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Uncertain Climate Policy and the Green Paradox

by

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Abstract

Unintended consequences of announcing a climate policy well in advance of its implementation have been studied in a variety of situations. We show that a phenomenon akin to the so-called "Green-Paradox" holds also when the policy implementation date is uncertain. Governments are compelled, by international and domestic pressure, to demonstrate an intention to reduce greenhouse gas emissions. Taking actual steps, such as imposing a carbon tax on fossil energy, is a different matter altogether and depends on a host of political considerations. As a result, economic agents often consider the policy implementation date to be uncertain. We show that in the interim period between the policy announcement and its actual implementation the emission of green-house gases increases vis-à-vis business-as-usual.

"......If you have to shoot, shoot, don't talk!" – Tuco in *The Good, the Bad and the Ugly.*

Keywords: Climate policy, carbon tax, uncertainty, green paradox.

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1 Introduction

An increasing body of economic literature suggests that the very large potential damage due to emissions-induced climate change calls for effective regulation measures to limit the accumulation of atmospheric pollution. The costly measures would be justified only if the response they entail actually advances the desired goal of reduced emissions. Recent studies reveal, however, that this is not always the case, and climate policies may paradoxically give rise to more emissions relative to the laissez-faire scenario. For example, partial participation in an international emission reduction program may introduce a leakage effect, whereby the response of the non-participating parties more than offsets the reduction activities of the participants. The resulting "Green Paradox" is analyzed, for example, by Sinn (2008) and by Eichner and Pethig (2009). A similar paradoxical outcome may stem from the regulator's wish to allow the parties prepare in advance to the proposed policy measures and spread their adjustment efforts over time. A model based on this mechanism has been developed by Di Maria et al. (2008) who study the response of coal or oil fields owners to an advance announcement of an anticipated climate policy and find that the inelastic supply of the non-renewable resources might induce them to lower prices prior to the policy implementation, encouraging enhanced emissions.

At the core of the mechanisms driving these results lies a finite resource stock that owners wish to exploit before the announced policy interrupts their supply activities. In a recent contribution, Smulders et al. (2009) show that scarcity is not the sole driver of such effects and obtain the paradoxical outcome in a model with an unlimited supply of fossil energy. Introducing regulation via a carbon tax, which effectively raises the price of fossil energy, and assuming that the regulator announces the plan to levy the tax well in advance, they show that the early announcement distorts resource allocation processes in a number of ways. In particular, it reduces consumption and increases saving, thus giving rise to a larger capital stock. The larger capital stock, in turn, enhances the demand for fossil energy by firms that use capital, energy and labor as factors of production. Thus, announcing a policy aimed at reducing the use of fossil energy well in advance gives rise to the opposite effect until the policy is actually realized. The result holds both when the regulation policy involves a mild tax rate which reduces fossil use but does not induce the use of alternative, clean (solar) energy as well as when the tax rate is high enough to trigger a transition to solar energy.

In this work we extend the results of Smulders et al. (2009) by considering uncertainty as yet another driver of paradoxical effects. We incorporate uncertainty into the model by assuming that the government announces the intention to levy the carbon tax, but the date of implementation depends on political conditions and is therefore uncertain. The distinction appears to be important as it affects the underlying mechanism that drives the paradox. In particular, the continuity of the consumption process plays a key role in deriving the early announcement effect when the implementation date is known in advance. In contrast, under uncertain implementation date, the consumption path undergoes a discontinuous jump at the (random) time when the policy is implemented. Nevertheless, we establish the "green paradox" also under uncertainty, and show that it is driven by the same economic forces: anticipating that the tax will reduce energy use in the future induces households to enhance saving today in order to accumulate more capital that can substitute for the lower energy input. Prior to implementation of the tax policy, the increased capital stock is associated with increased energy input, hence the paradoxical outcome. Indeed, since uncertainty regarding implementation appears to be a common feature characterizing climate policies, the negative effect of the paradox may be significant.

Of course, the saving efforts must come at the expense of consumption, and the realization of the effect depends on a condition relating the production elasticity of capital to the elasticity of marginal utility of consumption. As explained by Smulders et al. (2009), this condition would be satisfied in any empirically relevant calibration, and the paradoxical nature of the uncertainty effect appears to be robust.

2 Setup

We begin with a brief summary of the unregulated case on which the early announcement analysis is based.

