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Optimal incentive contracts to avert firm relocation

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Abstract

A unilateral policy intervention by a country (such as the introduction of an emission price) can induce firms to relocate to other countries. We analyze a dynamic game where a regulator offers contracts to avert relocation of a firm in each of two periods. The firm can undertake a location-specific investment (e.g., in abatement capital). Contracts can be written on some contractible productive activity (e.g., emissions), but the firm's investment is not contractible. A moral hazard problem arises under short-term contracting that makes it impossible to implement outcomes with positive transfers in the second period. The regulator resorts to high-powered incentives in the first period. The firm then overinvests and a lock-in effect prevents relocation in both periods. Paradoxically, the distortion in the first-period contract can be so severe that higher transfers are needed to avert relocation compared to a (hypothetical) situation without the investment opportunity.

Keywords: moral hazard; contract theory; limited commitment; firm mobility; abatement capital
JEL classification: D82, D86, L51, Q58

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1 Introduction

In a globalized world economy, a firm's location is a strategic choice. Changes in tax regimes, market conditions, or regulations can render production more profitable in one country compared to another, and may induce firms to relocate or outsource production to other countries. Policy makers often perceive such relocation as harmful, because it can cause losses of jobs or reductions in tax revenues. Hence, they sometimes take measures to prevent firms from relocating, or try to design policies that minimize the incentives for firms to relocate.[1]

We study the issue of firm relocation in a dynamic setting, where a local regulator seeks to prevent the relocation of a firm to some other country in each of two periods.[2] The firm can undertake a location-specific investment that is neither observable to the regulator nor verifiable and, hence, not contractible. The regulator, however, can make transfer payments to the firm contingent on other indicators of the firm's productive activity, such as its output or emissions. While the firm's optimal choice of these activities is related to the investment, they are not fully revealing – some activities remain unobservable to the regulator so that the firm's investment cannot be inferred.

We show that a moral hazard problem arises when contracts can only be written on a short-term basis, so that the regulator must offer to the firm a new set of contracts in each period. Such short-term contracting is especially relevant because with changing majorities and legislations, regulators or policy makers may not be able to commit to contractual obligations and future regulations for a sufficiently long period of time. In particular, because firms' location decisions and investments related with them are usually long-term, limited commitment is likely to be a major concern in this context. Under short-term contracting, the firm can adopt a 'take-the-money-and-run strategy'. In this case, the firm stays for only one period in its home country and benefits from first-period transfers, but (secretly) lowers its investment, planning to relocate in period 2. We demonstrate that under limited commitment, a moral hazard problem arises that leads to distortions in the allocation.

As a benchmark case, we first consider long-term contracting ('full commitment'). In this case, the regulator can offer contracts to the firm that last for two periods and specify transfers as well as the firm's choice of its (verifiable) production decisions for both periods. The regulator's problem under long-term contracting is simple, because the interests of the regulator and the firm are to some extent aligned. While the firm

[1]For example, in 1999 the Finnish telecommunications company Nokia received a subsidy from the German state North Rhine-Westphalia to maintain production of mobile phones in the region. The subsidy was conditioned upon a guarantee to maintain at least 2.856 full-time jobs. Nevertheless, in 2008 Nokia announced plans to shut down production and finally relocated to Romania. For more details see www.spiegel.de/international/germany/the-world-from-berlin-nokia-under-attack-in-germany-a-529218.html.

[2]We discuss the relevant literature and its relation to our findings in the next subsection.

seeks to maximize its profits, the regulator seeks to avert the firm's relocation at minimal costs, which requires maximal profits. Hence, all productive variables are set to their profit-maximizing levels, and the transfer just compensates the firm for not relocating.

This picture changes drastically under limited commitment, where only short-term contracts can be utilized. In this case, the regulator cannot commit to any transfer in the second period that is larger than what is required to avert relocation *within* that period. Furthermore, the firm is free to relocate in period 2 without accepting any contract offer in that period. And whenever the firm *plans* to relocate in the second period, it lowers its investment in period 1. A larger transfer in period 2 would then be required to avert relocation, but the regulator does not observe the firm's under-investment. The resulting conflict between the regulator's parsimony (averting relocation with minimal transfers in period 2) and the firm's opportunism (reducing the investment in period 1, planning to relocate in period 2) leads to a dilemma: no outcomes can be implemented that involve any positive transfers in period 2.

To circumvent this implementation problem, the regulator often tightens the regulation in the first period, in order to incentivize the firm to invest more. If the regulation is sufficiently tight, a 'lock-in effect' arises: adopting a take-the-money-and-run strategy is then no longer profitable for the firm. Hence, even without transfers in period 2, the firm prefers to stay permanently, and invests accordingly. The regulator, thus, exploits the *lock-in effect* of the investment to preempt the implementation problem.

More specifically, we show that the optimal long-term contract is only implementable under short-term contracting if relocation is not very attractive. Otherwise, the implementation problem arises. The regulator then resorts to more high-powered incentives in the first period, in order to induce the firm to invest more. This leads to an over-investment, compared to what would have been optimal under full commitment. If the relocation option is sufficiently attractive, the resulting distortion in the final outcome can be so severe that higher transfers are required to avert relocation than in a hypothetical situation where the firm's investment opportunity does not exist.

From a policy perspective, our analysis indicates that transfers conditioned only on the location of a firm at a certain point in time (i.e., within a period) may be less effective in averting relocation on a permanent basis than regulations that involve also binding targets for a firm's output or employment. To account for the implementation problem, contracts should be tougher early on, to induce a higher investment by the firm.

An interesting and timely application of our general model can be found in the context of climate policy.[3] It is well-known that a unilateral introduction of an emission price by a

[3] An alternative application features a regulator (or principal) who seeks to induce a pharmaceutical company (or agent) to develop a new drug. The model developed in this paper applies if the regulator cannot observe the firm's overall R&D effort to develop the drug, but can subsidize investments in research equipment. Under limited commitment, the firm can pocket any transfers that take place in the first period, and quit the project in the second period.

country can induce firms to relocate to other countries with less stringent environmental regulation ('pollution haven hypothesis'). Firm relocation is an important channel of 'carbon leakage', or more generally the leakage of emissions to other countries.[4] The problem of firm relocation may be particularly relevant for policy makers given their concern for jobs and international competitiveness. To foster intuition, we therefore frame our general analysis in the context of this environmental application. Hence, we will refer to the firm's observable activity as *emissions*, while other activities of the firm (such as output) remain unobservable to the regulator. If the firm stays in its home country for at least one period, it can undertake an investment in *abatement capital* or in some low-carbon technologies that allow the firm to reduce its operating costs in the light of an emission price established in the home country. In this context, transfers may, e.g., be implemented by allocating emission allowances to firms for free during an early phase of a cap-and-trade scheme. Our results indicate that in order to have a permanent effect upon firms' location decisions, the allocation of emission permits should be made contingent on observable measures of a firm's productive activity (such as emissions or output), rather than on the basis of a firm's past emissions (so-called 'grandfathering'; see Schmidt and Heitzig (2014)).

