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Carbon leakage: Grandfathering as an incentive device to avert firm relocation

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Abstract

Emission allowances are sometimes distributed for free in an early phase of a cap-and-trade scheme to reduce adverse effects on the profitability of firms. This paper investigates whether grandfathering can also be used to avert the relocation of firms to countries with lower carbon prices. We show that under certain conditions, relocation can be averted in the long run, even if the grandfathering scheme is phased out over time and immediate relocation is profitable in its absence. This requires that the permit price triggers sufficient investments into low-carbon technologies or abatement capital that create a lock-in effect which makes relocation unprofitable.

Keywords: emissions trading, abatement capital, low-carbon technology, lock-in effect, unilateral climate policy
JEL classification: H23, L51, Q58

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1 Introduction

When emissions trading schemes are implemented, regulators do not always require that all permits are auctioned from the start. For example, the EU initially decided to allocate emission allowances to firms in the regulated industries for free.[1] However, assuming that regulators cannot maintain the transfers to firms that are implicit in grandfathering or other allocation schemes of free allowances indefinitely, these transfer schemes must be phased out over time, until full auctioning is required. The free allocation of permits is meant to alleviate some of the adverse effects of an emissions price on the profitability of the regulated firms. It may also give firms more time to adapt to the new conditions (e.g., via investments into low-carbon technologies).

From an economic point of view, the free allocation of permits can be rationalized if it is used to correct for certain (possibly pre-existing) market failures. E.g., Gersbach and Requate (2004) show that an output-based rebate can be welfare-improving in a symmetric Cournot oligopoly because it helps to alleviate the welfare losses due to imperfect competition. Alternative explanations for the free allocation of permits relate to the politics of implementation. Sterner and Isaksson (2006) argue that the refunding of environmental charges (e.g., via grandfathering) can "reduce resistance from the polluters, and make refunded emissions payments politically easier to implement at a sufficiently high charge level to have significant abatement effects."[2]

It is widely acknowledged that unilateral (instead of world-wide) regulation of polluting industries (e.g., the introduction of a regional cap-and-trade scheme) can induce firms to relocate to other countries with less stringent environmental targets. Indeed, firm relocation is one of the main channels of *carbon leakage*.[3] Nevertheless, the idea that the refunding of revenues from environmental regulation (e.g., via grandfathering) may be used as an incentive device to *avert relocation* has attracted surprisingly little attention in the literature. Critics may argue that — even if grandfathering can be an effective tool to avert relocation in the short run — it will certainly be ineffective in the long run, assuming that the free allocation of permits is only a temporary policy option that cannot be maintained indefinitely.

We challenge this view and demonstrate that grandfathering *can* be an effective policy tool to avert relocation *in the long run,* even when it has to terminate in finite time. Most importantly, we show that this holds in situations where immediate relocation is

[1] The European directive on the EU-ETS allowed governments to auction up to 10% of the allowances issued in phase II of the trading scheme (2008–2012). (http://ec.europa.eu/clima/policies/ets/auctioning_en.htm, European Commission, 15/03/2011).

[2] Rauscher (1995) shows that tax competition can lead to "undesirably low levels of environmental regulation".

[3] Other channels of carbon leakage are decreases in fossil fuel prices induced by a reduction in global demand, or changes in trade patterns (e.g., Felder and Rutherford, 1993).

profitable in the absence of grandfathering. The driving force behind this result are sunk investments into low-carbon technologies or emission-saving equipment ('abatement capital') that create a lock-in effect which can prevent relocation also after the phasing-out of the transfers. In order to be effective, the lock-in effect must be sufficiently strong to make relocation unprofitable, once the transfers to the firm (induced by the free allocation of permits) terminate. The investments in abatement capital are triggered by a rise in the emissions price in the home country (e.g., due to the introduction of an emissions trading scheme). Grandfathering gives firms initially located in the home country an incentive to continue to produce in this country for a certain period of time. During this period of time, the firms face the emissions price. The longer they plan to stay, the higher the incentives to invest in abatement capital. Conversely, the more they have invested, the less they suffer from the emissions price, because the investment reduces the operating costs in light of the emissions price. These two effects are mutually reinforcing, and in combination, they can *permanently* avert relocation under the condition that the investment costs are sunk, and cannot be recovered when a firm relocates.

If a firm relocates, this can also be interpreted as an 'investment'. Namely, by shifting its location to a foreign country, a firm can avoid the emissions price in its home country and, therefore, reduce its marginal production costs. Hence, in our model, a firm has two alternative investment options. If it relocates, it incurs a fixed relocation cost.[4] If it stays, it can undertake a costly investment in abatement capital to reduce the emissions costs. An abatement capital investment is upfront, but the benefits of reduced emissions costs accrue gradually over time. This explains the intertemporal trade-off in our model: either the firm 'invests' in the relocation option, or it continues to produce in its home country where it benefits from the flow of grandfathered allowances. Only if the firm plans to stay permanently in its home country, it optimally exploits the option to invest in abatement capital.

In order to illustrate the lock-in effect that drives our results, consider the following introductory example. Suppose, there are two periods.[5] The firm can relocate (once and for all) from its home country A to a foreign country B in any period, or stay in A in both periods. If the firm stays, it can invest in abatement capital at the beginning of period 1. The abatement capital stock is, then, available in both periods if the firm does not relocate. Suppose the investment decision is binary, relocation is for free, and there is no discounting or depreciation. Let the firm's per-period profit in A be 3 (units of money) if the firm has invested, and 1 if the firm has not invested in abatement capital but continues to produce in A.[6] The per-period profit in B is 2. If the firm invests, it incurs a

[4]The fixed relocation cost is, however, not crucial for any of our results. The lock-in effect that drives our results exists also without a relocation cost.

[5]Our full model is in continuous time.

[6]The per-period profit in A is lower without the investment because the firm faces a carbon price

fixed cost of 5/2. Given these numbers, it is easy to verify that the firm prefers immediate relocation (total profit of 4) over the possibility to stay in A permanently with investing (3.5) or without investing (2). However, if the regulator offers a temporary transfer to the firm of 1/2, contingent only on the firm not relocating in period 1, then the option to invest and to stay in A in both periods becomes as profitable as immediate relocation. Furthermore, this option also dominates relocation after period 1 with investing (3) or without investing (3.5), due to the lock-in effect of the abatement capital investment. As this simple example demonstrates, a temporary transfer can induce the firm to stay in its home country also after the transfers have stopped, even when immediate relocation is profitable in the absence of transfers.

In the literature, 'grandfathering' is often defined as the free allocation of permits in proportion to some historical variable (e.g., emissions) of the firm.[7] We do not model the allocation of permits as a function of a firm's past activities. Instead, we derive optimal grandfathering schemes under the condition that relocation is averted with a *minimum of transfers* to a firm. In our model, the rate of permits allocated to a firm for free is conditioned only on the firm being located in its home country. Our results may apply in any situation where the adverse effects of a policy-induced increase in an input price (e.g., due to a carbon tax) on firms' profitability are cushioned by the introduction of a second policy tool, namely a location-based transfer scheme to avert relocation. The free allocation of permits in an emissions trading scheme is a good example how such transfers can be implemented in practice. However, our focus on grandfathering schemes is chosen for illustrative purposes only. Throughout the paper, we use the terms 'transfer' and 'grandfathering' interchangeably.

1.1 Related literature

This paper is related to various strands of literature which focus, respectively, on the issues of carbon leakage, policy-induced relocation of firms, and compensation or refunding schemes of revenues from environmental regulation.

Carbon leakage, or more generally the leakage of emissions, is usually measured in terms of the relative increase in emissions outside the country or region imposing a unilateral regulation to reduce emissions, over the decrease in emissions in the country that adopts the regulation (e.g., IPCC, 2007). Several authors use CGE-models to derive theoretical predictions about leakage rates (e.g., Babiker, 2005; Kuik and Gerlagh, 2003; Paltsev, 2001). A review of estimated leakage rates and a meta-analysis can be found in Gerlagh and Kuik (2007). The fourth assessment report (TAR) (IPCC, 2007) concludes

in country A (but not in country B). An investment in abatement capital allows the firm to reduce its emissions costs in A.

[7]See, e.g., Ahman and Zetterberg (2005), Böhringer and Lange (2005), Sterner and Isaksson (2006).

that most equilibrium modeling of leakage from Kyoto action is in the order of five to twenty percent. However, considerable uncertainty about leakage rates remains (Babiker, 2005). A second strand of literature analyzes carbon leakage empirically (Sijm et al., 2004; Szabo et al., 2006; Barker et al., 2007). Overall, the evidence on the issue remains mixed.[8] Using a stylized theoretical model, Di Maria and van der Werf (2008) show that when directed technological progress is taken into account, the amount of carbon leakage can be significantly reduced. Harstad (2012) shows that leakage can be avoided if countries in a climate coalition buy fossil fuel deposits in foreign countries to preserve them, rather than to regulate their own emissions.[9] Our contribution to the literature on leakage is to demonstrate that location-based transfer schemes can be an effective means to avert firm relocation and, thus, to reduce leakage rates as well as to mitigate other adverse effects (e.g., on employment). Most importantly, we find that under some conditions, *temporary* grandfathering (or other transfer) schemes can permanently avert relocation.

