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Endogenous Discounting and Climate Policy

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Abstract

Under risk of abrupt climate change, the occurrence hazard is added to the social discount rate. As a result, the social discount rate (i) increases and (ii) turns endogenous to the global warming policy. The second effect bears profound policy implications that are magnified by economic growth. In particular, we find that greenhouse gases (GHG) emission *should* be terminated at a finite time so that the ensuing occurrence risk will vanish in the long run. Due to the public bad nature of the catastrophic risk, the second effect is ignored in a competitive allocation and unregulated economic growth will give rise to excessive emissions. In fact, the GHG emission paths under the optimal and competitive growth regimes lie at the extreme ends of the range of feasible emissions. We derive the Pigouvian hazard tax that implements the optimal growth regime.

Keywords: abrupt climate change; hazard rate; discounting; economic growth; emission policy;

JEL Classification: H23; H41; O13; O40; Q54; Q58

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1 Introduction

Among the possible impacts of global warming, those associated with abrupt climate change are particularly disturbing (Alley et al. 2003, Stern 2007, IPCC4 2007). Abrupt events refer to non-marginal changes in the climate system, triggered, e.g., as the (smooth) global warming process crosses some threshold level, that may inflict large-scale and irreversible damages at unpredictable dates. The combination of unpredictable, abrupt occurrence and catastrophic damage poses a delicate policy challenge. We study optimal greenhouse gases (GHG) emission policy for a growing economy under threats of catastrophic climate change.

The catastrophic threat is represented by a hazard rate that depends on the atmospheric GHG concentration and characterizes the probability of the event occurrence time.[1] While the competitive (market) allocation takes full account of the hazard rate per se, it fails to account for the *change* in hazard associated with economic activities, as the hazard is in effect a pure public bad.[2] As a result the competitive (unregulated) growth regime is suboptimal. We characterize the optimal growth regime by means of a Pigouvian hazard tax on emission, which depends on the sensitivity of the hazard to the GHG

[1]There are two main reasons for our lack of perfect knowledge regarding global warming induced catastrophes. First, the conditions that trigger occurrence may be genuinely stochastic. Second, we may have only partial knowledge of the parameters that characterize these conditions. In this work we concentrate on the first cause and consequently assume that the hazard rate function is known.

[2]This is part of what Stern (2007) called "...the greatest and widest-ranging market failure ever seen."

concentration and vanishes for an exogenous hazard. We find that under risk of catastrophic occurrence a growing economy *should* terminate GHG emission at a finite time and the ensuing occurrence risk will eventually vanish. In contrast, under an unfettered market allocation, emission is driven to an economically maximal rate at a finite time and remains at that rate thereafter. The ensuing hazard will thus stabilize at the maximal rate in the long run. We show how the proposed Pigouvian hazard tax implements the optimal growth regime in a competitive environment.

The analysis bears directly on the key issues regarding global warming policy, namely the extent and timing of GHG emission reduction. The received view recommends a gradual approach of a modest reduction in the short run and sharper cuts in the longer run (Nordhaus 1999, Nordhaus and Boyer 2000). This view has been challenged by Stern (2007), who recommended a more vigorous and early response, giving rise to a lively debate (see Arrow 2007, Dasgupta 2007, Nordhaus 2007, Weitzman 2007a). The debate revolves on the parameters ρ (the pure rate of time preference), η (the elasticity of marginal utility) and g (per capita growth in consumption) that comprise the social discount rate $\rho+\eta g$ by which costs and benefits should be discounted. With a catastrophic risk, the hazard rate is added to the social discount rate. At a first glance it may appear that this weakens the case for an early vigorous response (as the inclusion of the hazard increases the social discount rate). However, while ρ, η and g are exogenous parameters,[3]

[3]We assume exogenous technical change. In general g will also be affected by the

the hazard rate depends on the emission policy and is therefore endogenous. The presence of the hazard rate in the social discount rate, thus, turns the latter endogenous to the global warming policy. This endogeneity feature underlies our analysis and is the raison d'être for the Pigouvian hazard tax.[4]

Early studies of possible climate policy responses to catastrophic threats include Clarke and Reed (1994) and Tsur and Zemel (1996). Nordhaus and Boyer (2000), Mastrandrea and Schneider (2001) and Stern (2007) study effects of catastrophic damages on GHG emission policy within elaborate integrated assessment models. Recent contributions to this vein include Nævdal (2006), Karp and Tsur (2007), Weitzman (2007b), and Tsur and Zemel (2008). The present analysis builds on Tsur and Zemel (2008) who studied the regulation of environmental threats in a stationary economy. They proposed a Pigouvian hazard tax on emission that implements the optimal allocation and showed that it reduces, but does not eliminate, emission. Incorporating growth, we find a significant difference: the Pigouvian hazard tax is so adjusted as to cease emission altogether at a finite time in order to eliminate the ensuing catastrophic risk. Thus, the GHG emission paths under the optimal and competitive growth regimes lie at the extreme ends of the range of feasible emissions.

The next section describes the general setup. Section 3 presents the main

climate change policy but this dependence is weaker than that of the hazard.

[4]Stern's (2007) rationale for a positive ρ is the presence of an exogenous extinction hazard such as that due to a devastating meteorite (see also discussion in Beckerman and Hepburn 2007). The hazard here, which is associated with a global warming induced catastrophe, depends on the emission policy and is therefore endogenous.

results by characterizing the competitive (unregulated) and socially optimal growth regimes. Section 4 concludes and the appendix contains technical derivations.

2 The economy

To the economic structure considered in Tsur and Zemel (2008) we add an exogenous labor-augmenting technical change. The economy consists of a final good manufacturing sector, an intermediate good (energy) sector, households (that own capital and labor) and a regulator. We briefly describe the economy, focusing on the added (growth) component.