Related Literature

Our paper contributes to a growing body of literature that tackles the problem of limited commitment in repeated moral hazard problems. E.g., Manso (2011) considers the problem of an agent who is motivated to innovate. The optimal long-term contract that induces the agent to experiment is shown not to be implementable with a sequence of short-term contracts. It is further shown that under certain conditions, outcomes with experimentation completely fail to be implementable. Bergemann and Hege (1998) study the problem of providing venture capital in a dynamic agency model and argue that short-term contracts can never substitute long-term contracts. In their model, however, problems of implementation do not arise. In another paper, Bergemann and Hege (2005) study the funding of a research project with uncertain return and date of completion. Only short-term contracts are considered and a distinction is made between observable and unobservable effort. As opposed to our results, they show that unobservable effort leads to a Pareto-superior outcome, compared to observable investment.

The more general literature on repeated moral hazard is surveyed by Chiappori et al. (1994), who derive a principal's optimal contract when motivating an agent to exert costly effort. Rey and Salanié (1990) and Fudenberg et al. (1990) provide sufficient conditions for the implementability of the optimal long-term contract via a sequence of short-term contracts. However, they do not characterize the sequence of short-term contracts when

[4] Another channel is via changes in fossil fuel prices. For an overview, see Babiker (2005).

the optimal long-term contract is *not* implementable. Fudenberg et al. (1990) report two examples for environments where optimal long-term contracts fail to be implementable with short-term contracts, but do not go deeper into this problem.[5]

Our setting also embodies a form of the ratchet effect. Pioneered by Weitzman (1980), the ratchet effect has found its ways into the literature on contracting with limited commitment. Examples are Lazear (1986), Gibbons (1986), Freixas et al. (1985), and Laffont and Tirole (1988). While Lazear (1986) argues that high-powered incentives can overcome the ratchet effect, Laffont and Tirole (1988) prove a result on the impossibility of implementing full separation with a continuum of types. All these works study models of adverse selection. The issue is then to compensate the agent today for being exploited in the future, because ex-ante private information is typically revealed over time. We instead study a model of moral hazard, where the exploitation in the future has severe consequences on the problem of implementing effort in the first place.

A recent paper that studies the ratchet effect in a model with moral hazard is Bhaskar (2014). He studies a dynamic principal-agent problem with moral hazard and learning. The difficulty of the job, undertaken by the agent, is a priori unknown to both parties. Conditional on first-period effort and output, both principal and agent update their beliefs. When shirking, the agent's posterior differs from the principal's, which gives rise to a ratchet effect that leads to a failure of implementability that is similar to the one presented in our paper. The agent can adopt a 'take-the-money-and-run' strategy, which makes deviations from interior values profitable.

Due to the commitment problem under short-term contracting, our paper is also related to the literature on incomplete contracts, e.g. Hart and Moore (1988). As in this literature, we allow contracts to depend on some observable characteristics, but not on investments. Our analysis of short-term contracting establishes a new channel for a contractual hold-up: although the contracts we analyze are rich enough to mitigate hold-up within a period (or under full commitment), the threat of exploitation in future periods resurrects the hold-up problem under limited commitment. As compared to the classical results in that literature (see Che and Sákovics (2004) for an overview), we identify over-investment as another possible consequence of incomplete contracting. Joskow (1987) finds empirical evidence for a link between the contractual commitments of future trade and importance of relationship-specific investment. Our paper provides a theoretical foundation: when the contract length falls short of the time in which investments are recouped, efficient investment cannot be implemented.

In a model of repeated climate contracting between countries, Harstad (2012) finds results that are related to ours. Countries repeatedly negotiate climate contracts that specify emission levels. Between the contracting stages they invest in abatement tech-

[5]Our model can be seen as a version of Example 1 in Fudenberg et al. (1990). The intuition behind their Example 2, however, fits better with the observed implementation problem in our paper.

nology. The author finds that shorter contract duration leads to tougher contracts and lower emission levels are agreed upon. However, investments remain at an inefficiently low level, whereas in our model contracts are tougher *and* investments are inefficiently high.

The problem of firm relocation has been studied in different strands of literature. Horstmann and Markusen (1992), e.g., study the impact of a trade policy on market structure. They report that 'small policy changes can produce large welfare effects when equilibrium market structure shifts'. Also tax competition in general affects firm location, Wilson and Wildasin (2004) and Bucovetsky (2005) provide an overview.[6] The impact of unilateral environmental regulation on firms' location decisions was first analyzed formally by Markusen et al. (1993).[7] In a two-country model, firms decide where to locate after governments have determined environmental taxes. Firms' location decisions are, therefore, very sensitive to differences in tax policies, as confirmed by Ulph (1994) in a numerical calibration of the model. Our paper complements this literature in that it provides a method to counterbalance the adverse effects on firm location.

Schmidt and Heitzig (2014) study the dynamics of 'grandfathering' schemes. They show that such transfer schemes can permanently avert firm relocation even when they terminate in finite time. In contrast to our paper, full contractual commitment by the regulator is assumed. Their findings conform with our results on long-term contracting. In particular, with full commitment, simple transfer schemes are sufficient, as the regulator need not interfere directly with the firm's productive decisions. The promise of transfers that last for a sufficiently long period of time induces the optimal investment by the firm, and permanently averts its relocation. With limited commitment, however, our results indicate that these simple grandfathering schemes are no longer optimal and contracts should be made contingent on other observable characteristics, such as emissions.

The remainder of the paper is organized as follows. Section 2 introduces the model and Section 3 studies the relocation issue when the firm is not regulated. Section 4.1 characterizes the benchmark case of long-term contracting. Short-term contracting is investigated in Section 4.2. Extensions of the model, such as an observable but non-contractible investment, and an alternative objective function of the regulator that depends directly on the firm's emissions, are presented in Section 5. They serve us as a robustness check. Section 6 concludes. All formal proofs are relegated to the Appendix.

[6] See also Haufler and Wooton (2010).

[7] See also Markusen et al. (1995). Other examples include Motta and Thisse (1994), who analyze the relocation of firms already established in their home country in response to a unilateral anti-pollution policy pursued by the government in their home country. Further, Ulph and Valentini (1997) analyze strategic environmental policy in a setting where different sectors are linked via an input-output relation.

2 Model

2.1 The firm

We analyze the following two-period model: There is one firm that is initially located in country A, where it earns per-period profits of $\pi_A(e, a)$. The variable e reflects some productive activity, and a is the stock of capital available to the firm. For illustrative purposes, we will interpret these variables in terms of our environmental example (motivated in the introduction) throughout the paper. Then e stands for the firm's *emissions*, and a is the firm's stock of *abatement capital*. Note that the profit function $\pi_A(e, a)$ is given in a *reduced form*. In particular, all other potential factors (e.g. input and output quantities, prices) are always chosen optimally by the firm, for any given values of e and a. Below, we show how to derive the firm's profit in the reduced form $\pi_A(e, a)$ in a specific example.

