-rt}\mathrm{d}t}{\int_0^T \left[A(t)a\left(Q(t)^{no\;CD}\right)\right] e^{-rt}\mathrm{d}t} \right) \tag{41}$$

We observe that the introduction of clean-up certificates can lower the cumulative compliance cost if the degree of additionality is not too high. Hence, if the regulator allows a temporary overshoot of the budget, the resulting near-term cost savings can be sufficient to achieve a lower long-term target without increasing cumulative compliance cost. However, if clean-up certificates are created mostly by attaching carbon debt to existing certificates (high λ), cumulative compliance cost increase due to the increase in ambition. This result is aggravated in the case of no technological progress. In contrast, in the optimistic scenario even high degrees of additionality still result in aggregate cost savings.

Finally, Figure 7d shows the impact of the introduction of clean-up certificates on cumulative climate damages, relative to the case of no carbon debt. To calculate this impact, we assume that the social cost of carbon follow an exogenously given trajectory.[9] In particular, we calculate the climate damage impact according to

$$\textit{Climate damage impact} = \left(\frac{\int_0^T \left[Q(t)^{CD}SCC(t)\right] e^{-rt}dt}{\int_0^T \left[Q(t)^{no\;CD}SCC(t)\right] e^{-rt}dt} \right) \tag{42}$$

where $SCC(t)$ is a piecewise linear function based on the annual social cost of carbon estimates up to the year 2080 from a recent report by the U.S. EPA (2023).[10] Figure 7d suggests that

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[9] Note that this assumptions ignores the potential impact of the choice of λ on global mitigation pathways.

[10] We use the estimated social cost of carbon for a discount rate of 2 percent. Refer to Appendix B for more details.

introducing clean-up certificates can lead to higher or lower cumulative damages, depending on the degree of additionality. If clean-up certificates generate many new emission certificates (low λ), cumulative climate damages are higher. In this case, the near-term damage from overshooting the budget outweighs the climate benefits from future net-negative emissions. In contrast, if clean-up is mostly additional (high λ), the cumulative climate damage of the EU-ETS is lower.

3.3. Reform space with broad political support

We illustrate the option space for a reform that receives support from politically relevant groups that focus on specific outcome variables. Governments may care about the fiscal implications related to the revenues from carbon pricing and may prefer outcomes with non-decreasing revenues. Firms and consumers prefer outcomes with lower carbon prices and lower compliance costs. Finally, environmental groups, but also voters or governments, may want to reduce climate damages with a reform. In the following, we analyze whether the introduction of clean-up certificates can lead to a “Pareto” improvement for these key social groups.[11]

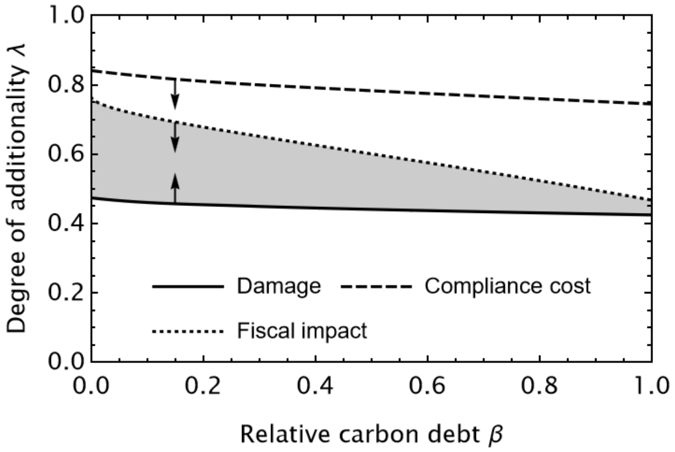

Figure 8: Indifference curves for damage (solid line), compliance cost (dark dashed line) and fiscal impact (light dashed line), indicating (β,λ) combinations leading to the same outcome as without carbon debt. Arrows point into the direction of improvement with respect to ”no carbon debt”. The shaded area indicates the set of possible “Pareto” improvements.