Authors that analyze the *relocation* of firms in response to a unilateral environmental policy often use stylized partial equilibrium models. Petrakis and Xepapadeas (2003), e.g., analyze the location decision of a monopolist when a unilateral carbon tax is introduced. Motta and Thisse (1994) also assume that firms are already established in their home country, but may shift their production to a foreign country. In contrast, Markusen, Morey and Olewiler (1993) assume that firms enter the market at the beginning of the game. This makes the location choice more flexible, which explains the large impact of an energy tax that Ulph (1994) finds in a calibration of this model. Ulph and Valentini (1997) analyze the location decisions of firms in a market with an upstream and a downstream industry. In this paper, we also adopt a partial equilibrium approach, and analyze the behavior of a regulator who tries to avert the relocation of a firm in some industry. In order to keep the model as general as possible, we derive most of our results without specifying the competitive environment of the firm.[10] Our results can be applied to various competitive frameworks, such as Cournot or Bertrand competition.

The literature on *refunding schemes* of policy revenues from an environmental regulation adopts both theoretical and numerical approaches. Bovenberg, Goulder and Jacobsen (2008), e.g., use a general equilibrium model to analyze how pollution control costs change when polluting industries are compensated for reduced profits due to the environmental regulation. Fischer (2010) compares output-based refunding schemes of revenues from a carbon price with fixed rebate programs. Ahman and Zetterberg (2005) compare

[8]Reinaud (2005) surveys estimates of leakage rates for energy-intensive industries. The author concludes that "the ambiguous results of the empirical studies in both positive and negative spillovers warrant further research in this field" (p. 197).

[9]Golombek and Hoel (2004) analyze a two-country model with abatement efforts and investments into low-carbon technologies chosen individually by each country. The authors show that R&D spill-overs can create negative carbon leakage rates.

[10]For the purpose of our analysis, it suffices to specify the firm's flow of profit as a function of the (exogenous) emissions price in its home country, and (endogenous) investments in abatement capital.

emission-based allocations of free permits in an emissions trading scheme with production-based allocations (with actor-specific emission factors, benchmarking, and best available technology). Bernard, Fischer and Fox (2007) show that the rebating of environmental levies can be justified when firms in a regulated sector compete with other firms from unregulated sectors. Fischer and Fox (2012) compare the effectiveness of different policy approaches to reduce carbon leakage. Hepburn, Quah and Ritz (2013) use an asymmetric Cournot model to analyze how large the grandfathering rate should be for a firm to achieve profit neutrality under a cap-and-trade scheme (relative to the unregulated case). Although profit neutrality is an important reference case to assess compensation schemes for firms that are adversely affected by the introduction of an emissions price, we argue that it may be a too strong requirement when firm relocation (and the associated loss of employment) is the regulator's main concern. We, thus, analyze optimal grandfathering schemes that avert relocation with a minimum of transfers to the regulated firm.

Location-based transfer schemes (such as grandfathering) are not the only policy instrument that can avert firm relocation. An alternative that is often debated is border carbon adjustment (BCA). Under full BCA, tariffs are used to impose the domestic carbon price on goods imported from countries with a lower (or no) carbon price. Furthermore, the revenues of the emissions price are rebated to domestic firms that export their goods to these countries. Böhringer, Balistreri and Rutherford (2012) conduct a multi-sector CGE cross-model comparison to analyze the virtues and limitations of BCA for a specified emissions reduction scenario, given a coalition of Annex 1-countries of the Kyoto Protocol, including the United States of America but without the Russian Federation. The authors find that BCA can effectively reduce leakage, but also point to difficulties in implementing BCA.[11] We argue that grandfathering can be an alternative policy instrument which may be easier to implement because it does not interfere directly with trade issues. It could also supplement BCA measures when full BCA is politically infeasible.[12]

The remainder of this paper is organized as follows. Section 2 introduces the general model and characterizes grandfathering schemes designed to avert relocation. In Section 3, the model is further specified, allowing us to derive optimal policy schemes in closed-form. Section 4 introduces an alternative specification of the model. Section 5 concludes. All proofs are relegated to the Appendix.

[11] E.g., the authors write: "In policy practice, however, such a comprehensive BCA system appears rather unrealistic – desirability and feasibility of BCA depend on legal, practical and political considerations that must be balanced against the theoretical potential for efficiency gains." (page S99).

[12] Böhringer, Carbone and Rutherford (2012) compare three different instruments against carbon leakage with regards to their efficiency as well as their distributional impacts: BCA, industry exemptions from emissions regulation, and output-based allocation of emission allowances.

2 General model

We consider the relocation behavior of a firm in a country A that can relocate once and fully to a certain country B at some time $T \in [0, \infty]$, and we are interested in grandfathering schemes by which the government of A can give the firm an incentive to stay in A forever, where the latter is equivalent to "relocation at $T = \infty$". Let $\Pi(T)$ denote the net present value of the firm at time zero, *excluding* any monetary transfers from the government, if it relocates at $T \in [0, \infty]$ and optimizes its other behavior (investments, production, etc.) accordingly.

Although in this section, we only assume that Π is bounded and continuously differentiable in T, let us shortly look at an example. Given the additive specification of our model that we introduce in Section 3, the function Π is of the following form:

$$\Pi(T) = \alpha - \beta e^{-rT} + \gamma e^{-2rT} \text{ (example)}, \tag{1}$$

where r is the firm's discount rate and $\alpha > 0$, β, and $\gamma > 0$ are parameters that depend on the firm's profit and abatement options in A and B and its relocation costs.[13] Figure

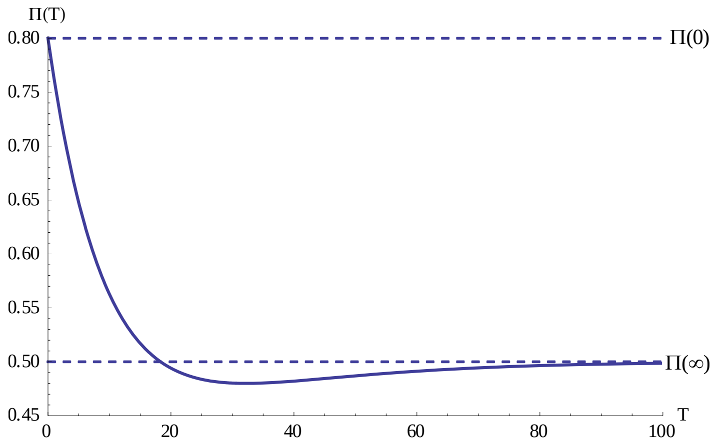

Figure 1: Numerical example with immediate relocation.

1 illustrates the shape of $\Pi(T)$ under example (1), for the parameter values $\alpha = 0.5$, $\beta = 0.2$, and $\gamma = 0.5$.[14] Note, that the function $\Pi(T)$ implicitly contains the firm's optimal investment in abatement capital, given the emissions price it faces in country A,

[13] More specifically, we have $\alpha = \pi_A^*(p)/r + \gamma$, $\beta = -(\pi_B - \pi_A^*(p))/r + F + 2\gamma$, and $\gamma = p^2/2kr^2$, where $\pi_A^*(p)$ is the firm's profit flow in A in the absence of abatement capital, investment costs in abatement capital are quadratic with a scale parameter k, F are time-independent non-recoverable relocation costs, π_B is the profit flow in B, and p is the emissions price in A.

[14] These values are obtained for $r = 0.05$, $\Delta\pi(p) = 0.04$, $\pi_A^*(p) = 0$, $p = 0.1$, and $k = 4$.

taking into consideration the investment costs as well as the planned relocation time T.[15]

Given the specification in (1), $\Pi(T)$ can either be (i) increasing over the entire range $T \in [0, \infty)$, (ii) decreasing over $T \in [0, \infty)$, or (iii) decreasing between $T = 0$ and some finite time $T > 0$, and increasing thereafter (as in the example of Figure 1).[16] In case (i), it holds that $\Pi(\infty) > \Pi(0)$. Clearly, in this case, no transfers are needed to avert relocation, since the option to stay in A permanently dominates. In case (ii), immediate relocation is the firm's dominant choice in the absence of transfers, even when the firm optimally exploits its possibilities to invest in abatement capital. In this case, transfers can avert the firm's relocation, but must be maintained indefinitely. However, as we will see later in this section, in case (iii), transfers that terminate in finite time can be sufficient to avert the firm's relocation permanently.

Let us return to our general model. Hence, we no longer assume the special form of Π in (1). (We only assume Π is bounded and continuously differentiable in T.) We define a *grandfathering scheme* as a function $g : [0, \infty) \to \mathbb{R}$ specifying the flow of transfers $g(t)$ from the government to the firm at all times $t \geqslant 0$, and we explicitly allow it to be negative (e.g., via taxation). For instance, $g(t) < 0$ could mean that the government requires the firm to return at time t *more* emissions permits than is needed to match its emissions at t.[17] If $g(t) \geqslant 0$ for all t, we say that g is *non-negative.* If there is some T such that $g(t) = 0$ for all $t \geqslant T$, we say that *g phases out before T*. We denote the smallest T for which this condition is fulfilled (for the given g) by τ, which is the point in time where the grandfathering scheme terminates.