Emission levels are chosen by the firm in each period, and we denote e_τ the emission level in period $\tau \in \{1, 2\}$. The capital stock a is established at the beginning of period 1 and is thereafter available for both periods of production.[8] We further assume that abatement capital is immobile, i.e. it can only be utilized in country A.[9] The cost of installing a capital stock of $a \geq 0$ is given by the strictly convex cost function $K(a)$, with $K(0) = K'(0) = 0$. The firm's discounted profit from producing in country A in *both* periods, when choosing emission levels e_1 and e_2 as well as capital a is, therefore,

$$\pi_A(e_1, a) - K(a) + \delta\pi_A(e_2, a), \tag{1}$$

where $\delta > 0$ is the discount factor.[10]

We assume that at the beginning of each period, the firm has the possibility to relocate to some other country, in the following referred to as 'country B'. In country B, the firm earns a fixed per-period profit of π_B.[11] Relocation is once and for all, and for simplicity assumed to be costless. If the firm relocates immediately (i.e. at the beginning of period 1) to country B, it earns a total profit of

$$V_B = (1 + \delta)\pi_B. \tag{2}$$

In this case, the firm has no incentive to invest in abatement capital. The firm can also

[8] In particular, we assume away depreciation. Allowing for a positive rate of depreciation would, however, not change our main results.

[9] Examples include investments in more energy-efficient production technologies, or investments in physical capital such as a building.

[10] We allow for $\delta > 1$, which admits time periods of different length and/or economic importance.

[11] In the context of our environmental example, country B may, e.g., be a country that does not regulate emissions. Hence, even if capital were mobile, a prior investment in abatement capital does not affect the firm's profit after relocation.

stay in A for only one period, and relocate to B at the beginning of period 2. This strategy, referred to as 'location plan AB', amounts to a discounted profit of

$$\pi_A(e_1, a) - K(a) + \delta\pi_B. \tag{3}$$

We use the following technical assumptions regarding the profit function $\pi_A(e, a)$, defined on an open interval $(\underline{e}, \overline{e})$, with $-\infty \leq \underline{e} < \overline{e} \leq \infty$.[12]

Assumptions:

(A1) $\pi_A(e, a)$ is strictly concave in e, and for all $a \geq 0$ we have $\frac{\partial \pi_A}{\partial e} = +\infty$ for $e \to \underline{e}$, as well as $\frac{\partial \pi_A}{\partial e} < 0$ for $e \to \overline{e}$.

(A2) $\pi_A(e, a)$ is strictly concave in a, and $\frac{\partial \pi_A}{\partial a} > 0$ holds at $a = 0$ for all $e \in (\underline{e}, \overline{e})$; furthermore, $\frac{\partial \pi_A}{\partial a}$ is bounded from above for all $e \in (\underline{e}, \overline{e})$.

(A3) The Hessian of $\pi_A(e, a)$ is negative definite.

(A4) $\frac{\partial^2 \pi_A}{\partial e \partial a} < 0$.

(A5) $\exists\ \varepsilon > 0$ such that whenever $\partial \pi_A/\partial e = 0$ then $\partial \pi_A/\partial a > \varepsilon$.

The first three assumptions are technical: (A1) states that $\pi_A(e, a)$ is a regular profit function in e for all possible values of a (i.e., there exists a unique interior maximizer) and rules out boundary solutions for e. Assumption (A2) implies that investment exhibits diminishing returns, and it is never optimal to choose $a = 0$ (unless the firm relocates immediately). (A3) guarantees concavity of implicitly defined functions (such functions are introduced later on).
The last two assumptions describe the relation between emissions and investment: (A4) is a single-crossing property, and implies that emissions and investment are substitutes.[13] Assumption (A5) implies that whenever the firm is free to choose e optimally, it is always better off with a larger capital stock when the investment costs in a are ignored.

Example. Consider a polluting firm that produces an output quantity q, emitting e units of greenhouse gases. The firm faces the inverse demand $P(q) = 3 - q/2$. Marginal costs of production are constant and normalized to zero. The emissions price in A (e.g., following the introduction of a cap-and-trade scheme) is equal to 1 in both periods. Consequently, the firm's per-period profit in country A, gross of abatement capital installation cost, is

$$\tilde{\pi}_A(e, q) = (3 - q/2)q - e.$$

[12]Negative values for e can be interpreted as selling emission rights on the market.
[13]Intuitively, if the firm has a larger abatement capital stock then its *optimal* emissions are lower.

Emissions are a function of output and the firm's abatement capital stock. For simplicity, we assume that the firm's emissions are additive in q and a, i.e. $e(q, a) = q - a$. Inserting this into $\tilde{\pi}_A(e, q)$, we obtain the firm's profit function in the *reduced form*:[14]

$$\pi_A(e, a) = 3a + 2e - (a + e)^2/2. \tag{4}$$

We will return to this simple example frequently throughout the paper, in order to illustrate our findings.

2.2 The regulator

In country A a regulator (or policy maker) is concerned with the firm's option to relocate. In particular, as soon as the firm relocates, welfare in country A is reduced by some fixed amount $L > 0$, e.g., due to job losses or lower tax revenues.[15]

Because of the potential loss L, the regulator's main interest is to avert relocation of the firm on a permanent basis. To this end, the regulator offers to the firm contracts in a take-it-or-leave-it manner. We assume that the firm's emissions in each period are contractible. However, the investment in abatement capital is neither observable to the regulator nor verifiable. Contracts thus specify a location-specific transfer to the firm, denoted by t, and emission levels that the firm has to comply with (in order to obtain the transfer). The firm can reject any contract offer and either relocate to country B, or produce in country A at its own, un-subsidized expense.

The regulator maximizes the following welfare function

$$W = -\chi_1 t_1 - \chi_2 \delta t_2 - (1 - \chi_2) L, \tag{5}$$

where $\chi_\tau = 1$ if the firm operates in country A in period τ (and accepts the contract offered in that period), and $\chi_\tau = 0$ otherwise.[16] The regulator and the firm use the same discount factor $\delta > 0$.

Throughout the paper, we distinguish between long-term and short-term contracts. The former specify emission levels and transfers for each individual period, i.e. a long-term contract is a quadruple (t_1, e_1, t_2, e_2). This implicitly assumes that the regulator

[14] It is easy to verify that the function $\pi_A(e, a)$ fulfills our earlier assumptions.

[15] The assumption that L is independent of whether the firm relocates in period 1 or in period 2 highlights the regulator's interest in averting relocation on a *permanent* basis (rather than on a temporary one). In our environmental example, an emission price is implemented by some higher authority (e.g., on the federal level), while transfers are paid by a local regulator who's primary objective it is to avert the firm's relocation. Hence, the firm's emissions do not directly affect the regulator's payoff. In Section 5, we introduce an alternative payoff function for the regulator that also depends on the firm's choice of e, as well as on the period in which the firm relocates. The regulator may then also benefit from averting relocation only in period 1. We will show that our main results are unaffected by these changes.

[16] Because relocation is by assumption irreversible, $\chi_2 = 1$ requires that also $\chi_1 = 1$ holds.

can fully commit to all present and future contractual obligations. Commitment here is two-sided, i.e. also the firm, after signing the contract, is committed to staying in country A throughout the contract duration.[17]

The timing with long-term contracting is as follows. First, the regulator offers a contract. After observing the contract offer, the firm decides whether or not to relocate to country B. If the firm relocates, the game ends. Otherwise, it decides whether or not to accept the contract, and chooses a level of abatement capital investment.[18] Finally, production starts under the terms specified in the contract or, in case no contract was signed, the firm chooses its productive variables.

