International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Address: IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria

Email: permissions@iiasa.ac.at

Working paper

The Carbon Removal Obligation

Updated analytical model and scenario analysis

Johannes Bednar (bednar@iiasa.ac.at)
Artem Baklanov (baklanov@iiasa.ac.at)
Justin Macinante (j.d.macinante@ed.ac.uk)

WP-23-001

Approved by:

Name Elena Rovenskaya
Program: Advancing Systems Analysis
Date: 17 January 2023

THE UNIVERSITY *of* EDINBURGH
Edinburgh Law School

eci

UNIVERSITY OF OXFORD

Table of contents

ZVR 524808900

Disclaimer, funding acknowledgment, and copyright information:
IIASA Working Papers report on research carried out at IIASA and have received only limited review. Views or opinions expressed herein do not necessarily represent those of the institute, its National Member Organizations, or other organizations supporting the work.

We acknowledge financial support from FWF grant P-31796 Medium Complexity Earth System Risk Management (ERM) and support from the HSE University Basic Research Program for A.B. This work was supported by the CO2RE Hub, funded by the UK's Natural Environment Research Council (Grant Ref. NE/V013106/1).

Abstract

The framework for carbon removal obligations (CROs), introduced in ref[1], consists of two core mechanisms: (1) the principal CRO mechanism obliges the emitter of a tonne of CO_2 to remove a tonne of CO_2 from the atmosphere at maturity of the CRO; and (2) the CRO pricing instrument imposes a premium ('CRO Premium') on carbon debt, defined as the emissions overshooting the remaining carbon budget. The CRO Premium thus adjusts carbon price levels induced by the principal CRO mechanism to alter the emission profile according to some prespecified preferences.

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

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

About the authors

Johannes Bednar is Research Scholar at IIASA's Exploratory Modeling of Human-natural Systems (EM) group of the Advancing Systems Analysis (ASA) Program and a DPhil Student enrolled at the University of Oxford, Environmental Change Institute (ECI). (Contact: bednar@iiasa.ac.at)

Artem Baklanov Research Scholar at IIASA's Novel Data Ecosystems for Sustainability Research Group of the Advancing Systems Analysis (ASA) Program and Research Fellow at International Laboratory of Game Theory and Decision Making of HSE University. (Contact: baklanov@iiasa.ac.at)

Justin Macinante is Research Fellow in Climate Change at the Edinburgh Law School, University of Edinburgh. (Contact: j.d.macinante@ed.ac.uk)

1. Introduction

Carbon Removal Obligations (CROs) were introduced in ref[1] to resolve a fundamental policy failure associated with climate mitigation scenarios that rely on large scale carbon dioxide removal (CDR) to reverse the overshoot of a previously missed climate target. The CRO framework consists of two core mechanisms: (1) the principal CRO mechanism obliges the emitter of a tonne of CO_2 to remove a tonne of CO_2 from the atmosphere later at maturity of the CRO; and (2) the CRO pricing instrument imposes a premium ('CRO Premium') on carbon debt, defined as the emissions overshooting the remaining carbon budget. The CRO Premium adjusts carbon price levels induced by the principal CRO mechanism to alter the emission profile according to some prespecified preferences, e.g., to achieve a net-zero target for 2050.

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

The paper is structured as follows: section 2 introduces the updated analytical CRO framework (notably the novel CRO pricing instrument); section 3 explains the numerical model for applying the analytical framework and in section 0 we discuss the updated framework based on a set of illustrative climate mitigation scenarios.

2. Analytical CRO framework

We follow the convention that parameters use uppercase letters, and the free variables (controls) are denoted by α and μ.

2.1. Definition of the constrained abatement cost minimization problem

Assume that α and μ are abatement rates (see ref[1] for the definition of abatement rate), where α represents ERs and μ reflects CDR. The convex cost function associated with these abatement rates is defined as $f_c\big(t,\alpha(t),\mu(t)\big) = E(t)\left(\int_0^{\alpha(t)} f_\alpha(t,a)\,da + \int_0^{\mu(t)} f_\mu(t,a)\,da\right)$, where f_α and f_μ are marginal cost functions and E reflects baseline emissions. B denotes the remaining carbon budget, i.e., the cumulative net emissions until T=2100 compliant with a given target for warming in 2100. Moreover, $T_0 \le t \le T$. We aim to find an optimal solution, denoted by α^* and μ^*, of the problem

$$\min_{\alpha(t),\mu(t)\in\mathbb{R}^+} \int_{T_0}^{T} f_c\big(t,\alpha(t),\mu(t)\big)\exp\big(-R(t-T_0)\big)\,dt, \qquad [\,1\,]$$

subject to (s.t.)

$$\int_{T_0}^{T} E(t)\big(1-\alpha(t)-\mu(t)\big)dt \le B, \qquad [\,2\,]$$

$$v_i\big(t,\alpha(t),\mu(t)\big) \le 0 \;\forall\, t, i = 1,\dots,m \qquad [\,3\,]$$

$$w_j\big(t, \alpha(t), \mu(t)\big) = 0 \ \forall\ t, j = 1, \dots, n \qquad [\ 4\ ]$$

where v_i reflects a set of m inequality constraints and w_j a set of n equality constraints. These constraints represent additional policy targets, like those for gross emissions, gross removals, or net removals as defined in Table 2 below. Based on this problem we derive the CRO pricing instrument in two steps: The first reformulation replaces the constraints [3] and [4] by carbon price paths for gross emissions and removals. The second reformulation merges these price paths to obtain a single pricing instrument for carbon debt.

2.2. First reformulation of the problem

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

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

$$\min_{\alpha(t),\mu(t)\in\mathbb{R}^+} \int_{T_0}^{T} \Big(f_c\big(t, \alpha(t), \mu(t)\big) + P_\alpha(t)e(t) - P_\mu(t)r(t)\Big) \exp\big(-R(t - T_0)\big)\, dt, \qquad [\ 5\ ]$$

which yields the same optimal solution (α^*, μ^*) as the problem in [1]-[4].

