Capital Malleability and its Implications for Climate Policy Design

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Abstract

Integrated assessment models are widely used in economic analysis for deriving best-response policies to the threat of anthropogenic climate change. In this paper, we investigate how the degree of capital malleability influences the optimal climate policy design for alternative assumptions on climate damages and the timing of net-zero emissions policies. We compare a putty-putty setting, where capital is malleable both ex-ante and ex-post of investment decisions with a putty-clay setting where capital intensity cannot be changed ex-post. We find that optimal policy responses differ substantially as the short-term pressure for emissions abatement increases (i.e., climate damages are sufficiently high) or if there is uncertainty on the timing of a net-zero policy. With high climate damages, putty-clay requires much stronger emission intensity improvements than suggested by putty-putty due to the inertia of capital vintages. This must be reflected in command-and-control strategies when straight carbon pricing at the social cost of carbon is not feasible. We also show that hedging against policy uncertainty – such as the timing of net-zero emissions – can create substantial differences in the optimal abatement path between putty-putty and putty-clay.

Keywords

integrated assessment, putty-clay, cost-benefit analysis, social cost of carbon

JEL codes

C61, C68, D61, H23, Q58

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1. Introduction

Integrated assessment models (IAMs) of climate change constitute a wide-spread analytical framework for informing decision makers on the design of climate policies (for overviews see e.g. Weyant 2017; Bossetti 2023). These models aim to represent the causal chain through which (i) economic activities trigger anthropogenic greenhouse gas emissions, (ii) emissions of greenhouse gases translate into atmospheric concentration, temperature shift, and climate change, and (iii) climate change feeds back via the ecosystem to the economy.

IAMs can be used in cost-benefit analysis to derive an 'ideal' best-response policy such as optimal trajectories for carbon taxes or emissions control rates which equate the marginal costs of abatement with the marginal benefits from avoided climate damages. In view of substantial uncertainty on climate damages, they may also be used in a precautionary cost-effectiveness approach to minimize the cost of meeting exogenous emissions or temperature targets (Böhringer et al. 2007).

IAMs are constantly revised to reflect improved knowledge in natural sciences such as carbon cycle mechanisms, the temperature sensitivity to increases in greenhouse gases, or the type and magnitude of physical damages induced by climate change. Reflecting both empirical evidence but also normative value judgements, they are employed in economics to explore how alternative views on time preferences, the valuation of market and non-market goods, distributive justice, or technological development affect optimal policy responses.

While the systematic sensitivity analysis on contentious socio-economic issues such as the choices of discount rates or damage functions figures prominently in the IAM literature for a while, the role of capital malleability for climate policy design has hardly been addressed. The reasoning behind limited capital malleability is straightforward: Before investment takes place, economic agents have the choice over the production technology, but once the choice is made, it cannot be altered – in other words, once capital is installed its input coefficients are fixed for the capital's remaining life. This phenomenon has been addressed in economic theory as putty-clay distinguishing capital stocks according to ex-ante smooth substitutability and ex-post rigid complementarity. The putty-clay concept was initially introduced by Johansen (1959) and studied subsequently by various scholars in the context of growth and investments models (Solow 1962; Sheshinski 1967). In a putty-clay model the implicit substitution elasticities which drive the scope for economic adjustment are quite lower in the short run than in the long run (Atkeson and Kehoe 1999); there are typically higher costs for sudden as contrasted with gradual change in the economic environment – including costs for the premature retirement of capital (stranded investments).

Responses to climate change such as emissions abatement or emissions efficiency improvements involve capital investments where the degree of capital malleability can be crucial for the ease of structural adjustment, particularly in the short to mid run. Standard IAMs adopt the simplifying assumption of fully malleable capital, i.e., a putty-putty setting with smooth substitutability – both ex-ante and ex-post. As a matter of fact, IAMs typically ignore the limited malleability of capital (one notable exception is the ETA-MACRO model by Manne and Richels 1992).

In this paper we investigate how the degree of capital malleability changes optimal climate policy designs. For our analysis, we start from the DICE model (Dynamic Integrated model of Climate and the Economy) by Nordhaus (1994) which provides the seminal framework for most IAMs used by academic scholars, governments, and international organizations. DICE is a single sector Ramsey-growth model which incorporates stylized representations of the global economy and the global carbon cycle. It assumes a putty-putty setting where all capital stocks are malleable. We incorporate putty-clay adjustment into the original DICE model and also consider policy uncertainty under either learn-then-act or act-then-learn settings. We then use the revised DICE model to quantify the policy implications of capital malleability for alternative assumptions on climate damages and the timing of net-zero emissions policies. We find that putty-clay does not significantly change the design of optimal climate policy unless there is short-term pressure for emissions abatement. Such pressure could arise if climate damages are high or there is uncertainty on the timing of a net-zero emissions policy. With high climate damage, putty-clay requires much stronger emission intensity improvements than suggested by putty-putty due to the inertia of capital vintages. This can have important implications for command-and-control strategies if straight carbon pricing at the social cost of carbon is not feasible. We also show that hedging against policy uncertainty – such as the timing of net-zero emission constraints – can create substantial differences in the optimal abatement path between putty-putty and putty-clay. Last but not least, we find that the social cost of carbon and marginal abatement cost may substantially deviate in putty-clay since the opportunity cost of carbon in the putty-clay setting applies over the lifetime of an installed vintage.

The remainder of this paper is organized as follows. Section 2 provides an algebraic summary of the DICE model and our extension from a putty-putty setting to a putty-clay version. Section 3 describes our illustrative policy simulations for gaining insights into the implications of putty-putty versus putty-clay assumptions. Section 4 concludes.

2. Analytical framework: An extended DICE model

We start from the DICE model, a Ramsey-growth model which is combined with a simple climate model in order to provide a framework for cost-benefit assessment of climate policies. Our initial implementation of DICE remains close to the 2016 version of the model (DICE-2016R) by Nordhaus (Nordhaus 2017) except for we operate on more granular annual time steps rather than 5-10-year periods.

We then present our novel extension of DICE which permits switching from the original putty-putty setting to a put-clay setting. The two settings differ in their representation of both production and abatement technologies. In both model variants, emissions are determined jointly by the scale of output and the expenditure on abatement. However, while in the putty-putty version emission rates are determined independently in each year (and there is no distinction between production based on old versus new capital), in the putty-clay version emissions rates per unit of output are determined in the year that capital is installed.

