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Should Carbon taxes be Pre-announced? On Irreversible Investment, Real Options and Carbon Taxes

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Abstract

Climate change and its two-way relation with economic activity is stochastic and so is therefore the optimal tax internalizing the climate externality. But with capital irreversibility a stochastic time path for carbon prices slows down the reallocation from brown to green sectors because waiting then acquires an option value. We show that it is optimal to pre-announce a time path for future carbon taxes, eliminating the option value of waiting at the cost of suboptimality of the pre-announced taxes at the time they apply. We analyse for how long carbon taxes should be pre-announced and which factors influence that timespan.

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1 Introduction

The link between global warming, CO_2 emissions and fossil fuel use has been highlighted as early as the late 19th century by Arrhenius (1896). Stern (2006) tellingly called the impact of fossil fuel use on the Earth's temperature "the mother of all externalities". Recognizing the social costs of carbon emissions as an externality naturally leads to the recommendation of imposing a Pigouvian tax to internalise that externality. Much of the focus of the literature on the economics of climate change has been the challenge of pricing this externality, of pinning down the Social Cost of Carbon (SCC) and deriving the rate at which the corresponding Pigouvian tax should be set. [1]. Since the optimal Pigouvian tax is a function of the underlying climate and economy state variables which are driven by stochastic processes, the optimal Pigouvian tax itself is also a stochastic process. Kolmogorov's forward equations allow the derivation of ranges within which the future tax is likely to be with given probability, not more than that, and for most stochastic processes these ranges actually increase linearly in time. The main point of this paper is however that the stochastic nature of Pigouvian taxes provides an impediment to the investment effort that is also necessary to effect the energy transition towards a green economy. As a consequence pre-announcing future carbon taxes may be optimal after all in spite of the wedge that then emerges between pre-announced future carbon prices and the SCC at the time the corresponding taxes apply.

The literature on setting the optimal SCC does show that the SCC should smoothly rise over time, but only *in expected value terms*[2]. Since the time path is derived from intertemporal arbitrage, the *expected* optimal SCC always follows a smooth time path unless unforeseen shocks hit the system (see for example Traeger (2014), Cai and Lontzek (2019) or Olijslagers et al. (2024).

But while the *expected value* of the SCC may follow a smooth time path, the *actual value* of the optimal SCC is in fact a random variable itself, as we just argued, with quite possibly an even higher volatility than the price series emerging from the ETS. And stochasticity of the SCC raises the issue of the impact of the volatility of the SCC on the investment necessary to

[1]This literature is reviewed and extended in Olijslagers and van Wijnbergen (2023) and Olijslagers et al. (2024), who also derive the SCC under a wide variety of model structures and assumptions about the stochastic nature of climate shocks.

[2]but for an exception cf Cai and Lontzek (2019); see Olijslagers et al. (2024) for an extensive discussion of the slope of the SCC over time

effect the energy transition, the transition to a green economy. If capital is irreversible, there is an option value to waiting (see Epstein (1980) or Dixit and Pindyck (1994) for the general point and van Wijnbergen (1984),van Wijnbergen (1986) on the impact of uncertain reforms on investment timing); so the high volatility of carbon taxes that match the SCC at all moments in time may in fact delay the energy transition.

We thus end up with a trade off: pre-announcing a time path for carbon taxes may speed up investment response by reducing the option value of waiting, but also implies a suboptimal tax which does not match the SCC for most of the trajectory. This conflict is especially relevant when targets take the form of meeting a specified reduction target before a specific date, like the targets stipulated in the ill fated Kyoto agreement adopted already in 1997 but also in the currently operative Paris agreement concluded in 2015.

This paper focuses on the trade off between setting a Pigouvian tax matching the SCC at all moments in time on the one hand and the provision of effective investment incentives on the other. The paper is organized as follows. After the introduction in Section 1, Section 2 reviews the relevant strands of the literature this paper relates to. In Section 3 we work out a simple highly stylized model to outline the basic conflict created by uncertain carbon prices and the associated option-triggered investment delays on the one hand and the optimality of continuously adjusted carbon prices on the other hand. We show that pre-announcing future carbon taxes is in fact optimal in this environment, in spite of the wedge that creates between those future taxes and the SCC at the time these taxes apply. In section 4 we analyse for how long carbon prices should be pre-announced and which factors influence the length of the pre-announcement period.

2 Review of the literature

This paper draws on several strands in the literature. First of all the literature on the economics of climate change. Discussions on global warming go back very far in the climate Science/Physics literature: Arrhenius (1896) discussed the basic mechanisms as early as late nineteenth century, including even calculations of the magnitudes involved, no mean feat in pre-computer times. The discussion of the economics of climate change started in a major way with Nordhaus (see for an overview and references example W.Nordhaus (2017) and for example Weitzman (2007) and got a major boost from the report Nick Stern and his team produced for the UK treasury. (Stern (2006).

The early literature was largely deterministic, as is most of the climate science literature; the canonical contribution is of course by W. Nordhaus (Nordhaus (1992)) who arguably produced the first Integrated Assessment Model (IAM), in which a model of climate dynamics was coupled to a relatively standard General Equilibrium economics model. Weitzman explored early on many stochastics issues (see for example Weitzman (2012)). Later contributions increasingly introduced stochastic processes in the analysis [see for example Traeger (2014), Cai and Lontzek (2019)]. That more recent literature is extensively surveyed in Olijslagers(2023,2024), who focus on the SCC, measurable risk and risk aversion and on unmeasurable risk and Ambiguity Aversion, aversion to unmeasurable risk factors. Typically, stochastic models aiming at tracing out the time path of the SCC produce a smooth upward sloping time path of *expected* carbon prices (for exceptions cf DIETZ reference) and van Wijnbergen (1986). But the actual SCC timepath that comes out of such optimization exercises is a solution of a Dynamic Programming Problem, with continuous reoptimization. As a consequence the actual SCC, as the solution of a set of PDEs describing the evolution of stochastic state variables, is a stochastic process itself.

The emission rights trading system implemented by the EU is in fact criticized for the excessive volatility of the carbon prices that result from the auction mechanism (see for example Cantillon and Slechten (2023), Borenstein et al. (2015)). The ETS authorities have responded to that criticism by incorporating a specific buffer, the Market Stabilization mechanism, to reduce volatility, without however eliminating it.