2.3. Second reformulation towards the CRO model

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

As we show below, the problem in [6]-[9] also yields the same optimal solution (α^*, μ^*) as the previous problems.

$$\min_{\alpha(t),\mu(t)\in\mathbb{R}^+} \int_{T_0}^{T} \Big(f_c\big(t, \alpha(t), \mu(t)\big) + \ f_s\big(t, g(t)\big)d(t)\Big) \exp\big(-R(t - T_0)\big)\, dt, \qquad [\ 6\ ]$$

s.t. $\forall\, t \in [T_0, T]$
$d(t) \geq 0,$ [7]

$$\int_{T_0}^{T} d(\tau)\, d\tau = \int_{T_0}^{T} r(\tau)\, d\tau, \qquad [\ 8\ ]$$

$$\int_{T_0}^{t} d(\tau)\, d\tau = \int_{T_0}^{t+g(t)} r(\tau)\, d\tau. \qquad [\ 9\ ]$$

Note that the CRO Premium function f_s is imposed on carbon debt d rather than gross emissions/removals. The additional constraints [3] and [4] are fully reflected by f_s. Moreover, [8] reflects the principal CRO mechanism, i.e., that carbon debt needs to be compensated by gross removals, which replaces the carbon budget constraint in [2]. To apply the CRO Premium function f_s, creation of carbon debt (CRO issuance) needs to be linked to its compensation (CRO maturity), as in [9]. Compared to ref[1], the principal CRO mechanism covers gross removals r, i.e., all CDR activities, implying that the CDR market supplying the required removal units is solely linked to the CRO framework (and not the ETS as in ref[1]). The ETS, or another conventional carbon pricing scheme, is limited to emissions which need to comply with the time-distributed carbon budget $B_\alpha(t)$. Therefore, $B_\alpha(t)$ could be understood as the emission caps of the ETS.

Now let us show the steps that lead from [5] to [6]. We denote the set of all solutions of [5] by $\Omega = \underset{\alpha(t),\mu(t)\in\mathbb{R}^+}{\arg\min} \int_{T_0}^{T} \Big(f_c\big(t, \alpha(t), \mu(t)\big) + P_\alpha(t)e(t) - P_\mu(t)r(t)\Big) \exp\big(-R(t-T_0)\big)\, dt$.

Note the simple fact that $\underset{x}{\arg\min}\, f(x) = \underset{x}{\arg\min}(f(x) + K)$ where K is a constant. Then by subtracting the constant $\int_{T_0}^{T} P_\alpha(t) B_\alpha(t) \exp\big(-R(t-T_0)\big)\, dt$ from the objective function in [5], we obtain that
$\Omega = \underset{\alpha(t),\mu(t)\in\mathbb{R}^+}{\arg\min} \Big(\int_{T_0}^{T} \Big(f_c\big(t, \alpha(t), \mu(t)\big) + P_\alpha(t)e(t) - P_\mu(t)r(t)\Big) \exp\big(-R(t-T_0)\big)\, dt - \int_{T_0}^{T} P_\alpha(t) B_\alpha(t) \exp\big(-R(t - T_0)\big)\, dt\Big)$.

We simplify the expression to obtain

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

Next, let us recall the Theorem in ref[1], which assumes that $\phi \int_{[0,1]} x(t) f\big(t + T_R(t)\big) dt = \int_{[0,1]} y(t) f(t) dt$. Here, because of [8], $\phi = 1$. Moreover, we apply the Theorem by inserting $x(t) = d(t)$, $y(t) = r(t)$, $f(t) = P_\mu(t) \exp\big(-R(t-T_0)\big)$, and for the repayment term $T_R(t) = g(t)$. We therefore obtain $\int_{T_0}^{T} d(t)\, P_\mu\big(t + g(t)\big) \exp\big(-R(t + g(t) - T_0)\big)\, dt = \int_{T_0}^{T} r(t)\, P_\mu(t) \exp\big(-R(t-T_0)\big)\, dt$, hence,

$$\Omega = \underset{\alpha(t),\mu(t)\in\mathbb{R}^+}{\arg\min} \int_{T_0}^{T} \Big(f_c\big(t,\alpha(t),\mu(t)\big) + \big(P_\alpha(t) - P_\mu\big(t+g(t)\big)\exp\big(-Rg(t)\big)\big)\, d(t)\Big) \exp\big(-R(t-T_0)\big)\, dt$$

$$= \underset{\alpha(t),\mu(t)\in\mathbb{R}^+}{\arg\min} \int_{T_0}^{T} \Big(f_c\big(t,\alpha(t),\mu(t)\big) + f_s\big(t,g(t)\big)\, d(t)\Big) \exp\big(-R(t-T_0)\big)\, dt.$$

2.4. The CRO Premium function

The CRO Premium function in present value terms is defined as $\hat{f}_s(t,t') = \big(P_\alpha(t) - P_\mu(t + t')\exp(-Rt')\big)\exp\big(-R(t-T_0)\big)$. Assume that g^* is the repayment term associated with the optimal solution (α^*,μ^*), then $\hat{f}_{g^*}(t) = \big(P_\alpha(t) - P_\mu\big(t+g^*(t)\big)\exp\big(-Rg^*(t)\big)\big)\exp\big(-R(t-T_0)\big)$ is the cost-effective (optimal) CRO Premium path (red dashed line in Figure 2 a2-e2). This setting implies two scenarios for implementation of the CRO framework. For the scenario analysis in section 0 we assume that maturities are defined by the regulator, i.e., g is fixed to the optimal solution g^* in [6]. In this case it is required that emitters at issuance of CROs know the CDR cost function at CRO maturity. If g is not fixed by the regulator, the CRO Premium at each time depends on the set of all possible maturities, i.e., the single CRO Premium curve $\hat{f}_{g^*}(t)$ is replaced by a CRO Premium term structure $\hat{f}_s(t,t')$. In this case emitters at one point in time also need to correctly anticipate the behavior of future emitters in response to their own actions. We expect that a real-world implementation would be a mix of the constrained maturities and subsequent CRO Premium $\hat{f}_{g^*}(t)$ and the fully unconstrained case $\hat{f}_s(t,t')$, for instance, by limiting CRO maturities within reasonable bounds (e.g., up to 25 years).