Under short-term contracting neither the regulator nor the firm have the ability to make commitments that last for more than one period.[19] Hence, the regulator resorts to a sequence of spot contracts (t_τ, e_τ). The timing for this case is as follows.

1. Regulator offers contract (t_1, e_1).
2. Firm accepts/rejects and location choice A/B.
3. Firm chooses a and produces e_1. Transfer t_1 paid to the firm.
4. Regulator offers contract (t_2, e_2).
5. Firm accepts/rejects and location A/B.
6. Firm produces e_2. Transfer t_2 paid to the firm.

In the first period a short-term contract (t_1, e_1) is offered to the firm. After observing the contract, the firm decides on its location and whether or not to accept the contract. The game ends whenever the firm relocates. Otherwise, the firm invests in abatement capital and production takes place (according to the terms specified in the contract if accepted). At the end of period 1, the transfer is paid to the firm, in case it accepted the contract. Period 2 starts with a new contract offer (t_2, e_2) by the regulator (unless the firm already relocated in period 1). The firm observes the offered contract and decides whether or not to relocate in period 2. If it stays in A, the firm can accept the contract and produce according to the contractual terms or reject the contract, in which case it produces on its own account and does not receive any transfer payment in period 2. Again, the transfer is paid at the end of period 2.

[17]This formulation rules out contracts that keep the firm for the first period and impose relocation in the second period. Because such contracts are never desirable, their exclusion is without loss.

[18]The firm's decisions within a period are, of course, simultaneous.

[19]Intermediate cases of one-sided commitment are simple in our model. E.g., if the regulator has full commitment power but not the firm, postponing all transfers to period 2 – after the option to relocate has vanished – is sufficient to implement the full commitment outcome.

2.3 Equilibrium concept

We argue in the following that even though we study a dynamic game with imperfect information, we can use *Subgame Perfect Nash Equilibrium* (SPNE) as our solution concept, and hence, backward induction as solution method. This is obvious in the case of long-term contracting where the regulator moves only once and all remaining decisions are taken by the firm (after observing the long-term contract offered by the regulator).

Under short-term contracting, there is no proper subgame after stage 3 (see above), because the regulator does not observe the firm's choice of a. However, stages 5 and 6 constitute a proper subgame, because the firm has perfect recall. Furthermore, the sequentiality of stages 3 and 4 (firm's choice of a and second-period contract offer (t_2, e_2)) is inconsequential for the equilibrium outcome because no information is revealed between these two stages. Hence, we can effectively treat these two stages as *simultaneous* moves. This allows us to solve the game by backward induction.[20]

Furthermore, throughout the main part of the paper we focus on pure strategies. This is clearly without loss of generality when we analyze long-term contracts. With short-term contracting, randomization could be beneficial when the firm chooses its investment. However, as we formally prove in Appendix B, there are no additional equilibria in mixed strategies. Hence, focusing on pure strategy equilibria is without loss of generality also in the case of short-term contracting.

3 Preliminaries and the 'no-regulation' benchmark

In this section we consider the firm's problem in isolation and identify conditions under which relocation occurs. It will turn out convenient to use the following short-hand notations. Let

$$\pi_A^*(a) = \max_e \pi_A(e, a) \tag{6}$$

be the firm's *maximal profit* in one period after having installed capital stock a. Denote $e^*(a)$ the corresponding level of emissions. Using this, we can define

$$V_A(e_1) = \max_a \big(\pi_A(e_1, a) - K(a) + \delta\pi_A^*(a)\big). \tag{7}$$

This represents the firm's discounted profit when staying in country A in both periods, with first-period emissions *fixed* (e.g., in a contract) at a level of e_1, while choosing e_2 optimally in period 2, and choosing a optimally in period 1. The corresponding optimal

[20] The alternative would be to use Perfect Bayesian Nash Equilibrium. This requires specifying beliefs of the regulator in stage 4 about the firm's choice of investment. Because of the simple structure, these PBNE correspond to the SPNE.

level of investment is denoted by $a_A(e_1)$. Similarly,

$$V_{AB}(e_1) = \max_a \left(\pi_A(e_1, a) - K(a) + \delta\pi_B\right) \tag{8}$$

is the firm's profit under location plan AB with first-period emissions e_1, given an optimal investment for this location plan. The corresponding maximizer is denoted by $a_{AB}(e_1)$. The following Lemma states properties of these functions and their maximizers.

Lemma 1. *(1)* $e^*(a)$ *is unique and strictly decreasing,*

(2) $\pi_A^*(a)$ *is strictly increasing, concave, and* $\lim_{a\to\infty} \pi_A^*(a) = +\infty$*,*

(3) $a_A(e_1)$ *and* $a_{AB}(e_1)$ *are unique and strictly decreasing,*

(4) $V_A(e_1)$ *and* $V_{AB}(e_1)$ *are strictly concave and have unique maximizers,*

(5) $a_A(e_1) > a_{AB}(e_1)$ *for all* $e_1 \in (\underline{e}, \overline{e})$*.*

The first result confirms that a firm that has installed a larger abatement capital stock optimally chooses lower emissions. The second result rephrases our earlier assumption (A5) that $\partial\pi_A/\partial e = 0$ implies $\partial\pi_A/\partial a > 0$ and provides a first indication towards a lock-in effect, namely a sufficiently large investment renders relocation unprofitable even for large values of π_B. The functions $a_A(e_1)$ and $a_{AB}(e_1)$ are decreasing because in our model a stricter regulation in the first period corresponds to a *smaller* value of e_1 (emissions are regulated more tightly). Accordingly, the firm responds with a larger investment when e_1 is smaller (both under location plan AB or when the firm plans to stay permanently in A). The final result says that if the firm plans to stay in A in both periods, it invests more than when it plans to relocate after one period.

The next lemma is an immediate consequence of the investment cost being sunk.

Lemma 2. *For any level of first-period emissions, the option to relocate after one period is always inferior to either immediate relocation or no relocation (or both). More specifically, it holds for any* e_1 *that* $V_{AB}(e_1) < \max\{V_A(e_1), V_B\}$*.*

The Lemma establishes a *lock-in* effect. Whenever the firm finds it optimal to stay for one period in country A, it will undertake some investment. Intuitively, location plan AB can only be optimal if the net profit in period 1, i.e. profit from production minus the cost of installing capital, exceeds the profit in country B. But then the corresponding per-period profit of production in country A, gross of investment costs, clearly exceeds π_B when the firm implements $a_{AB}(e_1)$. So it must be profitable for the firm to stay in country A also for the second period. By raising its investment to the level $a_A(e_1)$, the firm can achieve an even higher profit.