The consequences of the stochasticity of the SCC in the presence of irreversible capital is the key topic dealt with in this paper. By discussing the consequences of the irreversibility of capital on the pace of the transition to a green economy when the SCC is a stochastic variable itself we draw on an entirely different literature. Neary (1978) analyzed the impact of capital irreversibility on adjustment speed after changes in external variables using a deterministic classical trade theory model. Epstein (1980) in an early contribution shows under which conditions gradual release of information will lead an agent to delay early decisions that would limit her options at a later stage. Ulph and Ulph (1997) build on and extend the analysis of Epstein (1980) in their analysis of global warming irreversibility and abatement. van Wijnbergen (1984) discusses the impact of uncertain future trade reform in the presence of irreversible investment and highlight the real options aspect of the problem that plays a key role in the current paper. A very well known discussion of real options, uncertainty and investment delay is in Dixit and Pindyck (1994)

An entirely different strand in the literature discusses the choice of quantity (Q) or Price (P) based instruments under uncertainty, with Weitzman (1974) the classic discussion in a static context. Mideksa and Weitzman (2019) extend the Weitzman framework to multiple jurisdictions, analyzing international non-coöperative games for global pollution control. But the Prices versus Quantities debate does not really address the issue we deal with in this paper; even if a P-approach is chosen, continuously reoptimizing the tax, as is called for in DP approaches, will produce a stochastic time path for the SCC also. Of course choosing for quantity intervention or a time path of emission rights could be implemented to smnooth carbon prices over time, but that is not what happens in practice (ETS volatility reference) nor is it what theory calls for in a stochastic environment with flexible capital allocation. Fuss et al. (2012) make a bridge from the real options literature to our topic by analyzing firm level investment decisions under technological uncertainty but they do not discuss the stochastic nature of carbon prices themselves nor the macroeconomic impact of the energy transition.

We put these various strands together. First we establish that the stochastic nature of the SCC leads to transition delays in a context of capital irreversibility. Preannouncing a non-stochastic time path for carbon prices would eliminate investment delays but unavoidably at the cost of suboptimality of future pre-announced carbon prices. We then ask the question whether (or under what circumstances) the advantages of a faster transition outweigh the costs of temporarily suboptimal carbon pices. Finally we extend the two period model to a multiple period setting to analyse for how long carbon prices should be pre-announced and which factors influence that pre-announcement period.

3 A stylized Model

We begin our analysis in an extremely stylized model with exogenous but stochastic carbon prices and show how in this environment there is an option value to waiting. Pre-announcing carbon prices eliminates the associated real option value and any incentive to delay, but at the cost of suboptimality of carbon prices in later periods.

We first explain, in section 3.1, how irreversible capital and uncertain carbon pricing produce a Epstein-Dixit-Pindyck type of real option value, leading to incentives to delay transition investment. Section 3.2 highlights the conflict that then emerges: should policymakers impose first best optimal carbon prices and accept the investment delays the associated uncertainty triggers; or is it better to avoid delaying the energy transition at the cost of not always following the first best carbon price process by pre-announcing a time path for carbon prices?

3.1 The option value of Liquid Assets under carbon price uncertainty

Consider a stylized three period/three asset world. The three assets are: a liquid or unproductive asset F, capital in the brown sector K_b and capital in the green sector K_g. As to time, period 0 only reflects the past, in which the existing capital stock in both sectors has been produced; when period 1 opens a unit of new investment can be allocated to either one of the three assets. Investing in F in period 1 allows for reinvestment in any asset in period 2 but investment in either type of capital in period 1 cannot be changed in period 2: capital is irreversible (and, for convenience, does not decay). Period 2 is the final period. Investing in F serves as a way of delaying the choice between investing in green or brown technology: F is a short term investment so at the beginning of period 2 the F carried over from period 1 can be converted into either type of capital at the beginning of period 2. Thus investment decisions are taken at the beginning of $t = 1$ and $t = 2$. We ignore discounting for the time being.

Investing in the liquid asset does not lead to emissions but has a low first period return ($\mu_F = 0$). Brown and green capital emit μ_b and μ_g carbon respectively per unit employed, where $\mu_g < 0 < \mu_b$ [3]. σ_1 and σ_2 represent the social cost of carbon (SCC) in period 1 and period 2 respectively. σ_1 is known at the beginning of t = 1 but σ_2 becomes known at the beginning of period 2 only. Under a Pigouvian tax policy the government imposes a tax equal to the social cost of carbon on the output of each unit of capital proportional to its emissions. Thus under a Pigouvian tax policy the optimal carbon tax in period 1, τ_1, equals σ_1 and is known at the beginning of t = 1. But the period 2 Pigouvian tax $\tau_2 = \sigma_2$ then is not known in period 1 and

[3] in fact we only need the somewhat lighter condition $\mu_g < \mu_F < \mu_b$

Table 1: Asset Returns at different times and states of nature under Pigouvian taxes

Asset returns	t=1: $\tau_1 = \sigma_1$	t=2, prob Π: $\tau_2 = \sigma_1 + \Delta$	t=2, prob 1-Π: $\tau_2 = \sigma_1 - \Delta$
K_b	r_L	r_L	r_H
K_g	r_H	r_H	r_L
F	$r_L < r_F < r_H$	r_F	r_F

will become known only just before investment decisions in period 2 have to be taken [4]. There is no time to build: investment in each period is immediately added to the capital stock that period. Capital is irreversible: neither capital stock can, once built, be converted into the other type.

The Social Cost of Carbon in period 2, σ_2, and the associated Pigouvian tax τ_2 is either high, with probability Π, or low, with probability $1 - \Pi$. In most cases we assume symmetry form the time being: $\sigma_2 = \sigma_1 \pm \Delta$. The more general case with asymmetric probabvilities; we analyse the more general case (infinite number of periods, a drift factor in the price process and asymmetric prob abilities) in Section **??**. A high σ_2 and corresponding carbon tax $\tau_2 = \sigma_2$ leads to high returns in the green sector and low returns in the brown sector; a low carbon price does the opposite. The asset returns in the various time periods and states of nature are summarized in Table 1. Note that the return on F is the same in each period and in this example lies between the good outcome r_H and the bad outcome r_L.