2.1 Firms

There are final good manufacturing firms and intermediate good (energy) supplying firms. The final good firms rent capital and labor from households and purchase energy in order to produce a homogenous final good, taking prices parameterically and seeking to maximize (instantaneous) profit at each time period. Summing over all final good firms gives the aggregate output

$$Y(k(t), x(t), A(t)) \tag{2.1}$$

as a function of capital (k), energy (x) and labor inputs, where

$$A(t) \equiv e^{gt} \tag{2.2}$$

is an exogenous labor-augmenting technical change process and the labor force is assumed constant, hence normalized to unity. The technology $Y(\cdot, \cdot, \cdot)$

is linearly homogenous, increasing and concave in each variable, with positive mixed derivatives.

Energy, $x = x_1 + x_2$, can be derived from polluting (x_1) or clean (x_2) sources. The former refers to fossil energy and the latter to non-emitting sources such as solar, wind, hydro or geothermal energy. Fossil energy (x_1) is manufactured (extracted, distilled and distributed) with an increasing and strictly convex cost function $Z(\cdot)$, reflecting the fact that as the supply rate increases, more expensive (or less efficient) sources need to be used. The fossil energy supply curve is thus the upward sloping marginal cost curve $Z'(\cdot)$.

We assume that the clean energy (x_2) production technology exhibits constant returns to scale with a constant marginal cost, denoted p_2. This is obviously an abstraction. On the one hand, economies of scale are likely to prevail for these immature technologies due to learning by doing or R&D aimed at enhancing their efficiency (none of which is considered here). On the other hand, sites suitable for harvesting these alternative energy resources are not unlimited, so expanding them significantly will give rise to increasing costs. Regardless of which trend dominates, allowing the marginal cost of clean energy to increase or decrease over certain domains will not change the main message of this work, provided the rate of change is smaller than that of the marginal cost of fossil energy.[5] The energy supply curve is therefore

[5]The results persist under a non-constant marginal cost of clean energy $p_2(x)$, provided it crosses $Z'(x)$ once from above.

given by

$$\min\{Z'(x), p_2\},$$

where $0 < Z'(0) < p_2$ is assumed (i.e., the most efficient fossil sources are less expensive than the clean resources).

The (inverse) demand for energy is given by its value of marginal product $Y_x(k, x, A) \equiv \partial Y/\partial x$. The allocation of $x(t) = x_1(t) + x_2(t)$ at time t equates supply and demand:

$$\min\{Z'(x(t)), p_2\} = Y_x(k(t), x(t), A(t)). \tag{2.3}$$

At each point of time, given $k(t)$ and $A(t)$, the competitive (unregulated) allocation of $x_1(t)$ and $x_2(t)$ is determined according to

$$Y_x(k(t), x_1(t) + x_2(t), A(t)) = Z'(x_1(t)) \tag{2.4a}$$

and

$$Y_x(k(t), x_1(t) + x_2(t), A(t)) \le p_2, \text{ equality holding if } x_2(t) > 0. \tag{2.4b}$$

Let

$$\bar{x}_1 \equiv Z'^{-1}(p_2) \tag{2.5}$$

represent the maximal fossil energy supply rate (above which clean energy is cheaper). When k and A give rise to $Y_x(k, \bar{x}_1, A) > p_2$, condition (2.4b) holds as an equality. In this case $x > \bar{x}_1$, $x_1 = \bar{x}_1$ and $x_2 = x - \bar{x}_1 > 0$.

2.2 Catastrophic climate change

Using the polluting resource at the rate x_1 entails emission at the rate $e(x_1)$ of GHG which accumulate in the atmosphere to form the stock Q according to

$$\dot{Q}(t) = e(x_1(t)) - \delta Q(t). \tag{2.6}$$

The emission function satisfies $e(0) = 0$ and $e'(x_1) > \varepsilon > 0$ for $x_1 \in [0, \bar{x_1}]$, and $\delta > 0$ is the rate of natural decay.[6] Increasing atmospheric GHG concentration modifies the mean global temperature, which in turn affects large scale natural processes with potential catastrophic consequences. Each link in this chain of events (leading from changing GHG concentration to the ensuing damage) is influenced by a myriad of uncertainties (Pindyck 2007, Schelling 2007). The event occurrence date is therefore random with a distribution that depends on the GHG concentration. This distribution induces a hazard rate function $h(\cdot)$, such that $h(Q(t))dt$ measures the conditional probability that the catastrophe will occur during $[t, t + dt]$ given that it has not occurred by time t when the GHG concentration is $Q(t)$. We normalize $h(\cdot)$ at $h(0) = 0$ and assume that it is strictly increasing over the relevant domain, i.e., $h'(Q) > \varepsilon > 0$ for $Q \in [0, \bar{Q}]$, where $\bar{Q}$ is the maximal GHG concentration defined as follows. If $x_1(t)$ is fixed at the maximal rate $\bar{x}_1$ of

[6] $Q(t)$ measures the difference between the current atmospheric GHG concentration and the preindustrial level, where the latter is the stock level at which natural emission and decay are equal.