Figures 8 and 9 show the combinations of relative carbon debt β and additionality λ that result in an improvement across the dimensions of fiscal impact, cumulative compliance cost, and cumulative climate damage.[12] Except in the case of no technological progress, the set of combinations

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[11] Note that the effect on the fiscal revenues does not reflect real costs for society but rather the political economy consideration of governments that prefer a larger budget. Hence, from the perspective of seeking consent for the policy, we include the fiscal revenues in the “Pareto” set. However, if one focused on real costs and benefits, the fiscal budget effect would not constrain the “Pareto” set.

[12] As the initial carbon price always decreases (as $\lambda < 1, \beta > 0$) or remains unchanged ($\lambda = 1$ or $\beta = 0$), we disregard

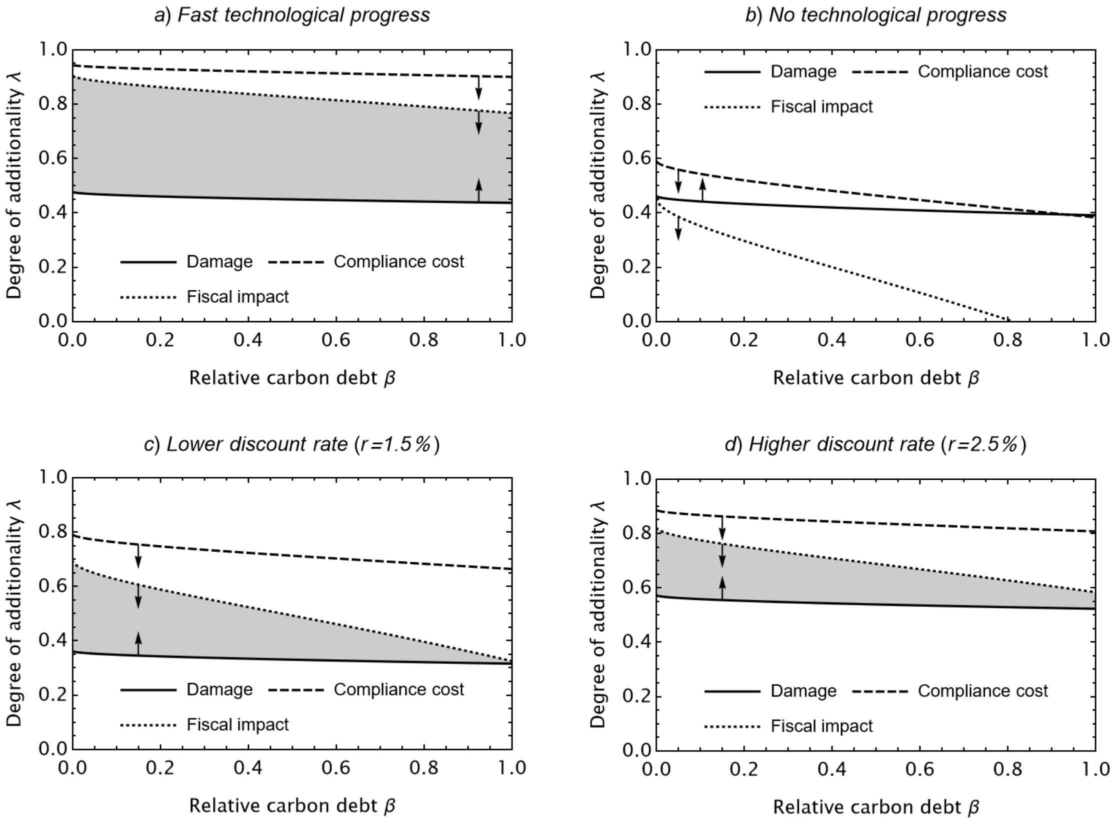

Figure 9: Indifference curves for alternative assumptions about the rate of technological progress and discount rates. Arrows point into the direction of improvement with respect to ”no carbon debt”. The shaded area indicates the set of possible “Pareto” improvements.

