האוניברסיטה העברית בירושלים
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Discussion Paper No. 13.07

Climate change policy in a growing economy under catastrophic risks

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August 19, 2007

Abstract

Under risk of catastrophic 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, it implies that greenhouse gases (GHG) emission *should* gradually be brought to a halt. 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. We find that 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; environmental catastrophes; economic growth; emission policy; hazard rate;

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

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1 Introduction

A changing climate pattern shifts the dynamics of many natural processes, including ocean currents, glacier melting and degradation of habitats of plant and animal species. Although the accumulation of greenhouse gases (GHG) that drives the climate change is gradual, it can trigger abrupt events of catastrophic scales at unpredictable dates (Alley et al. 2003, Stern 2007, IPCC4 2007). The combination of unpredictable, abrupt occurrence and catastrophic damage poses a delicate policy challenge. Early studies of possible policy responses to catastrophic risks in the context of climate change include Clarke and Reed (1994) and Tsur and Zemel (1996). Recent contributions include Mastrandrea and Schneider (2001), Nævdal (2006), Karp and Tsur (2007) and Weitzman (2007b).

Climate change is largely attributed to anthropogenic emissions of GHG that have been accelerated with the economic growth of the post Industrial Revolution era. A question arises regarding whether economic growth is inevitably associated with enhanced GHG emissions and the ensuing climate change risks. One view accepts the growth-emission link as a special case of a more general (and more widespread) view that economic growth and environmental quality represent conflicting interests and entail tradeoffs. Another view recognizes the forces underlying the "inverted-U curve" phenomenon that tend to mitigate, and in some cases even reverse, the degrading effects of economic growth on environmental quality (see Arrow et al. 1995, Dasgupta et al. 2002, and references they cite).

We find that the first view is consistent with competitive (unregulated) economic growth (i.e., with how a laissez-faire economy *would* grow), whereas the second view is consistent with optimal economic growth (i.e., with how an economy *should* grow). We show that under risk of catastrophic occurrence, a growing economy should decrease and eventually eliminate the emission of GHG. However, due to the public bad nature of the catastrophic hazard, this outcome will not be realized by the invisible hand and unregulated economic growth will instead give rise to excessive emissions. We propose a Pigouvian hazard tax on emission that implements the optimal growth regime.

Our analysis builds on Tsur and Zemel (2007) 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. In a growing economy, we find that the Pigouvian hazard tax is so adjusted as to cease emission altogether at a finite time in order to eliminate the ensuing catastrophic risk. In contrast, the competitive (unregulated) allocation gives rise to (economically) maximal GHG emissions.

The catastrophic risk is represented here by a hazard rate function that depends on the atmospheric GHG concentration and measures the probability of catastrophic occurrence. When the hazard function is known (i.e., there is no uncertainty regarding its shape or parameters),[1] the hazard rate

[1]There are two main reasons for our lack of perfect knowledge regarding global warm-

per se is well accounted for by the competitive allocation. However, agents fail to account for the *change* in hazard due to their actions, since the hazard is in effect a pure public bad (non-excludable, non-rivalry). As a result the competitive growth regime is suboptimal. Indeed, the Pigouvian hazard tax developed here depends on the sensitivity of the hazard to the GHG concentration and vanishes for exogenous hazards that are independent of the GHG stock.

This observation 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 and Boyer 2000). This view has been challenged recently by a comprehensive study, led by Stern (2007), recommending a much more vigorous and early response and 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 capital 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.[2] At a first glance it might appear that this weakens the case for an early vigorous response (since

ing 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.

[2]Stern Review's main justification for a positive ρ is the presence of a catastrophic hazard (see Beckerman and Hepburn 2007).

the hazard increases the social discount rate). However, while ρ, η and g are exogenous parameters[3], 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.

The next section extends the stationary economy of Tsur and Zemel (2007) to a growing economy with (exogenous) labor-augmenting technical change and defines the Pigouvian hazard tax. Section 3 presents the main 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 (2007) 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.

[3]In this work we assume exogenous technical change, so g is exogenous. In general g may also be affected by the climate change policy but this dependence is weaker than that of the hazard.