2.1 The unregulated economy

Early responses to expectations regarding the future introduction of a climate policy are studied in the framework of Tsur and Zemel (2009) who analyzed the penetration of solar technologies into competitive energy markets. We outline briefly the main components of this model and the results that drive the present analysis. The economy consists of a final good sector, an energy sector, and capital owning households. The final goods are produced using energy x and capital k as inputs. We employ the Cobb-Douglas production technology

$$y(k,x) = Fk^{\alpha}x^{\gamma} \tag{2.1}$$

with $\alpha + \gamma < 1$ and $F > 0$.[1] The energy sector consists of fossil energy firms that supply energy at the price ζ and of solar energy firms that invest in solar infrastructure (capital) s. Once the latter has been installed, the generation of solar energy entails no additional cost but is limited by the available stock s of solar capital. The two sources of energy are perfect substitutes, hence

$$x = x^f + bs \tag{2.2}$$

where x^f is fossil energy and $b > 0$ is an efficiency parameter measuring how much solar power can be delivered from one unit of solar capital. Solar energy is supplied at the going market price and the forward-looking solar firms base their investment decisions on their forecast regarding the evolution of future energy demand. The solar stock, then, evolves according to

$$\dot{s} = \iota - \delta s \tag{2.3}$$

where ι is the investment rate and $\delta > 0$ is the capital depreciation rate.

Household have a concave utility function $u(\cdot)$ over consumption c of final goods and seek to maximize the present-value utility stream over an infinite horizon

$$\int_0^{\infty} u(c(t))e^{-\rho t}dt \tag{2.4}$$

subject to the budget constraint

$$\dot{k} = y(k, x^f + bs) - \zeta x^f - \iota - \delta k - c, \tag{2.5}$$

where ρ is the pure (utility) rate of discount.

Absent market failures, the competitive equilibrium processes are determined by finding nonnegative $\{c(t), x^f(t), \iota(t)\}$ that maximize (2.4) subject to (2.3),(2.5), $k(0) = k_0 > 0$ and $s(0) = 0$.

The competitive allocation is characterized in Tsur and Zemel (2009) in terms of the critical price

$$\zeta^c = (\rho + \delta)/b \tag{2.6}$$

and three conditions:

[1] All quantities are given in per capita terms, hence the labor input is omitted. The CD specification is not essential for our analysis, but it allows for a simple and transparent derivation.

1. The condition for fossil energy use, equating its price to the marginal product of energy

$$y_x = F\gamma k^\alpha x^{\gamma-1} = \zeta \tag{2.7}$$

yielding

$$x = \left(\frac{F\gamma}{\zeta}\right)^{1/(1-\gamma)} k^{\alpha/(1-\gamma)}. \tag{2.8}$$

2. A steady state (Ramsey) condition,

$$y_k = F\alpha k^{\alpha-1} x^\gamma = \rho + \delta, \tag{2.9}$$

yielding

$$x = \left(\frac{\rho+\delta}{F\alpha}\right)^{1/\gamma} k^{(1-\alpha)/\gamma}. \tag{2.10}$$

3. A simultaneous growth condition, equating the marginal product for both types of capital

$$y_k = b y_x \tag{2.11}$$

yielding

$$x = (b\gamma/\alpha)k. \tag{2.12}$$

Tsur and Zemel (2009) establish the following characterization:

Proposition 1. (i) When the fossil energy price ζ falls short of ζ^c, no investment in solar ever takes place, $s(\cdot) \equiv 0$, and the competitive processes converge to a steady state $(\hat{k}, \hat{x})$ determined by conditions (2.7) and (2.9). (ii) When the fossil energy price ζ exceeds ζ^c the competitive processes converge to an exclusively solar steady state with $(\check{k}, \check{x})$ determined by conditions (2.9) and (2.11), where $\check{x}^f = 0$ and $\check{s} = \check{x}/b$.

Economies satisfying condition (i) are referred to as fossil-based economies, while those satisfying condition (ii) are called solar-based. These terms describe long term behavior. In the interim, when the initial capital stock k_0 is small, energy is derived exclusively from fossil sources and investment in solar capital is delayed (or avoided if the economy is fossil-based), while fossil energy use is determined by (2.8).

2.2 Regulation

The discussion so far has focused on the economic and technological aspects of the distinction between fossil and solar technologies, ignoring the externalities associated with the use of the former, due, e.g. to the polluting emissions it entails. A common policy addressing such externalities entails imposing Pigouvian taxes on emissions. In our setting, such a policy is equivalent to increasing the fossil price ζ. If the "carbon tax" τ is imposed abruptly, the parties will respond promptly by switching from the competitive processes corresponding to the initial (low) price ζ^l to the higher price $\zeta^h = \zeta^l + \tau$. Imposing such a policy by surprise entails discontinuities in the consumption and saving processes, which may raise political opposition. Support-seeking regulators, thus, may choose to announce the tax policy well ahead of its actual implementation in order to allow agents to adjust gradually to the forthcoming changes. The early announcement effects of this policy were shown by Smulders et al. (2009) to give rise to a 'green paradox', whereby the use of fossil energy will actually increase, rather than decrease, during the intermediate period between the announcement of the tax policy and its actual implementation. This result holds both when the tax rate leaves the originally fossil-based economy at the same type classification (albeit less energy intensive) and when τ is large enough to bring ζ^h well above the critical price ζ^c of (2.6), turning the economy into a solar-based type. In both cases, agents know the implementation date precisely and adjust their behavior so as to ensure a smooth consumption process, even though this entails results that diametrically oppose the regulator's original aim.