We assume that at time $t = 0$, the government chooses and bindingly commits[18] to a grandfathering scheme g, that the firm knows g from time zero on, and that at each point in time $t \geqslant 0$ at which it has not yet relocated to B, the firm can relocate immediately at t or can plan to relocate at any future time $T \in (t, \infty]$. Assuming a rational firm with perfect foresight and exponential discounting, we can infer that as soon as the firm knows g, which is at time zero, it will determine the optimal relocation time $T \in [0, \infty]$, will plan to relocate at T, will not change this plan between $t = 0$ and $t = T$, and will indeed relocate at T.[19] Hence we only need to analyze the firm's choice of T at time zero.

[15] Clearly, the longer the firm plans to stay in A, the more it will invest.

[16] To see this, note that $\Pi'(T) > 0$ is equivalent to $\beta > 2\gamma e^{-rT}$ (using (1)). This is fulfilled for $T \to \infty$ when $\beta > 0$, and violated for $T = 0$ when $\beta < \gamma$, which is equivalent to $\Pi(0) > \Pi(\infty)$ (otherwise, no transfers are needed to avert relocation). Hence, case (iii) is relevant iff $0 < \beta < \gamma$. Intuitively, as shown in Section 3, the benefits of an upfront investment in abatement capital accrue gradually over time. Therefore, the longer a firm plans to stay in country A (larger T), the more it invests. But the more it invests, the longer it optimally wants to stay. If this 'positive feedback' is strong enough, $\Pi(T)$ has an increasing part (starting at some sufficiently large value of T).

[17] This could be interpreted as paying back a "permit loan" and could be realized via a "carbon bank".

[18] It is important that the regulator can commit at $t = 0$ to future transfers. Otherwise, the transfers could be terminated as soon as the firm has invested in abatement capital. In the absence of commitment power, this time-inconsistency would create a hold-up problem.

[19] Without perfect foresight, the firm might reconsider its choice after time zero if it cannot bindingly

We assume that the regulator's objective when designing the transfer scheme is to avert the firm's relocation permanently, with a minimum of transfers to the firm. E.g., relocation may be associated with a loss of employment, implying welfare costs that exceed the amount of transfers required to avert the firm's relocation. Furthermore, we assume that the regulator makes transfers at any time t contingent only on the firm still being located in A at that time. Hence, the regulator cannot subsidize investments in abatement capital directly. Although this assumption is restrictive, we believe that it may be reasonable in some situations (e.g., because investments in low-carbon technologies or other types of abatement capital are unobservable to the regulator or not contractible).[20]

From the perspective of the firm, the additional payoff from the grandfathering scheme g has a value of

$$G(T) = \int_0^T g(t)e^{-rt}\, dt. \tag{2}$$

Hence the firm will (weakly) prefer to stay in A forever iff

$$\Pi(\infty) + G(\infty) \geqslant \Pi(T) + G(T) \text{ for all } T. \tag{3}$$

In particular, any transfer scheme that averts the firm's relocation must (as a minimum requirement) fulfill $\Pi(\infty)+G(\infty) \geqslant \Pi(0)+G(0)$. Hence, the option to stay permanently in country A (and invest in abatement capital accordingly) must — given the prospect of future transfers — be at least as attractive to the firm as the option to relocate immediately. Condition (3) can be rewritten more conveniently as follows:

$$R(T) \geqslant L(T) \text{ for all } T, \tag{4}$$

where

$$\begin{aligned} L(T) &\equiv \Pi(T) - \Pi(\infty), \\ R(T) &\equiv G(\infty) - G(T) = \int_T^\infty g(t)e^{-rt}\, dt. \end{aligned}$$

If condition (4) holds, we say that g *deters relocation permanently.* In other words, the government will succeed in deterring relocation permanently if it chooses the grandfathering scheme g large enough so that for each possible relocation time T, the *'Remaining*

commit to a plan, which would complicate the analysis.

[20]If the regulator discounts future payments to the firm at the same rate as the firm, and averts relocation at minimal costs (see below), then he is indifferent between the location-based transfer schemes that we analyze in this paper, or an equivalent direct subsidy for abatement capital investments. If direct subsidies involve higher transaction costs (e.g., monitoring costs) then the regulator has a strict preference for the location-based transfer schemes.

grandfathering value' $R(T)$ meets the *'Lower bound'* $L(T)$ given by the firm's opportunity costs of staying in A forever rather than relocating to B at time T. Note, that this comparison takes place at time $t = 0$ (not T), where the firm takes into account its investment opportunities in abatement capital as well as the optimal time path of its other decision variables (e.g., output) for *any given* value of the planned relocation time T.

Given Π and G, the firm determines its optimal relocation time T by maximizing $\Pi(T) + G(T)$. If there were an interior solution $T < \infty$ (which the government however will make sure does not exist), it could be derived by solving the following first-order condition[21]

$$0 = \frac{\partial(\Pi(T) + G(T))}{\partial T} = \Pi'(T) + g(T)e^{-rT}. \tag{5}$$

If (5) holds for *all* T, we say that g equals the *critical scheme* g_{crit} given by

$$g_{\text{crit}}(t) \equiv -e^{rt}\Pi'(t). \tag{6}$$

In this case, the firm is indifferent between staying or relocating at *any* time $T \in [0, \infty]$, hence, $\Pi(T) + G(T) = \Pi(0)$ holds for all T. Note that this critical scheme need not be non-negative and will not phase out in finite time in general.

Our first general result provides a simple sufficient condition for permanent deterrence in terms of the critical scheme g_{crit}:

Proposition 1. *There is always a scheme g that deters relocation permanently. A sufficient condition is that it meets the critical scheme so that $g(t) \geqslant g_{crit}(t)$ for all t.*

Clearly, if a grandfathering scheme $g(t)$ deters relocation permanently, the non-negative scheme given by $\tilde{g}(t) \equiv \max\{g(t), 0\}$ does so as well.[22] E.g., in the example of equation (1), we have $g_{\text{crit}}(t) = -\beta r + 2\gamma r e^{-rt}$, which is strictly decreasing and does not phase out in finite time. Furthermore, g_{crit} is non-negative iff $\beta \leqslant 0$. If $0 < \beta < \gamma$, $g_{\text{crit}}(t)$ turns negative for sufficiently large t.[23] In this case, a *temporary* grandfathering scheme can be designed that averts relocation permanently (see Section 2.2).

In Section 2.1, we will see that the sufficient condition $g(t) \geqslant g_{\text{crit}}(t)$ given in Proposition 1 is, however, *not* a necessary condition, since grandfathered permits can be redis-

[21]The function G is also assumed to be differentiable almost everywhere. It might not be differentiable at some $\tau < \infty$ if the transfer scheme terminates at this point, so $g(.)$ need not be continuous at τ, with $g(t) > 0$ for $t \leqslant \tau$, and $g(t) = 0$ for $t > \tau$. For the specific model of Section 3, we will show that such schemes are optimal under certain conditions.

[22]Formally, since g deters relocation permanently, we have $R(T) = \int_T^\infty g(t)e^{-rt}\,dt \geqslant L(T)$ for all T. Given $\tilde{g}(t) \equiv \max\{g(t), 0\}$, we have (for arbitrary T) $\int_T^\infty \tilde{g}(t)e^{-rt}\,dt \geqslant \int_T^\infty g(t)e^{-rt}\,dt$. Hence, also $\tilde{g}$ deters relocation permanently.

[23]This holds if the cost parameter k for investments in abatement capital lies in a certain range – see Proposition 4 in Section 3; the condition $0 < \beta < \gamma$ is equivalent to (14). $\beta < \gamma$ assures that $\Pi(0) > \Pi(\infty)$ holds (otherwise, no transfers are needed to avert relocation), and $\beta > 0$ assures that $\Pi(T)$ has an increasing part.

tributed along the time axis up to a certain extent. Also note that although it may seem natural to consider non-negative schemes only, it might be possible for the government to claim back later some of what it spent on grandfathering earlier, by putting $g(t) < 0$ for some t. By (6), Proposition 1 implies that such a scheme will be possible whenever $\Pi(T)$ has an increasing part, i.e., when $\Pi'(T) > 0$ for some T.

2.1 Optimal grandfathering schemes

Although from Proposition 1 it may seem intuitive that $g(t) \geqslant g_{\text{crit}}(t)$ is also a *necessary* condition for a scheme to deter relocation permanently, this is not true. The reason is that, with a proper premium to make up for discounting, grandfathering can always be *delayed* without harm.[24]

Lemma 1. *If g deters relocation permanently and $\hat{g}$ is derived from g by "shifting discounted transfers to later times" so that $\int_0^T \hat{g}(t)e^{-rt}\,dt \leqslant \int_0^T g(t)e^{-rt}\,dt$ for all $T < \infty$ and $\int_0^\infty \hat{g}(t)e^{-rt}\,dt = \int_0^\infty g(t)e^{-rt}\,dt$, then also $\hat{g}$ deters relocation permanently.*

In particular, the government can delay the grandfathering scheme's start to an arbitrary time point t_1 without destroying the deterrence effect, by putting $g(t) = 0$ for all $t \leqslant t_1$ and choosing $g(t)$ large enough later on. Whether this makes the transfer scheme more or less costly to the regulator depends on whether the government is more or less patient than the firm. Let ϱ be the government's discount rate.