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 (see details in Tsur and Zemel 2007)

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

as a function of capital, energy 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 and satisfies the standard curvature conditions.

Energy, $x = x_1 + x_2$, can be derived from polluting (x_1) or clean (x_2) sources. The former refers to fossil energy; the latter refers 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 (coal, oil or natural gas of various qualities). 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, say 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.[4] The energy supply curve is therefore given by

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

where $0 < Z'(0) < p_2$ (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)

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

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

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

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 are large enough, $Y_x(k, \bar{x}_1, A) > p_2$ and 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 $e(\cdot)$ satisfies $e(0) = 0$ and $e'(\cdot) > 0$, and $\delta > 0$ is the rate of natural decay.[5] 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

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

of events (leading from changing GHG concentration to the ensuing damage) is influenced by a myriad of stochastic effects (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 the period $[t, t + dt]$ 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 (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 $2 - 4.5^oC$ 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 $2 - 5^oC$ and $3 - 10^oC$ 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: under doubling of GHG concentration, the global mean warming will exceed 5^oC (close to the warming since the last ice age) at a 20% chance. 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 or a few sufficient statistics. The 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. 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.

We consider a post-event regime in which consumption is reduced to a certain, fixed level from the occurrence date onwards. Other post-event regimes (such as consumption that grows from some reduced initial post-event level) can be postulated without changing the main message regarding the effect of hazard endogeneity on emission policies.

2.3 Households

Let T represent the (random) event-occurrence time. Following occurrence ($t \geq T$), consumption is reduced to the constant post-event rate c_p. Consuming at the rate c generates the utility flow

$$u(c) = \frac{c^{1-\eta} - \xi}{1-\eta},$$

where η is the elasticity of marginal utility and ξ is some given parameter. We normalize by setting $\xi = c_p = 1$, so that a consumption stream $\{c(t),\ t \geq 0\}$ generates the utility stream

$$\tilde{u}(t) = \begin{cases} u(c(t)) & \text{when } t \leq T \\ 0 & \text{otherwise} \end{cases} \tag{2.10}$$

and the payoff $\int_0^T u(c(t)) \exp(-\rho t) dt$, where ρ is the pure rate of time preference. The expected payoff is[6]

$$E\left\{\int_0^T u(c(t))e^{-\rho t} dt | T > 0\right\} = \int_0^\infty u(c(t))e^{-\Gamma(t)} dt, \tag{2.11}$$

where

$$\Gamma(t) = \int_0^t [\rho + h(Q(\tau))] d\tau = \rho t + \Omega(t) \tag{2.12}$$

[6]Since the event is damaging rather than rewarding, the normalization that the post-event value vanishes requires that the expected pre-event payoff is positive. This imposes some restrictions on the parameters of the models.

and

$$\Omega(t) = \int_0^t h(Q(\tau))d\tau. \tag{2.13}$$

Assuming $\rho + g(\eta - 1) > 0$ ensures that the expected payoff is finite. Equation (2.12) reveals how the hazard rate is added to the pure rate of time preference to form the "hazard-inclusive" 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 2007)

$$\dot{k}(t) = Y(k(t), x_1(t) + x_2(t), A(t)) - p_2 x_2(t) - Z(x_1(t)) - c(t). \tag{2.14}$$

Households choose their consumption-saving plan according to

$$v^c(k_0) = \max_{\{c(t)\geq 0\}} \int_0^\infty u(c(t))e^{-\Gamma(t)}dt \tag{2.15}$$

subject to (2.14), given $k(0) = k_0$. In solving this problem, households assume that the intermediate inputs $x_1(\cdot)$ and $x_2(\cdot)$, and the ensuing processes $e(x_1)$, $Q(\cdot)$, $\Gamma(\cdot)$ and $\Omega(\cdot)$ are exogenous. In the competitive (unregulated) allocation, $x_1(t)$ and $x_2(t)$ are determined according to (2.4a)-(2.4b).

2.4 Regulator

The socially optimal allocation is the outcome of

$$v^s(k_0, Q_0) = \max_{\{c(t), x_1(t), x_2(t)\}} \int_0^\infty u(c(t))e^{-\Gamma(t)}dt \tag{2.16}$$

subject to (2.6), (2.14), $\dot{\Omega}(t) = h(Q(t)),\ x_1(t) \geq 0,\ x_2(t) \geq 0$ 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 (2.16).