Consider first the cumulative return V on investing one unit in period $t = 1$ in brown capital. It will earn a low return r_L in period 1 but may earn a high return in period 2 if the carbon price is low, which occurs with probability $1 - \Pi$. If the second period price turns out to be high, which occurs with probability Π, brown capital will earn a low return in period 2 also. Therefore the cumulative expected return on investing in irreversible brown capital in period 1 is:

$$V(K_b) = r_L + \Pi * r_L + (1 - \Pi) * r_H \tag{1}$$

Investing in F at t = 1 yields r_F in the first period and allows the investor to invest in whatever the highest return capital stock is in period t = 2; the return on this strategy is

[4] This assumption about timing of period 2 decisions is what Ulph and Ulph (1997) call perfect learning

therefore:

$$V_{nc}(F) = r_F + r_H \tag{2}$$

where the subscript nc stands for 'no commitment', the allocation decision can be made after σ_2 and τ_2 have become known. The return difference between the return on investing in F until information is released on period 2 and then reallocate F to the highest yield capital on the one hand and the return on immediately committing to the brown sector on the other hand equals:

$$\begin{aligned} V_{nc}(F) - V(K_b) =& r_F + r_H - (r_L + \Pi * r_L + (1 - \Pi) * r_H) \\ =& r_F + \Pi * r_H - (1 - \Pi) * r_L \\ =& r_F - r_L + \Pi(r_H - r_L) > 0 \end{aligned} \tag{3}$$

Therefore at t = 1 investing in F always dominates investing in brown capital since by assumption $r_L < r_F < r_H$); returns in the first period are higher and period 2 investment can be delayed until after the period two state of nature has been revealed, which with probability Π offers a further gain of $(r_H - r_L)$.

Consider next the return on immediately committing to green capital instead of to brown capital or to F and waiting until information will be revealed in period 2:

$$\begin{aligned} V(K_g) =& r_H + \Pi * r_H + (1 - \Pi) * r_L \\ =& (1 + \Pi) * r_H + (1 - \Pi) * r_L \\ =& r_H + r_L + \Pi * (r_H - r_L) \end{aligned} \tag{4}$$

Committing to green delivers a high return in period 1 and, with probability Π, also a high return in period 2, but it underperforms the liquid asset F in period 2 with probability (1-Π). And it always dominates investing in brown:

$$\begin{aligned} V(Kg) - V(K_b) =& r_H + r_L + \Pi * (r_h - r_L) - (r_L + \Pi * r_L + (1 - \Pi) * r_H) \\ =& 2\Pi * (r_H - r_L) > 0 \end{aligned} \tag{5}$$

Equations 3 and 5 indicate that investing in brown in period 1 is dominated both by investing in F in period 1 and waiting for information to be released in period 2, and by immediately investing in green.

So the relevant comparison is between a waiting strategy (investing in F in period 1 and then into whichever capital has been revealed to be most profitable in period 2) versus immediately committing to the high-return investment K_g in period 1 at the risk that the period 2 return will disappoint:

$$
\begin{aligned}
V_{nc}(F) - V(K_g) =& r_F + r_H - (r_H + \Pi * r_H + (1-\Pi) * r_L) \\
=& r_F - \Pi * r_H - (1-\Pi) * r_L \\
=& \underbrace{(1-\Pi) * (r_H - r_L)}_{A} - \underbrace{(r_H - r_F)}_{B} \lesseqgtr 0
\end{aligned} \tag{6}
$$

Equation 6 shows that the difference between $V_{nc}(F)$, the value of a waiting strategy, and $V(K_g)$, the value of precommitting to green, is ambiguous. The term (A) equals the expected benefit of not being caught out by a low price while having committed to green when the price is low in period 2; this happens with probability $(1-\Pi)$. Against that benefit stands term (B), the loss in period one because F has a lower return than K_g in that period.

Equation 6 also suggests there is a break-even value for Π, the probability that the second period Pigouvian carbon tax is high, at which the two effects balance out. Call this break-even value Π^*:

$$
V_{nc}(F|\Pi^*) - V(K_g|\Pi^*) = 0 => \Pi^* => \frac{r_F - r_L}{r_H - r_L} \tag{7}
$$

using an obvious minor change in notation to denote the value of V conditional on Π, the probability of a high Pigouvian carbon price. Equation 7 leads to the result shown in equation 8: the optimal investment strategy is different for low Π than it is for high Π:

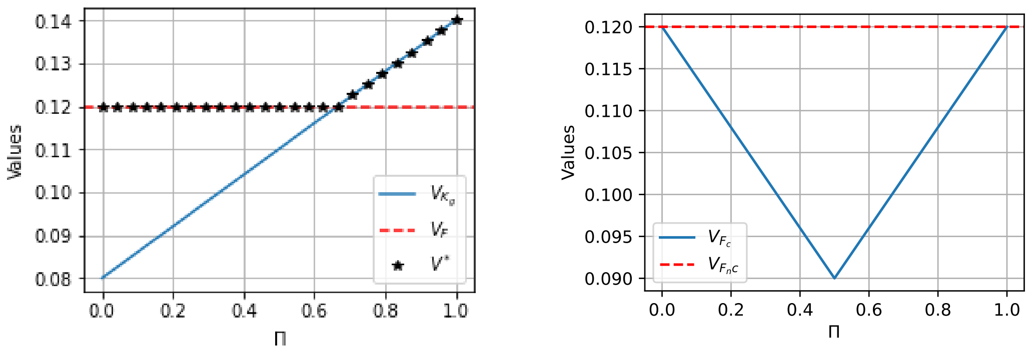
$$
\begin{aligned}
\Pi <& \Pi^* => V_{nc}(F) > V(K_g) \\
\Pi >& \Pi^* => V_{nc}(F) < V(K_g)
\end{aligned} \tag{8}
$$

For low values of Π (a relatively large probability of a low carbon price) the waiting strategy outweighs precommitment to green capital; but for high values of Π the advantages of the first period of an early commitment to green outweigh the value of keeping the option of switching to brown capital in period two open.