(2.5) from some time t_0 on, the GHG stock evolves according to

$$Q(t) = \bar{Q} - (\bar{Q} - Q(t_0))e^{-\delta(t-t_0)} \tag{2.7}$$

towards its maximal level

$$\bar{Q} = e(\bar{x}_1)/\delta \tag{2.8}$$

and the hazard rate approaches the maximal rate

$$\bar{h} = h(\bar{Q}). \tag{2.9}$$

Recent evaluations (Stern 2007, IPCC4 2007) of likely outcomes of global warming are alarming. The current atmospheric GHG concentration is estimated at 430 ppm of CO_2e, compared with 280 ppm at the onset of the Industrial Revolution. Under a business-as-usual scenario, the concentration could double the pre-Industrial level by 2035 and treble this level by the end of the century. The recent IPCC report gives $2 - 4.5^{\circ}$C as a likely range for the increase in equilibrium global mean surface air temperature due to doubling of atmospheric GHG concentration with a non-negligible chance of exceeding this range (IPCC4 2007, p. 749). The Stern report gives $2 - 5^{\circ}$C and $3 - 10^{\circ}$C as likely ranges for equilibrium global mean warming due to doubling and trebling of GHG concentration, respectively (Stern 2007). Even more disturbing is the observation that the probability of outcomes that significantly exceed the most likely estimates is far from negligible. The pessimistic side of possible global warming outcomes can therefore give rise to truly catastrophic events (the usual list includes the reversal of the thermohaline circulation, a sharp rise in sea level, the spread of lethal diseases and massive species extinction).

Like the conditions that trigger an abrupt event, the damage it will inflict is fraught with uncertainties and is not easily quantified into a representative index. A common practice is to use post-event scenarios that are easier to understand, e.g., a GDP reduction from the occurrence date onwards or reduction of the growth rate by a certain percent (see, e.g., Stern 2007, Chapter 6). Such scenarios serve as the basis for evaluating a policy that recommends to spend a certain amount today (e.g., by reducing GHG emission) in order to eliminate or decrease the expected damage. Here we assume that upon occurrence consumption is reduced to a certain (predetermined) rate and grows at the (exogenous) growth rate thereafter. Other climate change impacts can be postulated without changing the main message regarding the effect of hazard endogeneity on emission policies.

2.3 Households

We maintain the iso-elastic utility of consumption

$$u(c) = \frac{c^{1-\eta} - 1}{1 - \eta} \tag{2.10}$$

where η is the elasticity of marginal utility, assumed larger than one (see, e.g., Dasgupta 2007, Arrow 2007, Weitzman 2007a). Let T represent the (random) event-occurrence time, at which date consumption falls to the (prespecified) rate c_p and increases at the rate g thereafter. The (planned) consumption stream $\{c(t),\ t \geq 0\}$, thus, generates the utility flow

$$\begin{cases} u(c(t)) & \text{for } t \leq T \\ u(c_p e^{g(t-T)}) & \text{for } t > T \end{cases} \tag{2.11}$$

and the payoff

$$\int_0^T u(c(t))e^{-\rho t}dt + e^{-\rho T}\psi, \tag{2.12}$$

where ρ is the pure rate of time preference and

$$\psi \equiv \int_0^\infty u(c_p e^{gt})e^{-\rho t}dt = \frac{1}{(\eta-1)\rho}\left[1 - \frac{\rho c_p^{1-\eta}}{\rho + (\eta-1)g}\right] \tag{2.13}$$

is the post event value.

The expected payoff is

$$E_T\left\{\int_0^T u(c(t))e^{-\rho t}dt + \psi e^{-\rho T}|T > 0\right\} = \int_0^\infty [u(c(t)) + h(Q(t))\psi]e^{-\Gamma(t)}dt,$$

where

$$\Gamma(t) \equiv \int_0^t [\rho + h(Q(\tau))]d\tau = \rho t + \Omega(t), \tag{2.14}$$

and

$$\Omega(t) \equiv \int_0^t h(Q(\tau))d\tau. \tag{2.15}$$

Using $\int_0^\infty [\rho + h(Q(\tau))] \exp(-\Gamma(\tau))d\tau = 1$ and defining

$$w(c) \equiv \frac{1}{(1-\eta)}\left[c^{1-\eta} - \frac{\rho c_p^{1-\eta}}{\rho + (\eta-1)g}\right], \tag{2.16}$$

the expected payoff can be expressed as

$$\int_0^\infty w(c(t))e^{-\Gamma(t)}dt + \psi. \tag{2.17}$$

The elasticity of the "shifted" utility $w'(\cdot)$ is η – the same as the elasticity of $u'(\cdot)$. Notice that for the event to be damaging rather than rewarding, the optimal expected payoff must exceed the post event value ψ, i.e., the first term of (2.17) is positive under the optimal policy. We assume that a consumption stream that satisfies this condition is feasible, which presupposes some restrictions on the model's parameters.

It is seen from equation (2.14) that the hazard rate is added to the pure rate of time preference to form the "hazard-inclusive" pure rate of time preference $\rho + h(Q)$. Adding ηg gives the corresponding "hazard-inclusive" social discount rate $\rho + h(Q) + \eta g$.

The returns from labor and capital (including profits from the energy sector) give the household budget constraint at time t (see details in Tsur and Zemel 2008)

$$\dot{k}(t) = Y(k(t), x_1(t) + x_2(t), A(t)) - p_2 x_2(t) - Z(x_1(t)) - c(t). \tag{2.18}$$

Households choose their consumption-saving plan according to

$$v^c(k_0) = \psi + \max_{\{c(t)\geq 0\}} \int_0^\infty w(c(t)) e^{-\Gamma(t)} dt \tag{2.19}$$

subject to (2.18), given $k(0) = k_0$. In solving this problem, households assume that the intermediate inputs $x_1(\cdot)$ and $x_2(\cdot)$ are exogenously determined according to (2.4a)-(2.4b). The ensuing processes $e(x_1)$, $Q(\cdot)$, $\Gamma(\cdot)$ and $\Omega(\cdot)$ are therefore also exogenous.