Proposition 2. *The optimal grandfathering scheme that permanently averts relocation with a minimum of transfers (evaluated at ϱ) is $g_{crit}(t)$ if the government is more patient than the firm ($\varrho < r$). If $\varrho > r$, the government always benefits from shifting discounted transfers to later times. If $\varrho = r$, the optimal scheme is not uniquely determined.*

In particular, an impatient government has no optimal scheme but is tempted to delay grandfathering indefinitely. In reality, since governments cannot make everlasting commitments, an impatient government would be tempted to put all mass on the latest credible time point.

In contrast, a patient government's optimal scheme is to use $g_{\text{crit}}(t)$. Note, that in general $g_{\text{crit}}(t) \neq 0$ for almost all t, hence, an optimal scheme under full commitment will never phase out, even when a phasing-out scheme would be possible.

2.2 Possibility of phasing out

Since in general $g_{\text{crit}}(t) \neq 0$ for most t, it might not be possible to deter relocation permanently without a grandfathering scheme that is permanent as well. The following

[24] Such a delay might even be necessary, e.g., if there is an emissions cap $E_{\max}(t)$ which the joint emissions of all firms in country A must not exceed, so that also the total value of grandfathered allowances $g(t)$ over all firms must not exceed the value $pE_{\max}(t)$.

Proposition, however, states a simple condition under which the transfers to the firm *can* be phased out in finite time, and nevertheless, the firm's relocation is averted permanently.

Proposition 3. *There exists a scheme that deters relocation permanently and phases out before τ iff $L(T) \leqslant 0$ for all $T \geqslant \tau$. Without loss of generality, the scheme can then be chosen non-negative.*

For example, given the additive specification of our model in Section 3 (see equation (1)), we have $\Pi(\infty) = \alpha$ and $L(T) = -\beta e^{-rT} + \gamma e^{-2rT}$, which stays below zero eventually iff $\beta > 0$. Hence in that example, relocation can be deterred permanently with a grandfathering scheme that phases out in finite time iff $\beta > 0$. This is consistent with the fact that for $\beta > 0$, also the critical scheme g_{crit} gets (and stays) negative eventually.

Expressed in terms of the function Π, temporary grandfathering schemes can be sufficient to deter relocation permanently if Π has an *increasing part* (increases in T for sufficiently large T).[25] Note, that if the condition in Proposition 3 is fulfilled for some τ, then, since $\Pi(T)$ was assumed to be continuous, there also exists a *smallest* τ ($\tau^{\min}$) for which it is fulfilled, and it seems natural to choose g so as to phase out at this earliest possible time if the regulator is constrained to use grandfathering schemes that do not involve negative transfers at any point in time.[26] Indeed, as we will see in the following Section, given the additive model specification, grandfathering schemes that follow $g_{\text{crit}}(t)$ for $t \leqslant \tau^{\min}$ and terminate at $\tau^{\min}$, are indeed optimal given this constraint when $\varrho < r$ (see Proposition 6).

3 Additive specification

The previous section analyzed how transfer schemes that are used to avert relocation can generally be designed. In order to derive more specific results, it is useful to impose more structure on the model. This allows us to derive analytical expressions, e.g., for the optimal policy scheme.

Suppose that before the introduction of a carbon price, the specific firm under consideration (in the regulated industry[27]) can achieve a constant profit flow of $\pi_{A,0}$ when producing in country A. If the firm relocates to country B, its profit flow is also constant

[25] To see this, note that the condition $L(T) \leqslant 0$ is equivalent to $\Pi(T) \leqslant \Pi(\infty)$.

[26] In Figure 1, $\tau^{\min}$ is the intersection point of $\Pi(T)$ with the vertical dotted line for $\Pi(\infty)$. This is the point where $L(T) = \Pi(T) - \Pi(\infty)$ turns negative, while $g_{\text{crit}}(t)$ turns negative for a larger value of t. Intuitively, $\tau^{\min}$ is such that the firm is just indifferent (without transfers after $\tau^{\min}$) between an optimal investment in abatement capital for a *permanent* stay in A and no relocation, and a smaller investment (optimal for a stay only until $\tau^{\min}$) and relocation at that time. Hence, a transfer scheme that averts relocation permanently, must only make sure that the firm does not relocate *before* $\tau^{\min}$. Due to the lock-in effect of abatement capital, relocation at any later time is never profitable. We are grateful to an anonymous referee for pointing this out.

[27] Note, that the regulated firm need not be a monopolist. E.g., our results can easily be applied to analyze optimal grandfathering schemes that avert relocation when firms are engaged in Cournot

and equals π_B. At time $t = 0$, the regulator in A unilaterally introduces a carbon price of p, that remains constant thereafter, while emissions remain costless in country B. By investing in *abatement capital*, the firm is able to reduce its flow of emissions and, hence, its emissions costs when continuing to produce in country A.[28]

Now suppose that an abatement capital stock of a reduces the firm's emissions in country A also by a units[29], and that the firm's optimal choice of all other variables (such as input and output quantities) is *independent* of a. Hence, an investment in abatement capital allows the firm to reduce its flow of emissions, but does not affect the firm's operative decisions. Under this assumption, we can express the firm's profit flow in country A as

$$\pi_A^*(p) + pa, \tag{7}$$

where pa are the emissions costs that the firm *avoids* by investing in abatement capital. The remaining emissions costs are embedded in the profit flow $\pi_A^*(p)$, which is a function of the emissions price p. What is crucial for the additive structure of (7) to be valid is that $\pi_A^*(p)$ does *not* depend on a.[30] Therefore, the firm's investment in abatement capital can be analyzed separately from the firm's other decisions (e.g., output).[31] This simplifies the analysis considerably.

The simple additive structure in (7) is obtained, e.g., in situations where the firm (optimally) reduces its emissions *only* via abatement capital investments. In that case, the firm's profit flow in country A is $\pi_{A,0} - p(e_0 - a)$, where e_0 denotes the firm's baseline emissions (in the absence of abatement capital), and $p(e_0 - a)$ is the firm's total emissions cost flow. To convert this into the form (7), simply define $\pi_A^*(p) \equiv \pi_{A,0} - pe_0$.

However, the additive structure in (7) can also be obtained in cases where, in addition to investing into abatement capital, the firm also reduces its emissions via a contraction of output. To fix ideas, consider the following simple example. Let the firm be a monopolist in a market with an inverse demand (net of marginal production costs) of $1 - q$, where q is the firm's output quantity. Hence, before the introduction of an emissions price, the firm's profit flow in A equals $(1 - q)q$, which is maximized by choosing $q = 1/2$ and yields a profit flow of $\pi_{A,0} = 1/4$. Following the introduction of an emissions price of p, the firm's profit flow in A becomes $(1 - q)q - pe$, where e are the firm's emissions. If we assume that the emissions are additive in e and a: $e = q - a$, then the profit flow in A is $(1 - p - q)q + pa$.[32] This is maximized by choosing $q = q^*(p) = (1 - p)/2$, which yields

competition. More details and calculations for such an example can be obtained from the authors upon request.

[28] The abatement capital stock fully depreciates if the firm (at some point) relocates to B.

[29] By choosing the right scale for a unit of abatement capital.

[30] In Section 4, we present an alternative specification of the model where π_A^* depends on a, because the firm's emissions are not additively separable in output and abatement capital.

[31] The * in $\pi_A^*(p)$ indicates that all other decision variables of the firm are chosen optimally given p.

[32] An example for an abatement technology consistent with this formulation are investments in CCS

a profit flow of $(1-p)^2/4 + pa$. Hence, by defining $\pi_A^*(p) \equiv (1-p)^2/4$, we can convert this expression into the form in (7). Total abatement equals $e_0 - e = p/2 + a$, where $p/2$ is the firm's reduction in emissions (following the introduction of the emissions price p) achieved via output contraction, and a is the firm's abatement capital stock.

Returning to the general additive case, we are interested in situations where (e.g., due to higher transportation costs) the firm finds it more profitable to continue to produce in country A in the absence of an emissions price. This leads us to the following definition:

$$\Delta\pi(p) \equiv \pi_B - \pi_A^*(p) - rF, \tag{8}$$

where $F \geqslant 0$ is a fixed (and time-invariant) relocation cost incurred if the firm decides to shift its production from A to B.[33] *Given* $a = 0$, and in the absence of a transfer scheme, relocation from A to B is profitable iff $\Delta\pi(p) > 0$.[34] We are specifically interested in situations where $\Delta\pi(0) < 0$ holds *before* the introduction of a carbon price in A, but where $\Delta\pi(p) > 0$ holds when emissions become costly.

If the firm can invest in abatement capital to reduce its flow of emissions, the condition $\Delta\pi(p) \gtrless 0$ is no longer sufficient to determine the firm's location choice. For sufficiently large *sunk* investments in a, the firm always prefers to stay in A even when it faces the emissions price p, while it may relocate immediately when taking also the costs of this investment into consideration. This lock-in effect can be exploited by the regulator to *avert* the firm's relocation, by designing a suitable transfer scheme that gives the firm an incentive to undertake an investment in abatement capital. To this end, the regulator can implement a location-based transfer scheme that induces the firm to stay in A for a certain period of time. During this time, the firm faces the carbon price p. Anticipating this, it invests in abatement capital at $t = 0$ to reduce its emissions costs. Under some conditions, it suffices to subsidize the firm for a limited period of time in order to create a lock-in effect that is sufficiently strong to avert relocation *permanently.* In the following, we will characterize these conditions.