Figures 1a and 1b show the results graphically: $V_{nc}(F)$ is a flat line at $r_F + r_H$ independent

Figure 1: *The Option Value of Waiting to Invest*

(a) $V_{nc}(F)$,V_{Kg} and V*   (b) $V_c(F)$ and $V_{nc}(F)$



of Π (cf equation 25). Equation 4 shows the value of green capital for the two end points of Π; $\Pi = 0$ indicates there will be a low price in period 2 while $\Pi = 1$ indicates there will be a high price with certainty. The value of investing in green increases linearly in Π (cf equation 4) and the two lines intersect at $\Pi = \Pi^*$ (cf equation 7 and 1a).

$$\begin{aligned} V(K_g|\Pi = 0) =& r_H + r_L < V_{nc}(F|\Pi = 0) \text{ since } r_L < r_F \\ V(K_g|\Pi = 1) =& r_H + r_H > V_{nc}(F|\Pi = 1) \text{ since } r_H > r_F \end{aligned} \tag{9}$$

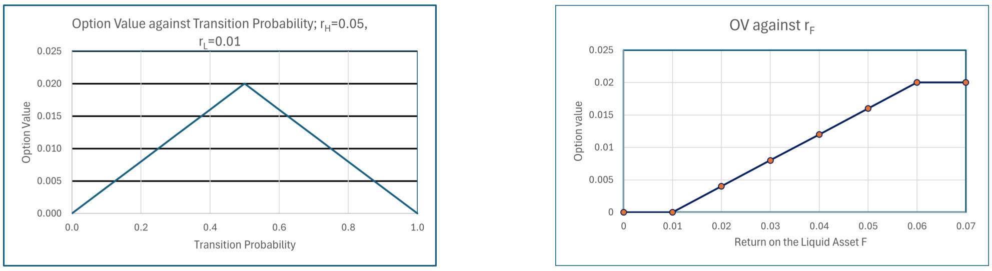
The diagram demonstrates what we already derived: for values of Π lower than Π^* the option value of waiting dominates the higher return of green capital in period 1. So the waiting strategy dominates and the optimal V^* equals $V_{nc}(F)$; correspondingly the red slotted line for $V_{nc}(F)$ is above the blue solid line depicting V_{Kg}. But if the probability of a high price in period 2 is high enough (i.e. $\Pi > \Pi^*$) then the higher return in period 1 under a green strategy more than compensates for the loss of the option value embedded in F that a choice for green also implies and V^* equals V_{Kg}. In the diagram this is reflected by the blue line being above the red slotted line. The two segments are combined in the line consisting of black stars for V^*.

To clarify that we indeed are dealing with a *real option*, compare the value of investing in F with and wito distinguish it from the *nc* strategy, with *c* standing for commitment. Investing in F when a decision on the investment in period 2 has to be made before information becomes available is then $V_c(F)$.

We already have $V_{nc}(F|\Pi)$ from Equation 25; to calculate the option value embedded in F we need to derive the value of F when the choice for t=2 investment needs to be made before τ_2

Figure 2: Option Value OV as a function of Π and r_F

(a) OV and the Transition Probability Pi (b) OV and r_F



is announced. The difference is the real option value of the flexibility that investing in F offers. Clearly this choice will depend on the likelihood of one or the other regime obtaining at t=2. For $\Pi < 1/2$ it is optimal at t = 1 to pre-commit to choosing brown for t = 2, for $\Pi > 1/2$ precommitment to green capital dominates:

$$\begin{aligned} V_c(F|\Pi) &= r + \Pi * r_L + (1-\Pi) * r_H \\ &= r + r_H - \Pi * (r_H - r_L) \text{ for } \Pi < 1/2) \\ &\text{and} \\ &= r + \Pi * r_H + (1-\Pi) * r_L \\ &= r + r_L + \Pi * (r_H - r_L) \text{ for } \Pi > 1/2 \end{aligned} \tag{10}$$

Figure 1b shows the value of F with and without the option to wait with the choice for period 2, respectively $V_{nc}(F)$ and $V_c(F)$. The difference between the two shows the value of the option to postpone the choice to the beginning of period 2 after the carbon price for that period becomes known.

The figure shows that the difference between $V_{nc}(F)$ and $V_c(F)$ is zero for $\Pi = 0$ and $\Pi = 1$ and reaches its maximum for $\Pi = 1/2$. This is to be expected: option values depend on volatility, which is zero at the end points of the distribution of Π and reaches its maximum for $\Pi = 1/2$.

Figures 2a and 2b show the option value as a function of Π and r_F respectively. The first was already discussed, while the second shows that the option value increases in the return on F.

the OV equals the difference between the benefit of having a choice at t = 2 minus the cost of choosing the liquid asset instead of K_g in period 1; this cost obviously goes down with higher

r_F so the OV goes up correspondingly.

3.2 The cost of waiting and the case for pre-announcing carbon prices

Like before we label the Pigouvian taxes τ_1 and τ_2. They internalise the social cost of CO_2 emissions σ_1 and σ_2, implying that τ_2 is a stochastic variable whose value will become known at the same time it becomes known whether σ_2 is high or low, at the beginning of period 2. Unit emissions are μ_b in the brown sector and μ_g in the green sector. Investing in F does not lead to any emissions, but not to high returns either [5]. The social costs of any chosen strategy are stochastic because σ_2, the SCC of period 2, is stochastic[6].

Define the *ex post* social costs of strategy V_i as:

$$SC_{ep}(V_i) = \mu_{i,1} * \sigma_1 + \mu_{i,2} * \sigma_2 \tag{11}$$

where $\mu_{i,j}$ represents the emissions of the investment chosen under strategy i in period j. The *ex ante* social costs of strategy i are:

$$SC_{ea}(V_i) = \mu_{i,1} * \sigma_1 + \mu_{i,2} * E_{t=1}\sigma_2 \tag{12}$$

Assume next that the Government has committed to reduce emissions by a given percentage before a specific deadline, so option related delays do matter. It therefore considers a tax policy announcing a specific time path for the carbon tax τ_2 before σ_2, the true social cost of emissions in period 2, is known. Call that pre-announced period 2 tax τ_2^a. A logical choice for τ_2^a would be $E_{t=1}\sigma_2$. Investors now face a known time path τ_1, τ_2^a for the carbon price. But a tax strategy that sets the period 2 tax at the *expected* value of σ_2 creates an ex post wedge between the carbon tax τ_2^a and the true social costs of emissions σ_2: in this stochastic environment there is a conflict between fully internalizing the SCC at any given current and future moment and a speedy transition.

[5] in a general equilibrium environment such a choice could induce a fall in r_F, partially offsetting the waiting for information effect on investment

[6] Except for a permanent choice for F, which would avoid additional emissions altogether; but this strategy is always dominated by a strategy of F in $t = 1$ and whatever sector, brown or green, offers high returns in $t = 2$.

