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Asset pricing and the carbon beta of externalities

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ABSTRACT

Climate policy needs to set incentives for investors who face imperfect, distorted markets and large uncertainties about the costs and benefits of abatement. These investors decide on uncertain investments according to their expected return and risk (carbon beta). We study carbon pricing and financial incentives in a consumption-based asset pricing model distorted by technology spillovers and time-inconsistency. We find that both distortions reduce the equilibrium asset return and delay investment in abatement. However, their effect on the carbon beta and the risk premium for abatement can be decreasing (when innovation spillovers are not anticipated) or increasing (when climate policy is not credible). We show that the distortions can be overcome by modified carbon pricing by a regulator, or by financial incentives, implemented in our model by a long-term investment fund. The fund pays a subsidy to reduce technology costs or offers financial contracts to boost investment returns to complement the carbon price. The investment fund can thus pave the way for carbon pricing in later periods by preventing a capital misallocation that would be too expensive to correct, thus improving the feasibility of ambitious carbon pricing.

1. Introduction

Carbon pricing is a key element of climate policy in many jurisdictions, including important players such as China and the European Union. Part of its appeal is that putting a price on an externality is a simple yet powerful way to correct the associated market failure and align economic activity and investment behavior with social well-being. However, the design of an optimal carbon pricing scheme faces many challenges. To begin with, the extent to which carbon prices can redirect private investment is sensitive to investment risks arising from substantial uncertainties, e.g. about economic growth and technological progress. Moreover, focusing solely on the climate change externality would deny any further market distortions. Market-based climate policy through carbon pricing depends on well-functioning markets. Understanding how to address uncertainty and investment risk and how to find complementary policies to overcome the additional market failures is therefore essential to making carbon pricing work.

Economic models have long been used to estimate optimal carbon prices. Early studies focused on climate change in a deterministic setting (Nordhaus, 1992). These *integrated assessment models* have become more complex by distinguishing world regions, energy technologies and multiple greenhouse gases (cf. Bertram et al., 2015). As a methodological backbone in assessment reports, these deterministic models are now an authoritative source of information on carbon pricing (IPCC, 2022).

Several studies incorporate uncertainty in economic decision making within these models, initially limiting uncertainty in large-scale integrated assessment models to a few alternative “states of the world” and restricting the analysis to open loop policies,

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i.e. policy decisions that are taken in recognition of uncertainty but fixed thereafter (e.g. De Cian and Tavoni, 2012; Giannousakis et al., 2021). Recent models have been using recursive dynamic programming methods to analyze feedback policy rules (Lemoine and Rudik, 2017). Under this approach, a policy maker will have the flexibility to adapt carbon pricing to unexpected changes in the state of the world. The optimal feedback policy under the recursive method is then a function of both time and state variables. The implication of uncertainty for carbon pricing can thus be studied more closely. Lemoine and Rudik (2017) reports that policies have been found to be more sensitive to uncertainty when models adopt recursive utility as opposed to standard expected utility.[1] Disentangling how uncertainties specifically affect investment decisions is not always possible (but see Lemoine and Rudik 2017 for an approach to decompose channels through which uncertainty takes effect), and, therefore, these models are often solved numerically.

To disentangle the effects of uncertainty on investors' decisions, a key aspect is the correlation of risks. By picking investments with low correlation, investors can diversify risk and reduce their overall exposure to uncertainty. To a risk-averse investor, investments that are likely to pay off when the remaining portfolio does not, such that its return has a low, even negative, correlation with other returns will have the added value of reducing overall risk. Consider, for example, how the return on investment in abatement is correlated with overall consumption in the economy. Uncertainty about the severity of climate change damages affects the benefits of abatement, as investments in abatement are especially beneficial when the impacts of climate change are severe. In this state of the world, consumption would be low (reduced by severe climate change impacts) and therefore would correlate negatively with the return on abatement investment. The opposite is the case when uncertainty about economic growth dominates. Economic growth determines emissions, making investments in abatement especially beneficial when emission levels are high, which coincides with high growth, prosperity, and high consumption. Consumption would therefore be positively correlated with the return on abatement investment. It is an empirical question which of the uncertainties dominates.

The consumption-based capital asset pricing model (CCAPM) provides a formal framework for these intuitions (Lucas, 1978). The correlation between asset returns and growth in consumption, measured by the *beta* of the investment, is decisive for the valuation (pricing) of investments relative to the benchmark of a (hypothetical) risk-free investment. The *beta* determines the risk premium, i.e. by how much the rate of return of an asset exceeds (or falls short of) the risk free rate of return in equilibrium; put differently, the risk premium is the additional return demanded by the investor in compensation for bearing the associated investment risk.[2]

Several authors report estimates of the sign and magnitude of the correlation between future consumption and the benefits of investing in emissions mitigation. Dietz et al. (2018) quantify the beta of mitigation in a cost–benefit analysis by introducing uncertainty in ten parameters in the DICE model of Nordhaus and Sztorc (2013). In this setting, the benefit of mitigation consists in reducing climate change damages. Their estimate of the correlation of marginal damage with consumption is a (positive) "climate" beta of about 1. In contrast, Gollier (2022) estimates the beta of mitigation in a cost-effectiveness analysis, i.e., for a carbon budget without consideration of climate change damages. Here, the benefit of mitigation consists in reducing future abatement costs. His estimate of the correlation of marginal abatement costs with consumptions is a "carbon" beta, also of about 1. A similar beta, therefore, applies for investment in mitigation in a cost-benefit and in a cost-effectiveness setting.[3] In contrast, Lemoine (2021) reports a negative beta of marginal damages and consumption.[4] This difference is likely due to a larger volatility of marginal damages, as Lemoine explains: in his model the beta turns positive when the scale parameter for damages is reduced by two thirds.[5]

Gollier (2022) builds a CCAPM to study the optimal carbon price compatible with a 1.5 degree target for the European Union. The model takes the perspective of a benevolent social planner and abstracts from further market distortions. Bennear and Stavins (2007), however, show that distortions have substantial implications for policy design. They identify two categories of distortions that merit the implementation of multiple policy instruments: (i) additional market failures, and (ii) exogenous constraints on the policy decision. We explore a distortion from each of the categories.

Innovation in clean technologies is decisive for the feasibility and costs of mitigation abatement. But the returns to innovation can only be imperfectly appropriated as innovations "spill over" to competitors (Jaffe et al., 2005; Fischer and Newell, 2008), so that social returns substantially exceed private returns, "typically" by a single-digit factor according to Popp (2010, 2019), for

[1] Recursive model studies have mostly focused on uncertainty about climate impacts and economic growth. The effect of damage uncertainty on climate policy is studied in Crost and Traeger (2014) and Rudik (2020) and more recently in Hambel et al. (2021), who find that the social cost of carbon is heavily driven by the assumptions of damage specification. In particular, introducing tipping points increases the social cost of carbon substantially (Lemoine and Traeger, 2014, 2016). The impact of growth uncertainty is studied in Jensen and Traeger (2014), Cai et al. (2013) and Cai and Lontzek (2019). While recursive models have the advantage of capturing how policy incorporates anticipated learning and the ability to calculate the optimal tax on carbon emissions, most of these models are solved numerically, with little attention to analytical insights (but see Golosov et al. 2014, Van den Bremer and Van der Ploeg 2021, Hambel et al. 2021 for examples of closed-formed solutions of stochastic integrated assessment models).

[2] While a positive risk premium indicates an extra return demanded by investors, a negative risk premium captures what part of the return investors are willing to forgo to diversify their overall risk with this investment.

[3] Note that climate beta and carbon beta coincide along a path where marginal damages and marginal abatement costs are equal, as it is common in cost-benefit analyses. Dietz et al. (2018), however, constrain their cost–benefit analysis by an upper limit to global warming at 2 degrees. The comparability of the betas from the two studies is thus limited to time periods that are not affected by the temperature constraint. Note also that the scenarios in the two settings differ in other aspects: Dietz et al. (2018) impose a 2 degree limit, whereas Gollier (2022) implements a cumulative emissions budget compatible with 1.5 degrees of warming. Furthermore, Gollier (2022) does not consider climate change damages. Still, both settings are similar in that they are deep decarbonization scenarios and very different from a "no policy" scenario.

[4] In Lemoine (2021) this implies a positive sign for the "insurance channel", cf. their footnote 22.

[5] Other examples of asset pricing models are Bansal et al. (2016) who explore the impact of long-term risks, as related to expected growth and volatility of future economic prospects, and of climate change on the social cost of carbon and asset prices, and Daniel et al. (2019) who estimate the social cost of delay in implementing CO_2 prices in a dynamic asset pricing model with recursive preference.

example by at least a factor of 2 (Bloom et al., 2013) or a factor of 4 (Jones and Williams, 1998, their "conservative estimate").[6] The regulator can address the innovation market failure either by finding a (technology-neutral) second-best carbon pricing that takes the distortion into account (Goulder and Mathai, 2000), or (following the intuition of the "Tinbergen rule") by introducing supplementary (technology-specific) policies that address the distortion directly (Fischer and Newell, 2008; Fischer and Preonas, 2010; Kalkuhl et al., 2012; Fischer et al., 2017; Lehmann and Söderholm, 2018).

In contrast, a regulatory failure to create a credible carbon price may arise from the inability of the government to commit itself, leaving economic agents in doubt as to whether an announced policy will be implemented (Kalkuhl et al., 2020). Consequently, economic agents will not act in accordance with the carbon price and may strategically choose to hold back from investing (Gersbach and Glazer, 1999). Harstad (2020) captures the lack of credible commitment by introducing time-inconsistent preferences for the government. As in Kalkuhl et al. (2020) the government in Harstad (2020) needs to find a way to commit itself, in the former case to be perceived as credible and in the latter case to prevent a future government from revising its decision. In Harstad (2020) commitment is achieved by triggering complementary investments that make the desired future decisions more attractive.

In the context of climate policy, both types of distortion have been shown to have a substantial impact on its success. Kalkuhl et al. (2012), for example, show that innovation market failure may result in a lock-in to inferior technology with associated consumption loss of up to 8%. Rezai and van der Ploeg (2017) evaluate welfare loss from a lack of commitment. In their integrated assessment model, the cumulative welfare loss of a second-best subsidy without commitment is equivalent to 95% of initial GDP compared to just 7% loss for the same policy with commitment. However, analyses of carbon pricing in stochastic climate-economy models have thus far abstracted from additional distortions.

In our paper, climate economics and asset pricing meet to improve our understanding of how additional distortions affect the pricing of risks, the associated risk premium demanded, and the optimal policy response to address the distortions. We study the asset pricing problem for emission abatement projects in a market economy where prices are distorted by a technology externality and the inability of the regulator to credibly commit to a carbon pricing policy.

We consider a decentralized economy that is populated by three agents: a firm-owning household, a regulatory authority and a long-term investment fund. The firm-owning household (henceforth simply household) is endowed with the (stochastic) economic product and chooses consumption to maximize (expected) welfare but must constrain total emissions to keep an emission permit budget. To this end, the household controls emissions by investing in emission abatement projects.

The regulatory authority is in charge of the carbon pricing policy, i.e. issuance of emission permits and their management. For simplicity, the overall budget of emission permits is not endogenously determined by climate change impact but determined by processes outside our model. For any country that is committed to the goals of the Paris Agreement, this seems a plausible assumption. The emission budget is implemented by a carbon price, and we consider two distortions of the price signal. First, an innovation market failure such that the benefits of technological learning cannot fully be appropriated. Second, noncredible announcement of the emission budget, such that households expect an injection of additional permits in the second period, and the incentive to invest is weakened.

The investment fund is investigated as a potential remedy to overcome distortions. By delegating investment subsidies to a separate entity, the regulator sets a policy in motion that they cannot easily revise.[7] Similar to large investment programs (cf. the relief and stimulus packages during the COVID-19 pandemic, or the Green Deal of the EU), the regulator creates and endows the fund but puts the execution of the subsidy beyond its own control. The fund anticipates household and government actions and supports abatement projects via a subsidy paid on project benefits and/or via an upfront technology subsidy. The latter works as the subsidy in Harstad (2020): It incentivizes investment in the first period that creates a path dependency such that a (more) efficient investment in the second period becomes preferable.