2.1 The DICE model

DICE is based on Ramsey's neoclassical growth model of optimal savings and investment to maximize economic welfare over time. A single world producer-consumer chooses between current consumption, investment in productive capital, and costly measures to reduce current emissions and slow climate change. By assumption, population growth and technological change (productivity growth) are both exogenous. The representative consumer maximizes the discounted utility of consumption over an infinite horizon, subject to a Cobb-Douglas production function which includes damages from climate change as a function of global mean temperature. In the absence of abatement measures, anthropogenic emissions occur in direct proportion to output. Emissions per unit output are assumed to decline exogenously at a fixed rate and can be further reduced by costly emission-control measures (abatement). The climate model captures in reduced form how emissions accumulate and increase the stock of greenhouse gases in the atmosphere. As this stock grows, it increases the amount of solar radiation trapped by the earth's atmosphere which in turn triggers an increase in global mean temperature.

In a parsimonious summary the DICE logic can be segmented into three blocks: an economic submodule, a climate submodule, and integrated assessment linkages which captures the inter-relationships between the economic and climate submodules.

Economic submodule

The economic submodule adopts standard assumptions of a neoclassical Ramsey model with exogenous growth. A global representative agent maximizes intertemporal welfare from consumption through an optimal (pareto-efficient) allocation of resources.

Using *t* as the time index, welfare is given as the discounted value of utility from consumption:

$$W = \sum_{t=1}^{T} (l_t r_t (C_t / l_t)^{1-\alpha}) / (1 - \alpha) \tag{1}$$

where:

W is intertemporal welfare,

C_t is aggregate consumption,
l_t is exogenous labor supply (population growth),
α is the generational inequality aversion,
r_t is the discount factor with $r_t = (1+\rho)^{-t}$and
ρ is the pure rate of social time preference.

Welfare maximization takes places subject to economic constraints which describe the production technology, capital accumulation, and output allocation.

Gross economic output is given by a Cobb-Douglas function:

$$Y_t = a_t l_t^{1-\gamma} K_t^{\gamma} \quad (2)$$

where:

Y_t is gross economic output,
a_t is the level of total factor productivity,
K_t is the capital stock, and
γ is the capital value share (capital elasticity in output).

The capital stock is determined through depreciation of the existing capital and new investment:

$$K_t = (1-\delta)K_{t-1} + I_t \quad (3)$$

where:

δ is the capital depreciation rate, and
I_t is investment.

Output net of abatement and damage costs is divided between consumption and investment:

$$C_t + I_t = Y_t(1-D_t) - AC_t \quad (4)$$

where:

D_t is the climate damage (as a fraction of gross output), and
AC_t is the cost of emissions abatement.

Note that climate damage and emissions abatement (as an economic response to avoid damage) are only present in the case of integrated assessment, i.e., when the climate cycle and damage feedback are incorporated. The economic submodule consists of equations (1) – (4).

Climate submodule

The climate submodule in DICE describes how CO_2 emissions enter the carbon cycle, affect concentration and radiative forcing, which in turn induces anthropogenic climate change through the increase in global mean surface temperature.

The climate cycle is captured in reduced from through three reservoirs j=AT, UP, and LO which are the atmosphere (j=AT), the upper oceans and biosphere (j=UP) and the lower oceans (j=LO):

$$M_{jt} = \phi_{0j} E_t + \sum_{i=1}^{3} \phi_{ij} M_{i,t-1} \quad (5)$$

where:

M_{jt} is the concentration of CO_2 emissions,
ϕ_{ij} is the emission transfer rate between reservoirs (*j* alias with *i*), and
E_t are emissions.

Radiative forcing is a function of CO_2 emission concentration in the atmosphere and exogenous forcing:

$$F_t = \eta\, log_2\left(M_{AT,t}/M_{AT,t=1750}\right) + f_t \quad (6)$$

where:

F_t is total radiative forcing (i.e. the increase of surface warming in watts per square meter), and

f_t is the forcing contribution by sources exogenous to the model.

Radiative forcing warms the atmospheric layer, which in turn warms the upper oceans and biosphere, thereby gradually warming the deep oceans. Due to thermal inertia of different layers (reservoirs) there are time lags in climate change. The links between radiative forcing and global warming through temperature changes in the atmosphere and the deeper oceans are given as:

$$T_{AT,t} = T_{AT,t-1} + \zeta_1 \left(F_t - \zeta_2 T_{AT,t-1} - \zeta_3 \left(T_{AT,t-1} - T_{LO,t-1}\right)\right) \quad (7)$$

$$T_{LO,t} = T_{LO,t-1} + \zeta_4 \left(T_{AT,t-1} - T_{LO,t-1}\right) \quad (8)$$

where:

$T_{AT,t}$ is the temperature in the atmosphere,
$T_{LO,ts}$ is the temperature in the lower oceans, and
$\zeta_1, \zeta_2, \zeta_3, \zeta_4$ are geophysical parameters of climate dynamics.

The climate submodule stand-alone consists of equations (5) – (8).

Integrated assessment linkage

For integrated assessment of climate change the economic submodule and the climate submodule are linked through a damage function which provides economic incentives for emissions abatement. In DICE climate damage as a fraction of gross output is assumed to be reasonably well approximated by a quadratic function of temperature change:

$$D_t = \varphi_1 T_{AT,t} + \varphi_2 T_{At,t}^2 \quad (9)$$

where:

φ_1, φ_2 are damage coefficients calibrated to estimates of monetized damages.

Emissions that enter the climate cycle consist of exogenous emissions and emissions which are directly linked to economic output and can be controlled through abatement action:

$$E_t = \sigma_t Y_t (1 - \mu_t) + e_t \quad (10)$$

where:

μ_t is the control rate of emissions linked to economic production,
e_t are exogenous emissions (e.g. land-use activities which are not modeled in DICE), and
σ_t is an exogenous efficiency improvement factor.