Setting the period 2 carbon tax equal to $E\sigma_2$ leads to the following period 2 carbon tax:

$$\begin{aligned}\tau_2^a &= E_{t=1}(\sigma_2) \\ &= \tau_1 + \Pi * \Delta - (1-\Pi) * \Delta \\ &= \tau_1 + (2\Pi - 1) * \Delta\end{aligned} \tag{13}$$

The bottom line reflects the assumptions made on the distribution of σ_2 in Table 1[7].

The *private* option value of investing in F now evaporates; there is no uncertainty about the period two financial returns anymore so postponing the sectoral choice until the beginning of $t = 2$ has no merit anymore. Label the value of F with precommitment to a second period choice $V_c(F)$; under this strategy the F investor commits ex ante to a specific sector for period 2.

Consider by way of example what happens when $\Pi = 0.5$. We already saw that for τ_1 K_g is the best choice in the first period; and equ.13 indicates that for $\Pi = 0.5$ we get $\tau_2^a = E\tau_2 = \tau_1$, so K_g is then again the best choice for period 2. From there follows the next equation, giving the value of respectively choosing F and choosing K_g in the first period:

$$\begin{aligned}V_c(F|\tau_1, \tau_2^a, \Pi = 0.5) &= r_F + r_H \\ V(K_g|\tau_1, \tau_2^a, \Pi = 0.5) &= 2 * r_H\end{aligned} \tag{14}$$

Clearly, with the carbon tax preannounced at the expected value of the social cost of carbon and the high and low price equally likely in period 2, the F strategy without precommitment is not attractive anymore. But F with precommitment is dominated by already choosing green investment in period 1; the option value has evaporated so F is not attractive anymore at all as a first period choice.

However, for a range of possible values of Π and possible outcomes for σ_2, the pre-announced carbon price τ_2^a when set equal to $E_{t=1}\sigma_2$ will be too low and for the complementary range it will be too high. For the bimodal distribution listed in Table 1, if τ_2 is set at $\tau_2^a = E_{t=1}\sigma_2$ we get:

$$\begin{aligned}\textit{with probability } \Pi &: \tau_2^a < \sigma_2 \\ \textit{with probability } 1 - \Pi &: \tau_2^a > \sigma_2\end{aligned} \tag{15}$$

[7] σ_2 goes up by Δ with probability Π and down by Δ with probability $1 - \Pi$

which will lead to a discrepancy between the private and social costs of emissions in period 2. Of course the social costs will depend on the extent to which this discrepancy leads to different investment choices than would obtain if carbon prices were to be set equal to the actual social cost of emissions in the corresponding period. This leads to a surprizingly simple expression for the social costs of pre-announcing second period carbon prices at the expected SCC.

From equation 8 we know that for $\Pi > \Pi^*$, investing in green capital dominates the Wait-and-See strategy of first investing in F; and choosing for green is also the strategy chosen when τ_2 is pre-announced and set equal to $\tau_2^a = E_{t=1}\sigma_2$ because investing in F then looses its option value:

$$\begin{aligned} \text{For } \Pi > \Pi^* : V^*(...|\tau_1, \tau_2) &= V(K_g) \\ V^*(..|\tau_1, \tau_2^a) &= V(K_g) \\ SC_{ea}^a(V^*|\Pi > \Pi^*) = SC_{ea}(V_g|\Pi > \Pi^*) &= \mu_{g,1} * \sigma_1 + \mu_{g,2} * E_{t=1}\sigma_2 \\ => SC_{ea}(V_g|\Pi > \Pi^*) - SC_{ea}^a(V^*|\Pi > \Pi^*) &= 0 \end{aligned} \tag{16}$$

where S_{ea}^a stands for the ex ante expected social costs of the optimal strategy under preannouncement and S_{ea} for the ex ante expected social costs of the Pigouvian tax schedule τ_1, τ_2.

But for lower Π the investment strategies under pre-announcement and under a stochastic time path for the carbon price are different, and so the social costs will be different too:

$$\begin{aligned} \text{For } \Pi < \Pi^* : \; V^*(..|\tau_1, \tau_2) &= V_F(..|\tau_1, \tau_2, \Pi) \\ V^*(..|\tau_1, \tau_2^a) &= V(K_g|\tau_1, \tau_2^a, \Pi) \\ => SC_{ea}^a(V^*|\Pi < \Pi^*) &= \mu_{g,1} * \sigma_1 + \mu_{g,2}(\Pi * \sigma_2^+ + (1-\Pi) * \sigma_2^-) \\ SC_{ea}(V^*|\Pi) < \Pi^*) &= \mu_{F,1} * \sigma_1 + (\Pi * \mu_{g,2} * \sigma_2^+ + (1-\Pi) * \mu_{b,2} * \sigma_2^-) \\ => SC_{ea}(V^*|\Pi < \Pi^*) - SC_{ea}^a(V^*|\Pi < \Pi^*) &= (\mu_{F,1} - \mu_{g,1}) * \sigma_1 + (1-\Pi) * (\mu_{b,2} - \mu_{g,2}) * \sigma_2^- \\ &> 0 \end{aligned} \tag{17}$$

$\mu_{F,1} > \mu_{g,1}$ and $\mu_{b,2} > \mu_{g,2} > 0$ which establishes the inequality in equation 17; an investment in F has no impact on CO_2 concentration while green investment actually leads to lower CO_2 concentration and brown investment pollutes more than green investment. So when when $\Pi < \Pi^*$ and carbon prices are pre-announced and thus different from the actual social costs of emissions in future periods, the social costs of the private response will nevertheless be lower. This is because the social costs of the suboptimality of the private carbon price in period 2 are in that case more than offset by social benefits of the faster investment response in the earlier period that is triggered by the reduction of uncertainty pre-announcement leads to. The overall result is clear with $SC_{ea} - SC^{a}_{ea} = 0$ for $\Pi^* < \Pi < 1$ and $SC_{ea} - SC^{a}_{ea} > 0$ for all $\Pi \subset (0, \Pi^*)$:

$$\begin{aligned} SC_{ea}(V^*) - SC^{a}_{ea}(V^*) =& \int_0^{\Pi^*} [SC_{ea}(V^*|\Pi < \Pi^*) - SC^{a}_{ea}(V^*|\Pi < \Pi^*)] f(\Pi) d\Pi \\ &+ \int_{\Pi^*}^{1} [SC_{ea}(V^*|\Pi > \Pi^*) - SC^{a}_{ea}(V^*|\Pi > \Pi^*)] f(\Pi) d\Pi \\ =& \int_1^{\Pi^*} [(\mu_{F,1} - \mu_{g,1}) * \sigma_1 + (1 - \Pi) * (\mu_{b,2} - \mu_{g,2}) * \sigma_2^-] f(\Pi) d\Pi + 0 \\ =& [(\mu_{F,1} - \mu_{g,1}) * \sigma_1]\Pi^* + [\mu_{b,2} - \mu_{g,2}) * \sigma_2^-] \int_0^{\Pi^*} (1 - \Pi) dF(\Pi) \qquad > 0 \end{aligned} \tag{18}$$

since $\int_0^{\Pi^*} (1 - \Pi) dF(\Pi) > 0$.