We find that distortions (technological externalities and commitment problems) affect the asset return as well as the risk premium of abatement. But while the direct (all else equal) effect on asset returns is a reduction in both cases, their direct effect on carbon betas and risk premiums is different. All else equal, technological learning introduces an additional benefit to investment which has a similar correlation with consumption as the asset return. Therefore, their correlations add up and amplify the risk premium. Incomplete appropriation of the benefits of technological learning hence produces a lower risk premium. The reduced risk premium facilitates investment — in contrast to the reduced asset return, which puts off investors. Numerically, we find that in equilibrium, the latter effect dominates such that we observe underinvestment in abatement in the first period relative to the socially optimal level.

In contrast, noncredibility of the emission budget raises the risk premium. When investors expect an expansion of the carbon budget beyond the initial announcement of the regulator, reducing first-period abatement links future abatement more closely to economic growth and associated emissions. This strengthens the correlation with consumption and subsequently raises the risk premium. Regarding the investment decision, underinvestment due to reduced asset return is reinforced by the higher risk premium.

We consider three policy options to address the distortions: modifying the carbon price via an intertemporal trading ratio for emission permits, an investment subsidy to boost the return of investment in abatement, and a technology subsidy to reduce the

[6] The case for multiple policy instruments is made in Bennear and Stavins (2007), policies to address innovation market failure are discussed in Jaffe et al. (2005).

[7] Delegation is a "commitment device" to improve the credibility of the regulator's policy. Brunner et al. (2012) discuss three such devices: (i) once a policy passes through the *legislation* process, it becomes harder to undo, (ii) by *delegation* control of the policy is passed to a separate entity, and instruments of *securitization* can bind the regulator to its policy by financial incentives. Helm et al. (2003) stress the ability of delegation to remedy the time-inconsistency problem and reduce policy uncertainty, in particular the incentive for the regulator to act opportunistically.

costs of the abatement technology. We show that in case of the technology externality, all instruments can be used to restore the first-best allocation. Moreover, the investment subsidy can complement a suboptimally low (nonzero) carbon price such that its combined incentive to abate matches any carbon price.

When the regulator lacks a commitment device, and thus the announced climate policy is not credible, a conflict of interest game emerges: Since the household is assumed to be unaware of any benefits of climate policy, it prefers a more lenient emission permit budget than the regulator. Once the household invests according to this preference, it becomes very costly for the regulator to then enforce a tight permit budget. When households anticipate that their preference will become a "self-fulfilling prophecy" they will act accordingly. This distortion, too, can be addressed by investment or technology subsidies that complement the suboptimally low investment incentive of the noncredible climate policy announcement. However, as the subsidies restore credibility of the permit budget announcement, the joint incentive of budget and subsidy would cause overinvestment in first-period abatement. The fund can work around this by making its subsidy contract conditional on the carbon price but there is no similarly easy fix for the technology subsidy.[8]

In summary, we highlight two main results. First, we confirm a key insight of Gollier (2022) in a decentralized economy with distortions: that the risk premium on abatement is substantial, putting the socially optimal rate of return well above the risk-free rate. This rate is decisive for discounting returns and the timing of abatement activities. Hence, ignoring risks has welfare costs and leads to a misallocation between consumption and investment projects. The primarily ethical debate on social discounting needs to be complemented by identifying and quantifying the macroeconomic risks for investors. Otherwise, climate economics would focus on the quantitatively less important component of the social discount rate.

Second, the impact of market failures on the risk premium deserves more attention, as private sector investors may misprice risk in the distorted economy relative to the socially optimal level of the risk premium. Similarly, we quantify the welfare losses and risk premiums of time inconsistency when regulators cannot commit to their policies. We highlight the sequencing of policies in which a long-term fund paves the way to ambitious carbon pricing when the regulator might fail to implement a credible long-term carbon price path.

The paper is organized as follows. Section 2 presents the social planner model for the normative benchmark and the decentralized economy. In Section 3 we explore policies. Sections 4 and 5 are dedicated to the calibration of the model and its numerical results. The final section offers the conclusion and outlook.

2. The model

The focus of our research is to explore instruments that support an efficient implementation of climate policy in an economy with additional distortions and uncertainty. We consider (a) inefficient timing due to the ignoring of technological spillovers, and (b) uncertainty about climate policy stringency due to lack of commitment power of the regulator. We first characterize the socially efficient solution from a social planner perspective. Our presentation closely follows the social planner model of Gollier (2022) but introduces technological learning. For the subsequent analysis of instruments, we introduce decentralized problems for all agents and solve for a market equilibrium of the decentralized economy.

2.1. Social planner benchmark

Assume a social planner who considers utility of consumption $u(C_t)$ in two periods $t = 0, 1$. Consumption C_t is the residual of income Y_t and abatement expenditures A_t. Income Y_t is an endowment and is associated with emissions $E_t = Q_t Y_t$ at an emission intensity of Q_t. The abatement level K_t reduces emissions in period t; furthermore, abatement K_0 in the first period has a spillover effect on future abatement cost, such that abatement at $t = 0$ affects abatement cost at $t = 1$: $A_1(K_0, K_1)$. For spillovers related to technology learning, K_0 reduces the cost of future abatement, i.e. $\partial A_1/\partial K_0 < 0$, as well as future marginal abatement costs, i.e. $\partial^2 A_1/\partial K_1 \partial K_0 < 0$. The planner's objective is to limit emissions to a carbon budget of T. We use the carbon budget rather than a Pigouvian carbon price that reflects the social cost of carbon as a simple way to capture the political motivation for climate policy in line with international policy targets that are beyond the scope of the model.[9] This choice is motivated by the current EU policy, which relies on a carbon budget consistent with carbon neutrality by 2050 in its *Green Deal*.

The problem of the planner is thus:

$$\max_{K_0} u(C_0) + e^{-\rho}\mathbb{E}[u(C_1)] \tag{1}$$

$$\text{such that } C_0 = Y_0 - A_0(K_0) \tag{2}$$

$$C_1 = Y_1 - A_1(K_0, K_1) \tag{3}$$

$$T = (Q_0 Y_0 - K_0) + Q_1 Y_1 - K_1 \tag{4}$$

[8] These results link our paper to the work on the interaction between government actions and asset prices. Pastor and Veronesi (2012), Baker et al. (2016) and Kelly et al. (2016) are examples of the impact of policy uncertainty on the prices of assets that are exposed to different degrees of climate policy risk. Our paper looks more precisely into the implications of a regulator's lack of commitment to implement a credible long-term carbon price trajectory on the beta of abatement investments and, therefore, their risk premium.

[9] Notice though, that the penalty term (Λ), introduced in Section 3.2.1, can formally capture the effects of climate change as anticipated by the government.

In principle, all future variables are uncertain. Note, though, that future consumption C_1 follows from (3) and future abatement K_1 follows from (4). Three of the remaining variables are assumed to be stochastic: economic growth (Y_1), abatement cost at $t = 1$ (A_1), and climate policy (T). The probability distributions are taken from Gollier (2022) and introduced in Section 4. We assume that there is no uncertainty about the emission intensity: uncertainty about Q_1 would only affect (4) and can be captured by the stochastic carbon budget T. For an interior solution, the first-order conditions of the planner yield the following asset pricing equation (for details, cf. Appendix A).

$$u'(C_0)A'_0 = e^{-(\rho)}\mathbb{E}\left[u'(C_1)\left(\frac{\partial A_1}{\partial K_1} - \underbrace{\frac{\partial A_1}{\partial K_0}}\right)\right] \tag{5}$$

Eq. (5) is the asset pricing condition for investment in abatement. The form is analogous to Gollier (2022, equation (2)) but includes the underlined term for pricing the technological spillover. Technology learning with $\partial A_1/\partial K_0 < 0$ thus implies an additional positive social return on investment.

To derive the risk premium, consider the abated emissions in Eq. (5) as an asset with cost A'_0 and expected gross return $R_1^A = \left(\partial A_1/\partial K_1 - \partial A_1/\partial K_0\right)/A'_0$. We use the following lemma to rewrite (5) using a beta-form representation of the risk premium.

Lemma 1. *Consider a representative agent with time-additive expected utility, with a subjective discount rate ρ and a constant relative risk aversion ξ, in a discrete-time setting with a risk-free asset. Assuming the relative growth rate of consumption $g_\tau^c = c_\tau/c_t - 1$ and gross return $R_\tau^A = \frac{A'_\tau}{A'_t}$ to be jointly lognormally distributed, then*

$$\frac{1}{\tau}\ln\left(\mathbb{E}\left[R_\tau^A\right]\right) = \frac{1}{\tau}\ln R^f + \frac{1}{\tau}\xi\sigma_{g^c}Corr\left[\ln R_\tau^A, \ln\frac{c_\tau}{c_t}\right]\sigma[\ln R_\tau^A]$$

and in beta-form

$$\mathbb{E}\left[\frac{A'_\tau}{A'_t}\right]^{\frac{1}{\tau}} = e^{r^f + \beta\eta}$$

with

$$\beta = \frac{Cov\left[r_\tau, \tilde{g}_\tau^c\right]}{Var\left[\tilde{g}_\tau^c\right]} \quad \text{and} \quad \eta = \frac{1}{\tau}\xi Var\left[\tilde{g}_\tau^c\right]$$

and r^f, r_τ, and $\tilde{g}_\tau^c$ represent respectively $\ln R^f$, $\ln R_\tau$, and $\ln\frac{c_\tau}{c_t}$. τ is the length of the considered time period.

The proof is provided in Appendix B. Based on Lemma 1, we have the expression for the two-period risk premium of abatement investments:

$$A'_0 = e^{-(r_f + \beta\eta)}\mathbb{E}\left[\frac{\partial A_1}{\partial K_1} - \frac{\partial A_1}{\partial K_0}\right] \tag{6}$$

That is, the growth rate of social marginal abatement costs should exceed the risk-free rate r_f by a risk-premium $\beta\eta$ where η and β are the systematic risk premium and "carbon beta" respectively, as defined in Lemma 1.

2.2. The market economy

The market economy is populated by three agents: a representative firm-owning household, a regulatory authority who imposes carbon pricing, and a long-term investment fund whose subsidies encourage additional abatement. This section introduces the agents in turn.

The household faces the intertemporal decision of allocating its income between consumption and abatement at $t = 0, 1$ for a limited budget for emissions. We will first assume that the announced permit budget T_0 of the regulator is credible and hence the regulator's policy goal will be met. Abatement is subject to technological learning but due to technological spillovers, only a share of the returns to technological progress can be appropriated by the household. Its abatement decision is therefore based on an incomplete anticipation of technological learning, and thus the market economy will not achieve the efficient allocation of abatement for a given carbon budget as in the social planner economy. In a second step, we therefore introduce several policy instruments to address the misallocation: the government can complement its budget of emission permits T_0 with an intertemporal trading ratio (γ) to control the growth rate of emissions. Additionally, we introduce an investment fund that can pay a technology subsidy (κ) and a bonus on long-term abatement projects (σ).

Later, in Section 3.2, we will relax the assumption of a credible announcement of T_0. The ensuing commitment problem of the regulator provides an additional distortion to the household decision.

Carbon pricing

The household is subject to regulation via an emission permit budget T_0 specified by the regulator. The regulator controls the growth rate of the resulting carbon price by discounting emission permits at an intertemporal trading ratio when banked. At $t = 1$ a banked permit covers e^{γ} emissions (instead of 1), i.e. the intertemporal trading ratio γ acts like an interest rate on saved permits.[10] For example, with a negative rate $\gamma < 0$ the regulator can incentivize early abatement. The necessary abatement at $t = 1$ can be expressed in terms of abatement at $t = 0$ and the emission permit budget:

$$T_0 = (Q_0 Y_0 - K_0) + e^{-\gamma}(Q_1 Y_1 - K_1) \tag{7}$$

Technology & investment subsidies

The long-term investment fund can play two roles by either reducing investment costs or enhancing the benefits of investment. First, investment costs are reduced by paying a subsidy at the rate of κ on abatement expenditures $A_0(K_0)$, which helps to internalize the technology externality. Efficient management of the fund's resources suggests that the fund pays the technology subsidy only for *additional* projects $\Delta_0 = K_0 - \bar{K}_0$ beyond a baseline $\bar{K}_0$ but this does not affect the incentive to invest.

$$\begin{aligned} C_0 &= Y_0 - A_0(\bar{K}_0) - \left(A_0(K_0) - A_0(\bar{K}_0)\right)(1-\kappa) + \Gamma_0 \\ &= Y_0 - A_0(K_0)(1-\kappa) - \kappa A_0(\bar{K}_0) + \Gamma_0 \end{aligned} \tag{8}$$

The budget constraint (8) also includes a lump-sum transfer Γ_0 by which the regulator can raise revenues to finance the subsidy expenditures of the fund, and to recycle revenues from carbon pricing in period $t = 0$ if emission permits T_0 are not freely allocated but auctioned.