2.4 Regulator

The socially optimal allocation is the outcome of

$$v^s(k_0, Q_0) = \psi + \max_{\{c(t), x_1(t), x_2(t)\}} \int_0^\infty w(c(t)) e^{-\Gamma(t)} dt \tag{2.20}$$

subject to (2.6), (2.18), $\dot{\Omega}(t) = h(Q(t))$, $x_1(t) \geq 0$, $x_2(t) \geq 0$ and $c(t) \geq 0$, given $k(0) = k_0$, $Q(0) = Q_0$ and $\Omega(0) = 0$. We denote by $\lambda(\cdot)$ and $\gamma(\cdot)$ the costate variables of capital $k(\cdot)$ and GHG stock $Q(\cdot)$, respectively, corresponding to the social allocation problem (2.20).

The regulator seeks to implement the social allocation in a competitive environment. Following Tsur and Zemel (2008), let

$$\beta(t) = \frac{-\gamma(t)}{\lambda(t)} \tag{2.21}$$

represent the shadow price of the GHG stock in capital (the numeraire) units. When the tax rate $\beta(t)$ is levied on emission $e(x_1)$ in a competitive environment, the energy supply curve (the left hand side of (2.3)) is modified to $\min\{Z'(x(t)) + \beta(t)e'(x(t)), p_2\}$. Thus, the conditions that govern the allocation of fossil and clean energy at time t change from (2.4a)-(2.4b) to

$$Y_x(k(t), x_1(t) + x_2(t), A(t)) \leq Z'(x_1(t)) + \beta(t)e'(x_1(t)),$$
$$\text{equality holding if } x_1 > 0 \tag{2.22a}$$

and

$$Y_x(k(t), x_1(t) + x_2(t), A(t)) \leq p_2, \text{ equality holding if } x_2 > 0. \tag{2.22b}$$

The Pigouvian hazard tax is the optimal $\beta(t)$ corresponding to the solution of (2.20). Suppose that this tax is levied on emission. Is the resulting, regulated-competitive allocation optimal? The answer, it turns out, is in the affirmative. We state this result in

Proposition 1. *The Pigouvian hazard tax implements the optimal allocation.*

The proof is similar to the proof given in Tsur and Zemel (2008) for a stationary economy (without technical change) and is therefore omitted.

The allocation (2.22) implies that with sufficiently high tax rate (such that $Z'(0) + \beta(t)e'(0) \geq p_2$) the supply rate $x_1(t)$ vanishes and energy is supplied solely from the clean source. We show in the next section that as the economy grows, the Pigouvian hazard tax $\beta(t)$ increases up to a point where this condition holds at all subsequent times.

3 Economic growth and GHG emission

Without technical change, Tsur and Zemel (2008) found that the Pigouvian hazard tax reduces the use of the hazardous input but does not eliminate it. It turns out that the effect of the hazard externality is even more pronounced in a growing economy. In a growing economy the optimal use of the hazardous input ceases at a finite time and the ensuing hazard rate vanishes in the long run. In contrast, the competitive allocation of x_1 reaches the maximal rate $\bar{x}_1$ of (2.5) at a finite time and the ensuing hazard will approach in the long run the maximal rate $\bar{h}$ of (2.9). The effect of growth, therefore, is to push the difference between the long run optimal and competitive GHG emissions to the extreme: no emission under the social allocation and maximal emission under the competitive allocation.

It is expedient to recast the economy in terms of the detrended quantities $\tilde{k}(t) \equiv k(t)/A(t)$, $\tilde{x}(t) \equiv x(t)/A(t)$, $\tilde{c}(t) \equiv c(t)/A(t)$ and the production function

$$\tilde{y}(\tilde{k}, \tilde{x}) \equiv Y(k, x, A)/A = Y(\tilde{k}, \tilde{x}, 1). \tag{3.1}$$

Convergence of the detrended processes to a steady state means that the economy approaches a path of steady-state growth. The difference between the competitive and optimal solutions is in the corresponding steady-state levels – in particular the allocations of the hazardous and clean energy inputs. Both the competitive and social intertemporal allocation problems include several state variables, hence global convergence properties cannot be readily established based on local stability analysis. Characterizing the evolution of the shadow prices, we establish global convergence to a steady state growth path for both problems.

Since $\tilde{y}_{\tilde{x}} = Y_x$, it follows from (2.4b) and (2.22b) that the total energy input $\tilde{x}$ satisfies

$$\tilde{y}_{\tilde{x}}(\tilde{k}, \tilde{x}) = p_2, \tag{3.2}$$

provided some clean energy is used. For any capital stock $\tilde{k}$, let $\tilde{x}(\tilde{k})$ be the $\tilde{x}$ level satisfying (3.2) and let

$$\varphi(\tilde{k}) = \tilde{y}_{\tilde{k}}(\tilde{k}, \tilde{x}(\tilde{k})) \tag{3.3}$$

represent the marginal product of capital. Define $\hat{k}$ as the solution of

$$\varphi(\hat{k}) = \rho + \bar{h} + \eta g, \tag{3.4}$$

where $\bar{h}$ is the maximal long run hazard rate, defined in equation (2.9). We assume that (3.4) admits a unique solution $\hat{k} > 0$ such that $\varphi(\tilde{k}) > \rho + \eta g + \bar{h}$ for $\tilde{k} < \hat{k}$ and $\varphi(\tilde{k}) < \rho + \eta g + \bar{h}$ for $\tilde{k} > \hat{k}$.[7] Define

$$\hat{x} \equiv \tilde{x}(\hat{k}), \tag{3.5a}$$

$$\hat{y} \equiv \tilde{y}(\hat{k}, \hat{x}) \tag{3.5b}$$

and

$$\hat{c} \equiv \hat{y} - p_2\hat{x} - g\hat{k}. \tag{3.5c}$$

With $\rho + g(\eta - 1) > 0$, it follows that $\hat{c} > 0$.[8]