Abatement cost are determined by a geometric cost function:

$$AC_t = \kappa_t Y_t^{\theta} \quad (11)$$

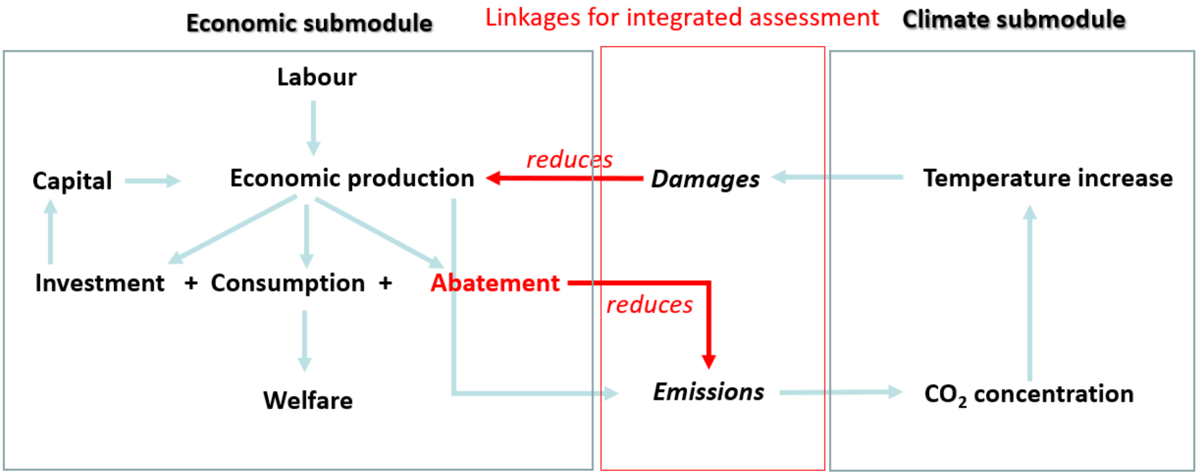
where:

AC_t is the abatement cost, and
κ_t,θ are exogenous parameters of the abatement cost function.

The core logic of the integrated assessment model then consists of three blocks covering (i) the economic submodule (equations (1)-(4)), (ii) the climate submodule (equations (5)-(8)) and (iii) the links between both modules (equations (9)-(11)).

Figure 1 provides a diagrammatic flow chart of the three blocks that from the DICE logic.

Figure 1: Flow chart of the DICE model logic



The model is solved as a nonlinear optimization problem after parametrization and initialization of variables to empirical values in the starting year.

2.2 The putty-clay extension

We extend the original DICE model to include alternative structural assumptions on the malleability of factor inputs to production. The putty-clay extension permits to study the dynamics of an economy in which once an investment decision is taken production characteristics for this vintage are fixed.

- The vintage model, through early retirement of inefficient vintages, has a higher average elasticity of energy demand (N.B. the implicit price elasticity of energy demand in the full vintage model depends crucially on the calibration assumptions – e.g. if the capital stock is less heterogeneous, the energy price effects mimic the putty-clay model more closely).
- Any type of ex-post rigidity limits the scope for adjustment and increases the costs of abatement.

When the price of energy changes through policy interventions (such as carbon taxes) there are induced changes in the rate of return to various vintages of capital. When energy price changes are sufficiently large, some capital stocks may be abandoned (➔ stranded investments).

In the putty-putty model, macro output in year t is a function of the exogenous labor force (Lt) and the capital stock (see equation (2)). In the putty-clay model we distinguish between three sources of macro-economic production (supply) in year t:

$$Y_t = Y_t^X + Y_t^N + Y_t^V \tag{12}$$

where:

Y_t^X denotes extant production,
Y_t^N denotes new vintage production, and
Y_t^V denotes old vintage production installed in the first year (or later).

Details of these three categories of macro supply are as follows.

Extant production is indexed by capital vintages installed prior to t_0 (being the first year of the model):

$$Y_t^X = \sum_{v<t_0} y_{vt}^X \tag{13}$$

where:

y_{vt}^X is the extant capital vintage in year *t*.

The supply by vintage is bounded be decision about abandonment between the initial year t_0 and year *t*:

$$y_{v\tau}^X \leq (1-\delta) y_{v\tau}^X \quad y_{v\tau}^X \geq 0 \quad \tau \, \epsilon [t_0, \dots, t] \tag{14}$$

where:

δ denotes the capital depreciation rate.

New vintage output depends on new vintage labor and new vintage capital (investments in the previous period):

$$Y_t^N = a_t (l_t^N)^{1-\gamma} I_{t-1}^{\gamma} \tag{15}$$

where:

l_t^N is the denotes the capital depreciation rate.

Aggregate production by vintages installed between t_0 and *t-1* is represented by Y_t^V which is subject to evaporative decay

$$Y_t^V \leq (1-\delta)(Y_{t-1}^N + Y_{t-1}^V) \tag{16}$$

Emission rates in year *t* from vintages installed prior to that year are fixed:

$$E_t = E_t^X + E_t^N + E_t^V + e_t \tag{17}$$

in which:

$$E_t^X = \sum_v \sigma_v^X y_{vt}^X \tag{18}$$

$$E_t^N = \sigma_t^N Y_t^N (1-\mu_t) \tag{19}$$

$$E_t^V = (1-\delta)(E_{t-1}^V + E_{t-1}^N) \tag{20}$$

Note that in the putty-clay framework there are two sources of emission reductions: emission controls for new vintage production (μ_t) and pre-mature retirement of extant vintages.

The putty-clay model begins from the assumption that climate damages affect supply from all sources:

$$C_t + I_t = Y_t(1 - D_t)(1 - AC_t) \tag{21}$$

in which abatement costs include those associated with both extant and new vintages:

$$AC_t Y_t = AC_t^N Y_t^N + (1-\delta) AC_{t-1}^V Y_{t-1}^V \tag{22}$$

3. Scenarios and simulation results

Our main objective is to investigate how capital malleability affects optimal climate policy which trades off costs and benefits of mitigation measures. To phrase in the words of Bill Nordhaus "The fundamental policy question involves how much reduction in consumption society should incur today to slow the consumption damages from climate change in the future" (Nordhaus 1994). An optimal response thereby maximizes the net present value of all consumption flows over time.

In our simulation analysis we denote the optimal climate policy as *optimal* and contrast it with a business-as-usual policy - denoted as *bau* - which takes damage spillover effects from climate caused by anthropogenic activities as a pure externality.

We preform sensitivity analysis with respect to two critical drivers for our cross-comparison between putty-putty (*pp*) and putty-clay (*pc*) model formulations.