Second, the long-term investment fund can subsidize abatement investments by paying a bonus on the benefits of abatement projects. To this end, the fund offers a financial contract at $t = 0$ that commits the fund to paying a bonus (σ) at $t = 1$ on top of the expected return, which is the value of abated emissions in period $t = 1$. Specifically, for any additional emission reduction Δ_0 (monitored and verified as additional relative to the baseline $\bar{K}_0$ by the fund), the fund pays a bonus σp_1 on the corresponding period $t = 1$ permits $\Delta_1 = e^{\gamma}\Delta_0$ where p_1 is the permit price at $t = 1$. As in (8), the budget equation for period $t = 1$ includes a lump-sum transfer Γ_1 of the regulator to finance the subsidy expenditures of the fund and recycle potential carbon pricing revenues.

$$\begin{aligned} C_1 &= Y_1 - A_1(K_0, K_1(\bar{K}_0 + \Delta_0)) + \underbrace{\sigma p_1 \Delta_1}_{\text{fund bonus}} - \underbrace{p_1 \omega}_{\text{new permits}} + \Gamma_1 \\ &= Y_1 - (1+\sigma) A_1(K_0, K_1(K_0)) + \sigma A_1(\bar{K}_0, \bar{K}_1) + \sigma p_1 \Delta_1 - p_1 \omega + \Gamma_1 \end{aligned} \tag{9}$$

To establish the price p_1, we include the option to buy ω new permits in the permit market in the household's budget Eq. (9). If additional permits were sold at $t = 1$, the permit budget T_0 would be inflated by $e^{-\gamma}\omega$ permits (in terms of period 0 permits). The following adjusted permit budget takes this into account. Together, (9)–(10) determine the demand for new permits.

$$T_0 + \underbrace{e^{-\gamma}\omega}_{\text{new permits}} = (Q_0 Y_0 - \bar{K}_0 - \Delta_0) + e^{-\gamma}(Q_1 Y_1 - K_1) \tag{10}$$

Note that unless the regulator relaxes the permit budget at $t = 1$ (which we consider in Section 3.2), the demand for new permits will meet an inelastic supply of $\omega = 0$ new permits by the regulator. In this case, the main benefit of introducing the permit market is to explicitly price emission permits at $t = 1$.

Market equilibrium

Together with the objective to maximize welfare, the household's problem hence becomes

$$\max_{\{K_0\}} u(C_0) + e^{-\rho} u(C_1) \tag{11}$$

$$\begin{aligned} \text{subject to (8), (9)} &: \text{ budget equations} \\ (10) &: \text{ emission permit budget} \\ \text{and given } (T_0, \gamma) &: \text{ the regulator's instruments} \\ (\sigma, \kappa) &: \text{ the fund's instruments} \end{aligned}$$

The first-order conditions of optimality for the household require the permit price p_1 to reflect marginal abatement costs ($\mathbb{E}[u'(C_1)p_1] = \mathbb{E}[u'(C_1)A_1']$) and investment to follow an asset pricing equation that balances (marginal) investment costs and their (discounted marginal) benefits (derived in Appendix C).

$$u'(C_0)(1-\kappa)A_0' = e^{-(\rho-\gamma)}\mathbb{E}\left[u'(C_1)\left((1+\sigma)p_1 - e^{-\gamma}\frac{\partial A_1}{\partial K_0}\right)\right] \tag{12}$$

The benefit of abatement K_0 is determined by the permit price p_1 (and technological learning). Eq. (12) shows how carbon pricing and the investment subsidy σ are complementary in setting the incentive for investment K_0. Any shortfall in the expected carbon price p_1 can be corrected by an appropriately set investment bonus σ. The following proposition records this finding.

[10] The concept of *intertemporal trading ratios* is due to Leiby and Rubin (2001). We assume that the regulator adjusts T_0 in anticipation of the allocation such that in the end emissions do not exceed the carbon budget T, i.e. for $\gamma \neq 0$ we have $T_0 = T + E_1(e^{-\gamma} - 1)$, where $E_1 = Q_1 Y_1 - A1(K0, K1)$ is the permit demand at $t = 1$.

Proposition 1. *Carbon pricing and the subsidy of the investment fund are complementary for the incentive to invest in abatement. By offering* $\sigma = p_1^*/p_1 - 1$ *the fund can lift the investment incentive of any* $p_1 > 0$ *to the level of a desired carbon price* p_1^*.

Proof. Follows directly from (12). □

If households cannot appropriate (or do not anticipate) any of the technology learning $\partial A_1/\partial K_0$ then they will act as if $\partial A_1/\partial K_0 = 0$. We model the partial appropriation of the return on innovation by introducing a scaling parameter ψ as a measure of the market failure into (12), where we substitute marginal abatement costs A_1' for p_1.

$$u'\left(C_0\right)(1-\kappa)A_0' = e^{-(\rho-\gamma)}\mathbb{E}\left[u'\left(C_1\right)\left((1+\sigma)A_1' - (1-\psi)e^{-\gamma}\frac{\partial A_1}{\partial K_0}\right)\right] \tag{13}$$

For $\psi = 1$ technological progress at time $t = 1$ from abatement at time $t = 0$ is a pure externality. That is, households do not take into account the feedback effect of abatement learning. For any $\psi < 1$, part of the externality is anticipated and thus internalized. For $\psi = 0$ there is no technology externality (we adopt this approach from Fischer and Newell 2008). Eq. (13) shows how the household prices the abatement investment. To see how risk takes effect in the asset pricing equation, we can re-express Eq. (13) using the risk free rate $r_f = \rho - \ln\left(\mathbb{E}[u'(C_1)]/u'(C_0)\right)$.

$$\begin{aligned}(1-\kappa)A_0' =& e^{-(r_f-\gamma)}\mathbb{E}\left[(1+\sigma)A_1' - (1-\psi)e^{-\gamma}\frac{\partial A_1}{\partial K_0}\right]\\ &+ e^{-\rho}\mathrm{Cov}\left(\frac{u'(C_1)}{u'(C_0)}, e^{\gamma}A_1'(1+\sigma) - (1-\psi)\frac{\partial A_1}{\partial K_0}\right)\end{aligned} \tag{14}$$

Eq. (14) underlines the specific role of covariance in pricing abatement. It is precisely the covariance term in (14) that translates into the risk premium. The technology externality (ψ), as it appears in the covariance term, will therefore have an effect on the risk premium.

Similarly, the instruments γ and σ will have a direct effect on the risk premium in addition to their effect on the expected risk-free return (first term on the right-hand side of (14)). In contrast to κ, these two policies affect the balance of marginal abatement costs (A_1') and the technological spillover term; hence, like ψ, the two affect the strength of covariance.

When asset return and marginal utility of consumption are uncorrelated, causing the covariance term in (14) to vanish, so will the risk premium. Intuitively, while the asset return remains uncertain, it would have no systematic effect on the marginal utility of consumption.

We summarize these insights in a proposition.

Proposition 2. *When technology learning (ψ) is external to the household's decision problem, asset pricing is distorted from the socially optimal rule in both, the risk-free return and the risk premium. Of the three instruments, the intertemporal trading ratio (γ) and the investment subsidy (σ) have a direct effect on the risk premium.*

With the assumption of (log)normality as in Lemma 1 we can rewrite (14) in beta form:

$$(1-\kappa)A_0' = e^{-(r_f+\tilde{\beta}\tilde{\eta})}\mathbb{E}\left[e^{\gamma}\left((1+\sigma)A_1' - (1-\psi)(\partial A_1/\partial K_0)\right)\right] \tag{15}$$

$$\tilde{\beta} = \frac{\mathrm{Cov}\left[\ln((A_1'(1+\sigma) - e^{-\gamma}(1-\psi)\frac{\partial A_1}{\partial K_0})/A_0'), \ln(C_1/C_0)\right]}{\mathrm{Var}\left[\ln(C_1/C_0)\right]} \tag{16}$$

$$\tilde{\eta} = \xi\mathrm{Var}\left[\ln\left(\frac{C_1}{C_0}\right)\right] \tag{17}$$

The asset pricing equations of the household (15) and the social planner (6) show a very similar structure. The marginal abatement in period 1, in the price equation derived for the household (15), is amplified by the intertemporal trading ratio γ. When there is no technology learning, the intertemporal trading ratio is optimal at zero. When $\gamma > 0$, it induces an underinvestment in the initial period. Eq. (16) reveals that not only the asset rate of return (expectation over the left-hand side in (15)) but also the risk premium affects the carbon beta, as evident by the influence of ψ, γ and σ on $\tilde{\beta}$.

3. Policy analysis

Carbon pricing, by setting T_0, is efficient if there are no distortions. In the following, we explore how the market equilibrium is distorted in comparison to the social planner solution. We begin by focusing on the case where the emission permit budget of the regulator is credible but later relax this assumption to consider the effect when the regulator has a commitment problem.

The perfect commitment to a fixed permit budget T_0 guarantees that the climate policy goal is not exceeded. But the intertemporal allocation of mitigation (K_0, K_1) may not be achieved when the carbon pricing signal is distorted by the innovation market failure (technology externality ψ).

The case in which the regulator cannot commit to T_0 is discussed as a sequential game with lack of commitment. When the regulator cannot commit to the announced high-ambition climate policy, investors may lock the economy into a low-mitigation path, forcing the regulator to reconsider the ambition of the climate policy.

3.1. Intertemporal distortions

The parameter ψ distorts the asset pricing equation of the household compared to the social optimum. To derive instruments σ and κ that address the distortions, we equate the asset returns expressions of the household and the social planner from Eqs. (5) and (13).

$$e^{-(\rho)}\mathbb{E}\left[u'(C_1)\left(\frac{\partial A_1}{\partial K_1}-\frac{\partial A_1}{\partial K_0}\right)\right]=e^{-\rho+\gamma}\mathbb{E}\left[u'\left(C_1\right)\frac{1}{(1-\kappa)}\left((1+\sigma)A_1'-(1-\psi)\,e^{-\gamma}\frac{\partial A_1}{\partial K_0}\right)\right] \tag{18}$$

The expression simplifies to

$$(1-\kappa)=\frac{(1+\sigma)e^{\gamma}\mathbb{E}[u'\left(C_1\right)A_1']+(1-\psi)\,\mathbb{E}\left[u'(C_1)\left(-\frac{\partial A_1}{\partial K_0}\right)\right]}{\mathbb{E}[u'(C_1)A_1']+\mathbb{E}\left[u'(C_1)\left(-\frac{\partial A_1}{\partial K_0}\right)\right]} \tag{19}$$

Eq. (19) shows which combinations of instruments can be used. The following section shows that each instrument is sufficient to restore the optimal allocation.

3.1.1. Intertemporal trading ratio

Eq. (19) contains the distortion $\psi>0$. For $\sigma=\kappa=0$ we have

$$e^{\gamma}=\frac{\psi\mathbb{E}\left[u'\left(C_1\right)\left(-\frac{\partial A_1}{\partial K_0}\right)\right]}{\mathbb{E}\left[u'\left(C_1\right)A_1'\right]} \tag{20}$$

If $\psi>0$ an appropriate choice of the intertemporal trading ratio γ can address this market failure.

3.1.2. Investment subsidy

For $\kappa=\gamma=0$, Eq. (19) can be rearranged to

$$\sigma\mathbb{E}[u'\left(C_1\right)A_1']=\psi\mathbb{E}\left[u'(C_1)\left(-\frac{\partial A_1}{\partial K_0}\right)\right]$$

Intuitively, σ boosts the benefit on investment (left-hand side) to compensate for the share of learning ψ that cannot be appropriated (right-hand side).

3.1.3. Technology subsidy

When $\psi>0$ (and $\sigma=\gamma=0$), it is optimal to set κ as:

$$\kappa=\frac{\psi\mathbb{E}[u'(C_1)(-\frac{\partial A_1}{\partial K_0})]}{\mathbb{E}[u'(C_1)(A_1'-\frac{\partial A_1}{\partial K_0})]}$$

That is, κ is set to the share ψ of the learning effect that is not anticipated (as part of the overall benefit in the denominator).