2.5. The 'carbon debt interest rate'

Note that [6] is similar to the objective function of the analytical CRO problem formulation in ref[1]. By comparing the original model in ref[1] with the updated model here one can easily derive a carbon debt interest term structure from $\hat{f}_s$. The carbon debt interest rate in the analytical model in ref[1] is imposed on the average removal costs at the time of CRO maturity, which is used as a proxy for the capital amount of (physical) carbon debt. Instead, imposing the carbon debt interest rate on either the spot market price or a CDR price index with reduced volatility might be feasible – at least until the CDR market is sufficiently mature to provide future and forward contracts[2]. Crucially, the capital amount of carbon debt influences the financial position of CRO holders, hence, their default risk.

3. Numerical framework

Similar to ref[1] we calibrate marginal abatement cost curves (MACCs) based on the marker scenario for SSP2 from the integrated assessment model (IAM) MESSAGE-GLOBIOM, including the scenarios for RCP 1.9, 2.6 and 3.4[3,4]. The MACC for ERs is defined as

$$f_\alpha(t,\alpha(t),\alpha) = \frac{D_\alpha}{\big(1 + A_\alpha(t)\big)^{M_\alpha}} \left(\frac{\alpha(t)}{U_\alpha(t) - \alpha(t)}\right)^{C_\alpha}. \qquad [\ 10\ ]$$

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

We calibrate two sets of cost curves, with low and high progress ratios (high and low endogenous learning potential), $L_\alpha = 0.65$ and $L_\alpha = 0.95$, respectively, which corresponds to the range given in ref[5]. Note that overall technological change is similar for the two sets of cost curve parameters. If the potential for endogenous technological change is high ($L_\alpha = 0.65$), then exogenous, purely time-dependent cost reductions through $U_\alpha(t)$ are low, and vice-versa.

We first fit the MACC model for fixed L_α and $U_\alpha(t) = \max(\alpha(t))$, to determine D_α and C_α. Then we fix these parameters to determine $\bar{U}_\alpha$, K_α and I_α. In Figure 1 we compare the gross emissions and removals pathways from the SSP RCP1.9 and RCP2.6 pathways with pathways resulting from our calibration.

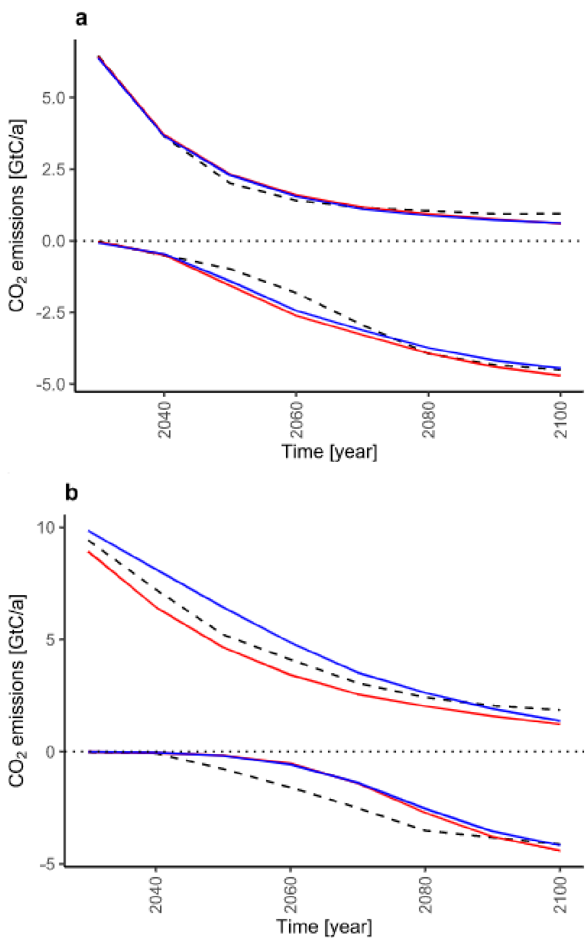

Figure 1. Gross emissions (above zero) and removals (below zero) of the climate mitigation scenarios from MESSAGE-GLOBIOM based on SSP2 (black dashed line), compared to output of the model used for this study, which was calibrated using the data from these scenarios. Red solid lines are emission profiles resulting from high endogenous learning potentials, blue lines are emission profiles with low endogenous learning potentials. Marginal abatement costs where fixed to the reported carbon price for RCP 1.9 in panel a, and for RCP 2.6 in panel b.

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

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

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

We use a remaining global carbon budget of B = 400 Gt CO_2 for the 2020-2100 period, which reflects a 67% likelihood of limiting warming to below 1.5°C[6]. For the temporal distribution of the carbon budget, we use $B_\alpha(t) = 0.8\, E(t)\big(1 - \alpha^*(t)\big) \exp\big(-Q(t - T_0)\big)$ where Q is set such that $\int_{T_0}^{T} B_\alpha(t)dt = B$. The additional targets underlying the scenarios, which are represented by the inequality constraints [3], are defined in Table 2. The model is solved in ten-year time steps, like the underlying data. We compute four sets of scenarios by using all possible combinations of the two sets of cost function parameters. The scenarios for $L_\alpha = L_\mu = 0.65$ are shown and discussed in section 4.1, whereas the other scenarios are illustrated in section 4.2.
From the solution of [1]-[4] and using the MACCs [10], the optimal CRO Premium path $\hat{f}_{g^*}$is determined by using spline interpolation between the ten-year time steps.

For the theorems in the Supplementary Information to apply we need to assume that learning (hence cumulative ERs $A_\alpha(t)$ and removals $A_\mu(t)$) are fixed to the optimal paths for the reformulation of the original problem towards the problem in [5]. For this, the standard assumption underlying carbon taxes is sufficient: emitters at each point in time abate to the level where marginal costs equal the price. Learning then follows as a result defining ERs and CDR according to that logic.