The regulator seeks to implement the social allocation in a competitive environment. Following Tsur and Zemel (2007), let

$$\beta(t) = \frac{-\gamma(t)}{\lambda(t)} \tag{2.17}$$

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

$$Y_x(k(t), x_1(t)+x_2(t), A(t)) \leq Z'(x_1(t))+\beta(t)e'(x_1(t)), \text{ equality holding if } x_1 > 0 \tag{2.18a}$$

and

$$Y_x(k(t), x_1(t) + x_2(t), A(t)) \leq p_2, \text{ equality holding if } x_2 > 0. \tag{2.18b}$$

The Pigouvian hazard tax is the optimal $\beta(t)$ corresponding to the solution of (2.16). It turns out that

Proposition 1. *When the tax rate $\beta(t)$ is levied on emission in a competitive environment, the resulting (regulated-competitive) allocation is optimal, namely $\beta(t)$ implements the optimal allocation.*

The proof is similar to the proof given in Tsur and Zemel (2007) for the stationary case and is therefore omitted.

The allocation (2.18) 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 (2007) found that the Pigouvian 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. For a growing economy the optimal use of the hazardous input must cease 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 value $\bar{x}_1$ of (2.5) at a finite time and the economy continues to grow under the maximal hazard rate $\bar{h}$ of (2.9). The effect of growth, then, 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 consider the problem 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

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

We show that the detrended processes converge to a steady state, which 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.

Since $\tilde{y}_{\tilde{x}} = Y_x$, it follows from (2.4b) and (2.18b) 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

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

[7] This assumption holds, for example, for the Cobb-Douglas technology.

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

and

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

The assumption $\rho + g(\eta - 1) > 0$ ensures that $\hat{c} > 0$.[8]

The long run behavior of the competitive economy is characterized in the following proposition (proofs are presented in the Appendix):

Proposition 2. *Under competitive growth: (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 $k(t) = \hat{k}A(t)$, $x(t) = \hat{x}A(t)$ 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 $\hat{x}^s$, $\hat{y}^s$

[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 $\hat{c} = \hat{y} - p_2\hat{x} - g\hat{k} > [\varphi(\hat{k}) - g]\hat{k} = [\rho + g(\eta - 1) + \bar{h}]\hat{k} > 0$.

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: a maximal hazard ($\bar{h}$) under the competitive allocation, and a vanishing hazard under the optimal regime.

For a stationary economy (with $g = 0$) Tsur and Zemel (2007) 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 $p_2\bar{x}_1 - Z(\bar{x}_1)$. The benefit is the forgone damage due to 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, which increases over time up to the point where emission is ceased (see proof of Proposition 3).

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 observation 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 result is a consequence of economic growth: the cost-benefit ratio associated with emission reduction diminishes as the economy grows, hence abatement becomes ever more desirable.

As climate change processes extend over long periods, any policy response is highly sensitive to the magnitude of the discount rate. For this reason policy debates often revolve around the values of the parameters that comprise the social discount rate. We find that the endogeneity of the "hazard-inclusive" social discount rate is instrumental in determining global warming policies. In particular, it leads to the termination of GHG emission at a finite time and affects the scheduling of emission abatement. These considerations are realized via the Pigouvian hazard tax that implements the optimal policy.

Appendix

A Proofs

Proof of Proposition 2: We use the '~' notation for detrended quantities, e.g. $\tilde{c}(t) = c(t)/A(t)$ and write the objective of (2.15) as

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

where

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

and

$$b(t) \stackrel{\text{def}}{=} \int_0^t [h(Q(\tau)) - \bar{h}] d\tau. \tag{A.2}$$

Thus, from some time t_0 on, when x_1 is fixed at $\bar{x}_1$, we can use (2.7) and the fact that $h'(\cdot)$ is bounded in $(0, \bar{Q})$ to obtain

$$0 > \dot{b}(t) = h(Q(t)) - \bar{h} > -Be^{-\delta t}, \tag{A.3}$$

for some positive constant B.