that improve all three dimensions is non-empty, implying that there could be space for political support for introducing clean-up certificates. We observe that to reduce compliance costs and increase fiscal revenue, the degree of additionality must not be set too high. Conversely, to decrease cumulative climate damages, the degree of additionality cannot be set too low. Therefore, the “Pareto set” exists in an area approximately above $\lambda = 0.5$ and gets smaller as the carbon debt increases. As shown in Figure 9a, the set expands for faster technological progress, which (a) reduces compliance costs and (b) reduces the collateral value and therefore improves carbon revenues. However, in the scenario with no technological progress, there exists no combination of parameters that achieves an improvement across all three dimensions (Figure 9b). However, even without technological progress there exist a (narrow) space where abatement cost as well as climate damages are reduced, implying improvements for industry, consumers and environmental groups and, hence, scope for agreement if governments can be convinced to consider the real effects rather than the fiscal revenues. Finally, a change in the discount rate leads to a vertical shift of the option space. As shown in Figure 9c, a lower discount rate with higher estimates of

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this dimension.

the social cost of carbon leads to a downward shift of the set. Conversely, a higher discount rate with lower estimates of the social cost of carbon shifts the set upwards (Figure 9d).

4. Institutional aspects: time inconsistency and liability

In the formal model, we implicitly made two strong assumptions: (i) the regulator can credibly commit to its policy, and (ii) there exist a functioning intertemporal permit market where firms do not fail to meet their removal obligations. We consider these aspects and potential institutional amendments related to introducing clean-up certificates in this section.

4.1. Commitment problem of the regulator

The assumption of an exogenously given and fixed time horizon T requires that the regulator can credibly commit to the end date of the policy. The regulator, however, has an incentive to reconsider and postpone T because the obligation of settling the "carbon debt" can be met at lower costs in the future. In our setting, the net-present value of costs are reduced by technological progress and discounting and therefore decline with time (if $g < 0$ and $r > 0$). Consequently, it is always beneficial to move the end of the policy further into the future and the regulator's policy thus suffers from time inconsistency.

The fundamental reason for this inconsistency is the disregard of climate damages in the optimization problem of the social planner. If the benefits of reducing carbon emissions are unaccounted for, the social planner values any relaxation of the carbon budget, the ambition level, or the compliance period as beneficial. This problem is not unique to the introduction of clean-up certificates, however, as it also present in a conventional emissions trading scheme. The first-best approach to address this problem would be to adjust the emission trading scheme such that it yields a welfare-maximizing outcome. In principle, this outcome could be achieved by introducing intertemporal trading ratios to correct for the sub-optimal time path of the carbon price arising due to unaccounted climate damages (Kling and Rubin, 1997; Leiby and Rubin, 2001). However, this requires a rather complex ETS reform and an institution that determines the trading ratios according to a pre-defined rule.

The lack of credible commitment can alternatively be addressed by delegation to an independent authority with a clear and narrow mandate that can only be changed by a qualified political majority. After establishing the desired final period T, the regulator could delegate control of the clean-up certificates to an independent agency, for example, a European Carbon Central Bank (ECCB) for the EU ETS as proposed in Edenhofer et al. (2023). The carbon central bank receives the mandate to manage emission permits (regular allowances and clean-up certificates) with the aim to guarantee a cost-efficient achievement of the climate target in period T. As the carbon central bank is created rather than elected, it would be more resilient to lobbying and influence from interest groups than regulators that depend on re-election.

4.2. Limited liability problem of the private sector

Firms that acquire clean-up certificates commit themselves to removing the associated emissions before the final period T. As the clean-up certificates have a debt component, there will be strong incentives for firms to close down business or to go bankrupt to refrain from paying the debt (i.e. from removing the carbon later). The removal obligation could even be transferred to another firm that declares bankruptcy on purpose. The incentive problem due to the limited liability of firms is often referred to as the "judgment proof problem" (Shavell, 1986).