The three policy instruments (γ, κ and σ) play, in essence, a similar role in attempting to correct the distortions arising from the externalities or factors of political economy. However, the timing of their implementation is different. κ as a technology subsidy is paid upfront to reduce abatement costs in period 0. Therefore, there is no commitment problem for κ. However, both γ and σ, are announced in $t=0$ and implemented in $t=1$ and thus susceptible to a commitment problem. For σ, the problem is less severe, as σ is a contractually agreed bonus and benefits from the commitment power of the legal system. Furthermore, independence from the regulator gives the investment fund more control over its investments.

3.1.4. Instruments and the carbon beta

To further characterize how optimal instruments relate to the carbon beta, we divide the optimal asset pricing Eqs. (6) and (15).

$$\frac{\mathbb{E}\left[(1+\sigma)\,A_1'+(1-\psi)\left(-\frac{\partial A_1}{\partial K_0}\right)\right]}{(1-\kappa)\mathbb{E}\left[\frac{\partial A_1}{\partial K_1}-\frac{\partial A_1}{\partial K_0}\right]}=e^{(r_f+\tilde{\beta}\eta)-\gamma-(r_f+\beta\eta)} \tag{21}$$

The optimal κ is

$$\kappa=1-e^{(\beta-\tilde{\beta})\eta+\gamma}\frac{\mathbb{E}\left[(1+\sigma)\,A_1'+(1-\psi)\left(-\frac{\partial A_1}{\partial K_0}\right)\right]}{\mathbb{E}\left[A_1'-\frac{\partial A_1}{\partial K_0}\right]} \tag{22}$$

The optimal σ is

$$\sigma=e^{(\tilde{\beta}-\beta)\eta-\gamma}(1-\kappa)\frac{\mathbb{E}\left[\frac{\partial A_1}{\partial K_1}-\frac{\partial A_1}{\partial K_0}\right]}{\mathbb{E}\left[A_1'\right]}-\frac{\mathbb{E}\left[A_1'\right]+\mathbb{E}\left[(1-\psi)\left(-\frac{\partial A_1}{\partial K_0}\right)\right]}{\mathbb{E}\left[A_1'\right]} \tag{23}$$

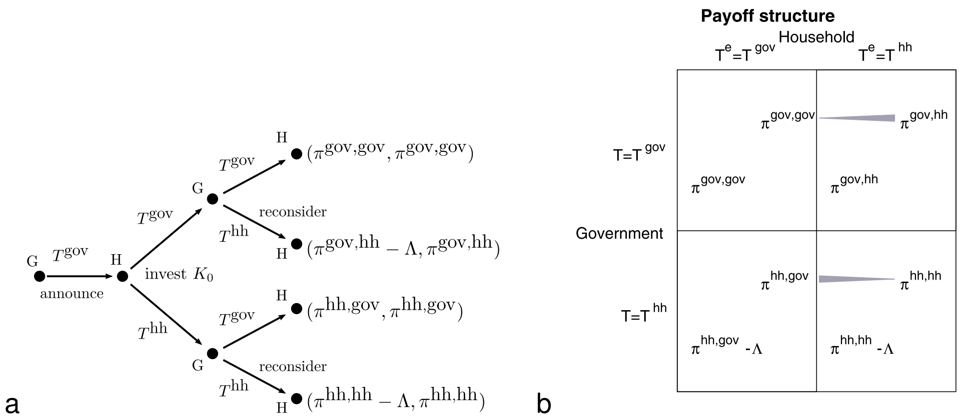

Fig. 1. Commitment problem: The game structure is shown in extended form (panel a) where the government (G) announces the intended budget (T^{gov}), households (H) invest according to T^{gov} or T^{hh} (stage 1) before G decides (stage 2) to remain steadfast (T^{gov}) or tumble in their resolve (T^{hh}). Panel b summarizes the payoff structure.

The optimal instruments κ in (22) and σ in (23) are increasing in the spread between the social carbon beta and the market carbon beta $(\tilde{\beta} - \beta)$. Both optimal instruments, κ and σ, increase with $\tilde{\beta}$ as well as the spread. Hence, when markets estimate a risk premium above the risk premium of the social planner, one of the subsidy instruments of the fund can be increased to compensate, and vice versa if the market's risk premium is lower.

In summary, the instruments of the investment fund can be used to affect asset returns and thus steer the economy towards the socially optimal equilibrium. The risk premium is affected by the innovation market failure, and the optimal policies need to be adjusted accordingly. The direction and significance of this effect, however, remain unclear. In Section 5, we turn to numerical simulations to shed light on the role of the carbon beta as the key determinant of the risk premium and to estimate the order of magnitudes of the distortionary effects on the intertemporal allocation. But first, we discuss the commitment problem of the regulator.

3.2. *Climate policy commitment problem*

A regulator who is not bound to carry out the announced climate policy may reconsider the emission permit budget at $t = 1$ and opt for a more lenient policy by issuing additional emission permits. The regulator may be prompted to reconsider the original policy if the investor does not invest as expected at the time the policy was announced. Gersbach and Glazer (1999) argue that investors may trigger the reconsideration by the regulator by strategically choosing not to invest. Below, we suggest a discrete game of regulator and investor that creates a similar incentive problem. When we use the numerical model to compute the payoff structure for plausible assumptions in Section 5.2, we find that it is indeed rational for the investor to hold up the investment.

3.2.1. *The commitment problem*

To introduce the commitment problem into the model, we consider the case where the regulator and the household consider two discrete possibilities for the ultimate emission budget. When the regulator remains steadfast, no further emissions permits are issued, and the final budget will be equal to the announced budget $T_0 = T^{gov}$. Otherwise, a regulator who topples in their resolve will issue additional emission permits, eventually imposing a high emission budget of $T_0 = T^{hh}$ with $T^{hh} > T^{gov}$.

We assume that when the regulator can commit to the emission budget $T_0 = T^{gov}$ at $t = 0$, the expectation of the household about the emission budget in $t = 1$ will be in line with the announcement, i.e. $T^e = T^{gov}$. When the announcement is not credible, the household will expect $T^e = T^{hh}$. This setup gives rise to a simple two-stage game in which the household can make the investment decision K_0 based on $T^e = T^{gov}$ or $T^e = T^{hh}$ in $t = 0$, whereupon the regulator faces the decision at $t = 1$ to stick with the announced emissions budget $T = T^{gov}$ or issue more permits to a total of $T = T^{hh}$ (cf. Fig. 1a).[11]

The household realizes a payoff π^{ij} $(i, j \in \{gov, hh\})$ when acting in expectation of T^j while the regulator implements T^i. For the regulator, we assume a benevolent objective function, such that the regulator, too, maximizes household payoff π^{ij}. The regulator, however, incurs the cost of not meeting the announced emission budget, which we capture in a penalty term Λ. The penalty may include the anticipated climate change damages to the economy, loss of reputation and cost of noncompliance with international climate treaties (cf. Kalkuhl et al., 2020, for a similar approach). Obviously, the level of Λ will be decisive for the preference of the regulator and the structure of the game.

[11] Strategic behavior by the representative household implies some kind of coordination among the individual households. We assume that households can coordinate by observing each others' investment behavior and can communicate in the sense of tacit collusion.

Fig. 1b presents the payoffs in a 2×2 matrix. If the decision of the regulator is given, the household will always prefer to act in accordance with it, as this allows an efficient and hence welfare maximizing abatement choice (K_0, K_1). We can therefore conclude $\pi^{gov,gov} > \pi^{gov,hh}$ and $\pi^{hh,hh} > \pi^{hh,gov}$ from our model. We indicate this preference by arrows in Fig. 1b.

If there were no costs to political failure (i.e. $\Lambda = 0$) both players would share the same preferences and the game would have two Nash equilibria in symmetric strategies: (T^{gov}, T^{gov}) and (T^{hh}, T^{hh}). Our modeling assumptions further imply $\pi^{hh,hh} > \pi^{gov,gov}$ because the smaller budget implies higher abatement costs. Hence for $\Lambda = 0$ the game has the structure of a no-conflict coordination game (assurance game): there are two alternative Nash equilibria but there is no conflict as the players prefer the same equilibrium.

For higher penalty values (i.e. $\Lambda > \pi^{hh,hh} - \pi^{gov,gov}$) the more interesting case of a conflicting-interests game emerges: the regulator will prefer the ambitious policy equilibrium (T^{gov}, T^{gov}) when the penalty exceeds the difference in payoff between the two equilibria. We summarize our analysis of the game structure in the following proposition.

Lemma 2. *The game between regulator and household defined in Fig. 1 has two Nash equilibria in (T^{gov}, T^{gov}) and (T^{hh}, T^{hh}). Depending on the policy cost relaxing the permit budget (Λ), the structure is either an assurance game or a conflicting interest coordination game:*

1. *Assurance game: for $\Lambda = 0$ both players prefer the low ambition equilibrium (T^{hh}, T^{hh}). The outcome of the sequential game is (T^{hh}, T^{hh}).*
2. *Conflicting interest coordination: if $\Lambda > \pi^{hh,hh} - \pi^{gov,gov}$ the regulator prefers (T^{gov}, T^{gov}) in conflict with the household's preference. The outcome of the sequential game depends further on Λ:*
   (a) *For $\Lambda \leq \pi^{hh,hh} - \pi^{gov,hh}$ the outcome remains (T^{hh}, T^{hh}).*
   (b) *For $\Lambda > \pi^{hh,hh} - \pi^{gov,hh}$, the outcome remains (T^{gov}, T^{gov}) as T^{gov} becomes a dominating strategy for the regulator.*

Proof. Stability of the Nash equilibria follows from the discussion above. In the sequential game, the household can commit by moving first, and thus determine which equilibrium is played. The preference of the household is always for the low ambition equilibrium (T^{hh}, T^{hh}). However, when the regulator always, and despite its inefficiency, prefers the stringent policy (T^{gov}, T^{hh}) to the efficient but low ambition (T^{hh}, T^{hh}) (i.e. $\Lambda > \pi^{hh} - \pi^{gh}$), T^{gov} is a dominant strategy for the regulator. In the sequential game, the household will anticipate this and also play T^{gov}. □

In the following, we are interested in the case of conflicting interest between the regulator and the household where the regulator's commitment problem introduces a deviation from the announced policy (case (a)). Therefore, we select $\Lambda \in (\pi^{hh,hh} - \pi^{gov,gov}, \pi^{hh,hh} - \pi^{gov,hh})$.

Intuitively, the distortion arises from the realization of the household that by delaying investment, as if they knew that the regulator would issue more permits up to T^{hh} at $t = 1$, the household creates a situation where the inefficiency of rushing through abatement at the last minute for T^{gov} at $t = 1$ is so costly that the regulator prefers to revise the policy and to issue additional permits.

3.2.2. Investment fund policies

We can see how the lack of commitment affects the household's incentive to invest from Eq. (12). The permit price p_1 therein is closely related to the shadow price of the emission permit budget equation (Eq. (10), see also λ in Eq. (C.5)), such that inflating the permit budget T_0 via additional permits ω at $t = 1$ implies a lower p_1.

As discussed before, the permit price determines the return on investment. The asset pricing Eq. (12) shows how the investment subsidy σ can counteract this effect by amplifying the remaining carbon price, and the technology subsidy (κ) can achieve a similar effect by reducing investment costs ($\kappa > 0$ in Eq. (12)). When the investment incentive falls short due to the lack of commitment of the regulator, the investment fund can lift the investment incentive to the socially desired level by setting the appropriate subsidy as in Proposition 1. But there is a catch: when the investment is steered to its socially desired level the regulator can keep the announced permit budget T^{gov} without additional costs. The investor will anticipate that the original budget T^{gov} becomes credible, and will thus invest according to a high carbon price (following from T^{gov}) plus the investment subsidy. The result will be an overinvestment at $t = 0$.