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

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

4. CRO-based climate mitigation scenarios

The separation of ERs and CDR in the model described in section 2 enables the CRO pricing instrument to separately control price and quantity levels of ERs and CDR. This section, hence, investigates two drivers of divergent price levels, including policies with separate targets for CDR and ERs[7,8], as well as endogenized technological change. It further illustrates the CRO Premiums required to induce these price levels. The analysis is based on a set of idealized 1.5°C climate mitigation scenarios shown in Figure 2, similar to the archetypes in ref[9]. The scenarios are based on the analytical model in section 2, computed with the numerical model in section 3. Each of the scenarios reflects a plausible target for either gross emissions, gross removals or net removals, as described in Table 3. To assess the feasibility and implications of the different targets, the mitigation scenarios are qualitatively compared with each other along a set of indicators in Table 4. The first set of indicators summarizes the long-term convergence of price and emission levels, with implications for mitigation beyond the achievement of the carbon budget target in 2100. The second set of indicators shows changes of policy costs compared to the 'standard scenario' as well as the aggregated financial flows resulting from CRO Premium payments as percentage share of policy costs. The third set of indicators quantifies in various ways the level of near-term ambition associated with the mitigation scenarios.

4.1. Results

Emission profiles of the mitigation scenarios including a representation of the additional emission or removal targets are shown in panels a1-e1; the associated price paths for ERs and CDR as well as the trajectories of CRO Base Premiums in panels a2-e2 of Figure 2. Panels a3-e3 show cumulative carbon emissions overshooting the carbon budget. Issuance of CROs is linked to their maturities in the repayment term structures shown in Figure 2 a4-e4.

For the scenarios presented in Figure 2 the endogenous learning potentials for CDR and ERs are high ($L_\alpha = L_\mu = 0.65$), and exogenously imposed cost reductions ('learning over time') are low. A sensitivity analysis with respect to the share of endogenous versus exogenous learning is carried out. Hence, Figure 2 is replicated for the resultant scenarios in Figure 3-Figure 5.

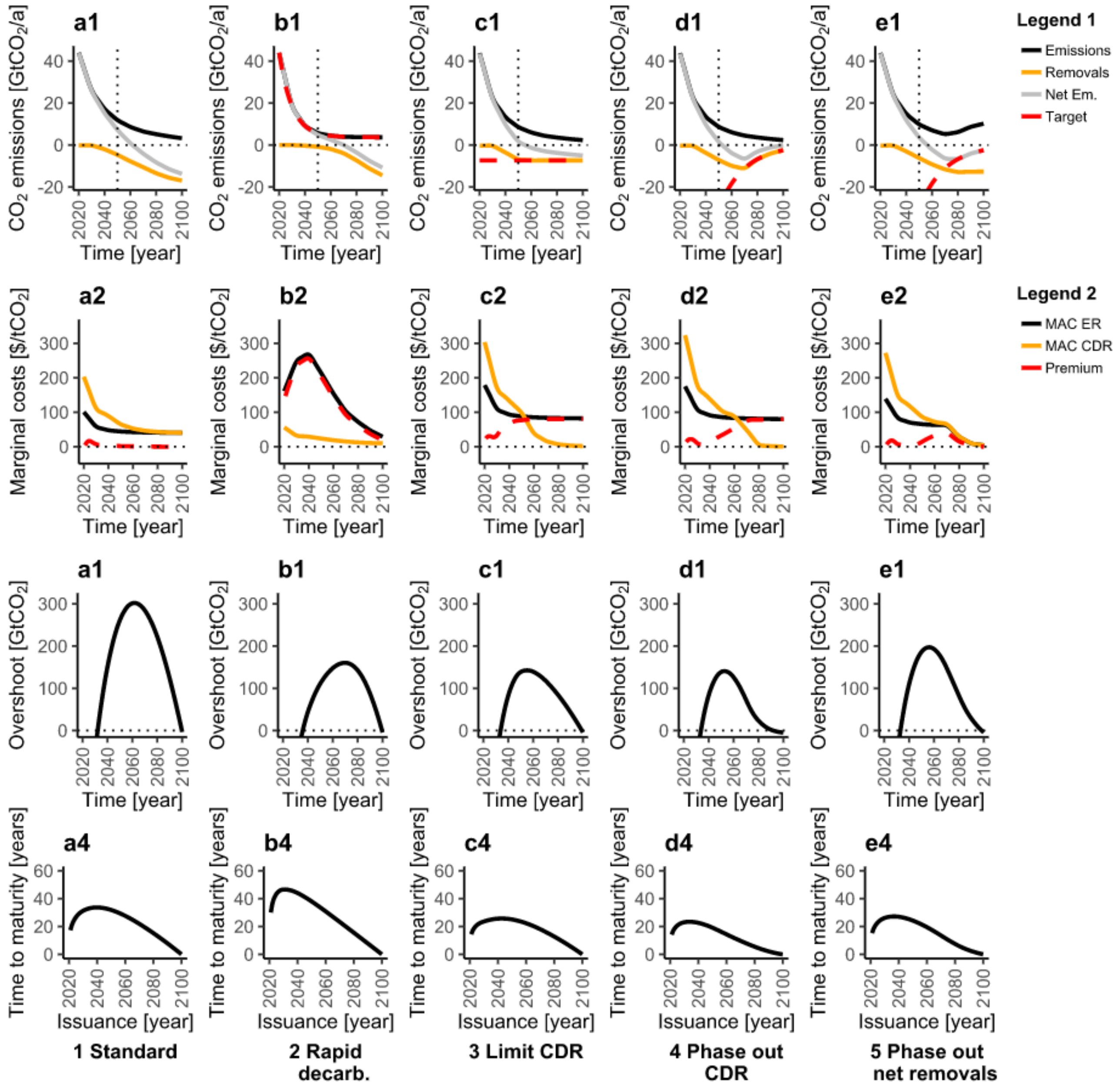

Figure 2. *Climate mitigation scenarios based on a 1.5°C carbon budget (400GtCO2) and additional targets for gross emissions and removals, as well as net removals.* ***Panels a1-e1:*** *Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). The respective targets (red dashed line) are defined as upper or lower bounds.* ***Panels a2-e2:*** *Present value marginal cost paths of conventional emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO premium (red dashed line). The CRO premium is defined as the present value of marginal costs of ERs at issuance of the CRO minus the present value CDR price at maturity.* ***Panels a3-e3:*** *Cumulative C02 emissions above the carbon budget.* ***Panels a4-e4:*** *The repayment term structure links the issuance of CROs to their maturities.*