We refer to the unregulated case as business-as-usual (BAU). The long run behavior of the unregulated economy is characterized in the following (proofs are presented in the Appendix):

Proposition 2. *Under BAU: (i) GHG emission reaches the maximal rate $e(\bar{x}_1)$ at a finite time and remains at that level thereafter, giving rise to the maximal long-run GHG concentration $\bar{Q} = e(\bar{x}_1)/\delta$ and hazard rate $\bar{h} = h(\bar{Q})$; (ii) the economy reaches a balanced growth path along which*

[7] This assumption holds e.g. for the Cobb-Douglas technology.

[8] Use the linear homogeneity of $Y(\cdot, \cdot, \cdot)$ and Euler's Theorem to write $Y(k, x, A) = Y_k k + Y_x x + Y_A A$. Dividing by A, noting that $\tilde{y} = Y/A$, $Y_k = \tilde{y}_{\tilde{k}}, Y_x = \tilde{y}_{\tilde{x}}$ and $Y_A > 0$ yields $\tilde{y}(\tilde{k}, \tilde{x}) > \tilde{y}_{\tilde{k}}\tilde{k} + \tilde{y}_{\tilde{x}}\tilde{x}$. Use (3.2)-(3.5) and the assumption that $\rho + g(\eta - 1) > 0$ to obtain $\hat{c} = \hat{y} - p_2\hat{x} - g\hat{k} > [\varphi(\hat{k}) - g]\hat{k} = [\rho + g(\eta - 1) + \bar{h}]\hat{k} > 0$.

$k(t) = \hat{k}A(t)$, $x(t) = \hat{x}A(t)$ with $x_2(t) = \hat{x}A(t) - \bar{x}_1$, $Y(t) = \hat{y}A(t)$ and $c(t) = \hat{c}A(t)$.

The optimal policy, it turns out, tends to the other extreme, by eliminating emission altogether and driving the economy towards a hazard-free balanced growth path. Let $\hat{k}^s$ be the unique solution to

$$\varphi(\hat{k}^s) = \rho + \eta g. \tag{3.6}$$

As above, we assume that $\varphi(\tilde{k}) > \rho + \eta g$ for $\tilde{k} < \hat{k}^s$ and $\varphi(\tilde{k}) < \rho + \eta g$ for $\tilde{k} > \hat{k}^s$. Since $\rho+\bar{h}+\eta g > \rho+\eta g$, it follows that $\hat{k} < \hat{k}^s$. Define $\hat{x}^s$, $\hat{y}^s$ and $\hat{c}^s$ in the same way as their competitive counterparts in (3.5) with $\hat{k}^s$ replacing $\hat{k}$. The socially optimal allocation is characterized in:

Proposition 3. *Under the optimal growth regime: (i) GHG emission ceases at a finite time and the ensuing GHG concentration and hazard rate vanish in the long run; (ii) the economy approaches a hazard-free balanced growth path along which $k(t) = \hat{k}^s A(t)$, $x(t) = \hat{x}^s A(t)$, $Y(t) = \hat{y}^s A(t)$ and $c(t) = \hat{c}^s A(t)$.*

Equations (3.4) and (3.6) reproduce the familiar Ramsey (1928) condition, equating the marginal product of capital with the social discount rate along the optimal trajectory. The modification here is due to the presence of the long run hazard rate in the social discount rate: the maximal hazard $\bar{h}$ under the competitive allocation, and a vanishing hazard under the optimal regime. As the social discount rate is smaller than its competitive counterpart, the long run capital stock is larger under the social allocation than under the competitive allocation.

For a stationary economy (with $g = 0$), Tsur and Zemel (2008) showed that the Pigouvian hazard tax will not do away with GHG emission but only reduce its use to some "bearable" rate. Why is this policy (of maintaining some GHG stock at an equilibrium level and enjoying the benefits of the cheaper fossil energy) not desirable for a growing economy? The explanation is based on the evolution of the cost-benefit ratio as the economy grows. At each point of time, the additional cost inflicted by using the clean input rather than the (cheaper) polluting input is at most $p_2\bar{x}_1 - Z(\bar{x}_1)$. On the other hand, increasing the discount rate represents a loss of value. Thus, the benefit associated with reduced emissions is the forgone loss obtained with the smaller discount rate associated with the smaller hazard. While the cost remains bounded over time, the benefit increases as the economy grows. Thus, the cost-benefit ratio diminishes along the path of growth and eventually it proves worthwhile to eliminate the source of damage altogether.

These considerations are reflected in the Pigouvian hazard tax $\beta(t)$, which increases over time at the rate ηg (see equation (A.26) in the appendix). Thus,

$$Z'(0) + \beta(t)e'(0) = p_2$$

must hold at some finite time, at which time conditions (2.22) imply that the use of x_1 (and GHG emission) ceases altogether. Since g and η affect positively the rate of growth of β, each advances GHG abatement. The first, because a higher growth rate implies that there is more to lose due to the event occurrence; the second due to the risk aversion role of η.

4 Concluding remarks

Under risk of catastrophic climate change, the occurrence hazard rate augments the social discount rate, increasing and at the same time rendering it endogenous to the emission policy. The former (increasing) effect weakens the case for an early, vigorous reduction in GHG emission while the latter (endogeneity) effect operates in the opposite direction. The competitive growth policy ignores the endogeneity effect, whereas the social growth regime accounts for both. It is thus hardly surprising that the competitive and social allocations should differ. What is less obvious is the finding that the two allocations lie at the extreme ends of the range of possible long run emissions: maximal emission in the competitive regime and no emission under the social regime. This property is a consequence of economic growth and the *endogeneity* of the "hazard-inclusive" social discount rate.