Next, we rewrite (2.14) as

$$\dot{\tilde{k}}(t) = \tilde{y}(\tilde{k}(t), \tilde{x}(t)) - p_2\tilde{x}(t) - g\tilde{k}(t) - \tilde{c}(t) + e^{-gt}\bar{Z} \tag{A.4}$$

where $\bar{Z} \stackrel{\text{def}}{=} p_2\bar{x}_1 - Z(\bar{x}_1) > 0$ is the profit from the polluting resource when it is used at the maximal rate $\bar{x}_1$. Note that this constant is defined in terms of the full rate $\bar{x}_1$ (without detrending) hence the exponent in front of the last term of (A.4).

Let $\omega \stackrel{\text{def}}{=} \rho + g(\eta - 1) + \bar{h} > 0$. Expressed in terms of the detrended variables, the household problem is to maximize (A.1) subject to (A.4). The Hamiltonian for this problem is

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

and the necessary conditions for an optimal policy include:

$$\tilde{c}^{-\eta}e^{-\omega t - b(t)} - \tilde{\lambda} = 0 \tag{A.5}$$

and

$$\dot{\tilde{\lambda}} = -\tilde{\lambda}[\varphi(\tilde{k}) - g]. \tag{A.6}$$

Define

$$m(t) = \tilde{\lambda}(t)e^{\omega t + b(t)}, \tag{A.7}$$

yielding, using (A.6),

$$\dot{m} = -m[\varphi(\tilde{k}) - g] + m[\omega + \dot{b}] = m[\rho + g\eta + \bar{h} - \varphi(\tilde{k}) + \dot{b}]. \tag{A.8}$$

Let

$$\zeta(\tilde{k}) = \tilde{y}(\tilde{k}, \tilde{x}(\tilde{k})) - p_2\tilde{x}(\tilde{k}) - g\tilde{k}, \tag{A.9}$$

so that according to (3.2) and (3.3)

$$\zeta'(\tilde{k}) = \varphi(\tilde{k}) - g \tag{A.10}$$

and consider a capital stock $\tilde{k}$ below $\hat{k}$ of (3.4), so that $\varphi(\tilde{k}) > \rho + \eta g + \bar{h}$. In view of (A.3), the right-hand side of (A.8) is negative hence $m(\cdot)$ decreases in time. Thus, according to (A.5), the $\tilde{c}(\cdot)$ process increases in time below $\hat{k}$. Using (A.10) and $\omega > 0$, we find that $\zeta(\cdot)$ increases with $\tilde{k}$ in the region below $\hat{k}$. It follows that the optimal $\tilde{k}(\cdot)$ process must increase in this region. To see this suppose otherwise, that it decreases. Then, the right hand side of (A.4) must be 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. Similar considerations rule out a steady state below $\hat{k}$.

Consider now a capital stock above $\hat{k}$, with $\varphi(\tilde{k}) < \rho + \eta g + \bar{h}$. From (A.3) we deduce that following some time t_1, the right-hand side of (A.8) is positive hence the $\tilde{c}(\cdot)$ process decreases. This implies that after t_1 a policy of increasing $\tilde{k}(\cdot)$ during a time interval (or indefinitely) cannot be optimal since keeping $\tilde{k}(\cdot)$ constant during this interval (diverting the surplus resources to consumption) is feasible and yields a higher payoff. A steady state for $\tilde{k}(\cdot)$ above $\hat{k}$ can also be ruled out. 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.4) in a straightforward manner. □

Proof of Proposition 3: Following the proof of Proposition 2, we express the social problem (2.16) in terms of the detrended variables (the '~' variables) as

$$v^s(\tilde{k}_0, Q_0) = \max_{\{\tilde{c}(t), \tilde{x}(t), x_1(t)\}} \int_0^\infty \frac{\tilde{c}(t)^{1-\eta} - e^{g(\eta-1)t}}{1-\eta} e^{-\Gamma(t)-g(\eta-1)t} dt \tag{A.11}$$

subject to (2.6), (A.4), $\dot{\Omega}(t) = h(Q(t))$, $\Gamma(t) = \rho t + \Omega(t)$ and the usual nonnegativity constraints, given $k(0) = \tilde{k}_0$, $Q(0) = Q_0$, $\Omega(0) = 0$. (The hazardous input allocation $x_1(\cdot)$ is not detrended also in this formulation.) The Hamiltonian for this problem is