Here we extend the analysis to situations where the regulator announces the intention to levy the tax, but is unable or unwilling to commit to a specific date of implementing it. When the policy actually takes place, it implies a prompt adjustment to the higher fossil energy price and discontinuous disruptions cannot be avoided. The agents' response, therefore, differs from that following a pre-specified (known) implementation date. We refer to this scenario as 'uncertain announcement' and investigate whether it can also give rise to paradoxical outcomes. We restrict attention to the case of a mild tax rate which leaves the economy as a fossil-based type also after the tax is imposed. Higher tax rates implying a transition to solar-type economies entail a more tedious analysis, but the paradoxical effects are expected to be driven by the same mechanism, as in Smulders et al. (2009).

2.3 Allocation dynamics

The analysis is based on a comparison of the competitive processes following an uncertain announcement to those corresponding to a fixed low price ζ^l free of regulation. Here we characterize the latter processes. Employing the energy input at its demand (cf. (2.8)) gives the ouput

$$y = F\left(\frac{F\gamma}{\zeta}\right)^{\gamma/(1-\gamma)} k^{\alpha/(1-\gamma)} \tag{2.13}$$

and implies

$$\zeta x = y_x x = F\gamma k^\alpha x^\gamma = \gamma y.$$

Net production, then, can be expressed as a function of capital only:

$$y - \zeta x = (1-\gamma)y = F(1-\gamma)\left(\frac{F\gamma}{\zeta}\right)^{\gamma/(1-\gamma)} k^{\alpha/(1-\gamma)} \equiv A(\zeta)k^\beta, \tag{2.14}$$

where

$$\beta \equiv \alpha/(1-\gamma) < 1 \tag{2.15}$$

is the effective capital share and

$$A(\zeta) \equiv F(1-\gamma)\left(\frac{F\gamma}{\zeta}\right)^{\gamma/(1-\gamma)} \tag{2.16}$$

decreases in the fossil price ζ. Fossil based economies with different fossil prices follow the same dynamics, differing only in the parameter $A(\zeta)$. The optimization problem (2.4), thus, reduces to a single state (k) and single control (c) problem whose solution is governed by the pair of dynamic equations

$$\dot{k} = A(\zeta)k^\beta - \delta k - c \tag{2.17}$$

and

$$\dot{c} = c\sigma(c)[A(\zeta)\beta k^{\beta-1} - (\rho+\delta)], \tag{2.18}$$

where

$$\sigma(c) = -u'(c)/[u''(c)c] \tag{2.19}$$

is the intertemporal elasticity of substitution.

The steady state $(\hat{k}, \hat{c})$ of this system is given by the relations

$$A(\zeta)\beta\hat{k}^{\beta-1} = \rho + \delta \tag{2.20}$$

and

$$\hat{c} = A(\zeta)\hat{k}^\beta - \delta\hat{k} = \hat{k}[(\rho+\delta)/\beta - \delta] \equiv r_\infty \hat{k}, \tag{2.21}$$

where

$$r_\infty = (\rho+\delta)/\beta - \delta \tag{2.22}$$

is independent of ζ. The steady state consumption-capital relation coincides with the straight line $\hat{c} = r_\infty \hat{k}$ for all values of the fossil price below the critical price ζ^c.

For the autonomous system at hand we can write $c = c(k)$, hence $\dot{c} = c'(k)\dot{k}$ and equations (2.17)-(2.18) imply

$$c'(k) = \frac{\sigma(c(k))c(k)}{k} \frac{A(\zeta)\beta k^\beta - (\rho + \delta)k}{A(\zeta)k^\beta - \delta k - c(k)}. \tag{2.23}$$

Combined with the boundary condition $c(\hat{k}) = \hat{c}$, equation (2.23) determines consumption for every positive capital stock:[2]

Proposition 2. *If $\beta\sigma(c) < 1$ for all c then the $c(\cdot)$ curve lies* ***above*** *the straight line $c = r_\infty k$ for all $k \in (0, \hat{k})$ and it lies* ***below*** *this straight line for all $k > \hat{k}$.*[3]