Table 3. Description of climate mitigation scenarios

Climate mitigation scenario	**Scenario description**
1. Standard	Emission and price profiles are based solely on cost effectiveness considerations, i.e., there are no policy targets other than the carbon budget constraint.
2. Rapid decarbonization	A reduction target is imposed on gross emissions to achieve a fast transformation towards zero carbon technologies. No separate target is defined for CDR, which is ramped-up late in the century for overshoot reversal.
3. Limit CDR	Gross removals are limited at 7.3 $GtCO_2/a$ (=2 GtC/a) to reduce CDR specific risks and environmental impacts. The constant CDR level is better compatible with CDR capital renewal cycles and reduces the 'problem of phasedown'[10].
4. Phase out CDR	CDR is deployed only temporarily, because the long-term goal is to achieve full decarbonization of emitting sectors. Therefore, a phase-out target is imposed on gross removals towards 2100, which minimizes the problem of phasedown.
5. Phase out net removals	A phase-out target is imposed on net removals such that gross emissions and removals are balanced by 2100, and price levels converge. CDR continues to play a role beyond 2100, hence, residual emissions are permitted to grow if cheap CDR options are available for offsetting.

A single Hotelling price path for both, CDR and ERs, is used as a guideline by many detailed process-based IAMs to determine or define carbon price paths. Such a single price, which increases at the market interest rate, would be induced by a CRO Premium equaling zero. However, the scope of the Hotelling rule[11] is in fact very limited[12]. Even in the standard mitigation scenario in Figure 2a, where no target other than the carbon budget was imposed, prices increase at a lower rate than the market interest rate[1]. This is a consequence of endogenized technological change: to leverage the high learning potentials of CDR and ERs, both need to ramp-up faster than suggested by the Hotelling rule. To achieve this, initial prices need to be high, but then increase at a lower rate than the market interest rate to balance the initial growth burst. By contrast, in Figure 3 technological learning is almost independent of past ERs and removals, roughly resulting in a single Hotelling price path for CDR and ERs. In the long run, CDR and ER prices need to converge to a single Hotelling price also in Figure 2a, as learning potentials become depleted.
Note that the CRO Premium in Figure 2 a2-e2 (red dashed line) is generally positive, although the CDR price exceeds the price of ERs in four of the scenarios. Extended negative CRO premium periods are observed in Figure 4, where endogenous learning potentials of ERs are much smaller than of CDR. In this case, the negative CRO Premiums can be regarded as a public subsidy to assist a fast CDR ramp up and to induce learning-by-doing. However, such periods of 'CRO subsidies' are negligible as long as achievable endogenous learning rates of CDR and ERs are positive and in the same order of magnitude.

Table 4. Quantification of specific characteristics of the climate mitigation scenarios in Figure 2. Color scales indicate a value judgement, 'bad' (red) or 'good' (green). The yellow scale indicates low to high numbers where a judgement based on 'good' and 'bad' is not possible. Indicator 1.1 (Price convergence): Is necessary beyond 2100 to phase out the intertemporal CRO mechanism and gradually replace it with a contemporaneous mechanism for balancing gross emissions with removals. Indicator 1.2 (Emissions convergence): Net emissions converging to zero reduces the 'problem of phasedown'[10] once the climate target has been achieved. In scenarios where emissions do not converge, CDR assets might become stranded at larger scale. Indicator 2.1 (Policy costs) reflects the change of total present value abatement costs compared to the standard scenario.

[1] Note that prices in Figure 2 are shown in present value terms, i.e., they are discounted at the interest rate.

Indicator 2.2 (CRO Premium) quantifies total present value CRO Premium times the number of CROs issued as fraction of the total present value abatement costs of each scenario. Indicator 3.1 (CDR to ERs until 2050) reflects the ratio between total gross removals and emission reductions until 2050. Indicator 3.2 (CDR to ERs after 2050) reflects the ratio between total gross removals and emission reductions after 2050. Indicator 3.4 (Net zero year) shows the year where net emissions become negative. Indicator 3.5 (Max overshoot) equals the maximum level of cumulative net emissions from 2020 onwards above the carbon budget, as in Figure 2 a3-e3. Indicator 3.6 (Budget depletion year) Year where the remaining carbon budget becomes depleted. Indicator 3.7 (Max time to maturity) illustrates the maximum time to maturity derived from the repayment term structure in Figure 2 a4-e4.

			Climate mitigation scenarios				
Indicators			1 Standard	2 Rapid decarbonization	3 Limit CDR	4 Phase out CDR	5 Phase out net removals
1 Convergence	1.1	Price convergence	yes	yes	no	no	yes
	1.2	Emissions convergence	no	no	no	yes	yes
2 Costs	2.1	Policy cost	0%	+82%	+41%	+49%	+19%
	2.2	CRO Premium	9%	114%	78%	44%	27%
3 Near-term ambition	3.1	CDR to ERs until 2050	0.060	0.008	0.087	0.091	0.079
	3.2	CDR to ERs after 2050	0.182	0.098	0.110	0.110	0.177
	3.3	Total abatement until 2050 to after 2050	0.22	0.27	0.26	0.26	0.25
	3.4	Net zero year	2062	2070	2055	2053	2056
	3.5	Max overshoot	302 GtC02	160 GtC02	142 GtC02	141 GtC02	197 GtC02
	3.6	Budget depletion year	2032	2036	2034	2034	2033
	3.7	Max time to maturity	34 Years	47 Years	26 Years	23 Years	27 Years