Suppose that in order to build up an abatement capital stock of a, an investment cost of $K(a)$ is incurred. For simplicity, we assume away depreciation of abatement capital.[35] The investment takes place at $t = 0$, the time where the carbon price is introduced in

(carbon capture and storage) equipment. Other examples include investments in heat insulation for buildings belonging to the firm, or investments in more energy-efficient machines that are used at their capacity limit (irrespective of the firm's output).

[33] In (8), F is multiplied by r to convert the fixed relocation cost into an equivalent flow. Note, that the lock-in effect underlying our results does *not* require that $F > 0$.

[34] Assuming that the firm continues to produce in A if it is indifferent.

[35] Considering depreciation would complicate the formal analysis, while the main results remain unchanged (as long as the depreciation rate is not too large).

country A.[36] For the investment cost function, we assume a quadratic functional form:

$$K(a) = ka^2/2. \tag{9}$$

The parameter k is the slope of the marginal investment cost function in abatement capital.[37] Given these assumptions, at time $t = 0$, the firm seeks to maximize $\Pi(a, T) + G(T)$ over a and T, where

$$\Pi(a, T) \equiv (\pi_A^*(p) + pa)(1 - e^{-rT})/r + \pi_B e^{-rT}/r - ka^2/2 - Fe^{-rT}, \tag{10}$$

and $G(T)$ is the additional payoff from the grandfathering scheme, defined in (2).

If the firm plans to relocate from A to B at time T, the optimization over a yields the following first-order condition:[38]

$$\frac{\partial \Pi(a, T)}{\partial a} = p(1 - e^{-rT})/r - ka = 0.$$

Hence, given T, the firm's optimal abatement capital choice is

$$a^*(T) = (1 - e^{-rT})p/kr. \tag{11}$$

Note that this is increasing in T: the longer the firm plans to stay in A, the longer it faces the carbon price p and, therefore, invests more in abatement capital. If the firm plans to stay permanently in A, it chooses: $a^*(\infty) = p/kr$.

Inserting $a^*(T)$ into the discounted profit function $\Pi(a, T)$, we obtain the following reduced profit function $\Pi(T)$, which was defined more generally in Section 2:

$$\Pi(T) = \pi_A^*(p)(1 - e^{-rT})/r + \pi_B e^{-rT}/r - Fe^{-rT} + (1 - e^{-rT})^2 p^2/2kr^2. \tag{12}$$

Intuitively, $p^2/2kr^2$ is the discounted emissions cost (net of investment costs) that the firm *avoids* by optimally exploiting the possibility to invest in abatement capital, when the firm plans to stay permanently in A. Defining the parameters α, β, and γ as in Section 2, $\Pi(T)$ simplifies to the expression in (1) (see Figure 1 for a numerical example).

Differentiating $\Pi(a, T) + G(T)$ with respect to T, we obtain the critical scheme (using (8), (10), and the envelope theorem):[39]

$$g_{\text{crit}}(T) = \Delta\pi(p) - pa^*(T). \tag{13}$$

[36] Note, that the firm benefits from the abatement capital from time $t = 0$ onwards as long as it continues to produce in A. Therefore, the firm has no incentive to delay the investment.

[37] We further assume that k is sufficiently large so that the optimal abatement capital investment is always below e_0, the firm's baseline emissions.

[38] The second-order condition is clearly fulfilled when $k > 0$.

[39] The same result is obtained by differentiating $\Pi(T) + G(T)$, using (12), and then inserting (11).

This condition indicates that the rate of transfers to the firm required to make it indifferent between planning to relocate at T, and staying marginally longer in A, is a declining function of the abatement capital stock the firm builds up ($a^*(T)$). This is because a larger upfront investment in abatement capital induces a higher profit flow in A.

3.1 Optimal temporary grandfathering schemes

In Section 2.1, we showed that optimal grandfathering schemes generally do not terminate in finite time. If the regulator is more patient than the regulated firm, then the optimal scheme first requires positive transfers to the firm, to give the firm an incentive not to relocate. In the more distant future, by choosing a negative transfer rate, the regulator can collect some of the surplus from the investment in abatement capital. However, for policy makers, it is often not feasible to commit over an infinite time horizon. It may, thus, be desirable to apply temporary policy schemes that terminate in finite time.

Proposition 4. *In the additive model, a temporary grandfathering scheme can be designed to avert relocation permanently if the cost parameter k is in the following range:*

$$\frac{p^2}{2r\Delta\pi(p)} < k < \frac{p^2}{r\Delta\pi(p)}. \tag{14}$$

Intuitively, the carbon price in A triggers investments in abatement capital that reduce the operating costs in A (in light of the carbon price p). A grandfathering scheme that is phased out over time can avert relocation permanently if these (potential) cost reductions are large enough to render the option to relocate unprofitable, once the investment costs into abatement capital ($K(a)$) are sunk. This requires that the investment cost parameter k is sufficiently small, which explains the right inequality in (14). The left inequality implies that — in the absence of a grandfathering policy — the option to relocate immediately to B, is more profitable than the option to stay permanently in A, even when the possibilities to reduce the operating costs in A via an investment in abatement capital, are optimally exploited. (Otherwise, no transfers are needed to avert the firm's relocation.)

If an effective grandfathering scheme can be found that terminates in finite time, the question about the minimum duration of this policy intervention naturally arises.

Proposition 5. *In the additive model, the minimum duration of grandfathering required to avert relocation permanently is given by*

$$\tau^{min} = \frac{1}{r}\log\frac{p^2/2}{p^2 - kr\Delta\pi(p)}. \tag{15}$$

Intuitively, if grandfathering is phased out too quickly, then the firm may benefit from an initially generous rate of transfers, but does not invest enough in abatement capital to render the option to stay permanently in A profitable. Instead, the firm plans to relocate in finite time from the start and, thus, invests too little in abatement capital at $t = 0$. As a result, the lock-in effect does not occur.[40]

To illustrate the firm's relocation decision when a grandfathering scheme is implemented that phases out too quickly, consider the following numerical example. Suppose (for simplicity) that the rate of transfers to the regulated firm declines at a constant rate $\varphi > 0$, and that the initial transfer rate at $t = 0$ is given by g_0, hence: $g(t) = g_0 e^{-\varphi t}$ for $t \in [0, \infty]$. Suppose further that g_0 is chosen sufficiently large so that the firm achieves the same discounted profit when staying permanently in A (optimally exploiting its possibilities to invest in abatement capital) as when it relocates to B immediately. Hence, g_0 is chosen such that: $\Pi(\infty) + G(\infty) = \Pi(0)$ holds. Whether the firm relocates in finite time or (given the transfer scheme) stays permanently in A, depends on how quickly the transfers are phased out, hence, on the size of the parameter φ. Figure 2 illustrates that when φ is chosen too large, the firm's discounted profit reaches a maximum in finite time, and the firm relocates at this point.[41] If the grandfathering scheme is instead phased out

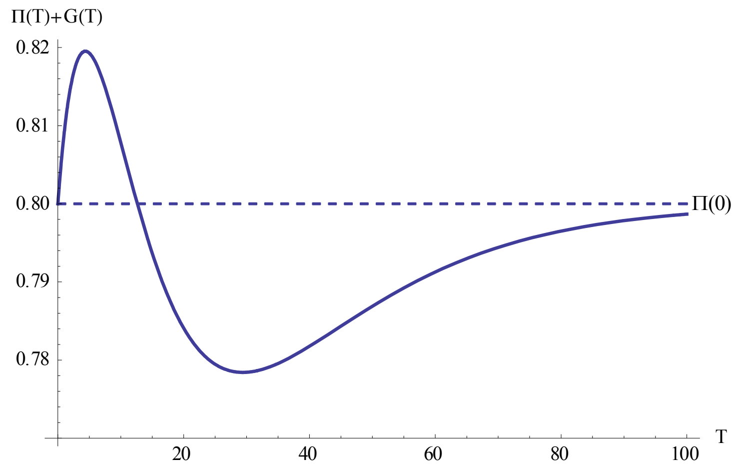

Figure 2: Numerical example with relocation in finite time.

less quickly (choosing g_0 such that $\Pi(\infty) + G(\infty) = \Pi(0)$ continues to hold), then the local maximum in Figure 2 disappears, and the firm is indifferent between the option to relocate immediately ($T = 0$) and staying permanently in A ($T = \infty$).

Although (for φ sufficiently small) relocation is averted permanently, and the grandfathering scheme just compensates the firm for the competitive disadvantage in its home

[40]Note, that $\tau^{\min}$ is zero if the left-hand side of (14) holds with equality, and infinite if the right-hand side holds with equality.