Proof. At $k = \hat{k}$, $c(\hat{k}) = r_\infty \hat{k}$ and equation (2.23) cannot be used directly to determine c' because both numerator and denominator vanish. However, $c'(\hat{k})$ can be obtained by applying l'Hôpital's rule, yielding the quadratic equation

$$\Theta(c') \equiv c'^2 - \rho c' - r_\infty \sigma(\hat{c})[\rho + \delta](1 - \beta) = 0 \tag{2.24}$$

with $\Theta(0) < 0$, while $\Theta(r_\infty) = r_\infty(r_\infty + \delta)(1 - \beta)(1 - \beta\sigma(\hat{c})) > 0$ hence the positive root $c'(\hat{k})$ of (2.24) is smaller than r_∞. Just below $\hat{k}$, then, the $c(\cdot)$ curve lies above the straight line $c = r_\infty k$. Suppose that the two curves cross at some state $0 < \tilde{k} < \hat{k}$ where $c(\tilde{k}) = r_\infty \tilde{k}$. Then $c'(\tilde{k}) \geq r_\infty$. However, at $\tilde{k}$ we can use (2.22) and (2.23) to obtain

$$c'(\tilde{k}) = \sigma(r_\infty \tilde{k}) r_\infty \frac{A(\zeta)\beta\tilde{k}^\beta - (\rho + \delta)\tilde{k}}{A(\zeta)\tilde{k}^\beta - (\delta + r_\infty)\tilde{k}} = \beta\sigma(r_\infty \tilde{k}) r_\infty < r_\infty, \tag{2.25}$$

and the curves cannot cross. The relation at $k > \hat{k}$ is established in a symmetric manner. □

[2] Strictly speaking, (2.23) corresponds to the market solution only for $k \leq \hat{k}$. For our purpose, however, it turns out expedient to characterize the properties of its formal solutions also at larger capital stocks.

[3] Symmetric considerations show that if $\beta\sigma(c) > 1$ for all c then the relation between $c(\cdot)$ and the straight line $c = r_\infty k$ is reversed. In this work we maintain the condition $\beta\sigma(c) < 1$ cited in the Proposition, because it corresponds to any empirically relevant calibration.

2.4 Different fossil energy prices

Next we compare two unregulated $c(\cdot)$ curves corresponding to different fossil prices. We consider the prices $\zeta^h > \zeta^l$ and use the superscripts h and l to denote all quantities associated with the high and low price, respectively. We assume that even the higher price ζ^h is insufficient to induce the economy to use solar energy, hence the dynamics of the previous subsection hold for both processes. Observe that r_∞ is independent of ζ and the steady-states corresponding to both fuel prices lie on the straight line $c = r_\infty k$. According to (2.20), $\hat{k}^l > \hat{k}^h$ and therefore $\hat{c}^l$ is proportionately larger than $\hat{c}^h$.

According to Proposition 2, $c^l(\hat{k}^h) > r_\infty \hat{k}^h = c^h(\hat{k}^h)$, hence the low-price consumption curve lies above its high-price counterpart at $k = \hat{k}^h$. We establish now that this property holds for all capital stocks.

Proposition 3. *If $\beta\sigma(c) < 1$ for all c then the $c^l(\cdot)$ curve lies above the $c^h(\cdot)$ curve for all $k > 0$.*

Proof. The Proposition holds for $k = \hat{k}^h$. Suppose that the two curves cross at some point $(\tilde{k}, \tilde{c})$ with $\tilde{k} \in (0, \hat{k}^h)$. It follows that $dc^l(\tilde{k})/dk \geq dc^h(\tilde{k})/dk$. Using (2.23) we find

$$\frac{A(\zeta^l)\beta\tilde{k}^\beta - (\rho+\delta)\tilde{k}}{A(\zeta^l)\tilde{k}^\beta - \delta\tilde{k} - \tilde{c}} \geq \frac{A(\zeta^h)\beta\tilde{k}^\beta - (\rho+\delta)\tilde{k}}{A(\zeta^h)\tilde{k}^\beta - \delta\tilde{k} - \tilde{c}}. \tag{2.26}$$

All terms of (2.26) are positive, because both k and c increase below their corresponding steady states. Thus,

$$(\rho+\delta)\tilde{k}A(\zeta^h) + \beta(\delta\tilde{k} + \tilde{c})A(\zeta^l) \leq (\rho+\delta)\tilde{k}A(\zeta^l) + \beta(\delta\tilde{k} + \tilde{c})A(\zeta^h).$$

or

$$\beta(\delta\tilde{k} + \tilde{c})[A(\zeta^l) - A(\zeta^h)] \leq (\rho+\delta)\tilde{k}[A(\zeta^l) - A(\zeta^h)].$$

Now, $A(\zeta^l) > A(\zeta^h)$, yielding

$$\beta(\delta\tilde{k} + \tilde{c}) \leq (\rho+\delta)\tilde{k}$$

or, using (2.22)

$$\tilde{c} \leq r_\infty \tilde{k},$$

violating Proposition 2. It follows that the two consumption curves do not meet in the interval $(0, \hat{k}^h]$.