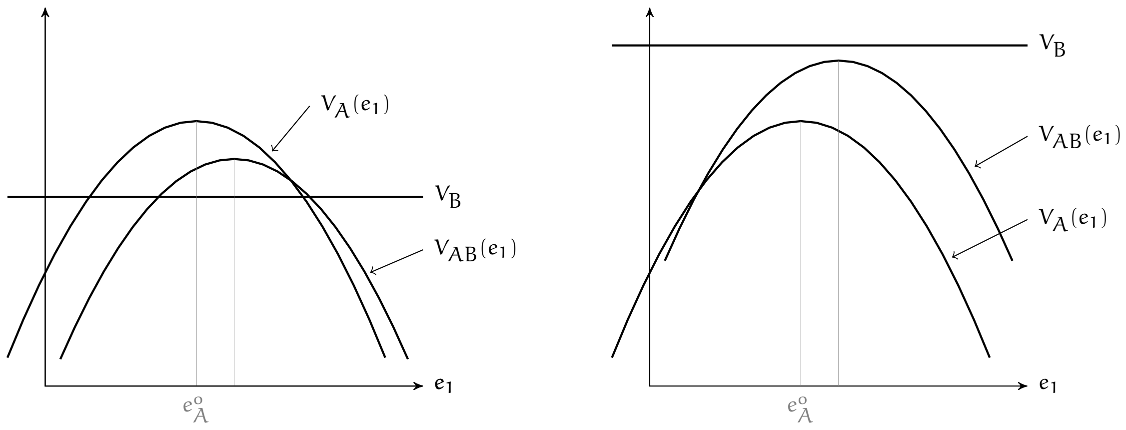

Figure 1: Profit functions $V_A(e_1)$, $V_{AB}(e_1)$, and V_B for low π_B (left) and high π_B (right).

Figure 1 illustrates the typical shape of the firm's profit function for the different location plans. Note, that raising π_B does not affect V_A, whereas it shifts V_{AB} as well as V_B upwards.

According to Lemma 2, the firm prefers either to stay in country A for both periods or to relocate immediately. Only the latter case is of interest for us, since it calls for regulatory intervention. To make this more precise, let e^o_A be the optimal (first-period) emission level when the firm plans to stay in country A for both periods. It is given by

$$e^o_A = \arg\max_{e_1} V_A(e_1). \tag{9}$$

Because the firm uses the same capital stock in each period, it is straightforward to verify that given this optimal choice of first-period emissions, it holds that $e_2 = e_1 = e^o_A$ if the firm is free to choose its emissions in period 2. Define $V^o_A := V_A(e^o_A)$ and $a^o_A := a_A(e^o_A)$. The following lemma is an immediate consequence of the preceding derivations.

Lemma 3. *Absent regulatory intervention, the firm strictly prefers immediate relocation whenever $\pi_B > \pi^o_B$, and no relocation otherwise. The critical value π^o_B is given by*

$$\pi^o_B := \frac{V^o_A}{1+\delta}. \tag{10}$$

Throughout the rest of the paper we maintain the assumption that $\pi_B \geq \pi^o_B$. Hence, in the absence of regulatory intervention the firm relocates immediately.

Example. Maximizing $\pi_A(e, a) = 3a + 2e - (a + e)^2/2$ over e, we find that the firm's optimal emissions (given a) are $e^*(a) = 2 - a$. Therefore $\pi^*_A(a) = 2 + a$. Let investment costs be given by the quadratic cost function $K(a) = a^2/2$. If the firm plans to stay in country A in both periods, and is constrained to emit (no more than) e_1 units in period

1 (e.g., by the regulator), it thus solves:

$$\max_{a}\ 3a + 2e_1 - \frac{(a+e_1)^2}{2} - \frac{a^2}{2} + \delta(2+a).$$

This yields $a_A(e_1) = (3 - e_1 + \delta)/2$ and $V_A(e_1) = \frac{1}{2}(5+\delta)(1+\delta) - \frac{1}{4}(e_1 - (1-\delta))^2$. The latter implies $e_A^o = 1 - \delta$ and $V_A^o = \frac{1}{2}(5+\delta)(1+\delta)$. The critical level of π_B for relocation is $\pi_B^o = \frac{1}{2}(5+\delta)$. If the firm plans to stay in country A for only one period, it solves:

$$\max_{a}\ 3a + 2e_1 - \frac{(a+e_1)^2}{2} - \frac{a^2}{2} + \delta\pi_B.$$

This yields $a_{AB}(e_1) = (3 - e_1)/2$, and $V_{AB}(e_1) = \frac{5}{2} - \frac{1}{4}(e_1 - 1)^2 + \delta\pi_B$. The firm's optimal choice of first-period emissions is $e_{AB} = 1$. Observe that the firm's emissions are higher and the abatement capital investment is smaller when it plans to relocate after one period (we find $a_A^o = 1 + \delta$ and $a_{AB} = 1$).

4 Regulation

This section studies the optimal regulatory policy in the presence of the threat of firm relocation. We first analyze the benchmark case of long-term contracting (full commitment), and then proceed to short-term contracting (limited commitment).

4.1 Long-term contracting

The regulator's payoff from not offering a contract is $-L$. Alternatively, the regulator can offer a long-term contract that requires the firm to produce in country A in both periods. In finding the optimal contract that permanently averts relocation, the regulator solves the following program

$$\begin{aligned}
&\min_{t_1,e_1,t_2,e_2,a}\ t_1 + \delta t_2 \\
\text{s.t.}\quad & t_1 + \pi_A(e_1,a) - K(a) + \delta\big(t_2 + \pi_A(e_2,a)\big) \geq V_B\ \text{, and} \quad \text{(PC)}\\
& t_1 + \pi_A(e_1,a) - K(a) + \delta\big(t_2 + \pi_A(e_2,a)\big) \geq \\
&\qquad t_1 + \pi_A(e_1,\tilde{a}) - K(\tilde{a}) + \delta\big(t_2 + \pi_A(e_2,\tilde{a})\big)\ \ \forall \tilde{a}. \quad \text{(MH-1)}
\end{aligned}$$

The participation constraint (PC) ensures that the firm prefers accepting the contract (and not relocating) to immediate relocation. Constraint (MH-1) is a moral hazard constraint, that ensures the firm chooses the *intended* level of investment. Because we assume two-sided commitment, the distribution of transfers across periods is inconsequential and we can substitute for the total transfer $t = t_1 + \delta t_2$.[21]

[21] This also relies on the assumption that regulator and firm have a common discount factor. With

Obviously the participation constraint (PC) is binding. Together with the moral hazard constraint (MH-1) the minimal (total) transfer t that is required to avert relocation in both periods when emissions are chosen at levels e_1 and e_2 is

$$t = V_B - \max_a \big(\pi_A(e_1, a) - K(a) + \delta\pi_A(e_2, a)\big). \tag{11}$$

The regulator's minimization program given above, therefore, corresponds to minimizing (11) with respect to e_1 and e_2. This is equivalent to maximizing $V_A(e_1)$ over e_1, which yields $e_1 = e_A^o$ as defined in (9). The minimal total transfer required to avert relocation is, therefore, $t = V_B - V_A^o$, and the regulator, accounting for the welfare loss from relocation, offers a contract that averts relocation if and only if this transfer does not exceed L. The following proposition summarizes.