Figure 2 shows that policies with separate targets rely on different price levels for ERs and CDR. From the set of targets underlying the scenarios, those limiting gross removals (scenarios 3 and 4) show considerably more near-term ambition than the standard scenario. However, these scenarios are also significantly more costly (indicator 2.1 in Table 4), with CRO pricing strategies relying on a positive Premium in the long run to suppress CDR. Generally, more near-term ambition has a positive impact on the net zero year (indicator 3.4 and timing of the peak of the overshoot in Figure 2 a3-e3) and the maximum overshoot level (indicator 3.5 and peak of the overshoot in Figure 2 a3-e3), which implies earlier carbon debt repayment, hence, reduced maturities (indicator 3.7 and Figure 2 a4-e4). This is beneficial, both, from an overshoot risk and contract risk perspective. A reduced overshoot and considerable delay of the carbon budget depletion (indicator 3.6) can also be achieved by inducing a rapid decrease of gross emissions (scenario 2). However, without the support of near-term CDR, policy costs are high, and the net zero year is delayed. Long maturities and large financial flows from CRO pricing might impede operationalization of this scenario by means of the CRO framework. Notably, of all policies, the phase-out of net removals (scenario 5), i.e., a policy based on a net emissions target[13], appears to balance best between costs and ambition. Moreover, it is the only scenario characterized by convergence of prices as well as emissions and could therefore be sustained beyond 2100 with relatively little policy intervention.

4.2. Sensitivity analysis

We perform a sensitivity analysis of the climate mitigation scenarios with respect to the degree of endogenous technological learning. The scenarios with high endogenous learning potentials for emission reductions (ERs) α and carbon dioxide removal (CDR) μ with progress ratios $L_\alpha = L_\mu = 0.65$ are shown in Figure 2, whereas the other scenarios are illustrated. Figure 3 shows scenarios with low endogenous learning potentials ($L_\alpha = L_\mu = 0.95$), cost reductions are mainly imposed exogenously as function of time. Figure 4, endogenous learning is low for ERs ($L_\alpha = 0.95$) and high for CDR ($L_\mu = 0.65$), whereas in Figure 5 endogenous learning is high for ERs ($L_\alpha = 0.65$) and low for CDR ($L_\mu = 0.95$).

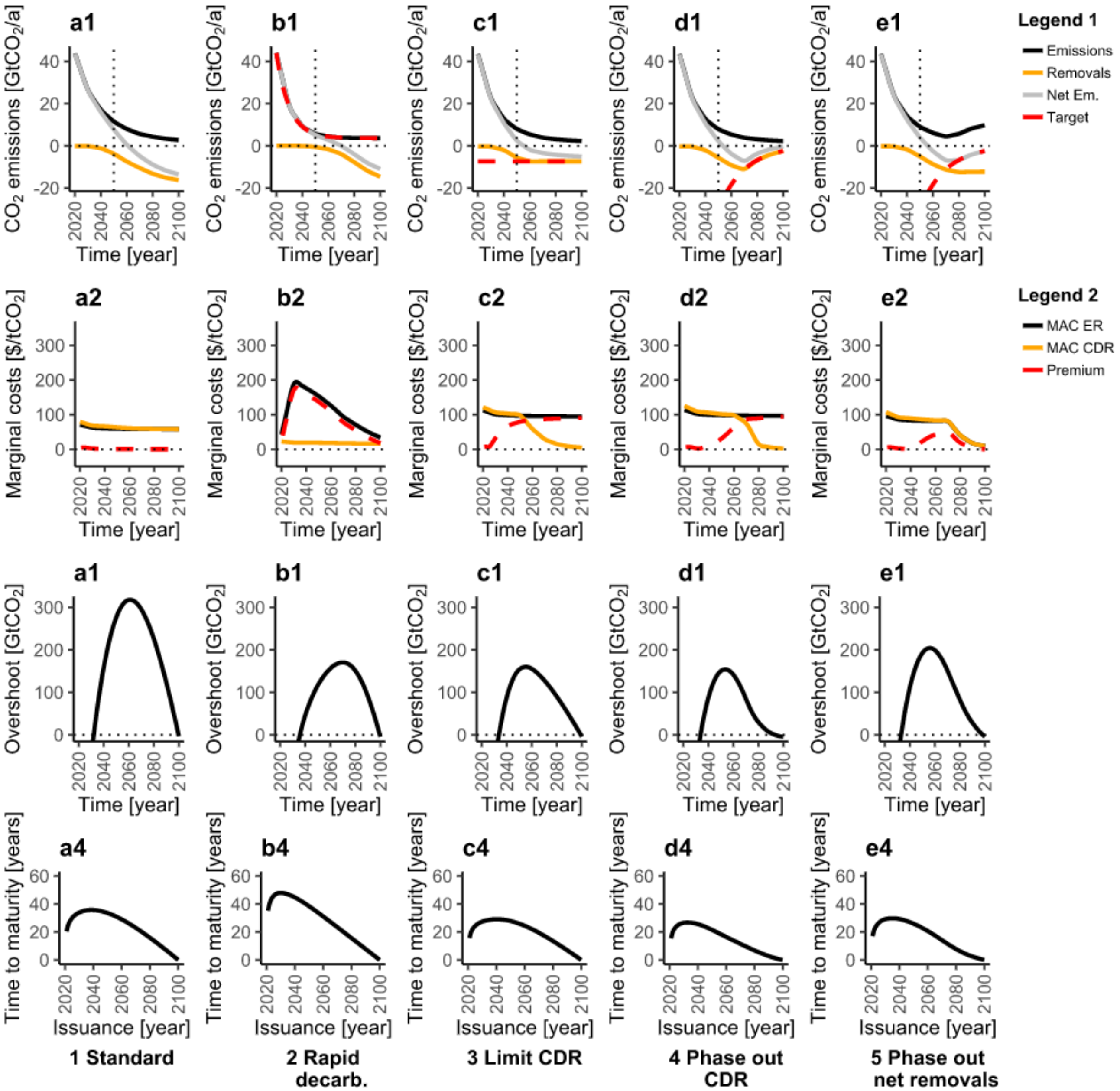

Figure 3. *Low endogenous learning potentials for emission reductions and removals. Climate mitigation scenarios based on a 1.5°C carbon budget (400GtCO$_2$) and additional targets for gross emissions and removals, as well as net removals.* ***Panels a1-e1:*** *Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). The respective targets (red dashed line) are defined as upper or lower bounds.* ***Panels a2-e2:*** *Present value marginal cost paths of conventional emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO premium (red dashed line). The CRO premium is defined as the present value of marginal costs of ERs at issuance of the CRO minus the present value CDR price at maturity.* ***Panels a3-e3:*** *Cumulative C0$_2$ emissions above the carbon budget.* ***Panels a4-e4:*** *The repayment term structure links the issuance of CROs to their maturities.*