[41]Figure 2 is plotted for $r = 0.05$, $\Delta\pi(p) = 0.04$, $\pi_A^*(p) = 0$, $p = 0.1$, $k = 4$ (same parameter values as in Figure 1), and $\varphi = 0.12$, $g_0 = 0.051$.

country induced by the introduction of the carbon price p, it is nevertheless in general not optimal to phase out the transfers at a constant rate. As shown in Proposition 2, if the regulator's discount rate ϱ is larger than the firm's discount rate r, he wants to shift transfers into the infinite future. Conversely, if $\varrho < r$, the regulator tries to 'frontload' the transfers. Only if $\varrho = r$ holds, the regulator is indifferent between all transfer schemes that fulfill the condition $\Pi(\infty) + G(\infty) = \Pi(0)$, and are phased out sufficiently slowly to avert relocation permanently. However, the condition $\varrho = r$ appears to be quite strong, and in many cases, it seems plausible to assume that the regulator is (at least slightly) more patient than the firm. Therefore, we will now focus on the case where $\varrho < r$ holds, and seek to characterize the optimal grandfathering scheme. Furthermore, attention is restricted to non-negative policy schemes that do not require negative transfers at any point in time. As a result of this, the optimal policy scheme will indeed be one where grandfathering terminates in finite time:

Proposition 6. *In the additive model, if $\varrho < r$ holds, the optimal non-negative grandfathering scheme that averts relocation permanently is given by*

$$g(t) = \begin{cases} g_{crit}(t) & if \qquad t \in [0, \tau^{min}], \\ 0 & if \qquad t > \tau^{min}. \end{cases} \tag{16}$$

It is straight-forward to show that $g_{\text{crit}}(t) = \Delta\pi(p) - (1 - e^{-rt})p^2/kr$ (see (13)) is strictly greater than zero for $t = \tau^{\min}$ if (14) is fulfilled. Hence, under the optimal non-negative scheme, transfers discontinuously drop to zero at the termination point $t = \tau^{\min}$. Given this policy scheme, the local maximum observed in Figure 2 disappears. As Figure 3 illustrates, the optimal non-negative scheme assures that the firm is just indifferent between planning to relocate at any $T \leqslant \tau^{\min}$, and planning to stay permanently in country A.[42] Note, that for values of $T > \tau^{\min}$, the curve $\Pi(T) + G(T)$ is obtained via a parallel shift of the original curve $\Pi(T)$ (see Figure 1) upwards so that the condition $\Pi(\infty) + G(\infty) = \Pi(0)$ is just fulfilled. In this range, no transfers are paid to the firm (as $g(t) = 0$ for $t > \tau^{\min}$ in the optimal scheme).

If the regulator is not constrained to use non-negative transfer schemes, then the optimal policy is to apply $g(t) = g_{\text{crit}}(t)$ for all t. This implies that the regulator continues to allocate emission allowances (transfers) to the firm for free beyond the point where they are required to avert relocation, but later on taxes the firm. The discounted net gain to the firm of this continuation is zero, while it is positive for the regulator who places a higher weight than the firm on future payoffs.

[42]Figure 3 is plotted for: $r = 0.05$, $\Delta\pi(p) = 0.04$, $\pi_A^*(p) = 0$, $p = 0.1$, and $k = 4$ (same parameter values as for Figure 1).

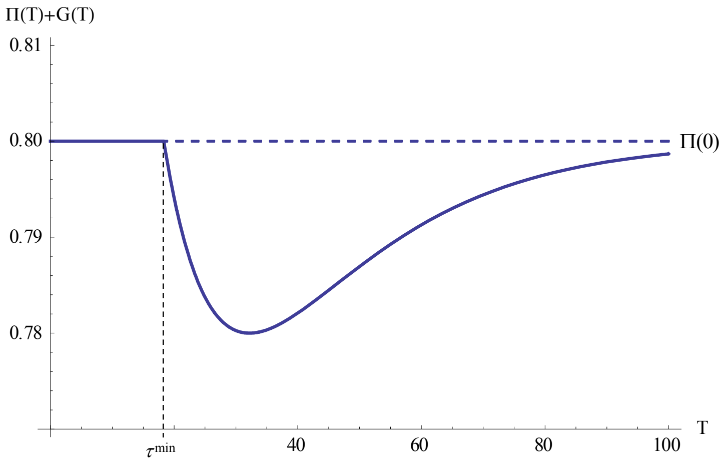

Figure 3: Optimal non-negative policy scheme.

4 Alternative model specification

In this section, we consider an alternative specification of our model, where (unlike in the previous section) the firm's emissions are *not* additively separable in output and abatement capital. For example, the flow of emissions may be given by

$$e = (1 - a)q, \tag{17}$$

where q is the firm's output. In this case, an abatement capital stock of a reduces the *emissions intensity* of output. The larger the firm's abatement capital stock, the higher is its optimal output in A, because abatement capital effectively reduces the firm's marginal production costs (in the light of the emissions price p). As a result of this, the firm's maximized profit flow $\pi^*_A(p, a)$ cannot be separated as in (7). The analysis of this more general model is much more complicated than in the additive case. Even under the simple specification (17), it is not possible to derive tractable analytical results (e.g., for the optimal policy scheme). The difficulty is that the firm's optimal investment in abatement capital depends on the firm's planned relocation time T. However, since $\pi^*_A(p, a)$ now also depends on a (e.g., via the firm's optimal output choice $q^*(a)$), the maximized profit flow now depends explicitly on the planned relocation time T (via $a^*(T)$). As a result of this, for *any given* policy scheme g, a specific set of differential equations must be solved in order to characterize the firm's optimal choice of a and T.

To circumvent this problem, we assume that the firm's investment in abatement capital is a binary decision variable. Hence, we assume that a can take on only one of two values: $a \in \{0, \bar{a}\}$. This simplification allows us to derive analytical results also for this specification of the model.[43]

Suppose that when the firm invests in abatement capital, it incurs a fixed cost of K, and its maximized profit flow in A (choosing input and output quantities etc. optimally, given $a = \bar{a}$) is given by $\pi_A^*(p, \bar{a})$. If the firm does not invest, then its maximized profit flow in A is $\pi_A^*(p, 0)$. If the firm relocates, its flow of profit is π_B.

Proposition 7. *In the alternative specification of the model, if $\varrho < r$ holds, the optimal non-negative grandfathering scheme that averts relocation permanently is: $g(t) = \pi_B - \pi_A^*(p, 0) - rF$ if $t \in [0, \tau^{min}]$, and $g(t) = 0$ for $t > \tau^{min}$. The termination point is*

$$\tau^{min} = \frac{1}{r} \log \frac{\pi_B - \pi_A^*(p, 0) - rF}{\pi_A^*(p, \bar{a}) - \pi_A^*(p, 0) - rK}, \tag{18}$$

and the relevant range of parameter values where it is possible to avert relocation permanently with a temporary grandfathering scheme is

$$0 < \pi_A^*(p, \bar{a}) - \pi_B + rF < rK < \pi_A^*(p, \bar{a}) - \pi_A^*(p, 0). \tag{19}$$

Hence, the flow of grandfathered allowances must be sufficiently large to compensate the firm for the competitive disadvantage in its home country caused by the carbon price p, when the firm does *not* undertake any investment in abatement capital. This constant subsidy flow must be maintained for a sufficiently long period of time (until $\tau^{\min}$) so that the firm is just indifferent between staying in A until the endpoint of the subsidy without investing in abatement capital, and staying permanently in A when investing in abatement capital at $t = 0$.

The finding that the optimal policy scheme now entails a constant rate of grandfathered allowances is a consequence of the binary abatement capital investment choice. This leads to a threshold-effect: either the firm invests in abatement capital and stays permanently in A, or the firm does not invest and relocates to B immediately. Nevertheless, also under this specification of the model, we find that a grandfathering scheme that terminates in finite time can be a sufficient policy instrument to avert relocation permanently.

Let us conclude this section with a simple numerical example.[44] Suppose, the firm's profit flow in A is 3 (units of money per unit of time) if the firm invests in abatement capital: $\pi_A^*(p, \bar{a}) = 3$. If the firm does not invest, its profit flow in A is $\pi_A^*(p, 0) = 1$. If the firm relocates to B, its profit flow is $\pi_B = 2$. Let $F = 0$. For the minimum duration

[43] Possible examples for such a binary decision include investments in more energy-efficient machines or CCS equipment, where in some cases only a limited number of choices (e.g., regarding the size of the investment) may be available to the firm.

[44] This is a continuous-time version of the simple example in the introduction.

of transfers to which the regulator must commit, we, thus, find (using (18))

$$\tau^{\min} = \frac{1}{r} \log \left(\frac{1}{2 - rK} \right),$$

and a constant transfer of $g(t) = 1$ for $t \leqslant \tau^{\min}$ (and $g(t) = 0$ thereafter) averts relocation cost-effectively when $\varrho < r$. In this example, the relevant parameter range for our results is (by (19)): $1/r < K < 2/r$. The left inequality implies that relocation is profitable in the absence of transfers, and the right inequality assures that a transfer scheme can be found that terminates in finite time, but induces the firm to invest and, thus, averts relocation permanently.

5 Conclusion

Grandfathering is often seen as a device to shield firms from adverse effects of an emissions price on their profitability. This paper formalizes the idea that the free allocation of allowances in the early phase of an emissions trading scheme may also be used as an incentive device to avert relocation to countries with lower carbon prices. It was shown that via a lock-in effect of investments in abatement capital, a grandfathering scheme that is phased out over time, can permanently avert relocation, even when immediate relocation would be profitable in the absence of a transfer scheme.

A necessary condition for the effectiveness of a location-based transfer scheme to affect firms' location choices in the long run is that there remains enough scope for investments in abatement capital or low-carbon technologies. Furthermore, we showed that the timing of a grandfathering policy is crucial for its effectiveness to avert relocation. If the free allocation of allowances is phased out too rapidly, firms in the regulated industry may enjoy the benefits of an initially generous policy, but do not invest enough in abatement capital to render the option to stay in their home-country profitable.