At $k > \hat{k}^h$ the inequality (2.26) and the signs of its terms are reversed, but a crossing of the consumption curves can be ruled out via the same considerations, recalling that the curves lie below the straight line $c = r_\infty k$ when the capital stock k exceeds their respective steady states. □

Proposition 3 lies at the core of the early announcement effects studied in Smulders et al. (2009). We proceed now to investigate how the analysis can be extended to study uncertain announcements.

3 Uncertain implementation date

Suppose that implementation of the carbon tax τ, under which the price of fossil energy increases from ζ^l to $\zeta^h = \zeta^l + \tau$, is considered to take place at some unknown future date T. The realization of T may depend on the successful ratification and implementation of some international treaty, or on other developments in the global arena, and is taken as exogenous to the economy under consideration. Thus, from the vantage point of the economy, the hazard rate π corresponding to the random T is constant. The payoff, conditional on T, is

$$\int_0^T u(c(t))e^{-\rho t}dt + e^{-\rho T}v(k(T)|\zeta^h),$$

where $v(k|\zeta)$ represents the value given a constant fossil price ζ:

$$v(k|\zeta) = \max_{\{c(t)\}} \int_0^\infty u(c(t))e^{-\rho t}dt \tag{3.1}$$

subject to (2.17), given $k(0) = k$. Note that $dv(k|\zeta^h)/dk = \lambda^h(k) = u'(c^h(k))$, where λ^h is the current-value shadow price of capital under the optimal policy corresponding to $v(k|\zeta^h)$.

A constant hazard π implies that T is exponentially distributed and the expected payoff is

$$E_T\left\{\int_0^T u(c(t))e^{-\rho t}dt + e^{-\rho T}v(k(T)|\zeta^h)\right\} = \int_0^\infty [u(c(t))+\pi v(k(t)|\zeta^h)]e^{-(\rho+\pi)t}dt.$$

The allocation problem with uncertain carbon tax date T becomes

$$v^\pi(k_0|\zeta^l,\zeta^h) = \max_{\{c(t)\}} \int_0^\infty [u(c(t)) + \pi v(k(t)|\zeta^h)]e^{-(\rho+\pi)t}dt \tag{3.2}$$

subject to (2.17) with $\zeta = \zeta^l$, given $k(0) = k_0$. We compare the emission path corresponding to $v(k_0|\zeta^l)$, under which no carbon tax is contemplated, with that corresponding to $v^\pi(k_0|\zeta^l,\zeta^h)$, under which a carbon tax τ will be imposed at an uncertain time T.

The capital process $k^\pi(\cdot)$ corresponding to $v^\pi(k_0|\zeta^l, \zeta^h)$ follows (2.17) with $\zeta = \zeta^l$ (the prevailing price until the tax is imposed) while equation (2.18) becomes

$$\dot{c}^\pi(t) = \sigma(c^\pi(t))c^\pi(t)\left[A(\zeta^l)\beta k^\pi(t)^{\beta-1} - (\rho+\delta) + P(k^\pi(t))\right], \tag{3.3}$$

where

$$P(k) \equiv \pi\left(\frac{u'(c^h(k))}{u'(c^\pi(k))} - 1\right). \tag{3.4}$$

Comparing (3.3) with (2.18), we see that the uncertainty in T, with $\pi > 0$, is represented by the $P(k)$ term, the sign of which depends on the relative magnitudes of $c^h(k)$ and $c^\pi(k)$. We turn now to study the effects of this term.

3.1 The consumption-capital trajectory

We consider the capital dependence of consumption under the π regime. Equation (2.23) becomes

$$\frac{dc^\pi(k)}{dk} = \sigma(c^\pi(k))c^\pi(k)\frac{A(\zeta^l)\beta k^{\beta-1} - (\rho+\delta) + P(k)}{A(\zeta^l)k^\beta - \delta k - c^\pi(k)}, \tag{3.5}$$

with the steady state values $\hat{k}^\pi$ and $\hat{c}^\pi$, given by

$$A(\zeta^l)(\hat{k}^\pi)^\beta - \delta\hat{k}^\pi - \hat{c}^\pi = 0 \tag{3.6}$$

and

$$\beta A(\zeta^l)(\hat{k}^\pi)^{\beta-1} - (\rho+\delta) + P(\hat{k}^\pi) = 0. \tag{3.7}$$

We compare these steady state values with their regulation-free counterparts.