The level at which atmospheric GHG concentration should be stabilized and how to approach this level are central issues in climate policy discussions. We find that a growing economy should eventually do away with GHG emission altogether so that the ensuing (anthropogenic) hazard vanishes in the long run. This strong result surely owes to the structure of our setup, particularly the constant price of the alternative (clean) technology and the exogenous growth mechanism. Extensions to relax these assumptions are needed to test for its robustness.

Appendix

A Proofs

Proof of Proposition 2: Define, following equation (2.16),

$$\chi \equiv \frac{\rho c_p^{1-\eta}}{\rho + (\eta - 1)g} \tag{A.1}$$

and write the objective of (2.19) as

$$\psi + \int_0^\infty \frac{\tilde{c}(t)^{1-\eta} - \chi e^{g(\eta-1)t}}{1-\eta} e^{-\Gamma(t) - g(\eta-1)t} dt, \tag{A.2}$$

where

$$\Gamma(t) = \int_0^t [\rho + h(Q(\tau))] d\tau = (\rho + \bar{h})t + b(t),$$

$$b(t) \equiv \int_0^t [h(Q(\tau)) - \bar{h}] d\tau, \tag{A.3}$$

$$\dot{b}(t) = h(Q(t)) - \bar{h} < 0, \tag{A.4}$$

where it is recalled that a tilde over a variable signifies detrending (division by $A(t) \equiv \exp(gt)$), e.g. $\tilde{c}(t) = c(t)/A(t)$.

Next, we rewrite (2.18) as

$$\dot{\tilde{k}}(t) = \tilde{y}(\tilde{k}(t), \tilde{x}(t)) - p_2 \tilde{x}(t) - g\tilde{k}(t) - \tilde{c}(t) + \pi(x_1) e^{-gt} \tag{A.5}$$

where $\pi(x_1) \equiv p_2 x_1 - Z(x_1) > 0$ is the profit from the polluting resource when it is used at the rate $x_1 \leq \bar{x}_1$ and is bounded by the maximal profit $\pi(\bar{x}_1)$. Note that the profit is defined in terms of the full rate x_1 (without detrending) hence the exponent in the last term of (A.5).

Let $\varpi \equiv \rho + g(\eta - 1) + \bar{h} > 0$. Expressed in terms of the detrended variables, the household problem is to maximize (A.2) subject to (A.5). The Hamiltonian for this problem is

$$H = \frac{\tilde{c}^{1-\eta} - \chi e^{g(\eta-1)t}}{1-\eta} e^{-\varpi t - b(t)} + \tilde{\lambda}[\tilde{y}(\tilde{k}, \tilde{x}) - p_2 \tilde{x} - g\tilde{k} - \tilde{c} + \pi(x_1)e^{-gt}]$$

and the necessary conditions for an optimal policy include:

$$\tilde{c}^{-\eta} e^{-\varpi t - b(t)} - \tilde{\lambda} = 0 \tag{A.6}$$

and

$$\dot{\tilde{\lambda}} = -\tilde{\lambda}[\varphi(\tilde{k}) - g]. \tag{A.7}$$

Define

$$m(t) = \tilde{\lambda}(t) e^{\varpi t + b(t)}, \tag{A.8}$$

yielding, using (A.7),

$$\dot{m} = -m[\varphi(\tilde{k}) - g] + m[\varpi + \dot{b}] = m[\rho + g\eta + \bar{h} - \varphi(\tilde{k}) + \dot{b}]. \tag{A.9}$$

Let

$$\zeta(\tilde{k}) = \tilde{y}(\tilde{k}, \tilde{x}(\tilde{k})) - p_2 \tilde{x}(\tilde{k}) - g\tilde{k}, \tag{A.10}$$

so that according to (3.2) and (3.3)

$$\zeta'(\tilde{k}) = \varphi(\tilde{k}) - g \tag{A.11}$$

and consider a capital stock $\tilde{k}$ below $\hat{k}$ of (3.4), so that $\varphi(\tilde{k}) > \rho + \eta g + \bar{h}$. We now show that after some finite date the optimal $\tilde{k}(\cdot)$ process must increase in this region. To see this suppose otherwise, that it decreases, remaining below $\hat{k}$. In view of (A.4), the right-hand side of (A.9) is negative hence $m(\cdot)$ decreases in time. Thus, according to (A.6), the $\tilde{c}(\cdot)$ process increases in time below $\hat{k}$. With $\pi(x_1)$ bounded for $x_1 \in [0, \bar{x}_1]$, the difference $c(t) - \pi(x_1)e^{-gt}$ must also increase at a sufficiently large t. Using (A.11) and $\varpi > 0$, we find that $\zeta(\cdot)$ increases with $\tilde{k}$ for $\tilde{k} < \hat{k}$. When $\tilde{k}(\cdot)$ decreases, the right hand side of (A.5) is negative and decreasing in time, hence the $\tilde{k}(\cdot)$ process must decrease at an ever growing rate, approaching zero at a finite time, which cannot be optimal[9]. The increasing consumption process also rules out a steady state below $\hat{k}$, hence $\tilde{k}(\cdot)$ must increase in this region.