The investment fund can work around this by a slight change of the financial contract. Instead of committing unconditionally to paying the optimal bonus σ^*, the contract could tie the bonus to carbon price level at $t = 1$:

$$\sigma = \begin{cases} 0 & \text{if } p_1 = p_1^* \\ \sigma^* & \text{otherwise} \end{cases} \tag{24}$$

Eq. (24) is reminiscent of the idea of a carbon contract for difference, which pays out the difference between a contractually agreed and the actual carbon price to the contract owner (see for example Richstein, 2018). The desired carbon price p_1^* in (24) corresponds to the contractually agreed price. Proposition 1 shows how to close the gap to a given carbon price, instead of directly remunerate the difference in a contract for difference.

This works for the investment subsidy σ but cannot be easily transferred to the technology subsidy κ, as κ is paid out at $t = 0$. When p_1 is observed at $t = 1$ the technology subsidy is already a sunk cost. The resulting incentive distorts the investment decision substantially away from the social optimum. We will numerically investigate this in Section 5.2.

Table 1
Overview of distortions. We report the effects of an externality in technology learning (parameter ψ), in two scenarios for the default learning rate of $lr = 20\%$ and a high learning rate of $lr = 40\%$, and the (equilibrium) effect of (wrongly) expecting a doubling of the carbon budget T by issuing additional permits in the second period. Welfare is given as the difference to undistorted equilibrium in *bps* of constant welfare-equivalent consumption levels.

Scenario		K_0	$E[K_1]$	p_0	$E[p_1]$	r_f	ϕ	η	$r_f + \phi\eta$	Welfare
Default	$\psi = 0.0$	37.1	62.4	84.9	119.2	1.32	1.06	2.26	3.70	0.0
	$\psi = 1.0$	33.4	66.1	78.8	128.5	1.27	0.88	2.26	3.26	−0.5
High lr	$\psi = 0.0$	38.9	60.6	87.9	106.5	1.35	1.16	2.26	3.97	0.0
	$\psi = 1.0$	33.0	66.5	78.1	126.8	1.27	0.87	2.26	3.23	−2.0
$T^e = T^{gov}$		37.1	62.4	84.9	119.2	1.32	1.06	2.26	3.70	0.0
$T^e = T^{hh}$		21.6	77.9	59.0	167.0	1.32	1.41	2.27	4.53	−11.9

4. Calibration

In most parameter choices, we follow the calibration to the European Union in Gollier (2022), which we summarize in Table D.4 in Appendix D. The time periods correspond to the 15-year long periods from 2021–2035 and 2036–2050. An overview of the resulting input distributions to the model are found in Fig. D.4. In the following we discuss the calibration for the model extension to technology learning.

Abatement cost function with learning

Continued use of a given technology builds experience which translates into an improved efficiency of the technology. A prominent approach that captures such technological *learning by doing* is to make its marginal cost dependent on the past cumulative investment (see Guo and Fan, 2017, for a recent example). Learning rates lr that measure the decrease in costs for each doubling of cumulative installed capacity are frequently estimated for renewable energy technologies. Long-term average estimates of learning rates are 15% for wind and 24% for solar PV Bolinger et al. 2022). Renewable energies are a good indicator for the potential of technological learning due to the large increases in capacity since 2010, but learning rates in other mitigation related technologies tell a similar story (e.g. recent estimates (since 2015) on learning rates for battery cost fall in the range 16%–24%, Mauler et al. 2021). Recent years have witnessed still higher learning rates for wind (40% in 2010–2020) and solar photovoltaics (45% in 2014–2020, both estimates from Bolinger et al. 2022).

When technological learning is calibrated using empirical estimates of learning rates, it is implicitly assumed that all cost reductions follow from the use of the technology, ignoring other sources of technological progress such as research and development, and international and interindustry spillovers (Clarke et al., 2006). We therefore select a *default* learning rate of $lr = 20\%$ from the middle of the range of long-term averages. In addition, we explore a scenario with an optimistically *high* learning rate of $lr = 40\%$, i.e. a continuation of the trend observed for renewable energy in recent years. The high learning rate establishes an upper bound on the severity of the innovation market failure (modeled by degree ψ to which the benefits of innovation cannot be appropriated), as the benefits of innovation increase with the potential of technological learning. The learning rate lr translates into the learning elasticity parameter as $lr = 1 - 2^{\alpha}$.

We build on the abatement cost function of Gollier (2022) at $t = 1$ ($A_1(K_1) = \theta K_1 + \frac{1}{2} b K_1^2$). In line with Guo and Fan (2017), we include the learning dynamics in the nonlinear term. Here, past experience is simply given by first-period investment K_0.

$$A_1(K_1, K_0) = \theta K_1 + \frac{1}{2} c_0 K_1^2 K_0^{-\alpha}$$

For consistency with the original calibration, we adjust $c_0 < b$ such that $A_1(K_1) \approx A_1(K_1, K_0)$, taking (K_0, K_1) from the equilibrium without technology learning.

5. Numerical results

In this section we consider two distortions that rationalize an underinvestment: technology learning as an externality to the household, and noncredibility of the emission budget such that households expect additional emission permits to be issued. For both distortions, we analyze their impact on asset pricing and the risk premium and suggest investment fund policies to overcome the resulting inefficiencies. To address the distortions, we consider the intertemporal trading ratio γ of the regulator and fund instruments consisting of subsidies on technology costs or a bonus on investment returns.

Table 1 summarizes the impact of the two distortions on key variables of the model. Both distortions delay abatement, and hence produce a steeper carbon price path. As a measure of the distortion generated when the regulator's announcement of the carbon budget is not credible, we show a scenario where the household invests in anticipation of a higher T but has to face the originally announced low T in the second period. The welfare costs of the distortion are greater for the commitment problem, and are given in the last column of the table as the relative change in equivalent constant consumption. For the commitment problem, the loss of welfare in basis points is 11.9 bps compared to just 0.5 bps for the innovation market failure. The welfare costs of the innovation market failure are substantially larger (four-fold) when we assume an optimistic, high learning rate but even with a learning rate of 40% instead of 20% the welfare costs are overall small. This is plausible considering that (substantial) first period underinvestment is made up in the second period, that is, the distortion is only an intertemporal inefficiency.

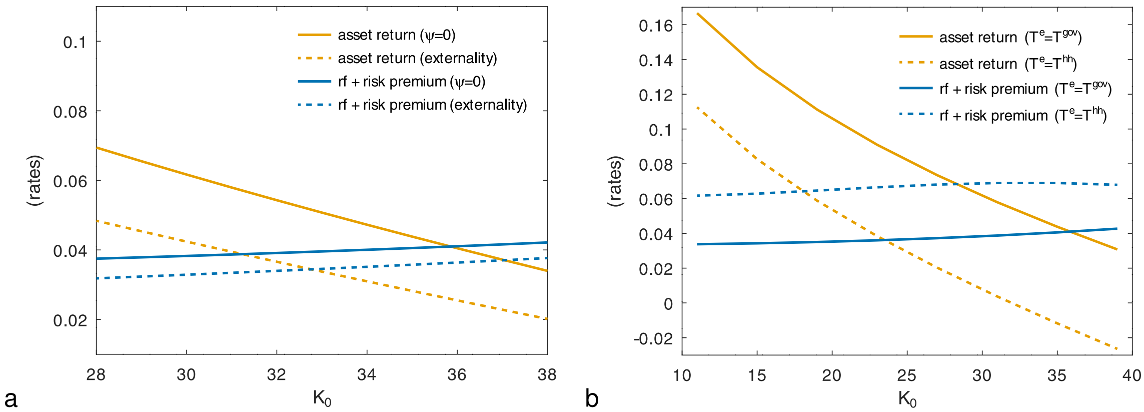

Fig. 2. Technology externality. Panel a shows the asset return as a function of K_0 around the equilibrium (in light orange) as well as the return demanded by investors (in dark blue), with external effects of innovation (dotted lines) and without (solid lines).[12] Intersecting curves of the same line style indicate an equilibrium. Panel b shows the analog graphs for the policy failure (Section 3.2) with the y-axis scaled to double the height of panel a. (The reader is referred to the web version of this article for the figures in colour.)

5.1. Technology externality

Fig. 2 shows asset return and the required rate of return by investors for the economy extended by technological learning. Asset returns were calculated from the expected benefit in (15) over investment costs (left-hand side), the required rate of return is given by $r_f + \tilde{\beta}\tilde{\eta}$ in the same equation. While (15) demands that the two expressions balance in equilibrium, Fig. 2 shows out-of-equilibrium values for a variation of K_0 (except where the corresponding lines intersect).

When technology learning is an externality ($\psi = 1$, dotted lines in Fig. 2a), the asset return is lower than with full appropriation ($\psi = 0$) because the social benefits of innovation are ignored by the household. All else being equal, this would shift the equilibrium to the left. That is, the household would underinvest in K_0.

However, $\psi = 1$ has a second effect: it reduces the carbon beta and hence the risk premium (shifting the red line downward). The carbon beta captures the covariance of the asset return with (growth rate of) consumption C_1.[13] To see why the carbon beta decreases in ψ, note that according to (14) the equilibrium balance of investment cost (left hand side) and benefits is affected by the covariance of marginal utility $u'(C_1)$ with the investment benefit. We can see the implication of technological learning being an externality by rewriting the covariance of this linear combination as

$$\mathrm{Cov}\left(u'(C_1), e^{\gamma} A_1'(1+\sigma) - (1-\psi)\frac{\partial A_1}{\partial K_0}\right) = (1+\sigma)e^{\gamma}\mathrm{Cov}\left(u'(C_1), A_1'\right) - (1-\psi)\mathrm{Cov}\left(u'(C_1), \frac{\partial A_1}{\partial K_0}\right) \tag{25}$$

Both terms, A_1' and $\partial A_1 \partial K_0$ depend only on K_1 in their stochastic realizations but vary in opposite directions as $A_1'' > 0$ (strictly convex abatement costs) while $\partial^2 A_1/(\partial K_1 \partial K_0) < 0$ (technology learning reduces marginal abatement costs). It is therefore plausible that the covariances in the right hand side of (25) have opposite signs. Their difference is, hence, increasing in ψ in absolute terms.

Intuitively, technological learning creates an additional benefit of investing, namely reduced abatement costs at $t = 1$. Both the direct return (abatement costs saved) and this indirect return (lower marginal abatement costs) scale with abatement K_1. Hence, the learning effect amplifies the benefit and strengthens the covariance with C_1 which is reflected in a larger carbon beta. With $\psi > 0$, the benefits of learning are not internalized, such that the resulting benefit is not as closely linked to consumption growth. Thus, the greater the extent to which technology learning is external (larger ψ), the lower the carbon beta from the perspective of the household.

In equilibrium, the reduced carbon beta implies a lower required rate of return which means a higher investment K_0. The implications of ψ on the asset return and the required rate of return including the risk premium thus work in opposite directions. In our calibration, the asset pricing effect is dampened by the risk premium effect but the former outweighs the latter: the overall effect of the technology externality is an underinvestment in K_0.

5.2. Policy failure: noncredible climate policy

In this section, we numerically explore scenarios where the regulator is unable to commit to the low emission budget $T_0 = T^{gov}$ announced at $t = 0$.

[12] The equation for the carbon beta $\tilde{\beta}$ in (16) is only approximate (using Taylor approximation and assumptions of log-normality). For equilibrium scenarios (Tables 1 and 2) we therefore compute the carbon beta as a residual of asset return and risk-free rate ($\tilde{\beta} = (r_A - r_f)/\tilde{\eta}$). The out-of-equilibrium $r_f + \tilde{\beta}\tilde{\eta}$ in Fig. 2a and b are computed from an OLS regression of r_A and $\ln(C_1/C_0)$ (cf. Gollier, 2022), and values therefore differ slightly from Tables 1 and 2.

[13] Since only the second period consumption C_1 is stochastic, the growth rate of consumption is fully determined by C_1.