First, there is the choice of the capital depreciation rate. Capital depreciation refers to the decline in value of a capital asset which occurs through physical depreciation, obsolescence or changes in the demand for the services of capital. A more recent study by Statistics Canada provides estimates derived from depreciation profiles for a diverse set of capital assets indicating a range of rates between 6-8% (Baldwin et al. 2015). The default value in DICE is set at 7% and we take this value as our reference number (*ref*) complementing it with a lower bound choice of 4% (*dk4*) and an upper bound choice of 10% (*dk10*) in our piece-meal sensitivity analysis.

Second, there is the choice of the damage function. There is ongoing debate among researchers about the appropriate form and parameters of the damage function. The standard DICE model adopts a quadratic damage function of temperature increase on economic output. Its parametrization – which we take as our reference case (*ref*) – has been criticized to come up with unrealistically low damage estimates (Hänsel et al. 2020). We therefore undertake sensitivity analysis using higher damage exponents as suggested by the meta-analysis of Howard and Sterner (2017) implying climate damages that are substantially higher than in the original DICE model - we refer to the high-damage variants in our sensitivity analysis below as *hsdam*.

Table 2 summarizes the different structural and parametric assumptions that are underlying our sensitivity analysis together with the acronyms which we use in our subsequent exposition of simulation results.

Table 2: Key assumptions of sensitivity analysis

Climate policy		
	bau	climate damages as pure externalities
	optimal	optimal trade-off between costs and benefits of emissions abatement
Capital malleability		
	pc	putty-clay (as in DICE)
	pp	optimal trade-off between costs and benefits of emissions abatement
Depreciation rate		
	dk4	4%
	ref	7% (as in DICE)
	dk10	Optimal trade-off between costs and benefits of emissions abatement
Climate damage		
	ref	damage function as in DICE
	hsdam	(higher) damage function as of Howard and Sterner (2017)

Figure 2 display the implications of alternative assumptions on climate damages and capital depreciation rates for emission levels under business-as-usual (*bau*). Higher damages lead to lower output which in turn implies (slightly) lower emissions. The more important impact on emissions stems from different depreciation rates. The lower the depreciation rate the higher is the economic growth and the higher are the emissions. The emission profiles under *bau* for model variants *pc* and *pp* are more or less identical.

Figure 3 shows different assumptions on climate damages and capital depreciation rates affect emissions for *optimal* climate policy. High climate damages (*hsdam*) are the key driver for emissions abatement in *optimal* as compared to *bau*. The putty-putty setting (*pp*) allows for a drastic adjustment in first period emission levels (intensities) in case climate damages are high. Due to emissions embodied in extant and old vintages, the putty-clay setting (*pc*) maintains a higher level of emissions throughout the horizon.

Figure 2: Implications of climate damages and capital depreciation for *bau* emission levels

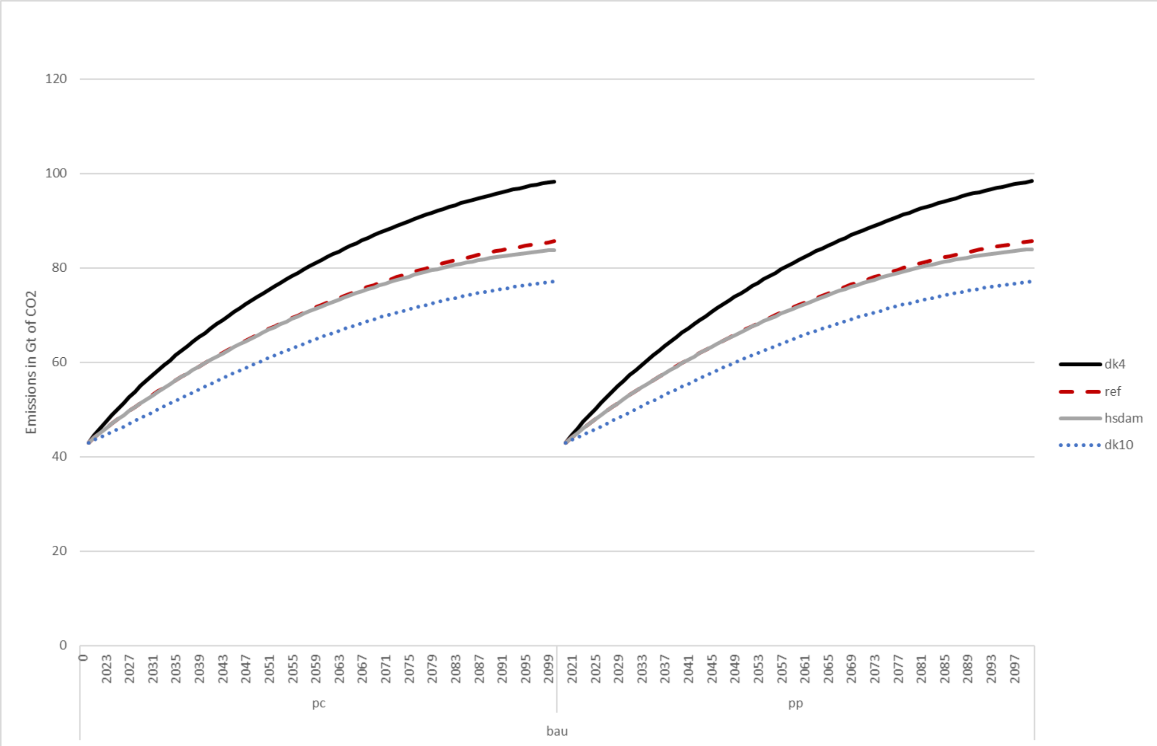
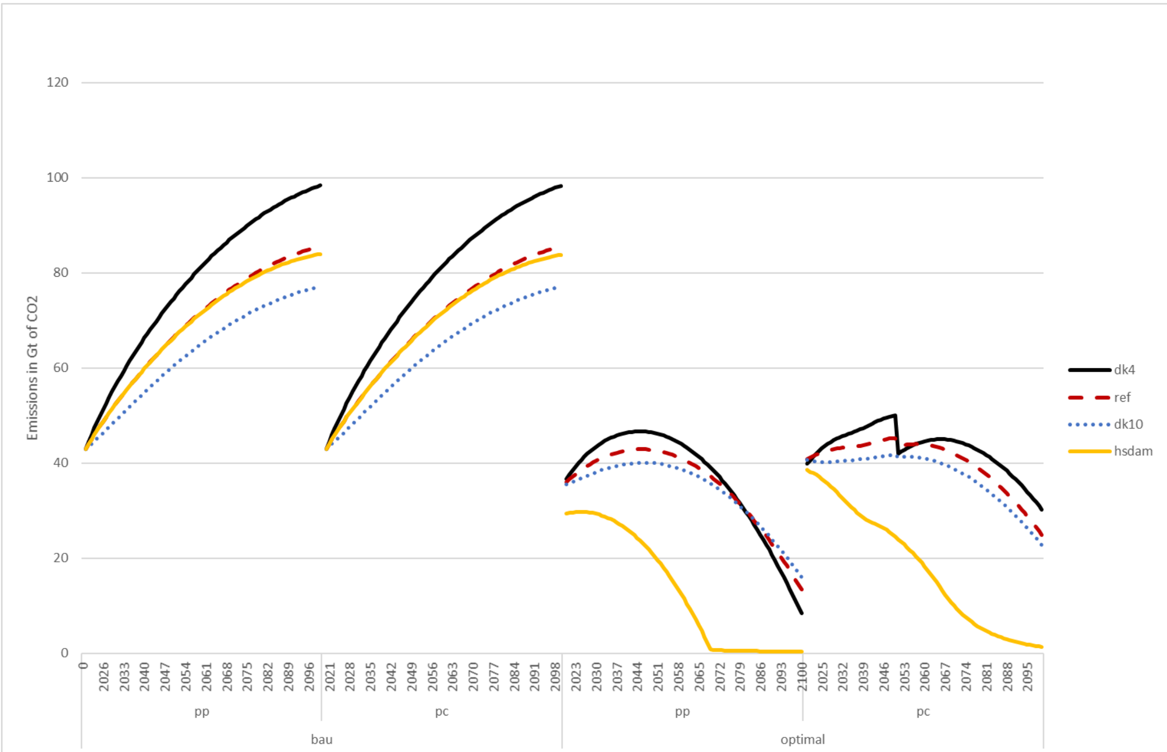