Proposition 1. *The optimal long-term contract specifies* $e_1 = e_2 = e_A^o$*, pays a total transfer of* $t^o := V_B - V_A^o$ *and the firm does not relocate, whenever* $L \geq t^o$*. Otherwise, the regulator offers the* null contract *and the firm relocates immediately.*

Notice the following alternative way of implementing the optimal long-term contract: Because of full commitment on the side of the firm, the regulator can simply offer the lump-sum subsidy t^o for the firm's commitment not to relocate in any of the two periods. This leaves the optimal choices of e_1 and e_2 at the firm's discretion. The firm then chooses emissions and investment so as to maximize its discounted profit from two periods of production in country A. But this implies $e_1 = e_2 = e_A^o$ and $a = a_A^o$, as we have shown in Section 3. Acceptance of the subsidy t^o is implied by its definition in Proposition 1. Hence, under full commitment, a simple location-based subsidization is sufficient to avert firm relocation with minimal transfers; the regulator does not need to interfere directly with the firm's productive activities.

Example. Applying Proposition 1, the optimal long-term contract specifies emission targets $e_1 = e_2 = e_A^o = 1 - \delta$. The firm's discounted profit in A is $V_A^o = \frac{1}{2}(1+\delta)(5+\delta)$, and a total transfer of $t^o = V_B - V_A^o = (1+\delta)\left[\pi_B - \frac{1}{2}(5+\delta)\right]$ is required to avert relocation. From the expression for t^o we also get $\pi_B^o = \frac{1}{2}(5+\delta)$.

4.2 Short-term contracting

We move on to the study of short-term contracting. Hence, we assume that the regulator cannot commit to a contract that specifies emissions and transfers for both periods and instead resorts to a sequence of short-term contracts. Also the firm cannot commit in period 1 to not relocating in period 2.

differing discount factors, the regulator would have a preference for either paying all transfers in period 1 or in period 2.

For each contracting party, limited commitment generates a new constraint. First, the regulator's second-period contract offer must be sequentially optimal. In particular, the second-period transfer can be no higher than required to avert relocation in that period. Second, the firm has the option to accept the first-period contract but nevertheless relocate in period 2. In order to prevent this, a sufficiently large second-period transfer has to be 'promised'. We show in this section that these two restrictions can only be compatible if the latter constraint is irrelevant, i.e. upon accepting the first-period contract the firm already prefers to stay for two periods and planned relocation is inferior. To achieve this, the regulator sets a stringent (i.e. low) first-period emission target e_1. This induces a lock-in that prevents relocation in both periods without transfers in period 2.

As before, offering no contract results in a welfare of $-L$. The relevant alternative to the null contract in period 1 is a contract offer that is accepted by the firm, and leads to an outcome where the firm does not relocate in period 2. Acceptance of the first-period contract, while taking the continuation play as given, is induced by constraint (PC). Similarly, the constraint for the firm choosing investment a provided it accepts the respective contracts in each of the two periods is given by (MH-1).

Furthermore, after having installed capital stock a in period 1, the firm is willing to accept the second-period contract offer (t_2, e_2) if and only if $t_2 + \pi_A(e_2, a) \geq \max\{\pi_B, \pi_A^*(a)\}$. Note that the firm has the option to produce in A at its own expense, earning a maximal profit of $\pi_A^*(a)$, which leads to zero transfers for large values of a. Hence, the second-period contract (t_2, e_2) is sequentially optimally provided the firm invests a, whenever

$$t_2 = \max\{0, \pi_B - \pi_A^*(a)\}, \qquad e_2 = e^*(a). \tag{SO}$$

As in the case of long-term contracting, the regulator's and the firm's interests are to some extent aligned: minimizing the transfer payment, the regulator seeks to maximize the firm's profit over e_2. What is crucial is that whenever $t_2 > 0$, this transfer just compensates the firm for not relocating in period 2. However, if $\pi_A^*(a) \geq \pi_B$, then no second-period transfer is required.[22]

The other new constraint concerns the firm's possibility to (secretely) plan relocation. Doing so, after having accepted the first-period contract (t_1, e_1), the firm chooses investment $a_{AB}(e_1)$, and earns a discounted profit of $t_1 + V_{AB}(e_1)$. This leads to the additional moral hazard constraint

$$t_1 + \pi_A(e_1, a) - K(a) + \delta\big(t_2 + \pi_A(e_2, a)\big) \geq t_1 + V_{AB}(e_1). \tag{MH-2}$$

The regulator's problem of finding the minimal transfer(s) that permanently avert

[22]We assume that when $\pi_A^*(a) \geq \pi_B$, the firm still accepts a contract offer with $t_2 = 0$ and emissions at the level $e_2 = e^*(a)$.

relocation can, therefore, be stated as follows:

$$\min_{t_1,e_1,t_2,e_2,a} t_1 + \delta t_2, \qquad \text{subject to (PC), (MH-1), (MH-2), (SO).} \tag{$\mathcal{P}_S$}$$

Before solving problem $\mathcal{P}_S$, let us first characterize the set of first-period emission levels that induce an equilibrium in the continuation game where the firm never relocates. Hence, we are looking for levels of e_1 for which there *exists* a contract (t_2, e_2) and an investment level a such that constraints (MH-1),(MH-2), and (SO) are satisfied. Notice that constraint (SO) essentially pins down (t_2, e_2) for a *given* level of investment a. Similarly, for a *given* second-period emission level e_2, we can derive a from constraint (MH-1).[23] Using the latter condition and $e_2 = e^*(a)$, we can thus rewrite constraint (MH-2) as follows

$$\delta t_2 + V_A(e_1) \geq V_{AB}(e_1). \tag{MH-2$'$}$$

In this representation the role of the second-period transfer becomes clear. When investing, the firm faces two options: Either it invests little and relocates in period 2, rejecting the second-period contract offer. Or it invests more, planning to stay in A in both periods and accepting the second-period contract offer. Because the actual investment level is not observable to the regulator, the second-period offer cannot be made contingent on it. When seeking to implement an outcome where the firm never relocates, the second-period contract offer (t_2, e_2) is implicitly contingent on the optimal investment level for the second option (no planned relocation), by conditions (MH-1) and (SO). But the resulting second-period transfer has to compensate the firm also for not secretly under-investing, i.e., by condition (MH-2$'$), it has to hold that $\delta t_2 \geq V_{AB}(e_1) - V_A(e_1)$. The following result shows that this condition restricts the range of implementable outcomes.