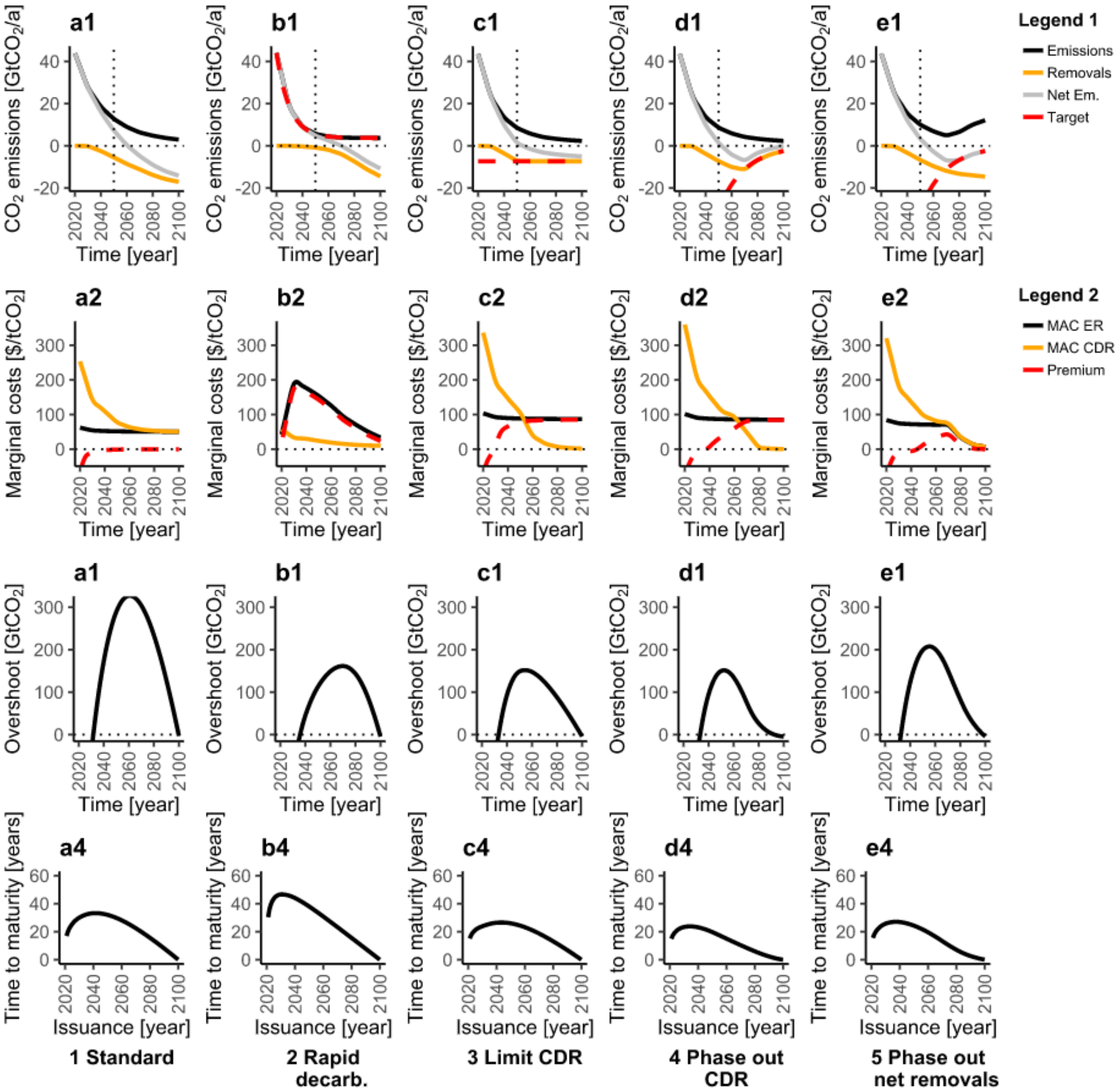

Figure 4*. Endogenous learning is low for emission reductions and high for removals. Climate mitigation scenarios based on a 1.5°C carbon budget (400$GtCO_2$) and additional targets for gross emissions and removals, as well as net removals.* ***Panels a1-e1:*** *Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). The respective targets (red dashed line) are defined as upper or lower bounds.* ***Panels a2-e2:*** *Present value marginal cost paths of conventional emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO premium (red dashed line). The CRO premium is defined as the present value of marginal costs of ERs at issuance of the CRO minus the present value CDR price at maturity.* ***Panels a3-e3:*** *Cumulative $C0_2$ emissions above the carbon budget.* ***Panels a4-e4:*** *The repayment term structure links the issuance of CROs to their maturities.*