Figure 3: Implications of climate damages and capital depreciation for *optimal* emission levels



Figures 4 and 5 show emissions and emission rates by vintages for the high damage case under *optimal* climate policy. The putty-clay (*pc*) setting locks emissions from extant as well as old vintages.

Emissions from old vintages go down with the depreciation rate. The contribution of old vintages to overall emissions is U-shaped, while instantaneous emissions from new vintages are declining away and we obtain zero emission from new vintages already after 2060. Emission intensities are given exogenously for extant vintages (*EMITX*). New vintage intensities are declining through the endogenous choice of abatement as well as exogenous changes in the technology (autonomous energy efficiency improvements).

Figure 4: Emissions by vintages for the high damage case and *optimal* climate policy

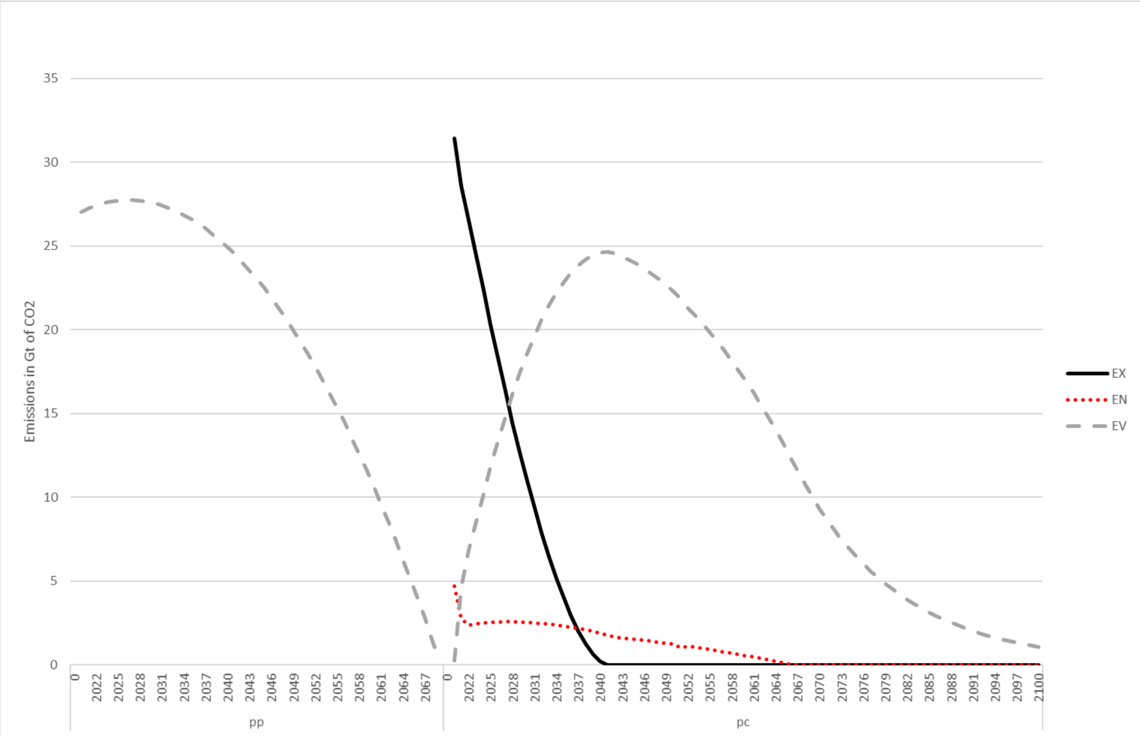


Figure 5: Emission rates by vintages for the high damage case and *optimal* climate policy