The above discussion implies the existence of some minimal stock $\tilde{k}_{min} > 0$ such that $\tilde{k}(t) > \tilde{k}_{min}$ for all t. We now show that x_1 reaches $\bar{x}_1$ at some finite time and remains at that rate thereafter. Let $\tilde{x}_{min}$ be the energy rate corresponding to $\tilde{k}_{min}$ such that $Y_x(\tilde{k}_{min}A, \tilde{x}_{min}A, A) = \tilde{y}_{\tilde{x}}(\tilde{k}_{min}, \tilde{x}_{min}) = p_2$ as defined by (3.2). Let $t_0 \equiv \log(\bar{x}_1/\tilde{x}_{min})/g$ so that $\bar{x}_1 \leq \tilde{x}_{min}A(t)$, for all $t \geq t_0$ (equality holding at $t = t_0$) and suppose that $x(t) < \bar{x}_1$ at some time $t > t_0$. Using $Y_{kx} > 0$, $Y_{xx} < 0$ and suppressing the time argument for convenience, we find

$$Y_x(\tilde{k}A, x, A) > Y_x(\tilde{k}_{min}A, x, A) > Y_x(\tilde{k}_{min}A, \bar{x}_1, A) > Y_x(\tilde{k}_{min}A, \tilde{x}_{min}A, A) = p_2$$

violating (2.4b). It follows that $x(t) \geq \bar{x}_1$ and $x_1(t) = \bar{x}_1$ at all $t > t_0$.

We can use (A.4), (2.7) and the fact that $h'(\cdot)$ is bounded in $(0, \bar{Q})$ to

[9]A vanishing capital implies ceasing producing and consuming, reducing utility to $-\infty$ from some finite time on.

obtain at all $t > t_0$

$$0 > \dot{b}(t) = h(Q(t)) - \bar{h} > -Be^{-\delta t}, \tag{A.12}$$

for some positive constant B.

Consider now a capital stock $\tilde{k}_1 > \hat{k}$, with $\varphi(\tilde{k}_1) < \rho + \eta g + \bar{h}$. From (A.12) we deduce that following some time t_1, the right-hand side of (A.9) is positive hence the $\tilde{c}(\cdot)$ process decreases. This implies that after t_1 a policy of increasing $\tilde{k}(\cdot)$ beyond $\tilde{k}_1$ during a time interval (or indefinitely) cannot be optimal since keeping $\tilde{k}(\cdot)$ fixed at $\tilde{k}_1$ during this interval (diverting the surplus resources to consumption) is feasible and yields a higher payoff. A steady state for $\tilde{k}(\cdot)$ above $\hat{k}$ is also ruled out by the decreasing consumption process. It follows that $\tilde{k}(\cdot)$ must approach $\hat{k}$ in the long run. The derivation of the constants of (3.5) follows from (3.2) and the budget constraint (A.5) in a straightforward manner. □

Proof of Proposition 3: Following the proof of Proposition 2, we express the social problem (2.20) in terms of the detrended variables as

$$v^s(\tilde{k}_0, Q_0) = \psi + \max_{\{\tilde{c}(t),\tilde{x}(t),x_1(t)\}} \int_0^\infty \frac{\tilde{c}(t)^{1-\eta} - \chi e^{g(\eta-1)t}}{1-\eta} e^{-\Gamma(t)-g(\eta-1)t} dt \tag{A.13}$$

subject to (2.6), (A.5), $\dot{\Omega}(t) = h(Q(t))$, $\Gamma(t) = \rho t + \Omega(t)$ and the usual non-negativity constraints, given $\tilde{k}(0) = \tilde{k}_0$, $Q(0) = Q_0$, $\Omega(0) = 0$. (The emitting input $x_1(\cdot)$ is not detrended also in this formulation.) The Hamiltonian for this problem is

$$H = \frac{\tilde{c}^{1-\eta} - \chi e^{g(\eta-1)t}}{1-\eta} e^{-\Gamma - g(\eta-1)t} +$$
$$\tilde{\lambda}[\tilde{y}(\tilde{k},\tilde{x}) - p_2\tilde{x} - g\tilde{k} - \tilde{c} + \pi(x_1)e^{-gt}] + \gamma[e(x_1) - \delta Q] + \mu h(Q),$$

where $\tilde{\lambda}$, γ and μ are the costate variables of $\tilde{k}$, Q and Ω, respectively. Necessary conditions for an optimum include

$$\tilde{c}^{-\eta} e^{-\Gamma - g(\eta-1)t} - \tilde{\lambda} = 0, \tag{A.14}$$

$$\tilde{y}_{\tilde{x}}(\tilde{k},\tilde{x}) - p_2 = 0, \tag{A.15}$$

$$\tilde{\lambda}[p_2 - Z'(x_1)]e^{-gt} + \gamma e'(x_1) \leq 0, \text{ equality holding if } x_1 > 0, \tag{A.16}$$

$$\dot{\tilde{\lambda}} = -\tilde{\lambda}[\varphi(\tilde{k}) - g], \tag{A.17}$$

$$\dot{\gamma} = \gamma\delta - \mu h'(Q), \tag{A.18}$$

$$\dot{\mu} = \frac{\tilde{c}^{1-\eta} - \chi e^{g(\eta-1)t}}{1-\eta} e^{-\Gamma - g(\eta-1)t} \tag{A.19}$$

and the transversality condition

$$\lim_{t\to\infty} H(t) = 0. \tag{A.20}$$

We show that $\lim_{t\to\infty} Q(t) = 0$. Suppose otherwise, then $x_1(t) > 0$ for arbitrarily large t. At these times, condition (A.16) holds with equality, giving

$$Z'(x_1) - (\gamma/\tilde{\lambda})e^{gt}e'(x_1) = p_2. \tag{A.21}$$

Since $Y_x = \tilde{y}_{\tilde{x}} = p_2$, we see that (A.21) agrees with (2.22a) where the tax rate is set at