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

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

$$\tilde{c}^{-\eta} e^{-\Gamma-g(\eta-1)t} - \tilde{\lambda} = 0, \tag{A.12}$$

$$\tilde{y}_{\tilde{x}}(\tilde{k}, \tilde{x}) - p_2 = 0, \tag{A.13}$$

$$\tilde{\lambda} e^{-gt}[p_2 - Z'(x_1)] + \gamma e'(x_1) \leq 0, \text{ equality holding if } x_1 > 0, \tag{A.14}$$

$$\dot{\tilde{\lambda}} = -\tilde{\lambda}[\varphi(\tilde{k}) - g], \tag{A.15}$$

$$\dot{\gamma} = \gamma\delta - \mu h'(Q), \tag{A.16}$$

$$\dot{\mu} = \frac{\tilde{c}^{1-\eta} - e^{g(\eta-1)t}}{1-\eta} e^{-\Gamma-g(\eta-1)t} \tag{A.17}$$

and the transversality condition

$$\lim_{t\to\infty} H(t) = 0. \tag{A.18}$$

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.14) holds with equality, giving

$$Z'(x_1) - (\gamma/\tilde{\lambda})e^{gt}e'(x_1) = p_2. \tag{A.19}$$

Since $Y_x = \tilde{y}_{\tilde{x}} = p_2$, we see that (A.19) agrees with (2.18a) where the tax rate is set at

$$\beta(t) = -(\gamma/\tilde{\lambda})\exp(gt). \tag{A.20}$$

We show that $\beta(t)$ diverges at large t, violating (A.19) 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.10) and (A.13) 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.4) in the form $\dot{\tilde{k}} = \zeta(\tilde{k}) - \tilde{c} + \exp(-gt)(p_2 x_1 - Z(x_1))$ 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.16) in the form

$$\gamma(t) = Me^{\delta t} + e^{\delta t} \int_t^\infty \mu(\tau) h'(Q(\tau)) e^{-\delta \tau} d\tau, \tag{A.21}$$

where $M \stackrel{\text{def}}{=} \lim_{t\to\infty} \gamma(t) \exp(-\delta t)$. A non-vanishing value of M implies that $\gamma(\cdot)$ increases exponentially at the rate δ, which violates the transversality condition (A.18). Thus, $M = 0$ and

$$\gamma(t) = h'(Q^s(t)) \int_t^\infty \mu(\tau) e^{-\delta(\tau - t)} d\tau \tag{A.22}$$

for some state $Q^s(t) \in [0, \bar{Q}]$. Integrating by parts and using (A.17) we obtain

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

where the last step is obtained by integrating (A.17) from t to ∞ with the condition $\lim_{t\to\infty} \mu(t) = 0$ (which follows from the transversality condition (A.18) when $\lim_{t\to\infty} Q(t) > 0$).

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

$$\gamma(t) = \gamma_1(t) e^{-\Gamma(t) - g(\eta-1)t} + \gamma_2(t) e^{-\Gamma(t)}, \tag{A.23}$$

where the functions $\gamma_1(\cdot)$ and $\gamma_2(\cdot)$ are bounded away from zero. We can now use (A.12) to express the tax rate $\beta(t) = -(\gamma(t)/\tilde{\lambda}(t)) \exp(gt)$ in the form

$$\beta(t) = -\tilde{c}^{\eta}(t)[\gamma_1(t)e^{gt} + \gamma_2(t)e^{\eta g t}] \tag{A.24}$$

and both terms diverge at large t. Which of these terms dominates the long term behavior depends on whether η is larger or smaller than unity, but one can verify that the sign of the coefficient of the dominant term is negative in either case, hence the tax rate is positive. With $e'(\cdot)$ bounded away from zero, we conclude that (A.19) cannot hold at large t, hence $x_1(\cdot)$ must vanish in finite time.

Comparing (3.2) and (A.13), 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 $\hat{c}^s$ follows that of their competitive counterparts. □

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