Proposition 2. *For a first-period emission level* e_1*, there exists a second-period contract* (t_2, e_2) *and an investment level* a *such that constraints* (MH-1)*,* (MH-2)*, and* (SO) *are satisfied if and only if* $V_A(e_1) \geq V_{AB}(e_1)$*.*

If the condition in the proposition is met, constraint (MH-2) has no bite. This can be seen best from its reformulation into (MH-2$'$). Provided that $V_A(e_1) \geq V_{AB}(e_1)$, any non-negative transfer t_2 satisfies the constraint. If, however, $V_A(e_1) < V_{AB}(e_1)$, constraint (MH-2$'$) imposes a lower bound on t_2, as argued above. Intuitively, in order to satisfy constraint (MH-2$'$), the second-period transfer not only has to account for the difference in second-period profits, but also for the respective difference in first-period profits that arises when the firm plans to stay in A in both periods, rather than to relocate after period 1. In particular, because the underlying investments differ in the two cases, first-period profits are strictly higher with planned relocation compared to no relocation, and

[23]This is also what we have done when deriving the optimal long-term contract. Note, that any combination e_1, e_2 leads to a unique investment level.

the second-period transfer – serving as reward – has to compensate for this difference. However, because the regulator has no commitment power, offering such a reward is not credible. Any sequentially optimal second-period transfer, i.e., any t_2 that satisfies (SO) only compensates the firm for not relocating within that period, and fails to take into account investment costs that were incurred prior to this period.

Notice a crucial consequence of Proposition 2: the condition $V_A(e_1) \geq V_{AB}(e_1)$ implies that no second-period transfer is required to avert relocation in period 2. In other words, an equilibrium with no relocation under short-term contracting necessarily implies a situation where the firm is *locked-in* after the first period.

Proposition 2 also allows us to determine when the optimal *long-term* contract is implementable via a sequence of short-term contracts:

Corollary 1. *The optimal long-term contract can be implemented via a sequence of short-term contracts if and only if* $V_A^o \geq V_{AB}(e_A^o)$*. This is equivalent to* $\pi_B \leq \pi_B^\sharp$*, where*

$$\pi_B^\sharp := \frac{1}{\delta}\big(V_A^o - \pi_A(e_A^o, a_{AB}(e_A^o)) + K(a_{AB}(e_A^o))\big) > \pi_B^o.$$

The respective sequence of contracts entails $(t_1, e_1) = (t^o, e_A^o)$*, and* $(t_2, e_2) = (0, e_A^o)$*.*

We now proceed with the analysis of optimal short-term contracts when $\pi_B > \pi_B^\sharp$. The following result makes the analysis more transparent, by mapping the condition $V_A(e_1) \geq V_{AB}(e_1)$ from Proposition 2 to a line segment.

Lemma 4. *Assume* $\pi_B > \pi_B^\sharp$*. Then there exists a unique value* $e^\sharp$*, with* $\underline{e} < e^\sharp < e_A^o$*, such that* $V_A(e_1) \geq V_{AB}(e_1)$ *holds if and only if* $e_1 \leq e^\sharp$*. The level* $e^\sharp$ *decreases with* π_B*.*

Hence, only sufficiently low emission targets for the first period can be utilized to implement an outcome without relocation in any period. By offering more high-powered incentives in the first period, the regulator enforces a sufficiently high abatement capital investment by the firm. This renders the relocation option in period 2 unprofitable when the firm optimally exploits its possibilities to invest in abatement capital. Planning to relocate after period 1 is, then, no longer optimal from the firm's perspective, because staying for only one period in A already involves a fairly large investment. The firm then prefers to invest even more, and realizes the rents from the investment also in period 2.

Finding the optimal first-period contract, i.e. the first-period emission level e_1 that implements an equilibrium where the firm stays for both periods in country A with the lowest (total) transfers, is now straightforward. Because $V_A(e_1)$ is strictly concave, implementing $e_1 = e^\sharp$ leads to lowest transfers and is, therefore, optimal. Regarding the cost of implementing such an outcome, the total transfer required is given by $t_1 = V_B - V_A(e^\sharp)$, and the regulator prefers this to immediate relocation whenever $t_1 \leq L$.

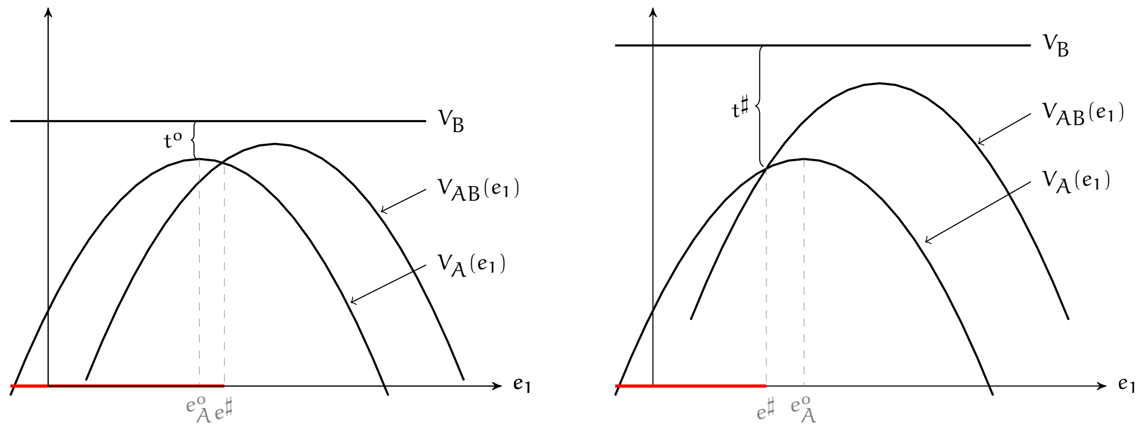

Figure 2: Optimal first-period contracts with short-term contracting; left: $e^o_A < e^\sharp$, right: $e^o_A > e^\sharp$. Implementable levels of e_1 are shown in red.

Proposition 3. *With short-term contracting the optimal first-period contract is*

- $(t_1, e_1) = (t^o, e^o_A)$, *if* $\pi_B \leq \pi_B^\sharp$ *and* $L \geq t^o$*;*
- $(t_1, e_1) = (t^\sharp, e^\sharp)$, *if* $\pi_B > \pi_B^\sharp$ *and* $L \geq t^\sharp$, *with* $t^\sharp := V_B - V_A(e^\sharp) > t^o$*;*
- *the null contract otherwise.*

In the first two cases the second-period contract is $(t_2, e_2) = (0, e^*(a_A(e_1)))$.

The implications of Proposition 3 are as follows: For moderate relocation profits π_B, the lack of commitment has no consequence for the optimal contract. Both with long-term and with short-term contracting, a transfer has to paid only in period 1, and the firm invests enough so that relocation in period 2 is no longer in its interest. Hence, for moderate values of π_B a one-period contract is sufficient to resolve the relocation problem on a permanent basis, even without regulation in period 2. This case is depicted in the left panel of Figure 2. Observe that at $e_1 = e^o_A$, it holds that $V_{AB}(e_1) < V_A(e_1)$. Hence, as the firm has to comply with the emission target e_1 in order to obtain the transfer t_1 in the first period, the option to relocate in period 2 is effectively ruled out.