There are two basic approaches to overcome this problem: (i) further financialization of the carbon debt or (ii) charging a collateral by a public institution. The first approach aims to transfer the carbon debt to financial intermediaries that are large enough – compared to the carbon debt – so that they can always be held liable. This approach corresponds to the original carbon removal obligation proposal by Bednar et al. (2021).[13] Following this proposal, a firm that uses a clean-up certificate needs to find a bank or insurance company that guarantees the removal to the regulator. Such a guarantee involves additional costs that will reduce the demand for clean-up certificates. Some of these costs are real (e.g., risk premiums associated to unexpected changes in future removal costs), while others are related to market failures (e.g., premiums associated with the default of the respective firm). There might also be economies of scale effects that increase costs for small-to-medium-size financial intermediaries that have to invest in new skills for assessing carbon markets and carbon removal technologies.

The second approach links the use of clean-up certificates to a collateral that is charged by a public institution. Recall from Section 2 that if there were no uncertainties on future removal costs, the collateral at time t would equal the discounted removal costs, i.e. $-\mu(T_2^{CD})e^{r(t-T_2^{CD})}$.[14] If the firm goes bankrupt, this collateral could be used by the public institution to finance the necessary removal. Alternatively, firms could transfer the removal obligation directly to the public institution by paying p_0 as a fee. In both cases, the liability for the removal shifts from private firms to the public institution. Hence, the public institution would need to determine the height of the collateral and ensure that the removal occurs even when removal costs are higher than expected. For this case, the institution would also need to be equipped with a credible financing mechanism. As with the time inconsistency problem, it would also be necessary to ensure sufficient independence for the institution to safeguard against political influence on the calculation of the level of the collateral. In the case of the EU, the European Carbon Central Bank could fulfill this function by determining the level of the collateral and ensuring that all removal obligations associated to clean-up certificates are carried out.

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[13] This approach is also similar to the carbon shares proposed by Lemoine (2020) that rely, however, on a carbon tax rather than an emissions trading scheme.

[14] With specific functional forms, the level of the collateral is

$$p_0 = \alpha A_0 e^{-(r-g)T+\sqrt{2\alpha(r-g)(\hat{B}-B)}} \tag{43}$$

4.3. Publicly financed removal

The institutional challenges related to the liability problem raise the fundamental question: is it easier to let the regulator pay directly for the net removal in the last phase of the emissions trading scheme? In principle, it would be possible to adjust the conventional carbon budget such that cumulative emissions until the beginning of the net-negative phase, T_2^{CD}, are identical to the ETS with clean-up certificates. The regulator would need to earmark a certain fraction of the revenues from carbon pricing in the first phase for the financing of the net-negative phase. The regulator would also need to credibly commit to implementing the optimal net removal path $Q(t) < 0$ for $t > T_2^{CD}$, for example, through reversed auctions on removals. If the introduction of the clean-up certificates leads to an increase in fiscal revenue as illustrated in Section 3, the financing of the net-negative phase would also be possible without additional revenues from alternative sources. In this case, an equivalent outcome with respect to fiscal cost, climate damages, compliance costs, and carbon prices could be achieved.

However, this approach, too, requires a strong institutional set-up. First, the net-removal flows must be be credibly announced early on to ensure investments in upscaling removals (which we have neglected in our model). Within the augmented emissions trading scheme, the credibility would be built-in due to the creation of the clean-up certificates that signal future removal demand to investors. Second, the time-inconsistency problem for the regulator tends to become even larger as she has to (i) pay for the removals in the last phase while (ii) withstanding opposition of firms and consumers against the high carbon price. In the augmented ETS, the carbon price can only be reduced by a deliberate intervention in the ETS (e.g. by postponing the compliance period). Third, the regulator needs to correctly calculate the optimal time when the net-removal phase begins, as well as the cumulative amount of net removals needed. Hence, any solution to directly finance net-removals is also institutionally and informationally demanding and hardly effective without delegation to a strong independent institution.

5. Conclusion

Augmenting emissions trading schemes to allow for a later phase of net-negative emissions constitutes a challenge for regulators. With emission permits, a regulator can limit the flow of emissions – to zero emissions in the extreme – but cannot turn their flow negative. Standard financial incentives for CDR, for example, via a subsidy on removal or programs to purchase removal credits, suffer from two key problems: (i) They require additional revenues in the future, and (ii) planned future removals might be subject to political rollbacks (in particular, with looming fiscal costs for removals that might become substantial).