$$\beta(t) = -(\gamma/\tilde{\lambda})\exp(gt). \tag{A.22}$$

We show that $\beta(t)$ diverges at large t, violating (A.21) and implying that $x_1(\cdot)$ must vanish from some (finite) time onward. Using $0 < h(Q) < \bar{h}$, we repeat the arguments of the proof of Proposition 2 to show that the interval $[\hat{k}, \hat{k}^s]$ is attractive in the long run (i.e., the optimal $\tilde{k}(\cdot)$ process increases below $\hat{k}$ and decreases above $\hat{k}^s$). For $\tilde{k} < \hat{k}^s$ the inequality $\varphi(\tilde{k}) \geq \rho + \eta g > g$ holds, hence (3.3), (A.11) and (A.15) imply (using Euler's Theorem as in footnote 8) that $\zeta(\tilde{k}) > 0$ and $\zeta'(\tilde{k}) > 0$.

We now show that in the long run the optimal $\tilde{c}(\cdot)$ process is bounded away from zero. Suppose $\lim_{t\to\infty} \tilde{c}(t) = 0$. Writing (A.5) in the form $\dot{\tilde{k}} = \zeta(\tilde{k}) - \tilde{c} + \pi(x_1)\exp(-gt)$ we find that following some finite time, if $\tilde{k} < \hat{k}^s$, the $\tilde{k}(\cdot)$ process increases in time at an increasing rate, crossing eventually the state $\hat{k}^s$ and violating the property that the interval $[\hat{k}, \hat{k}^s]$ is attractive. Similarly, if $\tilde{c}(\cdot)$ grows indefinitely in the long run, then the process $\tilde{k}(\cdot)$ must eventually decrease in time at an increasing rate, falling below $\hat{k}$. We conclude, therefore, that in the long run both $\tilde{k}(\cdot)$ and $\tilde{c}(\cdot)$ are bounded away from zero in finite intervals.

Next, we write the solution of (A.18) in the form

$$\gamma(t) = Me^{\delta t} + e^{\delta t} \int_t^\infty \mu(\tau) h'(Q(\tau)) e^{-\delta\tau} d\tau, \tag{A.23}$$

where $M \equiv \lim_{t\to\infty} \gamma(t)\exp(-\delta t)$. A non-vanishing value of M implies that $\gamma(\cdot)$ increases exponentially at the rate δ, which violates the transversality condition (A.20). Thus, $M = 0$ and

$$\gamma(t) = h'(Q^s(t)) \int_t^\infty \mu(\tau) e^{-\delta(\tau - t)} d\tau \tag{A.24}$$

for some state $Q^s(t) \in [0, \bar{Q}]$. Integrating by parts and using (A.19) and some algebraic manipulations, we obtain

$$
\begin{aligned}
& \frac{\delta(1-\eta)}{h'(Q^s(t))}\gamma(t) = (1-\eta)\mu(t) \\
+ & \int_t^{\infty} \tilde{c}^{1-\eta}(\tau) e^{-\Gamma(\tau)-g(\eta-1)\tau-\delta(\tau-t)} d\tau - \chi \int_t^{\infty} e^{-\Gamma(\tau)-\delta(\tau-t)} d\tau \\
= & \int_t^{\infty} \tilde{c}(\tau)^{1-\eta} [e^{-\delta(\tau-t)} - 1] e^{-\Gamma(\tau)-g(\eta-1)\tau} d\tau - \chi \int_t^{\infty} [e^{-\delta(\tau-t)} - 1] e^{-\Gamma(\tau)} d\tau,
\end{aligned}
$$

where the last step is obtained by integrating (A.19) from t to ∞ with the condition $\lim_{t\to\infty} \mu(t) = 0$ (which follows from the transversality condition (A.20) when $\lim_{t\to\infty} Q(t) > 0$).

Thus, with $h'(\cdot)$ and $\tilde{c}(\cdot)$ bounded away from zero, we obtain

$$\gamma(t) = \gamma_1(t) e^{-\Gamma(t)-g(\eta-1)t} + \gamma_2(t) e^{-\Gamma(t)}, \tag{A.25}$$

where the functions $\gamma_1(\cdot)$ and $\gamma_2(\cdot)$ are bounded away from zero. When $\eta > 1$, the second term dominates in the long run, reducing (A.25) to $\gamma(t) \approx \gamma_2(t) e^{-\Gamma(t)}$, where $\gamma_2(\cdot) < 0$. We can now use (A.14) to express the tax rate $\beta(t) \equiv -(\gamma(t)/\tilde{\lambda}(t)) \exp(gt)$ in the form

$$\beta(t) = -\tilde{c}^{\eta}(t)\gamma_2(t) e^{\eta g t} \tag{A.26}$$

which diverges at large t. With $e'(\cdot)$ bounded away from zero at the relevant x_1 range, we conclude that (A.21) cannot hold at large t, hence $x_1(\cdot)$ must vanish in finite time.

Comparing (3.2) and (A.15), we find that the conditions that define the total intermediate input rates are the same for the competitive and social allocations. With a vanishing x_1, we can repeat the arguments of Proposition 2 to conclude that the detrended '$\tilde{\ }$' variables approach the constant values $\hat{k}^s$, $\hat{x}^s$, $\hat{y}^s$ and $\hat{c}^s$ hence the social process approaches a balanced growth path with $\bar{h}^s = 0$ replacing $\bar{h}$ as the eventual hazard rate. The derivation of the social parameters $\hat{k}^s$ $\hat{x}^s$, $\hat{y}^s$ and $\hat{c}^s$ is similar to that of their competitive counterparts. $\square$

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