From (2.20) and (3.7) we obtain

$$A(\zeta^l)\beta[(\hat{k}^l)^{\beta-1} - (\hat{k}^\pi)^{\beta-1}] = P(\hat{k}^\pi). \tag{3.8}$$

According to (3.4), $P(\hat{k}^\pi)$ is small when π is small, hence $\hat{k}^\pi$ is close to $\hat{k}^l$ and (3.6) implies that

$$c^\pi(\hat{k}^\pi) = \hat{c}^\pi \approx \hat{c}^l = c^l(\hat{k}^l) \approx c^l(\hat{k}^\pi) > c^h(\hat{k}^\pi).$$

With $u''(\cdot) < 0$, it follows that $u'(c^\pi(\hat{k}^\pi)) < u'(c^h(\hat{k}^\pi))$ and $P(\hat{k}^\pi) > 0$. Turning again to (3.8) and recalling that $\beta - 1 < 0$, we find that $\hat{k}^\pi > \hat{k}^l$ when the hazard rate π is small. We show that this relation between the steady states extends to arbitrary positive values of π. Consider the steady state $\hat{k}^\pi$ as a function of π and assume that at some π value this function crosses the

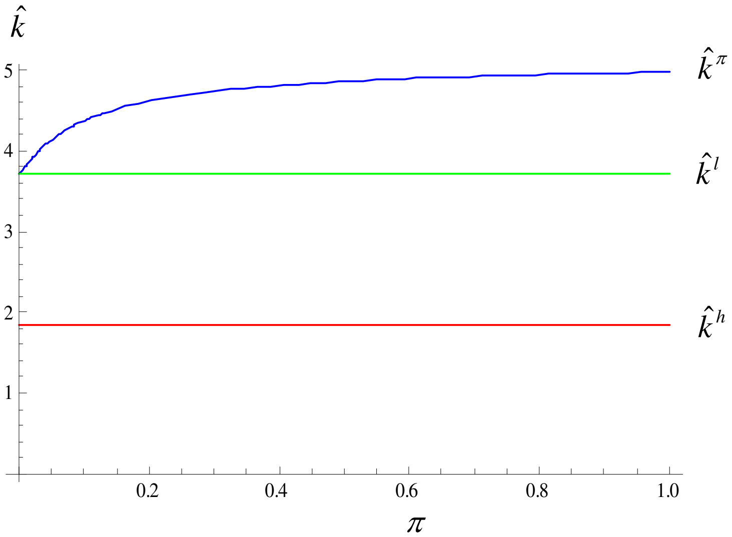

Figure 1: The steady state capital $\hat{k}^\pi$ as a function of the hazard rate π. The upper and lower horizontal lines indicate $\hat{k}^l$ and $\hat{k}^h$, respectively. The curves in all figures were derived under the above functions specifications and the parameter values: $\alpha = \gamma = 1/3,\ F = 1,\ \sigma = 1,\ \rho = \delta = 5\%$ annually, $\zeta^l = 1$ and $\zeta^h = 2$.

constant $\hat{k}^l$ so that the left hand side of (3.8) vanishes. However, (3.6) holds for both $c^\pi(\cdot)$ and $c^l(\cdot)$ hence $c^\pi(\hat{k}^\pi) = c^l(\hat{k}^\pi) > c^h(\hat{k}^\pi)$. According to (3.4) $P(\hat{k}^\pi) > 0$ hence the right hand side of (3.8) is positive, while the left hand side vanishes. Thus, the crossing cannot occur. We conclude, therefore that

$$\hat{k}^\pi > \hat{k}^l \ \forall \pi > 0, \tag{3.9}$$

as Figure 1 illustrates.

Next we compare the complete consumption curves by relating $c^\pi(k)$ to $c^l(k)$. Since $\hat{k}^l$ represents the steady state for the $k^l(\cdot)$ process, it follows that $\dot{k}^l(t) = 0$ at this state. However, the steady state $\hat{k}^\pi$ of $k^\pi(\cdot)$ exceeds $\hat{k}^l$, hence $\dot{k}^\pi(t) > 0$ when $k^\pi(t) = \hat{k}^l$. Thus, (2.17) implies $c^l(\hat{k}^l) > c^\pi(\hat{k}^l)$. We show that this relation cannot reverse at other capital states. Suppose otherwise, that $c^l(k^*) = c^\pi(k^*)$ (hence $P(k^*) > 0$) at some capital state $k^* < \hat{k}^l$ but $c^l(k) > c^\pi(k)\ \forall k \in (k^*, \hat{k}^l]$. It follows that $dc^l(k^*)/dk \geq dc^\pi(k^*)/dk$. However, we can write (3.5) as

$$\frac{dc^\pi(k^*)}{dk} = \frac{dc^l(k^*)}{dk} + \frac{\sigma(c^l(k^*))c^l(k^*)P(k^*)}{A(\zeta^l)k^{*\beta} - \delta k^* - c^l(k^*)} > \frac{dc^l(k^*)}{dk},$$