The clean-up certificates proposed in this study operate through an extension of ETS systems, committing emitters to undo their emissions by bundling emission permits with the obligation for later removal (carbon debt). By allocating carbon debt to emitters, emitters become responsible for financing CDR, thereby relieving future public finances of this burden. Though the private sector will pay for the removal, part of the removal costs may also accrue to the current fiscal budget: since clean-up certificates sell at a lower price than emission permits, removal is in part financed by forgone carbon pricing revenues. Additionally, overall compliance costs are kept at a minimum by exploiting the efficiency of the intertemporal carbon market of the ETS.

If carbon debt is introduced with the sole purpose of enabling a net-negative phase after the current ETS, the regulator should issue clean-up certificates by substituting emission permits from the carbon budget such that the subsequent CDR is fully additional. In this case, the environmental ambition of the ETS is increased by the extent of carbon debt issued. When the ambition of the ETS is not increased to the full extent of the carbon debt, clean-up certificates create a temporary overshoot of the original carbon budget that is undone when emitters carry out their removal obligation. Such an overshoot reduces compliance costs, albeit at the cost of deterring mitigation and inducing additional climate change damages due to higher emissions in the near term.

The degree to which clean-up certificates translate either to additional emission reductions or to a limited temporary overshoot of the carbon budget creates room for compromise between important players in policy-making. Importantly, these players may focus on different dimensions of the policy, such as the environmental concerns that motivate climate policy, the economic burden of compliance costs, or the fiscal implications for budget-constrained finance ministers. We find that clean-up certificates can be introduced in a way that improves all of these dimensions. This finding suggests a window of political support for increasing ambition levels. In our numerical analysis, we find that to reduce climate damages, roughly half of the carbon debt should be additional, i.e., replacing conventional emission permits. Otherwise, there is the risk that mitigation costs fall at the expense of the higher cumulative climate damages.

As a long-term policy that extends far into the future, clean-up certificates need to safeguard against moral hazards of emitters to leave carbon debt unpaid, and of regulators to revise their policy. While the former risk can be hedged by collateral requirements, it remains unclear whether financial markets can price these collaterals efficiently due to large uncertainties and long time horizons. To solve for both problems – the time inconsistency of the regulator and the pricing of the collateral – an independent institution like a European Carbon Central Bank could be established. While such an institution has been suggested for a number of tasks (e.g. valuing and issuing certificates, certification of removals, linking of carbon markets, providing technology support or stabilizing carbon prices, see Rickels et al. (2022); Edenhofer et al. (2023)) this paper emphasizes two new functions that follow from integrating net-negative emissions in an ETS.

Many open questions remain for future research. The regulation of an ETS with clean-up certificates needs to cover long time horizons. Due to these long time horizons, some key determinants in our analysis, such as the rate of technological progress, are only known with large uncertainties. While we considered some parameter variations, a stochastic analysis could provide more insights on the integration of clean-up certificates in the case of uncertainties. Furthermore, technological progress is exogenous in our analysis. Therefore, differences in technological learning for abatement and removal or the implications of learning-by-doing cannot be accounted for in our model. The question of how to complement clean-up certificates with technology support policies therefore remains open. Finally, our analysis takes a marginal perspective by assuming that climate change damages from a budget overshoot of the modeled economy can be captured by the social cost of carbon and does not trigger any tipping points. However, if a prominent player like the EU engaged in emissions overshoot, others might follow suit – triggering a substantial global overshoot and significantly increasing tipping point risks. Therefore, future research is needed on the governance of global overshoot and the role of carbon debt in an international context. The model presented in this paper could serve as the starting point for this important avenue for future research.

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Appendix

A. Permit trade model

The solution of the social planner model of Section 2 can be implemented by a market equilibrium of a competitive economy with emission permit trade. Consider a representative firm that buys permits $z(t)$ at price $p_X(t)$ and is required to hold the same amount of permits as it releases carbon into the atmosphere. The permit debt account $\mathsf{D}(t)$ tracks the net deficit of permits of the representative firm, that is, if $\mathsf{D} > 0$ the firm has "carbon debt", and if $\mathsf{D} < 0$ the firm has excess permits for additional emissions.