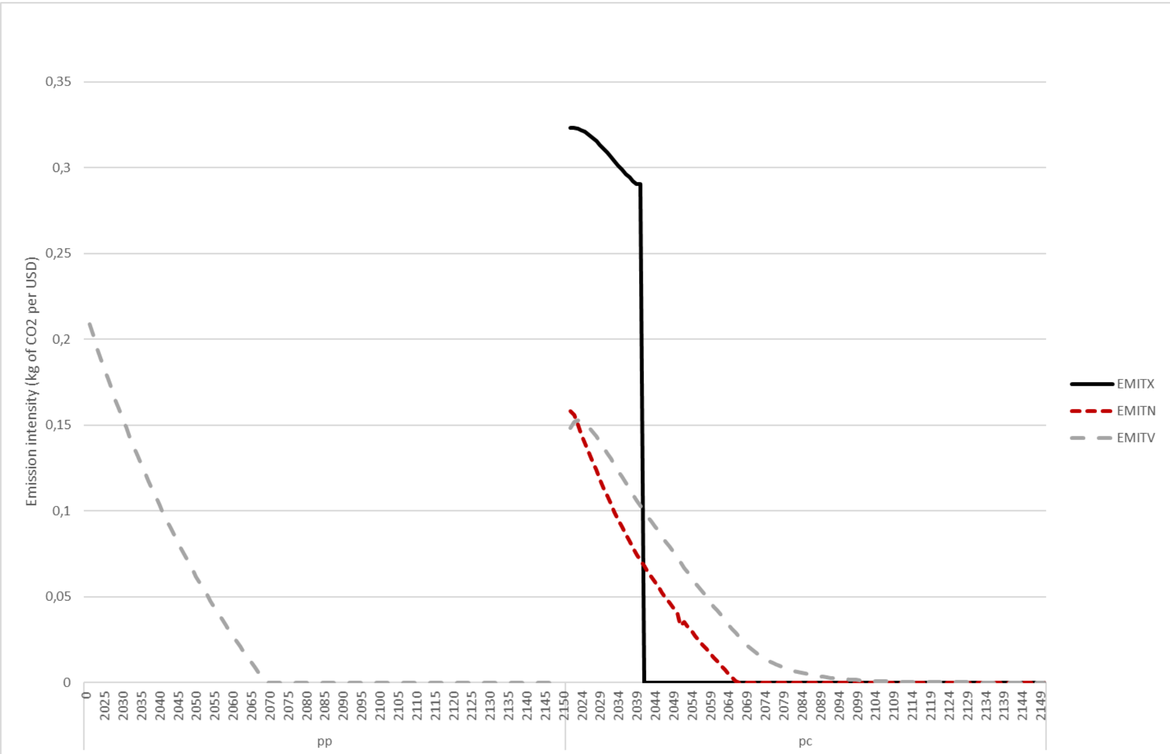


Figure 6 indicates the social cost of carbon (SCC) as a function of the depreciation rate and the damage function. The SCC denotes the dollar cost to society of each ton of carbon dioxide or other greenhouse gases emitted into the atmosphere. As a first-order effect, higher damages shift up the SCC curve. As a second-order effect, the smaller the depreciation rate , the higher the SCC: smaller depreciation rates lead to higher levels of production, investment, consumption and emissions – the climate is hotter and marginal climate damages, i.e. the SCC are higher. If we assume high damages, an *optimal* climate policy depresses emissions and hence marginal damages (SCC) from emissions quite markedly. Putty-clay (*pc*) shows slightly higher SCC than putty-putty (*pp*) – the reasoning behind is that in *pc* the output to which damage applies is slightly higher than in *pp*. Yet, the difference in SCC between *pp* and *pc* variants is small as they share very similar emission pathways.

Figure 6: Social cost of carbon as a function of climate damages and the depreciation rate

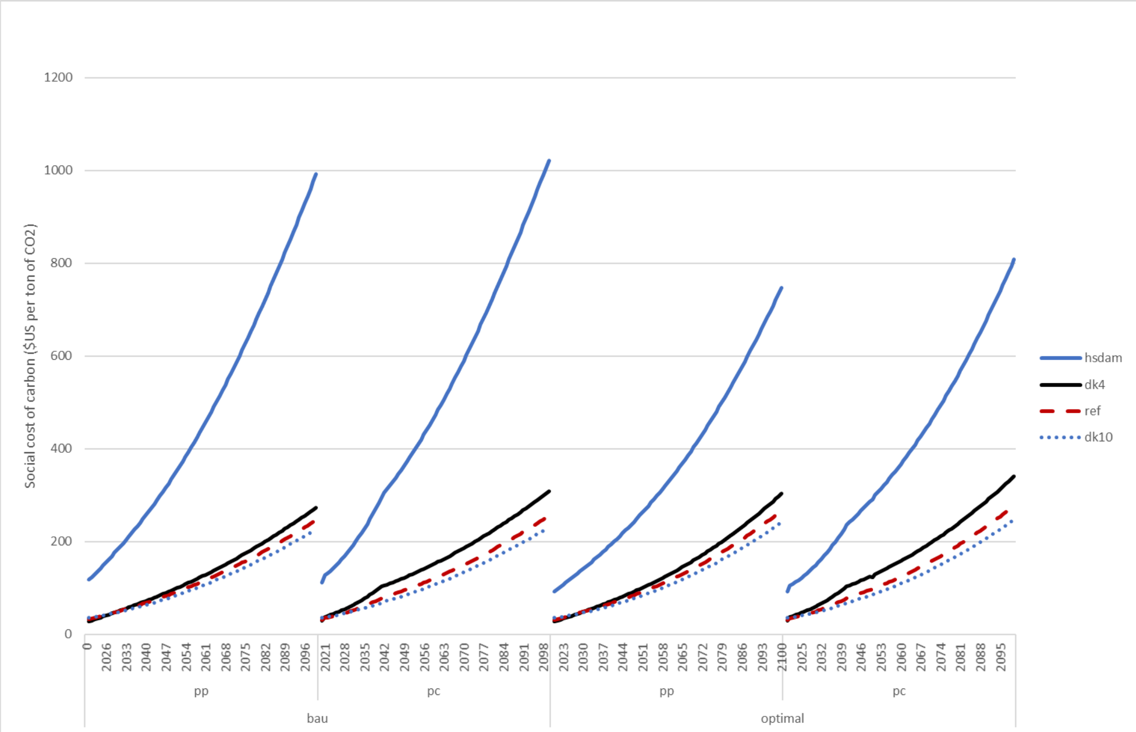


Figure 7 provides a policy-relevant insight into the divergence between the SCC and marginal cost of abatement as we move from the putty-putty (pp) assumption to the putty-clay (pc) assumption. In the *pp* model the social cost of carbon and the marginal abatement cost are identical. However, in the *pc* model the shadow price on carbon is higher than the social cost of carbon because it reflects the present value cost of emissions over the lifetime of the new vintage. The spread between marginal abatement cost and the SCC widens as we move towards a higher damage function.