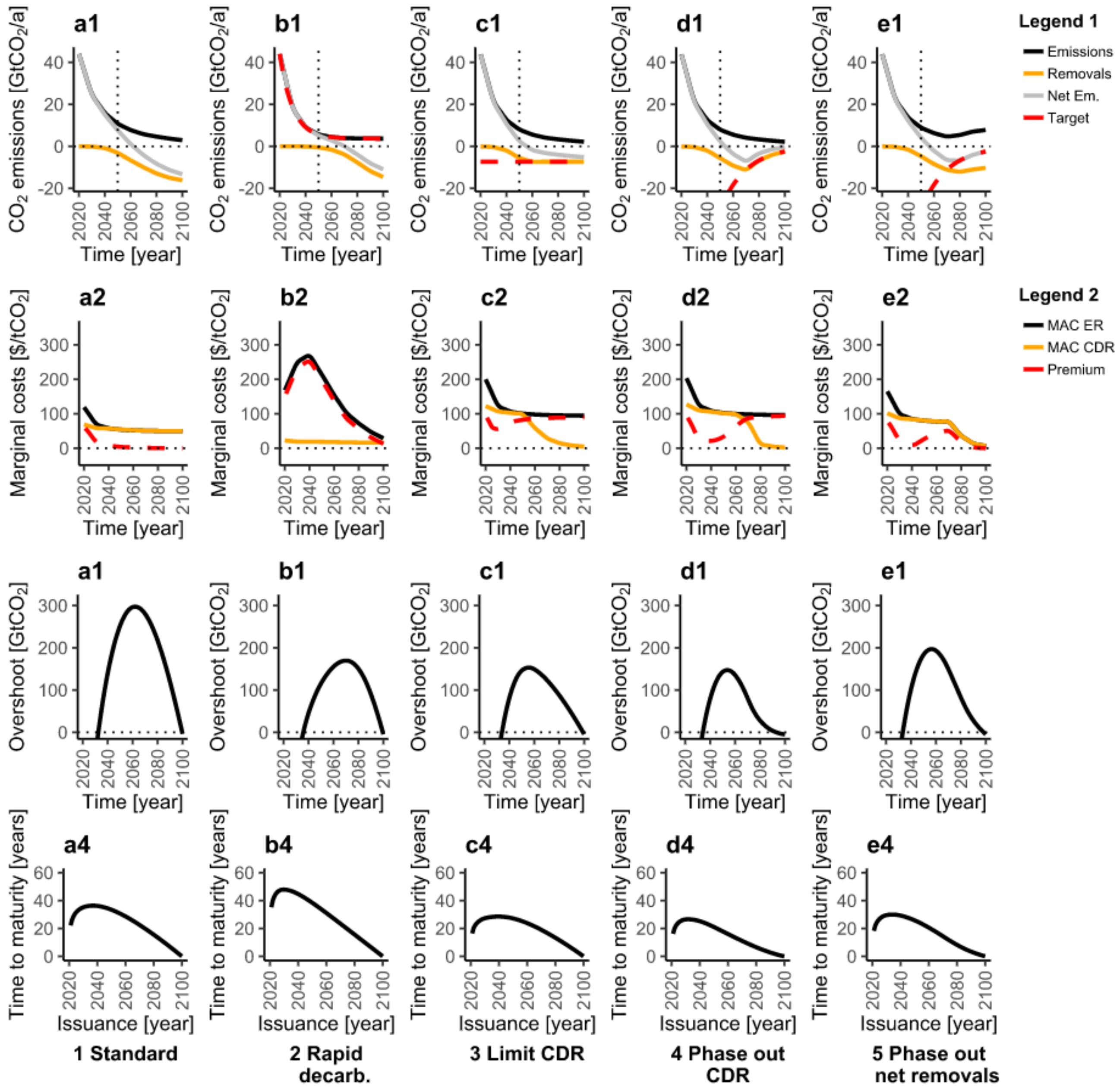

Figure 5. *Endogenous learning is high for emission reductions and low for removals. Climate mitigation scenarios based on a 1.5°C carbon budget (400GtCO$_2$) and additional targets for gross emissions and removals, as well as net removals.* ***Panels a1-e1:*** *Emission profiles, including gross emissions (black), gross removals (orange) and net emissions/removals (grey). The respective targets (red dashed line) are defined as upper or lower bounds.* ***Panels a2-e2:*** *Present value marginal cost paths of conventional emission reductions (ERs, black) and carbon dioxide removal (CDR, orange); as well as the present value CRO premium (red dashed line). The CRO premium is defined as the present value of marginal costs of ERs at issuance of the CRO minus the present value CDR price at maturity.* ***Panels a3-e3:*** *Cumulative C0$_2$ emissions above the carbon budget.* ***Panels a4-e4:*** *The repayment term structure links the issuance of CROs to their maturities.*

5. Bibliography

1. Bednar, J. *et al.* Operationalizing the net-negative carbon economy. *Nature* **596**, 377–383 (2021).
2. Coffman, D. & Lockley, A. Carbon dioxide removal and the futures market. *Environ. Res. Lett.* **12**, 015003 (2017).
3. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Change* **42**, 153–168 (2017).
4. Rogelj, J. *et al.* Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Change* **8**, 325–332 (2018).
5. Detlef P. van Vuuren. *Energy systems and climate policy: long-term scenarios for an uncertain future*. (Universiteit Utrecht, 2007).
6. Canadell, J. G. *et al.* Global Carbon and other Biogeochemical Cycles and Feedbacks. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Ch. 5* (in press) (2021).
7. McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B. & Markusson, N. O. Beyond "Net-Zero": A Case for Separate Targets for Emissions Reduction and Negative Emissions. *Front. Clim.* **1**, 4 (2019).
8. Geden, O., Peters, G. P. & Scott, V. Targeting carbon dioxide removal in the European Union. *Clim. Policy* **19**, 487–494 (2019).
9. Obersteiner, M. *et al.* How to spend a dwindling greenhouse gas budget. *Nat. Clim. Change* **8**, 7–10 (2018).
10. Parson, E. A. & Buck, H. J. Large-Scale Carbon Dioxide Removal: The Problem of Phasedown. *Glob. Environ. Polit.* **20**, 70–92 (2020).
11. Mattauch, L. *et al.* Steering the climate system: an extended comment. (2018).
12. Wijst, K. Optimal policy for carbon pricing: Challenging the Hotelling rule and dissecting mitigation cost uncertainties. (2018).
13. Smith, S. M. A case for transparent net-zero carbon targets. *Commun. Earth Environ.* **2**, 24 (2021).