The lock-in effect of sunk investments that reduce the operating costs in light of an emissions price, is likely to be empirically relevant when carbon prices are high enough. Firms from a larger number of industries may then consider the option to relocate to countries with less restrictive environmental regulation. The lock-in effect identified in this paper, can avert relocation permanently in those industries that do not yet operate at the technological frontier, or that have not fully exhausted the existing possibilities to invest in low-carbon technologies or energy-efficient equipment. An empirical analysis that investigates the practical relevance of our findings, would be an interesting starting point for future research.

The results in this paper were derived under the simplifying assumption that the regulator implements a grandfathering scheme *only* to avert relocation, using a minimum of transfers. There are, of course, various other reasons why governments may decide to allocate allowances for free. One of the motives may be to reduce pressure from lobbyist groups against the introduction of a carbon price. However, even if grandfathering is implemented for reasons other than those highlighted in this paper, the fact that it *can*, under some conditions, be an effective tool to avert relocation, seems to be an important insight. Our results may guide policy-makers towards a more effective design of grandfathering and other location-based transfer schemes. E.g., the finding that the free allocation of allowances should not be phased out too rapidly in order to have a permanent effect upon firms' location choices, seems crucial. Furthermore, the regulator must be able to commit to future transfers. Otherwise, firms will anticipate future reductions in transfers when deciding whether to invest in abatement capital or not, which creates a hold-up problem. Note that the lock-in effect that drives our results, may apply also in situations where firms are only indirectly affected by an emissions price. E.g., an increase in energy prices — following the introduction of a cap-and-trade scheme — can trigger the relocation of firms in energy-intensive industries. Also in those industries, location-based transfer schemes can be an effective tool to avert relocation.

A Appendix: Proofs

Proof of Proposition 1. We apply the definitions of L and R to show that $g(t) \geqslant g_{\text{crit}}(t)$ for all t implies that $R(T) \geqslant L(T)$ for all T. Using (6), we have (for arbitrary T)

$$L(T) = \Pi(T) - \Pi(\infty) = -\int_T^\infty \Pi'(t)\,dt = \int_T^\infty g_{\text{crit}}(t)e^{-rt}\,dt,$$
$$R(T) = \int_T^\infty g(t)e^{-rt}\,dt \geqslant \int_T^\infty g_{\text{crit}}(t)e^{-rt}\,dt = L(T).$$

Hence, $R(T) \geqslant L(T)$ for all T. □

Proof of Lemma 1. Consider some $T < \infty$. Since

$$\int_0^T \hat{g}(t)e^{-rt}\,dt \leqslant \int_0^T g(t)e^{-rt}\,dt \text{ , and } \int_0^\infty \hat{g}(t)e^{-rt}\,dt = \int_0^\infty g(t)e^{-rt}\,dt,$$

it follows that

$$\hat{R}(T) = \int_T^\infty \hat{g}(t)e^{-rt}\,dt \geqslant \int_T^\infty g(t)e^{-rt}\,dt = R(T).$$

Since $R(T) \geqslant L(T)$ as g deters relocation permanently, it follows that $\hat{R}(T) \geqslant L(T)$. This holds for all T, so also $\hat{g}$ deters relocation permanently. □

Proof of Proposition 2. By construction, the critical scheme g_{crit} fulfills $R(T) = L(T)$ for all T. Any other scheme $\hat{g}$ can be derived from g_{crit} by 1. adding transfers at some points t, 2. subtracting transfers at some t, and 3. shifting transfers (with a proper premium for discounting) so that $\hat{G}(\infty) = \int_0^\infty \hat{g}(t)e^{-rt}\,dt = G(\infty) = \int_0^\infty g_{\text{crit}}(t)e^{-rt}\,dt$. Adding transfers at some t implies $\hat{G}(\infty) > G(\infty)$, so that relocation is not averted with a minimum of transfers. Subtracting transfers at some t leads to $\hat{G}(\infty) < G(\infty)$, so that $\hat{R}(0) < L(0)$, which implies immediate relocation. Therefore, any optimal scheme $\hat{g}$ can be derived from g_{crit} by only shifting transfers, so that $\hat{G}(\infty) = G(\infty)$ must be fulfilled.

1. Case $\varrho < r$. Consider a shift of transfers to later times (starting from g_{crit}). By Proposition 1, the resulting scheme $\hat{g}$ also averts relocation permanently. However, since the firm discounts future transfers more than the regulator, the premium for discounting implies that the new scheme is more costly to the regulator than g_{crit}. Now consider a shift to earlier times. Following the same steps as in the proof of Proposition 1, it is straight-forward to show that after such a shift, there exists some $T < \infty$ such that $\hat{R}(T) < L(T)$. Hence, the shift of transfers induces relocation.

2. Case $\varrho > r$. Reversing the argument of case 1, it follows immediately that a shift of transfers to later times (with a proper premium for discounting so that $\hat{G}(\infty) = G(\infty)$ is

fulfilled) reduces the total value of transfers when evaluated at the regulator's discount rate ϱ. Hence, such a shift is always beneficial.

3. Case $\varrho = r$. As in the case $\varrho < r$, shifts of transfers to earlier times induce relocation. However, shifts to later times imply that $\hat{R}(T) \geqslant L(T)$ for all T, so that $\hat{g}$ averts relocation permanently. However, since $\hat{G}(\infty) = G(\infty)$ and $\varrho = r$, the discounted value of transfers evaluated at ϱ also remains constant, so that the optimal scheme is not uniquely determined. $\square$

Proof of Proposition 3. 1. Necessity. We show that, if there exists a scheme g that deters relocation permanently and that phases out before τ, then $L(T) \leqslant 0$ for all $T \geqslant \tau$. Suppose to the contrary that $L(T) > 0$ for some $T \geqslant \tau$, but g deters relocation permanently, so $R(T) \geqslant L(T) > 0$. Since $R(T) = \int_T^\infty g(t)e^{-rt}\,dt$, it must have $g(t) > 0$ for some $t \geqslant T \geqslant \tau$. Hence, g does not phase out before τ.

2. Sufficiency. We show that, given some $\tau < \infty$, if $L(T) \leqslant 0$ for all $T \geqslant \tau$, then there exists a scheme g that deters relocation permanently and phases out before τ. Let $g(t) = g_{\text{crit}}(t)$ for $t < \tau$, and $g(t) = 0$ for $t \geqslant \tau$, so that g phases out before τ. Then for all $T \geqslant \tau$, we have: $R(T) = 0 \geqslant L(T)$. For all $T \leqslant \tau$, we have

$$R(T) = \int_T^\infty g(t)e^{-rt}\,dt = \int_T^\tau \big(-e^{rt}\Pi'(t)\big)e^{-rt}\,dt = \Pi(T) - \Pi(\tau) = L(T) - L(\tau) \geqslant L(T),$$

since $L(\tau) \leqslant 0$. Hence, $R(T) \geqslant L(T)$ for all T, so g deters relocation permanently.

The last claim follows from Proposition 1. $\square$

Before we come to the proof of Proposition 4, we first state the following Lemma that will be exploited in the proof:

Lemma 2. *In the additive model, the condition $\Pi'(T) = 0$ has at most one solution that fulfills $0 < T < \infty$, and if so, it is a local minimum of Π. Hence, the maximum of Π is either located at $T = 0$ or at $T = \infty$.*

Proof of Lemma 2. Using (12), we obtain

$$\Pi'(T) = \left[\pi_A^*(p) - \pi_B + rF + (1 - e^{-rT})p^2/kr\right] e^{-rT}.$$

Using (8), and defining $\gamma \equiv p^2/2kr$ and $x \equiv -e^{-rT}$ for convenience, this yields (after a change of variables)

$$\Pi'(x) = (\Delta\pi(p) - 2\gamma)x - 2\gamma x^2.$$

For $T = 0$, we have: $x = -1$, and for $T = \infty$, we have $x = 0$. Furthermore, x is strictly monotonically increasing in T. Hence, $\Pi(T)$ has a local minimum (maximum) at T iff $\Pi(x)$ has a local minimum (maximum) at $x = -e^{-rT}$. Hence, to show the claim, it suffices to analyze the shape of $\Pi'(x)$ in the interval $x \in [-1, 0]$. If $\Delta\pi(p) - 2\gamma \geqslant 0$, then $\Pi'(x)$ is monotonically increasing in $[-1, 0]$. The maximum is, thus, located at $x = 0$ ($T = \infty$: no relocation). Only if $\Delta\pi(p) - 2\gamma < 0$, then $\Pi'(x)$ can become zero in the interval $x \in (0, 1)$, and $\Pi'(x)$ is increasing at this point, so $\Pi''(x) > 0$. Hence, at this point $\Pi(x)$ has a local minimum, which completes the proof. □

Proof of Proposition 4. By Lemma 2, in the absence of a transfer scheme, we only need to compare the firm's discounted profit for $T = 0$ and $T = \infty$ to determine the firm's location decision.