Figure 8 shows the effects of capital malleability on welfare (W) as well as for consumption (C) and investment (I) for high climate damages under optimal climate policy. Welfare through year *t* is measured as money-metric utility from consumption flows to year *t* discounted to the base-year (in our case: 2015). Impacts are reported in percentage change from business-as-usual. Optimal mitigation reduces the return to capital and in the near term decreases investment and increases consumption. For high damages long-term welfare gains are substantial. Present value welfare which integrates consumption gains over the horizon does not break even until 2100. The pp and pc model variants not substantially different in results.

Figure 7: Social cost of carbon and marginal abatement cost for *optimal* climate policy

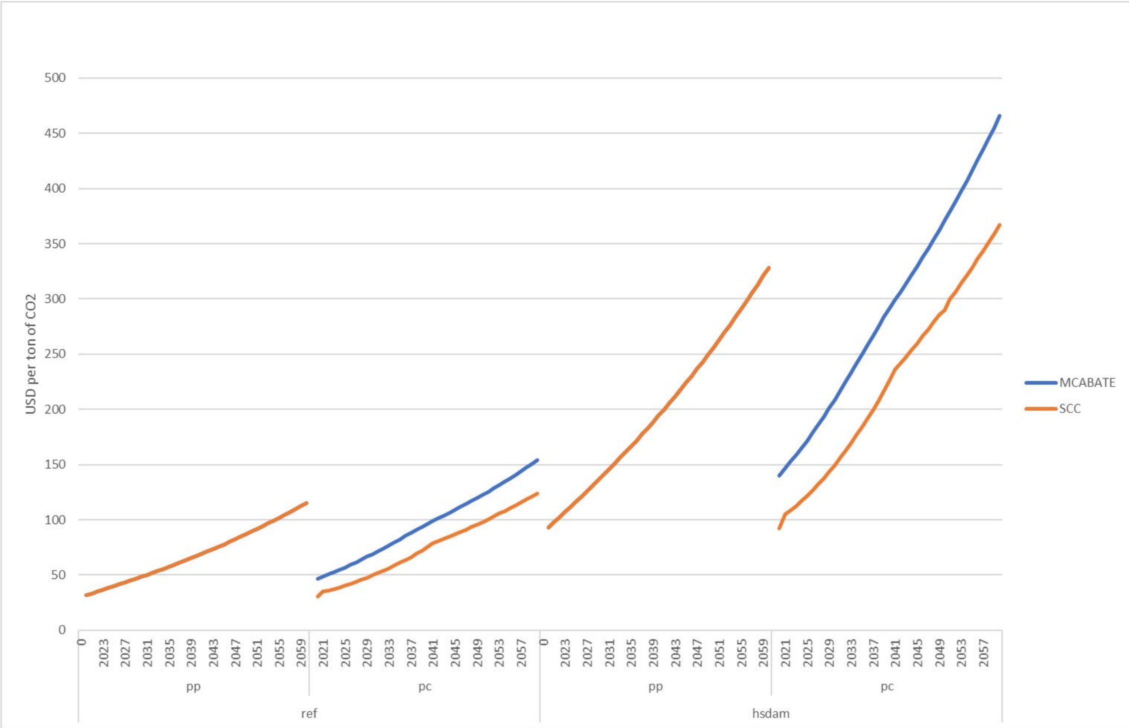
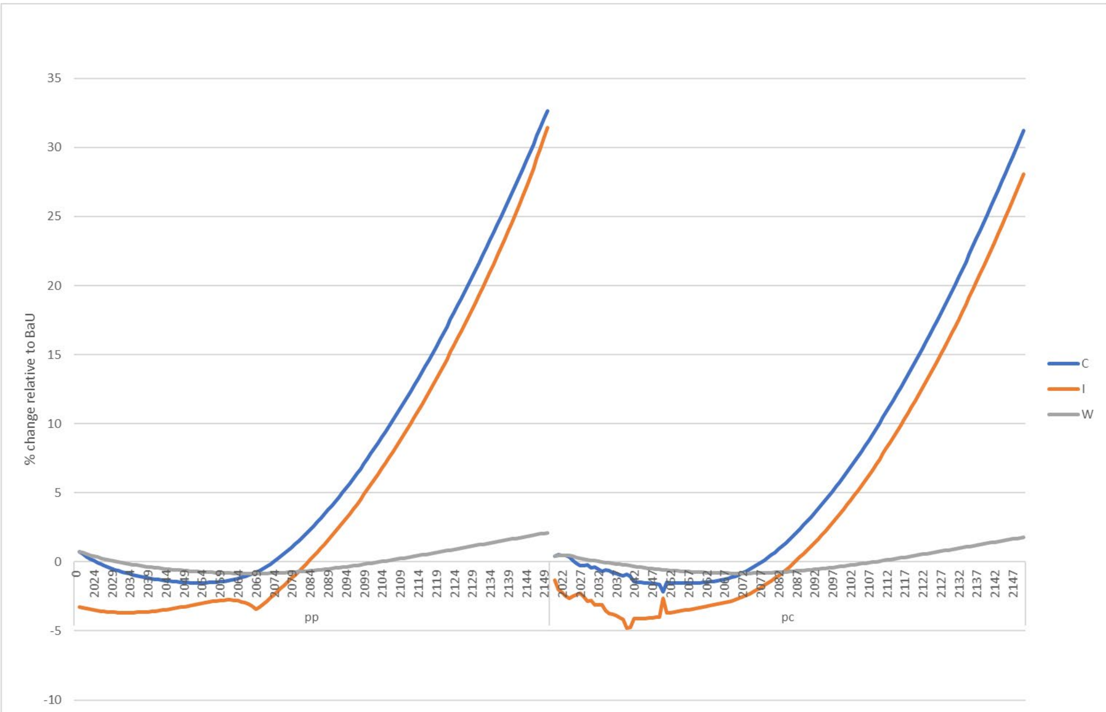


Figure 8: Implications of capital malleability for welfare under *optimal* climate policy



The design of climate change policy faces the challenge of several key uncertainties. For example, the potential benefits of reducing carbon dioxide and other greenhouse gas emissions are subject to uncertainties in the climate system such as the climate sensitivity, etc. Likewise, the potential costs of reducing emissions are characterized by substantial uncertainties about technological innovation, consumer responsiveness to energy price changes, etc.