In the first period the social costs are equal or lower under pre-announcing compared to the Pigouvian taxes case because pre-announcing avoids the option-related investment delay associated with a random future carbon price and therefore leads to lower emissions in period 1. In period 2 pre-announcing avoids the brown choice which also leads to lower emissions for those cases where Pigouvian taxes do lead to a brown choice. Thus pre-announcing carbon prices will lead to a faster energy transition at lower social costs because the investment delays triggered by future carbon price volatility are avoided when future taxes are set at their expected Pigouvian values ex post.

4 For how long should prices be pre-announced?

A drawback of the setup of Section 3 is that the two period setup does not allow us to discuss for how long the carbon taxes should be pre-announced. We therefore extend the model to multiple periods. This allows us to derive an answer to the question of whether and if so when the passage of time changes the conclusions on the relative merits of pre-announcing versus internalizing externalities in each period. In other words: for how long should the carbon tax schedule be pre-announced?

Time now runs to infinity:: $t = 0, 1, ...\infty$. Next assume an infinite sequence of overlapping two-period investment projects $k^t_{i,j}$ with $j = 1, 2$ a period index referring to whether the project is in its first or second period and t a time index: $t = 0, 1, ...\infty$. As before i is a strategy index and can take the values g for green, b for brown or F for the liquid asset allowing deferral of choice until period 2 of the project. Finally assume that carbon taxes, if they are pre-announced, will be set until $t = T$ after which the problem replicates itself.

The SCC is again a discrete time binary process but now one that now extends indefinitely. We will assume $\Pi < \Pi^*$ so there is an option value of waiting when prices in the second investment period are uncertain [8]

$$\sigma_t - \sigma_{t-1} \equiv X_t = \begin{cases} +\Delta \text{ with probability } \Pi \\ -\Delta \text{ with probability } 1 - \Pi \end{cases} \tag{19}$$

With one period ahead variance:

$$var^1_\sigma = \Pi * (1 - \Pi) * \Delta^2 \tag{20}$$

So the carbon price/Pigouvian tax τ_t if set equal to the SCC in the corresponding period is a discrete time random walk:

$$\begin{aligned} \tau_t &= \sigma_t \\ &= \sigma_0 + \sum_{j=1}^{j=t} X_j \end{aligned} \tag{21}$$

with k-period ahead variance:

$$\begin{aligned} var^k_\tau &= Var(\tau_{t+k}|\tau_t) \\ &= \sum_{t}^{t+k} var(j)_\tau) \\ &= k * \mathrm{var}_\Delta \end{aligned} \tag{22}$$

since the random draws are independently distributed. This defines the price path as a discrete time random walk (see for the continuous time equivalent for example Olijslagers and

[8] if $\Pi > \Pi^*$ green will be chosen anyhow even under temporary price uncertainty, see equation 8

van Wijnbergen (2023)).

Price expectations depend on Π^e, the expectation about future values of Π:

$$E(\tau_{t+k}|\tau_t) = \tau_t + k * (2\Pi^e - 1)\Delta \tag{23}$$

We consider two alternative mechanisms to generate price expectations: Full Information (FI) where investors know the actual probability Π governing pricing dynamics; and Static Expectations (SE), where capitalists weigh up- and down- jumps equally likely and as a consequence expect current prices to prevail over their prediction horizon (SE investors assume $\Pi = 1/2$:

$$\begin{aligned} E^{FI}(\tau_{t+k}|\tau_t) &= \tau_t + k * (2\Pi - 1)\Delta \\ E^{SE}(\tau_{t+k}|\tau_t) &= \tau_t \end{aligned} \tag{24}$$

Notice the similarity between a zero-drift but asymmetric random walk ($\Pi \neq 0.5$) and a symmetric random walk with drift: both lead to expected future values different from the current one.

4.1 Static Expectations SE

Again assume that investors at any given time they need to decide whether to wait or invest know the price in the period in which they initiate their two-period investment project but face an uncertain price for the second period of their two-period project. Accordingly each investor at all times faces the problem we already analyzed in Section 3. Therefore if taxes are set equal to the SCC in each period, and not pre-announced, a waiting strategy once again acquires an option value and becomes preferable over the green choice if the probability of a second period high carbon price is low enough. From Section 3.1 we get:

$$\begin{aligned} V_{nc}(F) =& r_F + r_H \\ V(K_g) =& r_H + r_L + \Pi * (r_H - r_L) \end{aligned} \tag{25}$$

so

$$\begin{aligned} V_{nc}(F) > V(K_g) \text{ if } \Pi < \Pi^* \\ \text{for } \Pi < \Pi^* = \frac{r_F - r_L}{r_H - r_L} \end{aligned} \tag{26}$$

Consider next the chain of events when taxes *are* pre-announced at $t = 0$ for T periods. If taxes are pre-announced we assume they are set at the expected value in the corresponding period:

$$\tau_k^{pr} | \tau_0 = \tau_0 + k * (2\Pi - 1)\Delta \tag{27}$$

For a symmetric random walk this collapses into:

$$\tau_t^{pr} = \tau_0 \tag{28}$$

For all $\Pi \geq 1/2$ it then follows that the green strategy prevails for all investments within the range $[0, T]$ when the time path is pre-announced in line with equation 28. But the actual social returns may well be different; when prices are below the pre-announced time path, which happens with probability $(1 - \Pi)$ in each subperiod within the pre-announcement period, the return is r_L instead of r_H:

$$\begin{aligned} V_{pr}^{t,*} = V_g^t &= r_H + \Pi * r_H + (1 - \Pi * r_L \\ &= r_H + r_L + \Pi * (r_H - r_L) \end{aligned} \tag{29}$$

like in equation 4.