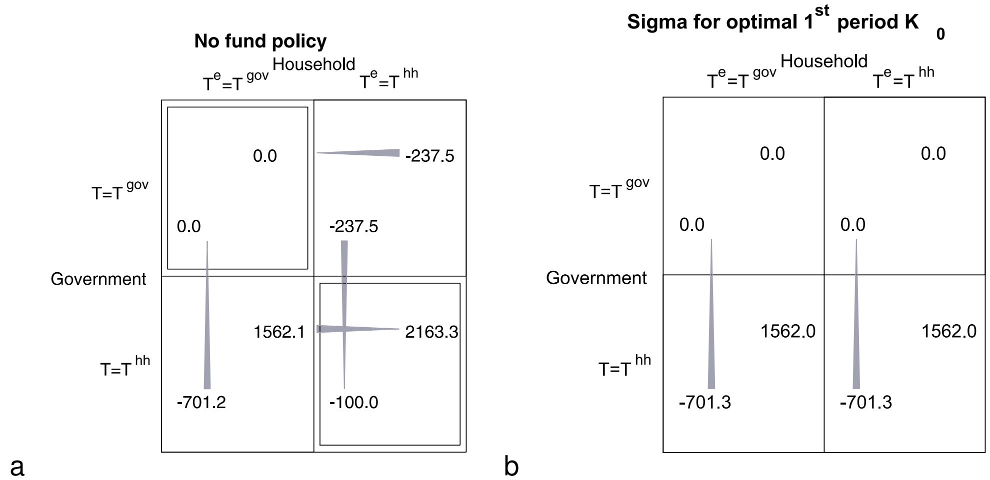

Fig. 3. Payoff structure for the commitment game. Gray arrows indicate preferences, gray boxes indicate Nash equilibria without interference from the investment fund (panel a) and with σ policy by the fund (panel b). Payoffs are in constant-equivalent consumption levels (billion US$ for the 30 year time period).

Fig. 2b visualizes the impact of shifting from a stringent budget of $T^{hh} = 40$ GtCO2e to a lenient budget of $T^{gov} = 80$ GtCO2e. The rate of return is substantially lower for the inflated budget, which reflects the deteriorated carbon price for this budget. This implies an underinvestment in K_0. Relaxing the permit budget also affects the carbon beta. The risk premium is considerably higher for the larger budget, mainly due to a more than two-fold increase of the carbon beta. Intuitively, for a lenient budget less abatement is required. In equilibrium, in particular the first-period abatement is reduced, delaying most of the abatement to $t = 1$. Second period abatement, which is decisive for carbon price and asset return is thus more closely linked to second period emissions. Economic output Y_1, which is tightly correlated with consumption C_1, determines emissions and therefore whether the permit constraint is binding or nonbinding. In the latter case, no more abatement is required and the carbon price is minimal; hence, uncertainty about abatement costs and climate become less relevant. When uncertainty about economic growth dominates, the remaining variance in asset returns will be more closely related to it, resulting in a larger covariance which translates into a higher carbon beta. When the investor subsequently demands a higher risk premium, the effect on K_0 works in the same direction as the reduced rate of return, thus amplifying the underinvestment.

Noncredible regulator

Fig. 3a shows the payoff matrix in constant equivalent consumption levels of the household's welfare. We normalize $\pi^{gov,gov}$ to zero to ease comparison. The payoff structure supports two outcomes as Nash equilibria when regulator and household decide simultaneously: (T^{gov}, T^{gov}) and (T^{hh}, T^{hh}), where regulator and household prefer different equilibria. In such a *conflicting interest coordination game* players can pick the game outcome if they can credibly commit to their strategy. In our case, the household moves first (deciding on investment K_0 at $t = 0$) and can therefore select (T^{hh}, T^{hh}).

Commitment by investment fund subsidies

The investment fund can support the regulator's policy announcement by subsidizing technology or investment in abatement at $t = 0$ to align investment K_0 with the regulator's target even when the household expects additional permits at $t = 1$. As discussed in Section 3.2.2, when the subsidy raises the incentive to invest to its optimal level, the commitment problem of the regulator is overcome thus eliminating the need to pay the subsidy. We take this into account by making the investment subsidy contract σ dependable on the carbon price at $t = 1$ (see Eq. (24)). This is not possible for κ and we discuss the consequences below.

Ideally, the fund subsidizes K_0 up to its optimal level for the T^{gov} budget. In this case, (T^{gov}, T^{hh}) is identical to (T^{gov}, T^{gov}), and these two become Nash equilibria instead of formerly (T^{hh}, T^{hh}).[14] This game-theoretic setting provides compelling insights into the sequencing of climate policy; the investment fund can pave the path for carbon pricing in later periods. The inability of the regulator to commit to the announced carbon price in a credible way creates a situation where households demand a higher risk premium and subsequently underinvest. When the investment fund pays subsidies, it incentivizes the household to increase abatement in earlier periods. This eliminates the conflict and reduces the risk premium to its socially optimal level. The intertemporal allocation of investment is not distorted. Additionally, due to the investment funds strategy, the social optimum is a Nash equilibrium. It should also be noted that carbon pricing needs to remain an essential part of the policy package, otherwise welfare costs will increase, and the budget constraint will be violated.

[14] Where payoffs in a Nash Equilibrium are *weakly greater* than any payoff that a player may achieve by changing strategies (all else equal).

Table 2
Commitment problem and policies σ, κ. To isolate the distortion by the commitment problem, we assume $\psi = 0$ (no externality in technological learning). Row 1 shows the social optimum for a credible $T^{gov} = 40$ (welfare maximizing σ is zero). The next scenarios show the outcome of strategy pairs (T^{hh}, T^{hh}) (row 2) and (T^{hh}, T^{gov}) (row 3). Row 4 shows a policy σ that restores K_0 as in row 1 but the government relaxed T in the second period, in contrast to row 5, where $T = T^{gov}$ is implemented. The bottom rows are analogous for κ instead of σ but while σ in row 5 is conditioned on p_1 (cf. Proposition 3), κ is paid unconditionally. We left return numbers blank where K_0 is decided based on the previous row. The last columns show the efficiency costs of inaction by the regulator. We show the loss of welfare (ΔW in percent balanced growth equivalent change) and abatement costs (ΔA_1 in percent change) relative to the optimal solution for the implemented carbon budget.

Baseline with no credible carbon budget $T^{hh} = T^{gov}$															
T^{hh}	T^{gov}	σ	p_0	$E[p_1]$	I_0	$E[B_1]$	$E[r_A]$	K_0	$E[K_1]$	r_f	ϕ	η	$r_f + \phi\eta$	ΔW	ΔA_1
40	40	0.00	84.9	119.2	84.9	147.8	3.69	37.1	62.4	1.30	1.06	2.26	3.69	0.000	0.0
Noncredible carbon budget with $T^{hh} > T^{gov}$															
T^{hh}	T^{gov}	σ	p_0	$E[p_1]$	I_0	$E[B_1]$	$E[r_A]$	K_0	$E[K_1]$	r_f	ϕ	η	$r_f + \phi\eta$	ΔW	ΔA_1
80	80	0.00	58.9	92.7	58.9	117.1	4.58	21.5	38.3	1.35	1.43	2.25	4.58	0.000	0.0
80	40	0.00	58.9	167.3	58.9	256.9		21.5	78.0					0.120	65.4
80	80	1.67	84.9	58.3	84.9	160.6	4.25	37.1	23.7	1.46	1.23	2.27	4.25	0.099	−54.6
80	40	1.67	84.9	119.2	84.9	346.4		37.1	62.4					0.000	0.0
T^{hh}	T^{gov}	κ	p_0	$E[p_1]$	I_0	$E[B_1]$	$E[r_A]$	K_0	$E[K_1]$	r_f	ϕ	η	$r_f + \phi\eta$	ΔW	ΔA_1
80	80	0.00	58.9	92.7	58.9	117.0	4.57	21.5	38.2	1.35	1.43	2.25	4.57	0.000	0.0
80	40	0.00	58.9	167.2	58.9	256.6		21.5	78.0					0.120	65.3
80	80	0.61	33.0	58.3	33.0	63.5	4.36	37.1	23.7	1.46	1.28	2.27	4.36	0.099	−54.6
80	40	0.61	46.2	78.9	46.2	86.9		57.3	42.4					0.155	−49.9

Proposition 3. *The suboptimal outcome of the sequential game with conflicting interest can be avoided by setting the subsidy instrument of the fund (σ) to its welfare maximizing level conditional on the current carbon price being too low, i.e. below the level consistent with $T = T^{gov}$:*

$$\sigma = \begin{cases} 0 & \text{if } p_1 = p_1^* \\ \sigma^* & \text{otherwise} \end{cases}$$

Table 2 presents additional numbers from the numerical simulations. Row 1 is the reference case with credible commitment, or (T^{gov}, T^{gov}). Rows 2 and 3 show computations for noncredible emission budgets: households expect additional permits and thus an overall budget well above the efficient budget of row 1. In row 2, the government provides additional permits; row 3 is the case where the government keeps to the originally announced budget. Rows 4 and 5 are analogous to rows 2 and 3 but include the fund policy σ, set according to Proposition 3. To compute rows 3 and 5 we ran the model for $T = T^{hh}$ to calculate the first stage decision of K_0. Then, taking K_0 as given we ran the model for the second stage of K_1 for $T = T^{gov}$. The investment decision in these row was taken with the expectation of a rate of return $E[r_A]$ reported in the row above, and therefore we omit values that related to the investment decision. Rows 6 shows results for κ^* set to the level that induces optimal investment K_0 despite $T^e = T^{hh}$. For row 7, we compute the household decision K_0 for $T^e = T^{gov}$ and the subsidy κ^*. That is, rows 6–7 are analogous to rows 4–5 except that κ is set unconditionally whereas σ follows Proposition 3.

Rows 1 and 2 mirror the equilibria in Fig. 1a for low and high T, respectively. As discussed above, moving to a larger emission budget lowers the asset return while increasing the equilibrium risk premium, and investment in equilibrium K_1 is reduced.

In equilibrium, the asset return is higher for the larger budget (row 2 versus row 1) due to a higher growth rate of the carbon price — but at a much lower price level (cf. p_0, $E[p_1]$). The carbon beta is substantially larger for the higher budget.

In the policy scenario (row 4), notice that the investment benefit B_1 includes the fund investment subsidy, such that the benefits (and subsequently the asset return) almost match the reference case benefits (row 1) despite a much lower carbon price at $t = 1$.

The two cost metrics ΔW and ΔA_1 in the last columns measure gains in welfare (in percent balanced growth equivalents) and abatement costs (percent), respectively, relative to the planner solution with the same carbon budget. Abatement costs are substantially higher in $t = 1$ where the household expects additional emission permits that are not supplied by the regulator (row 3). The welfare loss ΔW underlines the temptation of the regulator to revise the announced policy. The scenario with intervention by the investment fund (row 4) shows similar welfare losses; here, the decision of the regulator to enlarge the budget distorts the economy unnecessarily, as the fund policy has incentivized the efficient abatement decision K_0. However, the substantially reduced abatement costs (even below their efficient level) show that the fund policy has prepared the economy for a more ambitious carbon budget. In row 5, setting σ as in Proposition 3 in combination with the efficient carbon budget restores the efficient solution of row 1.

Rows 6–7 show analogous computations for a technology subsidy (κ) instead of the investment subsidy (σ). We highlight the following differences:

- The technology subsidy reduces investment costs rather than boosting their benefit, which is reflected in much lower I_0 and B_1.
- The resulting $r_A = \ln(B_1/I_0)$ is higher for κ as κ is paid regardless of the level of the carbon price.
- The high rate of return causes an inefficient overinvestment in K_0. The last column shows the welfare costs.

Table 3
Summary of distortion effects on asset return and risk premium. We distinguish the direct effect, keeping everything else the same (*ceteris paribus*), i.e. without adjustment of the investment decision K_0, and the entirety of equilibrium effects, i.e. after K_0 is adjusted to the new (distorted) equilibrium. We show reductions and increases relative to the undistorted equilibrium using ⊖ and ⊕.

	Asset return		Risk premium	
	ceteris paribus	Equilibrium	ceteris paribus	Equilibrium
Technology externality (ψ)	⊖	⊖	⊖	⊖
Noncredibility (T^{gov})	⊖	⊕	⊕	⊕

We summarize the results of the numerical analysis in Table 3, which reports the changes in asset prices and risk premium caused by the policy instruments under *ceteris paribus* conditions and in a general equilibrium setting. In the first case, the abatement investments are fixed; in the second setting, the abatement investments are adjusted to the optimal level. All else being equal, the technology externality reduces the risk premium, while noncredibility of the emission budget raises the risk premium.

6. Conclusions

This paper studies the incentives to invest in emission abatement as set by climate policy instruments in a CCAPM model. This modeling approach allows us to trace the carbon beta of abatement investments to climate policy instruments, e.g. carbon pricing, a subsidy on technology costs and a bonus on return on investment. Additionally, we considered the risk premium induced by the lack of commitment of the regulator.