In our preceding analysis we represented natural science uncertainty as a piece-meal sensitivity analysis on the damage function and abstained from similar analysis with respect to abatement cost uncertainty.

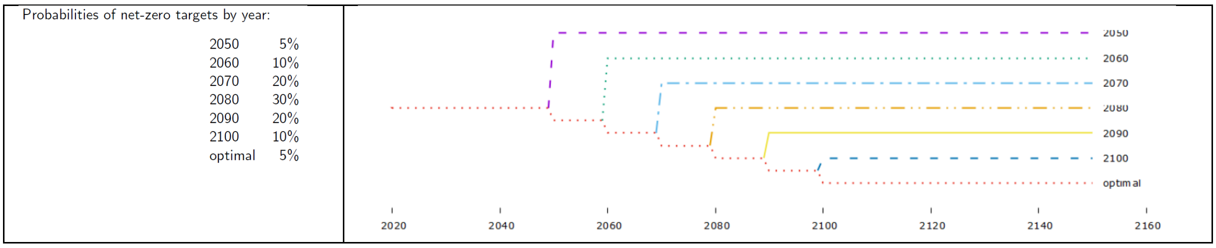
In the following, we address policy uncertainty regarding the issue when net-zero emissions targets will become binding as a credible policy regulation. Failure to account for uncertainties risks implementing market-based carbon tax schedules or command-and-control strategies on emissions intensities that seem appropriate today but are likely to either under- or overshoot once the uncertainty has been resolved in the future.

Hedging against uncertainties calls for an act-then-learn approach (see e.g., Manne and Richels 1992). Under act-then-learn decisions have to be made today without knowing which state of the world will occur tomorrow. This is fundamentally different from a learn-then-act situation where agents have the opportunity to learn the state of the world before taking action.

In our illustrative application we consider alternative policy scenarios for the timing of net-zero targets together with the probabilities of realization for these scenarios. We can reframe a deterministic learn-then-act decision problem into a stochastic act-then-learn decision problem by means of a decision tree structure specifying a discrete probability distribution for the years at which the net-zero emissions target eventually materializes.

Figure 9 provides the probabilities of net-zero emission targets by specific years including the possibility that climate policy will be determined by optimal endogenous cost-benefit analysis (scenario: optimal) rather than exogenous policy pressures. Figure 10 also visualizes the stochastic structure of the decision problem in an event-tree representation via state transitions.

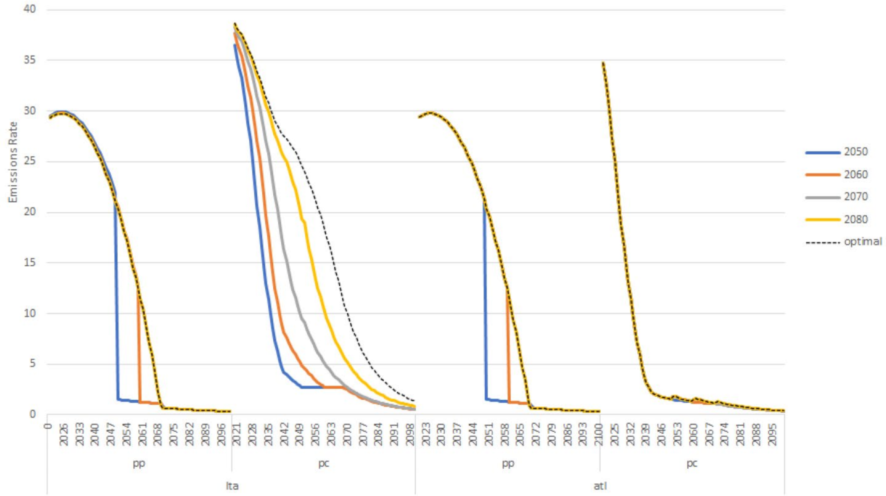
Figure 9: Probabilities of net-zero emission targets with event-tree representation



Uncertainty on the future realization of net-zero targets is handled through a stochastic re-formulation of the deterministic model. In the stochastic model, recourse plays a central role. Investments into physical capital stocks hedge against uncertainty about the timing of the net-zero target and it is intuitively clear that capital malleability determines the scope for recourse.

Figure 10 shows the implications of different degrees of capital malleability for the choice of emission rates under deterministic learn-then-act as compared to stochastic act-then-learn. The key message is that hedging against policy uncertainty leads to substantial differences in the choice of appropriated emission rates over time.

Figure 10: Implications of policy uncertainty and capital malleability on climate policy design (high damage case)



4. Conclusions

Integrated assessment models (IAMs) of climate change are widely employed in economic analysis to evaluate the potential costs and benefits of different policy options for reducing greenhouse gas emissions and mitigating climate change.

A fundamental strength of IAMs is their use for systematic sensitivity analysis addressing key uncertainties – both in natural research as well as socio-economic sciences – to put decision making on robust grounds. While the implications of several critical assumptions such as the choices of discount rates or damages function have been well elaborated over the last decades, there is very little analysis so far on the role of capital malleability for optimal climate policy design. Most IAMs are based on the putty-putty assumption of full capital malleability which is likely to overstate the adjustment possibilities of the economy to stringent emission constraints.

In this paper, we have extended the seminal DICE model by Nordhaus to accommodate a putty-clay structure where investment decisions once take fix capital intensity and emissions of vintages. We then compare how optimal climate policy design differs between a putty-putty and a putty-clay setting for alternative assumptions on climate damages and the timing of net-zero emissions policies. Our quantitative analysis indicate larger differences in optimal policy responses as the short-term pressure for emissions abatement increases (i.e., climate damages are sufficiently high) or if there is uncertainty on the timing of a net-zero policy. With high climate damages, putty-clay – due to the inertia of capital vintages – requires much stronger emission intensity improvements than suggested by putty-putty. This has important implications for command-and-control strategies if straight carbon pricing at the social cost of carbon is not feasible. We also show that hedging against policy uncertainty – such as the timing of net-zero emissions – can create substantial differences in the optimal abatement path between putty-putty and putty-clay.

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