A carbon budget B of the social planner economy maps to an initial allocation of permits $\mathsf{D}_0 = -B$, and the case of "no carbon debt" is reflected by a per-period constraint on carbon debt, $\mathsf{D}(t) \leq 0$.

Then, an introduction of carbon debt that increases the ambition of the permit trade system is subtracted from the carbon budget. In contrast, carbon debt that only facilitates inter-temporal borrowing implies a relaxation of the per-period constraint on carbon debt. We have

$$\mathsf{D}_0 = -B + \lambda D \tag{44}$$

$$\mathsf{D}(t) \leq (1-\lambda)D \tag{45}$$

Note that the model does not need to track carbon in the atmosphere (stock X), it suffices to know the permit debt account of the firm. The problem of the firm reads:

$$\begin{aligned}
&\max_{Q} \int_0^T -\left[A(t)a\left(Q(t)\right) + p_X z(t)\right] e^{-rt} dt \\
&\text{such that} \quad \dot{\mathsf{D}} = Q - z && \perp \mu && (46)\\
&\qquad\qquad \text{with } \mathsf{D}(0) = D_0 = -B + \lambda D && && (47)\\
&\mathsf{D}(t) \leq (1-\lambda)D && \perp \gamma && (48)\\
&\mathsf{D}(T) = 0 && && (49)
\end{aligned}$$

$$\mathscr{H} = -\left[A(t)a\left(Q\right) + p_X z\right] + \mu\left[Q(t) - z(t)\right] + \gamma\left[(1-\lambda)D - \mathsf{D}\right]$$

First-order conditions

$$\frac{\partial \mathscr{H}}{\partial Q} = -A_t a'(Q) + \mu = 0 \quad \Leftrightarrow \quad \mu = A_t a'(Q) \tag{50}$$

$$\frac{\partial \mathscr{H}}{\partial z} = -p_X - \mu \quad \Leftrightarrow \quad p_X = -\mu \tag{51}$$

$$\dot{\mu} = r\mu - \frac{\partial \mathscr{H}}{\partial \mathsf{D}} = r\mu - [-\gamma] \quad \Leftrightarrow \quad \dot{\mu} = r\mu + \gamma \tag{52}$$

Equation (51) shows that $(-\mu)$, which is the same in the planner model, is the permit price $p_X = -\mu$. First-order conditions (50) and (52) are the same as (5) and (6), the market equilibrium therefore implements the solution of the social planner economy. Note that the levels of X and D differ (cf. X_0 versus D_0).

B. Calibration to EU ETS

Calibration of g

To calibrate the constant rate of change g of the scaling parameter $A(t)$, we decompose g according to the Kaya identity:

$$g = \Delta_{GDP} - \Delta_{EI} - \Delta_{CI} \tag{53}$$

where Δ_{GDP} is the average annual GDP growth rate in the EU from 2025 to 2100, Δ_{EI} is the average annual reduction in energy intensity from 2010 to 2100, and Δ_{CI} is the average annual reduction in carbon intensity from 2010 to 2100. We take data from the "middle-of-the-road" scenario (SSP2) of the shared socio-economic pathways (Fricko et al., 2017) and set $\Delta_{GDP} = 0.95\%$, $\Delta_{EI} = 1.5\%$ and $\Delta_{CI} = 1.1\%$.

Calibration of α and A_0

To calibrate the abatement cost parameter α, we solve equation (13) for α and plug in the parameter values given in Table 1. In particular, Q_0 is equal to the amount of emissions in a comprehensive EU ETS in 2030 as modelled in Rickels et al. (2023). Similarly, we calibrate the initial value of the scaling parameter A_0 by solving (5) for A_0 and plugging in the parameter values given in Table 1. In particular, μ_0 is equal to the carbon price in a comprehensive EU ETS in 2030 as modelled in Rickels et al. (2023).