So there are social costs under pre-announcement, since taxes τ are then not always equal to σ in each period and the corresponding externality is not internalized in that case. Distortionary costs then arise when price wedges lead to the "wrong", i.e. socially suboptimal strategy choices. Social costs in any given period are assumed to be proportional to the variance of the wedge between social values and the pre-announced price:

$$SC_{pr}^t \propto var_\sigma^t = t * \Pi(1 - \Pi)\Delta^2 \tag{30}$$

for $t \subset [0.T]$. Without loss of generality we set the proportionality constraint equal to 1.

The total costs associated with pre-announcement over a period $[0, T]$ are then:

$$\begin{aligned} SC_{[0,T]}^{pr} =& \sum_0^T t * \Pi(1 - \Pi)\Delta^2 \\ =& T * \Pi(1 - \Pi)\Delta^2/2 \end{aligned} \tag{31}$$

Note that the social costs of pre-announcing increase in T. And higher Δ raises social costs too, even within the narrow confines of our underlying model on investment returns. This is because a higher Δ, even for given Π, increases the probability of a very low price below the threshold below which brown capital K_b becomes optimal while green is chosen under pre-announcement. Finally distortionary costs also go up with the factor $\Pi * (1 - \Pi)$ in 31 because that term is directly proportional to the option value of waiting, as we established in Section 3.1.

Next consider the strategy choices when taxes are *not* pre-announced. We know from 8 that if Π is not too close to 1 (i.e. when $\Pi \leq \Pi *$), it pays to wait and see which way second period prices go. We can use the formula's from equations 32 since we are again considering an investor having to make a two period decision knowing the first period's price but uncertain about the second period price. Consider first the case where $\Pi \leq \Pi *$, so the option choice dominates the choice for green:

$$V_{nc}^{t}(F|\Pi \leq \Pi *) = r_F + r_H > V_g^t(K_g|\Pi \leq \Pi *) \tag{32}$$

Equation 32 holds for all t, which tells us two things. First of all:

$$V_{nc}^{0}(F|\Pi \leq \Pi *) = r_F + r_H > V_g^0(K_g|\Pi \leq \Pi *) \tag{33}$$

And we know from Equation 18 that it pays to pre-announce the *period* 1 price in period 0 to avoid option-related waiting: the social costs of waiting exceed those of pre-announcing for the second period (i.e. period 1 when t starts at 0):

$$SC_W^0 > SC_{pr}^0 \tag{34}$$

And, second, 32 also tells us that the value of waiting does not change over time and neither does therefore SC_W^t.

But equation 18 tells us that the Social Costs of pre-announcing do increase over time, which allows us to derive an expression for T, the optimal length of time for which prices should be pre-announced: at T the social cost of pre-announcing just equal the social cost of waiting and exceed it afterwards:[9]:

$$
\begin{aligned}
\text{for } 0 < i < T: SC_W^i &> SC_{pr}^i \\
\text{for i = T: } SC_W^i &= SC_{pr}^i \\
\textit{for } i > T: SC_W^i &< SC_{pr}^i
\end{aligned}
\tag{35}
$$

Using equation 30 for the LHS and equation 16 and 17 for the RHS we get the following expression for T:

$$T\Pi(1-\Pi)\Delta^2 = \mu_F\sigma_1 + (1-\Pi)\mu_b(\sigma_1 - \Delta) \tag{36}$$

Rewrite equation 36 to facilitate taking derivatives as follows:

$$T = \frac{\mu_F\sigma_1 + (1-\Pi)\mu_b(\sigma_1 - \Delta)}{\Pi(1-\Pi)\Delta^2} \tag{37}$$

The derivative with respect to Δ is:

$$
\begin{aligned}
\frac{\partial T}{\partial \Delta} &= \frac{-2[\mu_F\sigma_1 + (1-\Pi)\mu_b(\sigma_1 - \Delta)]}{\Pi(1-\Pi)\Delta^3} - \frac{\mu_b}{\Pi\Delta^2} \\
&< 0
\end{aligned}
\tag{38}
$$

A higher Δ raises the distortionary costs of pre-announcing future prices and therefore leads to a shorter pre-announcement period T. Moreover a higher Δ also raises the costs of choosing the brown option under the waiting strategy, which happens with probability $(1-\Pi)$, cf the second term in equation 38. Both mechanisms call for a shorter pre-announcement period T for higher Δ.

The derivative with respect to the probability of a high price, Δ, is more complicated to sign because of the specific non-linearity of the option value formula in Π:

[9]Of course there is no guarantee that the value for T that solves equation 35 is a whole number. If it is not then $=$ needs to be replaced by $\geq$ in equation 35.

$$\frac{\partial T}{\partial \Pi} = \underbrace{-\frac{\mu_b(\sigma_1 - \Delta)}{\Pi(1-\Pi)\Delta^2}}_{(A)} \underbrace{-\frac{(1-2\Pi)[\mu_F\sigma_1 + (1-\Pi)\mu_b(\sigma_1 - \Delta)]}{[\Pi(1-\Pi)\Delta]^2}}_{(B)}$$

$$(A) < 0$$

$$(B) < 0 \; \textit{for} \; \Pi > 1/2; (B) > 0 \; \textit{for} \; \Pi < 1/2 \tag{39}$$

(A), the first term, is unambiguously negative: a higher Π reduces the likelihood of choosing brown in the waiting strategy which makes the waiting strategy less damaging and therefore leads to a shorter pre-announcement period since that pre-announcement period is designed to avoid the waiting strategy being chosen.

(B), the second term, is more complicated because the option value of waiting depends on $\Pi * (1-\Pi)$, a non-linear multiplicative term in the volatility of the price process. When $\Pi < 1/2$ volatility increases with higher Π. Since higher volatility increases the option value of waiting, term (B) in itself leads to a longer pre-announcement period T for $\Pi < 1/2$, potentially reducing or even offsetting the impact of term (A). But for $\Pi > 1/2$ volatility decreases with a higher Π, which *reduces* the option value of waiting and thus leads to a shorter pre-announcement period, as does term (A). The impact of a higher Π on T is thus certainly less negative when $\Pi < 1/2$ than it is for $\Pi > 1/2$ but possibly still negative because $(A) < 0$ for all values of Π.