Studying climate policy through the lens of financial economics provides several crucial insights. First, the covariance, and therefore the risk premium, play a role for the design of climate policy instruments. An investment that pays off when economic growth is low is worth more than an investment that pays off when wealth is abundant. This basic truth from financial economics carries over to abatement investment and hence climate policy analysis. Policy instruments change the investment pathway and return and, therefore, the carbon beta. We find that the effect of climate policy instruments on the risk premium of abatement investments may be increasing or decreasing depending on the nature of the distortion that is addressed by the instrument.

Second, financial market actors such as an investment fund can in principle address the distortions by setting financial incentives for green investment but need to take into account the potentially distorted risk perception of investors. Financial incentives for investors can complement a carbon pricing policy and cure its dynamic inefficiency or pave the path towards more ambitious carbon pricing. The policy failure experiments have also emphasized the importance of carbon pricing. Carbon prices that reflect a lack of commitment exhibit a substantial potential to cause an increase in the risk premium, which then acts as a brake on abatement and climate policy.

Third, the nascent literature on applying asset pricing theory to climate change mitigation has focused its analysis on how risk and uncertainty affect first-best mitigation policies and the associated social costs of carbon or carbon price trajectories which are consistent with the carbon budget. The approach taken in this paper is intended to connect the second-best analysis with this financial economics approach. We have shown that the risk premium is a fundamental endogenous variable determined by the regulator and agents on the financial markets, here, a long-term investment fund. The welfare losses of a distorted risk premium might be significant given the misallocation of capital.

This study takes a first step to discuss climate policy as an asset pricing problem in a second-best setting. While the simple framework illustrates the key role of correlated risks our analysis remains stylized in many aspects with room for improvements and extensions. Not all of the distortions that we considered are modeled endogenously, and integrating a micro-foundation for the distortion (as with the technology externality) could produce further insights. Of course, extensions could add additional distortions to the model. Short- and long-termism of investors or the introduction of incomplete markets into the model may be particularly interesting to shed light on the role of institutional investors.

While early assessments of optimal carbon pricing and second-best policy instruments relied on deterministic settings, more recent work has included uncertainties and asset pricing logic in the discussion of optimal carbon prices. Climate policy assessment can benefit enormously when climate economics is combined with financial economics. The large uncertainties that are ubiquitous in the assessment of climate policy can translate to substantial risk premiums in the calculus of investors, and it is important that policy instruments take this into account. Getting a better understanding of the level and structure of risk premiums will help avoid the misallocation of scarce resources. This is an important part of climate economics.

CRediT authorship contribution statement

Ottmar Edenhofer: Conceptualization, Formal analysis, Investigation, Writing – review & editing. **Kai Lessmann:** Formal analysis, Funding acquisition, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Ibrahim Tahri:** Formal analysis, Investigation, Writing – review & editing, Validation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Writeful's Language Check in order to eliminate language errors. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A. Asset pricing equation of the social planner

The Lagrangian reads

$$\begin{aligned}\mathcal{L} &= u(Y_0 - A_0(K_0)) + e^{-\rho}\mathbb{E}[u(Y_1 - A_1(K_0, K_1))] \\ &\quad + \lambda[(Q_0Y_0 - K_0) + (Q_1Y_1 - K_1) - T]\end{aligned} \tag{A.1}$$

We consider first-order conditions with respect to K_0 and K_1.

$$\frac{\partial \mathcal{L}}{\partial K_0} \stackrel{!}{=} 0 \Leftrightarrow u'(C_0)(-A_0') + e^{-\rho}\mathbb{E}\left[u'(C_1)\left(-\frac{\partial A_1}{\partial K_0}\right)\right] - \lambda = 0 \tag{A.2}$$

$$\Leftrightarrow u'(C_0)(-A_0') + e^{-\rho}\mathbb{E}\left[u'(C_1)\left(-\frac{\partial A_1}{\partial K_0}\right)\right] = \lambda \tag{A.3}$$

$$\Leftrightarrow u'(C_0)A_0' + e^{-\rho}\mathbb{E}\left[u'(C_1)\left(\frac{\partial A_1}{\partial K_0}\right)\right] = -\lambda \tag{A.4}$$

$$\frac{\partial \mathcal{L}}{\partial K_1} \stackrel{!}{=} 0 \Leftrightarrow e^{-\rho}\mathbb{E}\left[u'(C_1)\left(-\frac{\partial A_1}{\partial K_1}\right)\right] + \lambda[-1] = 0 \tag{A.5}$$

$$\Leftrightarrow e^{-\rho}\mathbb{E}\left[u'(C_1)\frac{\partial A_1}{\partial K_1}\right] = -\lambda \tag{A.6}$$

Eliminate λ.

$$u'(C_0)(A_0') + e^{-\rho}\mathbb{E}\left[u'(C_1)\left(\frac{\partial A_1}{\partial K_0}\right)\right] = e^{-\rho}\mathbb{E}\left[u'(C_1)\left(\frac{\partial A_1}{\partial K_1}\right)\right] \tag{A.7}$$

Rearranging yields the asset pricing Eq. (5).

Appendix B. Proof of Lemma 1

Lemma 1. *Consider a representative agent with time-additive expected utility, with a subjective discount rate ρ and a constant relative risk aversion ξ, in a discrete-time setting with a risk-free asset. Assuming the relative growth rate of consumption $g_\tau^c = c_\tau/c_0 - 1$ and gross return $R_\tau^A = \frac{A_\tau'}{A_0'}$ to be jointly lognormally distributed, then*

$$\frac{1}{\tau}\ln\left(\mathbb{E}\left[R_\tau^A\right]\right) = \frac{1}{\tau}\ln R^f + \frac{1}{\tau}\xi\sigma_{g^c}Corr\left[\ln R_\tau^A, \ln\frac{c_\tau}{c_0}\right]\sigma[\ln R_\tau^A]$$

and in beta-form

$$\frac{1}{\tau}\ln\left(\mathbb{E}\left[\frac{A_\tau'}{A_0'}\right]\right) = r^f + \beta\eta$$

or

$$\mathbb{E}\left[\frac{A_\tau'}{A_0'}\right]^{\frac{1}{\tau}} = e^{r^f + \beta\eta}$$

with

$$\beta = \frac{Cov\left[r_\tau, \tilde{g}_\tau^c\right]}{Var\left[\tilde{g}_\tau^c\right]} \tag{B.1}$$

$$\eta = \frac{1}{\tau}\gamma Var\left[\tilde{g}_\tau^c\right] \tag{B.2}$$

and r^f, r_τ, and $\tilde{g}_\tau^c$ represent respectively $\ln R^f$, $\ln R_\tau$, *and* $\ln\frac{c_\tau}{c_0}$.

Proof. The price of a risky asset can be expressed as[15]:

$$P_{i,\tau} = \mathbb{E}\left[m_\tau B_{i,\tau}\right]$$

with $B_{i,\tau}$ representing the payoff (benefit) of the risky asset and m_τ the stochastic discount factor (also known as the state-price deflator) which is defined as $m_\tau \equiv \varphi u'\left(c_\tau\right)/u'\left(c_0\right)$ with φ the discount factor

$$\mathbb{E}\left[m_\tau B_{i,\tau}\right] = \mathbb{E}\left[m_\tau\right]\mathbb{E}\left[B_{i,\tau}\right] + \text{Cov}\left[B_{i,\tau}, m_\tau\right]$$

$$P_{i,\tau} = \mathbb{E}\left[m_\tau\right]\mathbb{E}\left[B_{i,\tau}\right] + \text{Cov}\left[B_{i,\tau}, m_\tau\right]$$

According to the asset pricing model, even though expected returns can vary across assets and time, expected discounted returns should be the same equal to 1. Then,

$$1 = \mathbb{E}\left[m_\tau\right]\mathbb{E}\left[R_{i,\tau}\right] + \text{Cov}\left[R_{i,\tau}, m_\tau\right]$$

$$\mathbb{E}[R_{i,\tau}] = \frac{1}{\mathbb{E}\left[m_\tau\right]} - \frac{1}{\mathbb{E}\left[m_\tau\right]}\text{Cov}\left[R_{i,\tau}, m_\tau\right]$$

$$\mathbb{E}[R_{i,\tau}] = R_t^f - \frac{\text{Cov}\left[R_{i,\tau}, u'\left(c_\tau\right)/u'\left(c_0\right)\right]}{\mathbb{E}\left[u'\left(c_\tau\right)/u'\left(c_0\right)\right]}$$

$$\mathbb{E}[R_{i,\tau}] - R_t^f = -\frac{\sigma\left[u'\left(c_\tau\right)/u'\left(c_0\right)\right]}{\mathbb{E}\left[u'\left(c_\tau\right)/u'\left(c_0\right)\right]}\sigma_t\left[R_{i,\tau}\right] Corr\left[R_{i,\tau}, \frac{u'\left(c_\tau\right)}{u'\left(c_0\right)}\right] \tag{B.3}$$

Instead of using marginal utility of consumption, we establish a relation between *expected returns* and *consumption* itself. With the assumed CRRA preferences of the agent, $u(c) = c^{1-\xi}/(1-\xi)$, and the lognormally distribution of growth of consumption, we have:

$$\frac{u'\left(c_\tau\right)}{u'\left(c_0\right)} = \left(\frac{c_\tau}{c_0}\right)^{-\xi} = \exp\left\{-\xi \ln\left(\frac{c_\tau}{c_0}\right)\right\},$$

which is lognormally distributed, $\ln\left(\frac{c_\tau}{c_0}\right) \sim N\left(\bar{g}, \sigma_{gc}^2\right)$; therefore,

$$\mathbb{E}\left[\frac{u'\left(c_\tau\right)}{u'\left(c_0\right)}\right] = \mathbb{E}\left[\exp\left\{-\xi \ln\left(\frac{c_\tau}{c_0}\right)\right\}\right] = \exp\left\{-\xi\bar{g} + \frac{1}{2}\xi^2\sigma_{gc}^2\right\}$$

and

$$\frac{\sigma\left[u'\left(c_\tau\right)/u'\left(c_0\right)\right]}{\mathbb{E}\left[u'\left(c_\tau\right)/u'\left(c_0\right)\right]} = \sqrt{e^{\xi^2\sigma_{gc}^2} - 1} \tag{B.4}$$

for small $\xi^2\sigma_{gc}^2 \approx 0$ we can approximate $e^{\xi^2\sigma_{gc}^2}$ to be $1 + \xi^2\sigma_{gc}^2$, hence

$$\sqrt{e^{\xi^2\sigma_{gc}^2} - 1} \approx \xi\sigma_{gc} \tag{B.5}$$

$Corr\left[R_{i,\tau}, u'(c_\tau)/u'(c_0)\right]$ can be approximated as follow: Applying a first-order Taylor approximation of $\frac{u'(c_\tau)}{u'(c_0)} = \left(\frac{c_\tau}{c_0}\right)^{-\xi}$ around 1, we get:

$$\left(\frac{c_\tau}{c_0}\right)^{-\xi} \approx 1 - \xi\left(\frac{c_\tau}{c_0} - 1\right)$$

hence,

$$\begin{aligned} Corr\left[R_{i,\tau}, \frac{u'\left(c_\tau\right)}{u'\left(c_0\right)}\right] &= Corr\left[R_{i,\tau}, \left(\frac{c_\tau}{c_0}\right)^{-\gamma}\right] \approx Corr\left[R_{i,\tau}, 1 - \gamma\left(\frac{c_\tau}{c_0} - 1\right)\right] \\ &= \frac{\text{Cov}\left[R_{i,\tau}, 1 - \gamma\left(\frac{c_\tau}{c_0} - 1\right)\right]}{\sigma\left[R_{i,\tau}\right]\sigma\left[1 - \gamma\left(\frac{c_\tau}{c_0} - 1\right)\right]} = -\gamma\frac{\text{Cov}\left[R_{i,\tau}, (c_\tau/c_0)\right]}{\sigma\left[R_{i,\tau}\right]\sigma\left[(c_\tau/c_0)\right]} = -Corr[R_{i,\tau}, (c_\tau/c_0)] \end{aligned} \tag{B.6}$$

Plugging results from (A.4)–(A.5) and (A.6) back into [A.3], we get

$$\mathbb{E}[R_{i,\tau}] - R^f \approx \xi\sigma_{gc}\sigma\left[R_{i,\tau}\right] Corr[R_{i,\tau}, (c_\tau/c_0)] \tag{B.7}$$