1. Left inequality of (14): This inequality implies that in the absence of a transfer scheme, immediate relocation is more profitable than staying in A permanently, even when the potential cost savings in A that can be achieved via an abatement capital investment, are optimally exploited. Formally, this can be stated as follows:

$$\Pi(0) > \Pi(\infty).$$

Using (12) and (8), this condition yields the left inequality in (14).

2. Right inequality: This inequality implies that once the investment costs in abatement capital: $K(a^*(\infty))$ (optimizing the investment for a permanent stay in A) are sunk and, hence, neglected in the firm's decision making, then even in the absence of a transfer scheme, relocation is no longer profitable. Formally, this can be stated as follows:[45]

$$\Pi(0) < \Pi(\infty) + K(a^*(\infty)).$$

Using (12), (8), (9), and (11), this condition yields the right inequality in (14). By the continuity of the functions $\Pi(T)$, $K(a)$, and $a^*(T)$, this condition implies that a *temporary* transfer scheme that induces the firm to stay for a sufficiently long period of time in A, averts relocation permanently.

More formally, apply Proposition 3 and use $L(T) \leqslant 0$ for all $T \geqslant \tau$ to identify a condition under which the earliest possible phase-out time $\tau^{\min}$ is finite. This condition will coincide with the right-hand side of (14). Using (12) in the definition of L: $L(T) = \Pi(T) - \Pi(\infty)$, as well as $\gamma \equiv p^2/2kr$ and $x \equiv -e^{-rT}$ for convenience, we obtain (after a change of variables)

$$L(x) = (x^2 + 2x)\gamma/r - x\Delta\pi(p)/r.$$

[45]By adding $K(a^*(\infty)) = ka^*(\infty)^2/2$ on the right-hand side, the firm's discounted profit is as high as when (at $t = 0$), an abatement capital stock of $a^*(\infty)$ would be given to the firm for free. See (10).

Note that $x \to 0$ when $T \to \infty$. Using the above result, the condition $L(T) < 0$ yields (multiplying both sides by $1/x < 0$)

$$\Delta\pi(p) - (x+2)\gamma < 0.$$

Since the left-hand side is linear in x, it follows immediately that L changes its sign at most once, and if it does, then L turns negative for x (and hence, T) sufficiently large. The earliest possible phase-out time $\tau^{\min}$ is defined by the condition: $L(T = \tau^{\min}) = 0$. Hence, we will identify the point where $L(x) = 0$ holds, and then impose $x < 0$, which implies that $\tau^{\min} < \infty$, hence, the transfer scheme can phase out in finite time. Using our above results, $L(x) = 0$ yields

$$x = \Delta\pi(p)/\gamma - 2. \tag{20}$$

Imposing $x < 0$, and using the definition of γ, this yields the right inequality in (14). $\square$

Proof of Proposition 5. In the proof of Proposition 4, we identified a critical value of x where $L(x) = 0$ holds (see (20)). At this point, L turns negative. x was defined as: $x \equiv -e^{-rT}$. Using this definition in (20), and solving for T, we obtain the minimum duration of an effective transfer scheme as shown in the Proposition (see (15)). $\square$

Proof of Proposition 6. The regulator's problem is to $\min_{g(t),\tau} \int_0^\tau g(t)e^{-\varrho t}\,dt$, subject to the constraints: $R(T) \geqslant L(T)$ for all T, and $g(t) \geqslant 0$ for all $t \leqslant \tau$. In the proof of Proposition 4, we showed that $L(T)$ changes its sign at most once, and if so, then it turns negative when T becomes sufficiently large. By the construction of g_{crit}, the above constraints are, therefore, clearly fulfilled by the transfer scheme shown in the proposition (see 16). To show that this scheme also minimizes the cost of transfers (given the constraints), consider a shift of transfers.[46] As shown in the Proof of Proposition 2, a shift of transfers to earlier times induces relocation and, hence, violates the first constraint. Furthermore, since $\varrho < r$, a shift of transfers from earlier times ($t < \tau^{\min}$) to later times, which (with a proper premium for discounting) leaves the firm indifferent, implies that the total cost of the transfer scheme when evaluated at ϱ, is higher than before the shift. Hence, the scheme (16) is optimal, given the regulator's constraints. $\square$

[46] As shown in the proof of Proposition 4, any optimal scheme can be obtained by only shifting transfers, starting from the critical scheme g_{crit}. Note that the scheme in (16) is also obtained in this way, by shifting transfers from earlier times where $g(t) > 0$ and $t > \tau^{\min}$, to later times, until $g(t) \geqslant 0$ holds for all t.

Proof of Proposition 7. Given a planned relocation time T, the firm's discounted profit in the absence of a transfer scheme is

$$\Pi(T) = \begin{cases} \pi_A^*(p,\bar{a})(1-e^{-rT})/r + \pi_B e^{-rT}/r - Fe^{-rT} - K & \text{if} \qquad a = \bar{a}, \\ \pi_A^*(p,0)(1-e^{-rT})/r + \pi_B e^{-rT}/r - Fe^{-rT} & \text{if} \qquad a = 0. \end{cases} \tag{21}$$

Let us start characterizing the relevant range of parameter values (see (19)). Since the investment is a binary decision, the following two conditions must be fulfilled: $\Pi(0) > \Pi(\infty)$ (otherwise, a transfer scheme is not needed to avert relocation), and $\Pi(0) < \Pi(\infty) + K$ (relocation becomes unprofitable, once the fixed investment cost K is sunk). Using (21), these two conditions yield the first two inequalities in (19), setting $a = 0$ for $T = 0$, and $a = \bar{a}$ for $T = \infty$ (for otherwise, the investment could never be induced). The third inequality implies that a *temporary* policy intervention is sufficient to trigger the investment. It is determined further below.

Let us now analyze when, for any T, the firm invests. Given T, the firm invests if the profit in the first line in (21) is larger than in the second. This yields the following condition:

$$(\pi_A^*(p,\bar{a}) - \pi_A^*(p,0))(1-e^{-rT})/r \geqslant K.$$

Since the left-hand side of this condition is increasing in T, this implies that there exists a critical time T^{crit}, such that the firm invests iff $T \geqslant T^{\text{crit}}$. As in the proof of Lemma 2, it is convenient to define $x \equiv -e^{-rT}$ (so that $x \in [-1, 0]$ is strictly increasing in T). Hence, the critical time T^{crit} translates into a critical value x^{crit}. Solving the above condition for x (after the change in variables), we obtain

$$x^{\text{crit}} = -\frac{\pi_A^*(p,\bar{a}) - \pi_A^*(p,0) - rK}{\pi_A^*(p,\bar{a}) - \pi_A^*(p,0)}.$$

The firm invests iff $x \geqslant x^{\text{crit}}$.

We are now ready to determine the critical scheme g_{crit}, and the termination point of the optimal non-negative scheme, $\tau^{\min}$. Using (6) and (21), we find for the critical scheme:

$$g_{\text{crit}}(t) = \begin{cases} \pi_B - \pi_A^*(p,\bar{a}) - rF & \text{if} \qquad T \geqslant T^{\text{crit}}, \\ \pi_B - \pi_A^*(p,0) - rF & \text{if} \qquad T < T^{\text{crit}}. \end{cases} \tag{22}$$

This is also the optimal transfer scheme if the regulator is not constrained to use non-negative schemes, and can fully commit. Note that $\pi_B - \pi_A^*(p,\bar{a}) - rF < 0$, hence, the regulator taxes the firm from time T^{crit} onwards. However, this critical time is not identical to the termination point of the optimal non-negative transfer scheme, which is the minimum duration of any transfer scheme that averts relocation permanently, $\tau^{\min}$.

To determine $\tau^{\min}$, we apply Proposition 3 and, hence, use the condition $L(T) = 0$. Applying $x \equiv -e^{-rT}$, after the change in variables, this translates into the condition $L(x) = 0$. Using (21), we obtain for L:

$$Ł(x) = \begin{cases} \pi_A^*(p,\bar{a})x/r - \pi_B x/r + Fx & \text{if } x \geqslant x^{\text{crit}}, \\ \pi_A^*(p,0)(1+x)/r - \pi_B x/r + Fx - \pi_A^*(p,\bar{a})/r + K & \text{if } x < x^{\text{crit}}. \end{cases} \tag{23}$$

Suppose, $\tau^{\min} < T^{\text{crit}}$ holds, hence: $x^{\min} < x^{\text{crit}}$. Below, we will show that this assumption is correct. Given this assumption, the condition $L(x) = 0$ yields (using (23) and (8))

$$x^{\min} = -\frac{\pi_A^*(p,\bar{a}) - \pi_A^*(p,0) - rK}{\pi_B - \pi_A^*(p,0) - rF}.$$

Converting x into T, this yields the expression for $\tau^{\min}$ shown in the proposition (see (18)). If the denominator in (18) goes to zero, then $\tau^{\min}$ converges to infinity. Therefore, the condition $\pi_A^*(p,\bar{a}) - \pi_A^*(p,0) - rK > 0$ must be fulfilled for a temporary transfer scheme to exist that averts relocation permanently. This yields the third inequality in (19).

To complete the proof, it remains to be shown that $x^{\min} < x^{\text{crit}}$ is fulfilled. Using the above expressions for x^{crit} and $x^{\min}$, this condition can be rewritten as: $0 < \pi_A^*(p,\bar{a}) - \pi_B + rF$, which is the first inequality in (19) and, hence, is fulfilled by assumption. □

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