4.2 Generalizing the price epectations process: Full Information Expectations FI

Consider next the problem of deriving the optimal pre-announcement period when investors know Π and form expectations for when $\Pi \neq 0.5$. To determine the optimal T we once again need to balance the costs of pre-announcing versus the social costs of waiting when future prices are random. until time T versus the social loss when prices and externalities diverge under a pre-announcement regime; but this time the expression for the costs of waiting are different. The value for σ_1^T T periods ahead now depends on $\sigma_1(t+T)$ instead of on $\sigma_1(t)(=\sigma_1)$:

$$\sigma_1(t+T) = \sigma_1(t) + T(2\Pi - 1)\Delta \tag{40}$$

$$
\begin{aligned}
T\Pi(1-\Pi)\Delta^2 &= \mu_F E_T(\sigma_1(t+T)) + (1-\Pi)\mu_b(E_T(\sigma_1(t+T)) - \Delta) \\
&= \mu_F \sigma_1 + (1-\Pi)\mu_b(\sigma_1(t) - \Delta) + [\mu_F(2\Pi-1) + (1-\Pi)\mu_b(2\Pi-1)]T\Delta
\end{aligned} \tag{41}
$$

Simple reshuffling yields:

$$
\begin{aligned}
T &= \frac{\mu_F \sigma_1 + (1-\Pi)\mu_b(\sigma_1(t) - \Delta) + [\mu_F(2\Pi-1) + (1-\Pi)\mu_b(2\Pi-1)]T\Delta}{\Pi(1-\Pi)\Delta^2} \\
&= T_{SE} + \frac{(\mu_F + (1-\Pi)\mu_b)(2\Pi-1)}{\Pi(1-\Pi)\Delta^2}\Delta T \\
&= T_{SE} + \Gamma * (2\Pi - 1)T
\end{aligned} \tag{42}
$$

where $\Gamma = \frac{\mu_F + \mu_b(1-\Pi)}{\Pi(1-\Pi)\Delta^2}$. So we get a simple expression linking T_{SE} and T_{FI}:

$$
\begin{aligned}
T_{FI} &= \frac{T_{SE}}{1-\Gamma(2\Pi-1)} \qquad \text{for } 2\Pi \neq 1 \\
&\text{and} \\
T_{FI} &= T^{SE} \qquad\qquad\quad \text{for } 2\Pi = 1
\end{aligned} \tag{43}
$$

$0 < \Gamma < 1$ so we immediately get from equation 43 that:

$$
\begin{aligned}
&\text{for } \Pi > 0.5 : T_{FI} > T_{SE} \\
&\text{for } \Pi = 0.5 : T_{FI} = T_{SE} \\
&\text{for } \Pi < 0.5 : T_{FI} < T_{SE}
\end{aligned} \tag{44}
$$

Under price expectations that change over time (as they will do under FI for $\Pi \neq 0.5$) we thus find that for *rising* prices ($\Pi > 0.5$), the pre-announcement period will be *longer* under FI than under SE. But when prices are expected to fall over time ($\Pi < 1$, a case that is at variance with almost the entire literature on carbon pricing) the pre-announcement period will be shorter under FI than under SE. When they are expected to stay unchanged, the optimal announcement period is the same under SE and FI, as is to be expected since then the expected future prices are identical under the two expectation formation hypotheses. The marginal effect of small changes in Π on T thus depends on whether Pi is larger or smaller than 0.5 but is complex because both T_{SE} and Γ depend on Π also.

5 Conclusions

Almost anything relevant for climate change and its two-way relation with economic activity is inherently stochastic. The climate system is stochastic, the economy is a collection of stochastic processes and the interaction between the two is itself a source of stochastic disturbances. The unavoidable consequence is that the Social Cost of Carbon (SCC) is a stochastic process too, as is the Pigouvian tax reflecting the SCC. The main point we make in this paper is that in the presence of capital irreversibility such a stochastic time path for carbon prices will actually slow down the reallocation from brown to green sectors, the green transition, because of the option value of waiting in such an environment. Pre-announcing the time path of the SCC kills off the option value of waiting but does so at the cost of suboptimality of the future pre-announced SCC.

We show in a simple and very stylized two period framework with irreversible investment that when capital is irreversible the stochastic time path for Pigouvian taxes c.q. carbon prices does indeed bestow an option value to a strategy of waiting to invest. Pre-announcing the future values of carbon taxes kills off the option value and eliminates the incentive to delay the transition but at the cost of creating a wedge between carbon taxes and ex post future values of the social cost of carbon. We also show that in our example the cost of waiting dominates the social costs of not internalizing the shadow costs of carbon emissions. As a consequence it is optimal to pre-announce future carbon prices by setting them equal to their current expected value.

The logical next question is of course for how far ahead future carbon prices should be announced, how long should the pre-announcement period last? To answer that question we extend the time frame towards an infinite horizon. We show that the social costs costs of pre-announcing increase over time, which implies a natural approach to setting the optimal period for which prices should be pre-announced: at the end of the optimal pre-announcement period T, the social costs of waiting should just equal the social costs of pre-announcing for a period T. Since the latter increase over time and the former do not, pre-announcing is optimal for the period $[0, T]$ but becomes suboptimal for periods longer than the T that follows from the equality condition defining T.

By taking derivatives we show that higher price jumps Δ lead to higher distortionary costs of pre-announcing and thus to a shorter pre-announcement period. The impact of the probability of a higher probability Π of a high price on T is more complex: a higher Π in itself reduces the probability of the brown option being chosen and thus makes the waiting strategy less damaging. That calls for a shorter pre-announcement period. But a higher Π also leads to changes in volatility. For $\Pi > 1/2$ a higher Π reduces volatility and thus also leads to a shorter optimal pre-announcement period; but for $\Pi < 1/2$ a higher Π leads to a higher volatility and increasing option values, which calls for a longer pre-announcement period, partially or completely offsetting the primary impact via the lower probability of the brown strategy being chosen. Finally we show that under full information expectations about future prices, the pre-announcement period is shorter than it is under static expectations when prices are expected to rise over time but longer when they are expected to fall as time goes by.

These results may cast a new light on the discussion of whether carbon prices should be set each period by the regulator or determined by an auction mechanism like happens in Europe with the ETS. Presumably a pre-announced time path can be reproduced under the ETS by judiciously choosing how many rights are offered each period, but the value of the auction mechanism then becomes unclear.

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