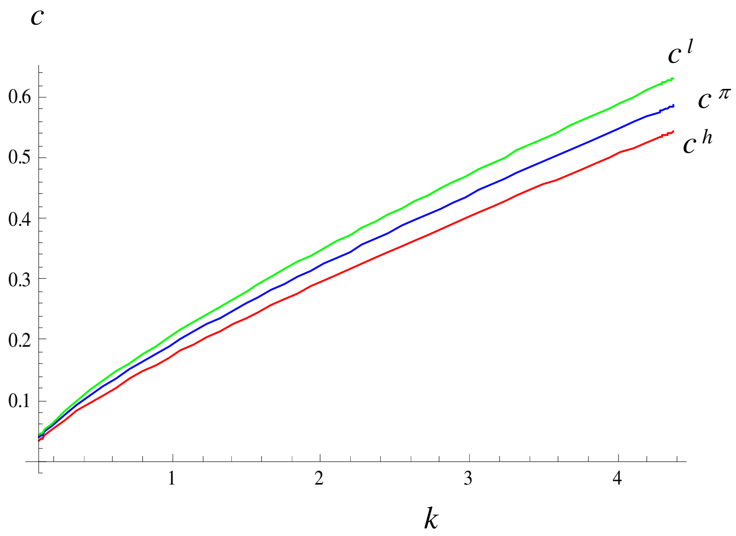

Figure 2: Consumption curves as functions of capital under uncertain T (c^π), low fossil energy price (c^l) and high fossil energy price (c^h). In this and the following figures we use the value $\pi = 0.1$ corresponding to $E\{T\} = 10$ years.

because the denominator of the second term is also positive at k^*. A crossing of the consumption curves (with $dc^l(k^*)/dk \leq dc^\pi(k^*)/dk$) can be ruled out also for $k^* > \hat{k}^l$ using the same argument, since the denominator is negative above $\hat{k}^l$. Thus,

$$c^\pi(k) < c^l(k) \; \forall k > 0.$$

We wish to compare the uncertain consumption curve also to its high price counterpart, $c^h(\cdot)$. We use (3.9) to deduce from (3.8) that $P(\hat{k}^\pi) > 0$ hence $c^h(\hat{k}^\pi) < c^\pi(\hat{k}^\pi)$. To establish the same relation for smaller capital stocks, we assume otherwise, that $c^h(\tilde{k}) = c^\pi(\tilde{k})$ at some stock $\tilde{k} < \hat{k}^\pi$, where $dc^h(\tilde{k})/dk \leq dc^\pi(\tilde{k})/dk$ but $P(\tilde{k}) = 0$. This, however, implies (2.26) which can be ruled out via the same arguments used to establish Proposition 3. We summarize these considerations in Figure 2 and in

Proposition 4. *If $\beta\sigma(c) < 1 \; \forall c$, then $c^h(k) < c^\pi(k) < c^l(k) \; \forall k \in (0, \hat{k}^\pi]$.*

Uncertainty, then, reduces consumption but not by as much as would be implied by a prompt implementation of the tax.

3.2 The “Green Paradox”

The time trajectories of k^l and k^π are given, respectively, by the implicit solutions of (2.17):

$$t = \int_{k_0}^{k^l(t)} \frac{dk}{A(\zeta^l)k^\beta - \delta k - c^l(k)} dk,$$

and

$$t = \int_{k_0}^{k^\pi(t)} \frac{dk}{A(\zeta^l)k^\beta - \delta k - c^\pi(k)} dk.$$

Thus, the relation $c^l(k) > c^\pi(k)$ implies that

$$k^l(t) < k^\pi(t) \; \forall t > 0,$$

as indicated in Figure 3. Indeed, this result provides the manifestation of the “Green Paradox” effect in the case of uncertain T. Since both $k^l(\cdot)$ and $k^\pi(\cdot)$ proceed under the same price of fossil energy and with the same production technology, the larger $k^\pi(\cdot)$ process entails enhanced energy use at each point of time (until implementation), in contrast to the original purpose of the announcement. As in the case of a certain early announcement, preparing for the anticipated tax consists of accumulating a larger capital stock so that when the tax is eventually levied, the larger capital stock will partly compensate for the reduced energy use implied by the tax.