[15] See Cochrane (2001) for more general asset pricing models.

with the additional assumption that both gross rate of return R_i of the asset and the consumption growth g^c are jointly lognormally distributed. In that case,

$$\mathbb{E}[\ln(R_\tau)] - \ln R^f + \frac{1}{2}\text{Var}[\ln R_\tau] = \xi\sigma_{g^c} Corr\left[\ln R_\tau, \ln \frac{c_\tau}{c_0}\right]\sigma[\ln R_\tau] \tag{B.8}$$

equivalently,

$$\ln(\mathbb{E}[R_\tau]) - \ln R^f = \xi\sigma_{g^c} Corr\left[\ln R_\tau, \ln \frac{c_\tau}{c_0}\right]\sigma[\ln R_\tau] \tag{B.9}$$

Following Gollier, P_0 is equivalent to A'_0 and $B_\tau = A'_\tau$, and φ the discount factor can be expressed as $\varphi = e^{-\rho\tau}$. Hence,

$$R_\tau = \frac{B_\tau}{P_0} = \frac{A'_\tau}{A'_0} = R^A_\tau \tag{B.10}$$

Then we can re-write Eq. (B.8) as

$$\begin{aligned}
&\mathbb{E}\left[\ln\left(\frac{A'_\tau}{A'_0}\right)\right] - \ln R^f + \frac{1}{2}\text{Var}\left[\ln\left(\frac{A'_\tau}{A'_0}\right)\right] = \xi\sigma_{g^c} Corr\left[\ln R_\tau, \ln\frac{c_\tau}{c_0}\right]\sigma\left[\ln(R_\tau)\right]\\
&\ln\left(\mathbb{E}\left[\frac{A'_\tau}{A'_0}\right]\right) = \ln R^f + \xi\sigma_{g^c} Corr\left[\ln R_\tau, \ln\frac{c_\tau}{c_0}\right]\sigma\left[\ln(R_\tau)\right]\\
&\ln\left(\mathbb{E}\left[\frac{A'_\tau}{A'_0}\right]\right) = \ln\left(\frac{1}{e^{-\rho\tau}\mathbb{E}\left[u'(c_\tau)/u'(c_0)\right]}\right) + \xi\sigma_{g^c} Corr\left[\ln R^A_\tau, \ln\frac{c_\tau}{c_0}\right]\sigma\left[\ln(R^A_\tau)\right]\\
&\ln\left(\mathbb{E}\left[\frac{A'_\tau}{A'_0}\right]\right) = \tau + \rho\tau - \ln\left(\mathbb{E}\left[\frac{u'(c_\tau)}{u'(c_0)}\right]\right) + \xi\sigma_{g^c} Corr\left[\ln R^A_\tau, \ln\frac{c_\tau}{c_0}\right]\sigma\left[\ln(R^A_\tau)\right]
\end{aligned}$$

The equity premium can be expressed in "beta-form"

$$\underbrace{\frac{1}{\tau}\ln\left(\mathbb{E}\left[\frac{A'_\tau}{A'_0}\right]\right)}_{g} = \underbrace{\rho - \frac{1}{\tau}\ln\left(\mathbb{E}\left[\frac{u'(c_\tau)}{u'(c_0)}\right]\right)}_{r^f} + \frac{1}{\tau}\xi\sigma_{g^c} Corr\left[\ln R^A_\tau, \ln\frac{c_\tau}{c_0}\right]\sigma\left[\ln(R^A_\tau)\right]$$

$$g = r^f + \beta\eta \tag{B.11}$$

with,

$$\beta\left[r_\tau, \tilde{g}^c_\tau\right] = \frac{\text{Cov}\left[r_\tau, \tilde{g}^c_\tau\right]}{\text{Var}\left[\tilde{g}^c_\tau\right]}$$

$$\eta = \frac{1}{\tau}\xi\text{Var}\left[\tilde{g}^c_\tau\right] \quad \square$$

Appendix C. Asset pricing equation of the household

To derive its asset pricing equation, we restate the problem of the household (11).

$$\begin{aligned}
\mathcal{L} = {} & u(Y_0 - A_0(K_0))\\
& + e^{-\rho}\mathbb{E}\left[u(Y_1 - A_1(K_0, K_1) + \sigma p_1 e^\gamma (K_0 - \bar{K}_0) - p_1\omega)\right]\\
& + \lambda[T_0 - (Q_0Y_0 - K_0) - e^{-\gamma}(Q_1Y_1 - K_1 - \omega)]
\end{aligned} \tag{C.1}$$

For the optimal abatement choice K_1 at $t = 1$ we have

$$\frac{\partial\mathcal{L}}{\partial K_1} = 0 \quad \Leftrightarrow \quad 0 = e^{-\rho}\mathbb{E}[u'_1(-A'_1)] + \lambda[e^{-\gamma}] \tag{C.2}$$

$$\lambda = e^{-\rho+\gamma}\mathbb{E}[u'_1 A'_1] \tag{C.3}$$

For period $t = 1$, we first consider the choice of additional permits ω.

$$\frac{\partial\mathcal{L}}{\partial\omega} = 0 \quad \Leftrightarrow \quad 0 = e^{-\rho}\mathbb{E}[u'_1 \cdot (-p_1)] + \lambda[-e^{-\gamma}] \tag{C.4}$$

$$\lambda = e^{-\rho+\gamma}\mathbb{E}[u'_1 p_1] \tag{C.5}$$

Note that the shadow price λ of the permit budget equation is the expected permit price p_1 (when properly discounted and converted to utility units). By substituting in (C.3) we learn that the permit price p_1 reflects marginal abatement costs A'_1:

$$e^{-\rho+\gamma}\mathbb{E}[u'_1 A'_1] = e^{-\rho+\gamma}\mathbb{E}[u'_1 p_1] \tag{C.6}$$

Table D.4
Benchmark calibration of the two-period model.

Parameter descriptions	Notations	Values
Annual rate of pure preference for the present	ρ	0.5%
Parameter of relative risk aversion	ξ	3
Annual probability of a macroeconomic catastrophe	p	1.7%
Mean growth rate of production in a business-as-usual year	μ_{bau}	2%
Volatility of the growth rate of production in a Business-as-usual year	σ_{bau}	2%
Mean growth rate of production in a catastrophic year	μ_{cat}	−35%
Volatility of the growth rate of production in a catastrophic year	σ_{cat}	25%
Production in the first 15-year period (in trillion US$)	Y_0	315
Carbon intensity of production in period 0 (in $GtCO_2e/GUS\$$)	Q_0	2.10×10^{-4}
Carbon intensity of production in period 1 (in $GtCO_2e/GUS\$$)	Q_1	1.85×10^{-4}
Expected carbon budget (in $GtCO_2e$)	μ_T	40
Standard deviation of the carbon budget (in $GtCO_2e$)	σ_T	10
Slope of the marginal abatement cost functions (in $GUS\$/GtCO_2e^2$)	b	1.67
Slope of marginal abatement cost with learning (in $GUS\$/GtCO_2e^2$)	c_0	5.04
Technology learning rate (in percent)	lr	20.0
Marginal cost of abatement in the BAU, first period (in $GUS\$/GtCO_2e$)	a_0	23
Expected future log marginal abatement cost in BAU	μ_θ	2.31
Standard deviation of future log marginal abatement cost in BAU	σ_θ	1.21
Degree of externality of technological learning	ψ	1.0
Penalty for relaxing the permit budget (const. equiv. cons. level)	Λ	2240

$$\mathbb{E}[u_1' A_1'] = \mathbb{E}[u_1' p_1] \tag{C.7}$$

Abatement K_0 at $t = 0$ follows from:

$$\frac{\partial \mathcal{L}}{\partial K_0} = 0 \quad \Leftrightarrow \quad 0 = u_0'(-(1-\kappa)\,A_0') + e^{-\rho}\mathbb{E}[u_1'(-\frac{\partial A_1}{\partial K_0} + \sigma p_1 e^{\gamma})] + \lambda \tag{C.8}$$

$$(1-\kappa)\,u_0' A_0' = e^{-\rho}\mathbb{E}[u_1'(-\frac{\partial A_1}{\partial K_0} + \sigma p_1 e^{\gamma})] + \lambda \tag{C.9}$$

$$= e^{-\rho}\mathbb{E}[u_1'(-\frac{\partial A_1}{\partial K_0} + \sigma p_1 e^{\gamma})] + \lambda \tag{C.10}$$

Again, we substitute for λ.

$$(1-\kappa)\,u_0' A_0' = e^{-\rho}\mathbb{E}[u_1'(-\frac{\partial A_1}{\partial K_0} + \sigma p_1 e^{\gamma})] + e^{-\rho+\gamma}\mathbb{E}[u_1' p_1] \tag{C.11}$$

$$= e^{-\rho+\gamma}\mathbb{E}\left[u_1'\left((1+\sigma)p_1 - e^{-\gamma}\frac{\partial A_1}{\partial K_0}\right)\right] \tag{C.12}$$

Finally, we can use (C.7) to substitute the permit price with marginal abatement costs.

$$u_0' A_0' = e^{-\rho+\gamma}\mathbb{E}\left[u_1'\,(1-\kappa)^{-1}\left((1+\sigma)A_1' - e^{-\gamma}\frac{\partial A_1}{\partial K_0}\right)\right] \tag{C.13}$$

Appendix D. Parameter values and distributions

The economic output Y_1, the marginal abatement cost parameter θ and the carbon budget T are stochastic variables with distribution adopted from Gollier (2022). Economic output is assumed to be lognormally distributed as $\log(Y_1) \sim N(\mu_{bau}, \sigma_{bau})$ during business as usual and $\log(Y_1) \sim N(\mu_{cat}, \sigma_{cat})$ during crisis times, which happen with a probability of $p = 1.7\%$. The marginal abatement cost parameter θ is lognormally distributed as $\log(\theta) \sim N(\mu_\theta, \sigma_\theta)$. The sample was truncated to exclude rare outliers ($\log(\theta) > \mu_\theta + 4\sigma_t heta$). The emission budget T is normally distributed with mean μ_T and standard deviation σ_T. Parameter values are in Table D.4.

Fig. D.4 visualizes the resulting joint distribution in panels a-c, as well as output distributions of for growth rate of consumption and asset return in panel d.

The two distinct mass concentrations in the joint distribution of aggregate output Y and carbon budget T are due to the calibration of economic growth with a high probability for business-as-usual growth rates (darker concentration) but allowing for (rate) economic crises (lighter concentration) in D.4a. This separation in business-as-usual and crisis also shows in D.4b with regards the joint distribution of aggregate output Y and technological uncertainty θ. Fig. D.4d gives us an idea about the relation between consumption and the asset return, which are positively correlated thus giving rise to a positive carbon beta.

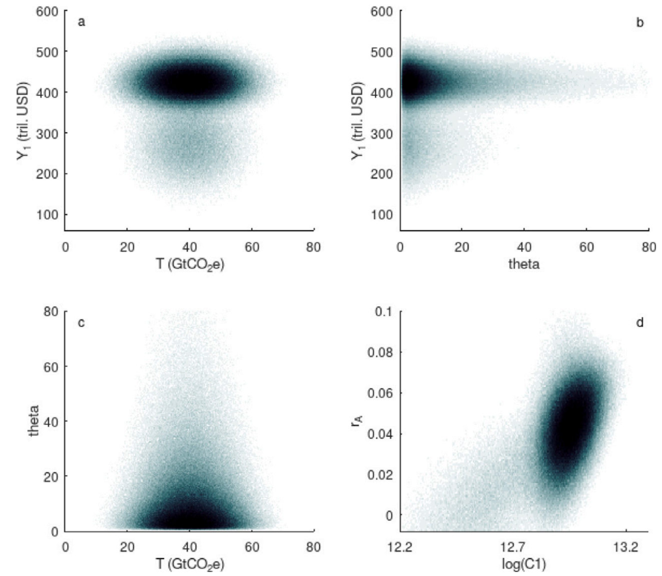

Fig. D.4. Visual overview of uncertainties. Panels a-c show pairwise joint distributions of the three stochastic variables from a Monte-Carlo simulation with 750'000 shots. Panel d shows the distribution of two model outputs (growth rate of consumption and asset return).

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