Social cost of carbon

We convert the annual estimates of the social cost of carbon provided in U.S. EPA (2023) from Dollar to Euro using a USD-EUR exchange rate of 0.94. To get a continuous function, we fit a

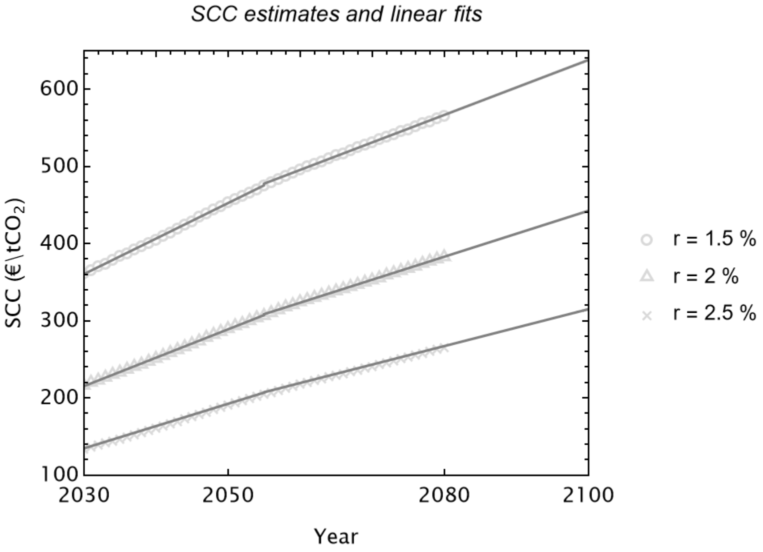

Figure 10: Annual estimates of the social cost of carbon for different discount rates from U.S. EPA (2023) and linear regression lines used for constructing the piecewise linear $SCC(t)$ function. Linear extrapolation starts in the year 2080.

piecewise linear function to the data using linear regression. Note that since estimates are only provided until the year 2080, we use linear extrapolation to calculate the social cost of carbon in the remaining years.

C. Time inconsistency problem

Figure 11 demonstrates the time inconsistency problem regarding the choice of the length of the time horizon. Extending the time horizon can reduce cumulative compliance cost due to discounting and prolonged technological progress. Consequently, policymakers at time $t = 0$ cannot credibly commit to the end date of the clean-up policy. Similarly, future policymakers would face similar incentives to extend the time horizon. This underscores the fundamental challenge of time inconsistency of the introduction of clean-up certificates.

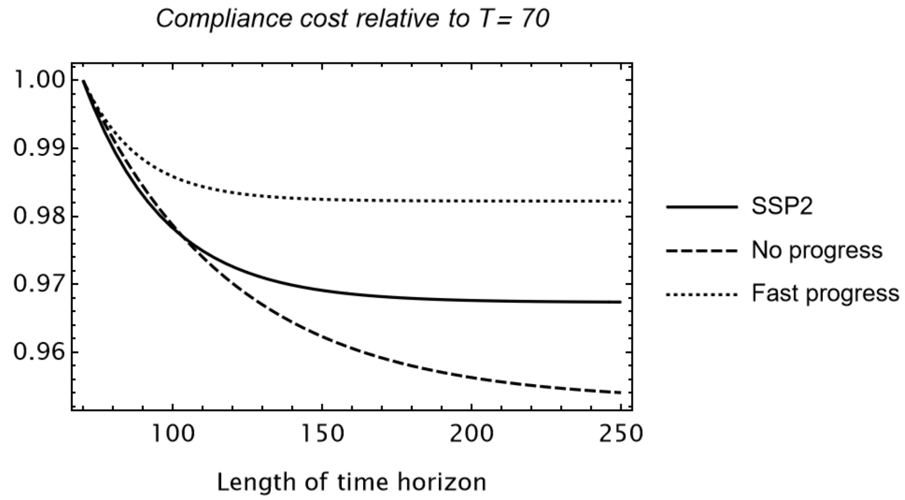

Figure 11: Time inconsistency of the choice of the time horizon for a given relative carbon debt of $\beta = 1$ and full additionality of clean-up ($\lambda = 1$). Cumulative compliance cost relative to a time horizon of 70 years decrease by shifting the end of the policy into the future. See Table 1 for calibration parameters.