Interestingly, a comparison of the corresponding consumption time trajectories does not display the same simple pattern in time: With a higher steady state consumption, $c^\pi(t)$ must exceed $c^l(t)$ at large time (but prior to actual implementation). This relation between the consumption processes, however, cannot extend all the way back to $t = 0$ (when the capital stock equals k_0 under both regimes) because if it did, the relation between the capital processes displayed in Figure 3 would be reversed. The two consumption processes, therefore, must cross at some finite time, as shown in Figure 4. Efforts to prepare for the tax (in terms of reduced consumption) are concentrated at the early stages of the growth process, while at later times, parts of the fruits of the oversized capital (relative to the prevailing low fossil energy price) are used again to finance enhanced consumption.

4 Concluding comments

The model presented in this work suggests yet another mechanism to produce “paradoxical” outcomes of climate policies without resorting to the

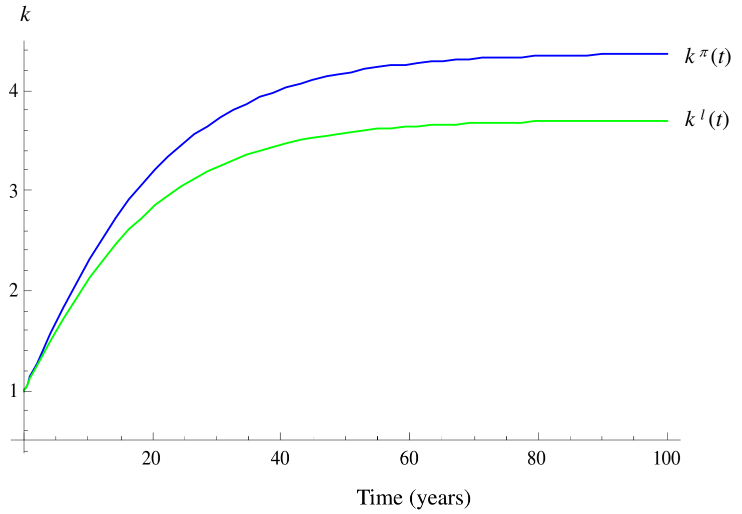

Figure 3: Capital time trajectories under uncertain T (k^{π}) and low fossil energy price (k^{l}).

scarcity of the fossil resource. Here, the effects are due to uncertainty regarding the timing of introducing the carbon tax. While the economic forces at work are similar to those driving the early announcement model of Smulders et al. (2009), the two mechanisms operate differently because in the present model economic agents cannot predict the tax implementation date at which they must ensure a smooth transition of the consumption process. In fact, consumption will undergo a discontinuous jump on this date and the adopted processes are tuned so as to minimize the expected utility loss associated with the jump. The solution involves delicate tradeoffs as manifested by the crossing of the time profiles of the consumption processes displayed in Figure 4. Nevertheless, the "paradoxical" effect of increased fossil energy use persists at all times until the tax policy is realized.

For brevity and simplicity of exposition, the results are presented in terms of the simplest specification of a Cobb-Douglas technology, constant hazard rate and a mild tax rate which does not imply a transition to a solar-based economy. As indicated by Smulders et al. (2009), none of these assumptions is essential and the "paradoxical" effect can be obtained in a more general setting, albeit at the cost of more tedious derivations.

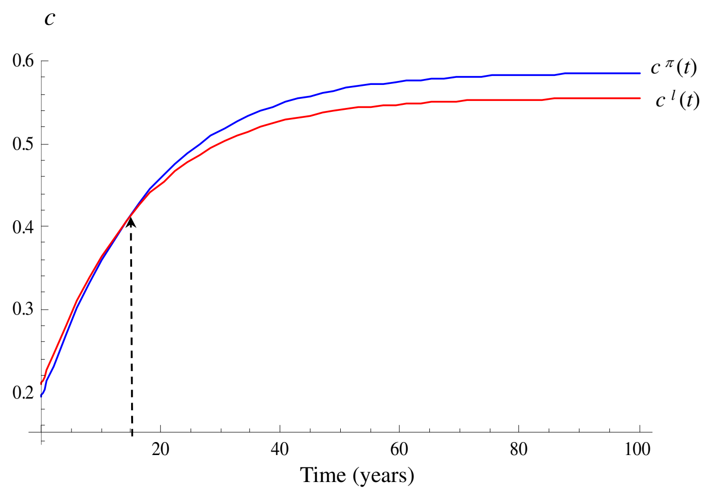

Figure 4: Consumption time trajectories under uncertain T (c^{π}) and low fossil energy price (c^{l}). The arrow indicates the time when the trajectories cross.

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