However, when the outside option in form of the relocation option is more attractive, limited commitment affects the design of the optimal contract in period 1, and the effect can be severe. A tension arises between the regulator's parsimony, i.e., offering a sequentially optimal second-period contract that minimizes transfer payments in that period, and the firm's opportunism, i.e., considering a 'take-the-money-and-run' strategy (sacking first-period transfers and relocating in period 2). This tension can only be resolved by preempting it via a tighter regulation in the first-period. This amounts to a downward-distortion in e_1, that is costly to the regulator. The transfer t_1 required to induce the firm to accept the first-period contract (rather than to relocate immediately) is larger than the total transfer under long-term contracting. This case is depicted in the right panel of Figure 2. An implication of Proposition 3 is, therefore, that with short-term contracting, the regulator prefers *not* to avert relocation already for lower values of the welfare loss L. In this sense, limited commitment leads to *more* relocation.[24]

Figure 3 shows combinations of the parameters π_B and L for which relocation is averted under short-term contracting, in comparison with long-term contracting. As the figure illustrates, the implementation problem that is underlying the results of Proposition 3 becomes more severe when the relocation option becomes more attractive (i.e., for larger values of π_B). In contrast, when $\pi_B \leq \pi_B^\sharp$, there is no implementation problem, because offering a contract in period 1 is already sufficient to avert relocation in both periods. If $\pi_B \leq \pi_B^o$ then no transfers are needed to avert relocation.

As a consequence of limited commitment also investments are distorted. In particular, the tougher first-period emission target e_1 leads to an over-investment in abatement capital by the firm.

Corollary 2. *Under the optimal sequence of short-term contracts, the implemented investment level is* a_A^o *for* $\pi_B \leq \pi_B^\sharp$ *(and* $L \geq t^o$*), and distorted upwards for* $\pi_B > \pi_B^\sharp$ *(and* $L \geq t^\sharp$*).*

Paradoxically, the distortions in e_1 and a can be so severe that the *existence* of an investment opportunity in abatement capital can overall be welfare-reducing. In other words, a seemingly welfare-enhancing investment opportunity, such as investment in abatement capital, may turn out to be welfare-diminishing if it leads to the described conflict of interest between the regulator and the firm. This holds if a higher transfer is required to avert relocation under short-term contracting than in a (hypothetical) situation where $a = 0$ is *exogenously* fixed from the start (and this is common knowledge).

Corollary 3. *If* π_B *is sufficiently large then* $t^\sharp > (1+\delta)(\pi_B - \pi_A^*(0))$*, i.e. the regulator would prefer a situation where* $a = 0$ *is exogenously fixed.*

We close this section by illustrating the above findings in our earlier example.

Example. The firm's profit when following location plan 'AB' with first-period emissions e_A^o is given by $V_{AB}(e_A^o) = \frac{5}{2} - \frac{1}{4}\delta^2 + \delta\pi_B$. We have $V_A^o \geq V_{AB}(e_A^o)$ if and only if $\pi_B \leq \pi_B^\sharp = 3 + \frac{3}{4}\delta$. Notice that $a_A^o = 1 + \delta$ and hence $\pi_A^*(a_A^o) = 3 + \delta > \pi_B$ whenever $\pi_B \leq \pi_B^\sharp$. This demonstrates the lock-in effect, which renders relocation unprofitable even absent any second-period transfer payment. If, however, $\pi_B > \pi_B^\sharp$ a transfer of $t_2 \geq \frac{1}{\delta}\{V_{AB}(e_A^o) - V_A^o\} = \pi_B - \pi_B^\sharp$ is required to implement the long-term contract. Provided the firm indeed chooses investment a_A^o, the sequentially rational second-period transfer is $\max\{0, \pi_B - \pi_A^*(a_A^o)\} = \max\{0, \pi_B - (3+\delta)\}$. Implementation fails, because the

[24]We implicitly assume here that there are several firms that are regulated, and the profit from relocation, π_B, or some other characteristic varies across firms.

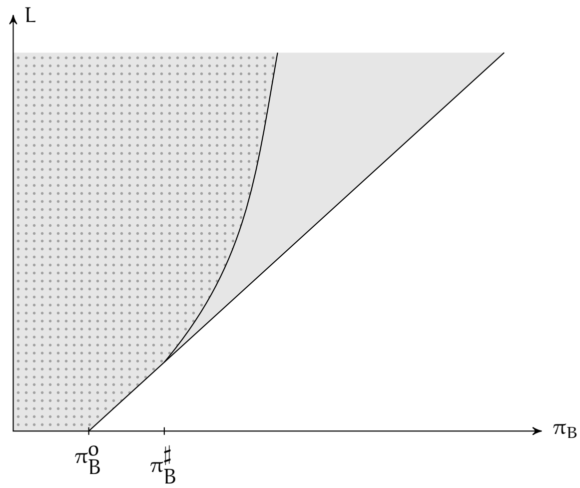

Figure 3: (π_B, L) - combinations for which relocation is averted; grey-shaded area: long-term contracting, dotted area: short term.

latter is strictly lower than $\pi_B - \pi_B^\sharp$, which mirrors the finding of Corollary 1. The critical value $e^\sharp$ is given by $e^\sharp = e_A^o - 2(\pi_B - \pi_B^\sharp) = 7 + \frac{\delta}{2} - 2\pi_B$. Consequently, for $\pi_B > \pi_B^\sharp$, the regulator specifies first-period emissions $e_1 = e^\sharp < e_A^o$. The resulting first-period transfer is $t^\sharp = V_B - V_A^o + (\pi_B - \pi_B^\sharp)^2 > V_B - V_A^o$ (if $L \geq t^\sharp$). Investment in this case is $a_A^\sharp = a_A^o + \pi_B - \pi_B^\sharp > a_A^o$.

To illustrate the finding of Corollary 3 notice that $\pi_A^*(0) = 2$. Hence, in the hypothetical situation where investment is impossible the firm earns a maximal per-period profit of 2 and relocation can be averted with a transfer of $\pi_B - 2$ per period. In this case there is no commitment problem, i.e. relocation can be averted permanently with a total transfer of $(1+\delta)(\pi_B - 2) = V_B - 2(1+\delta)$. Obviously, for large π_B this expression is smaller than $t^\sharp$.

5 Extensions

In this section we consider extensions of our main model, and analyze to what extent they have an impact on the central result of the previous section, regarding the implementability of outcomes under short-term contracting. First, we consider a situation where the firm's investment is *observable* to the regulator, but remains non-contractible.[25] Second, we focus on a more general objective function of the regulator, that (apart from the firm's location decision) also depends on the firm's emissions, and allows for a benefit to the regulator from averted relocation also in case the firm stays for only one period in A.

[25]Bergemann and Hege (2005) show in a model of project-financing with an infinite time horizon that non-observability of effort may actually be beneficial because it leads to a form of implicit commitment. In our model with a finite horizon, observability is always preferable. Nonetheless, short-term contracting still has severe consequences on implementation.

5.1 Observable Investment

Observability of the firm's investment relaxes the implementation problem studied in the previous section to some extent. The reason is, that the regulator can now make the second-period contract offer dependent on the level of investment actually *chosen* by the firm (and not just the anticipated level of a, as in the previous section). As a result, also emission levels $e_1 > e^\sharp$ can now be used to implement SPNE without relocation. Nevertheless, we will show that the optimal long-term contract can only be implemented when $V_A^o \geq V_{AB}(e_A^o)$ (as in the case with an unobservable investment).

Because the regulator now observes the firm's investment level a, the second-period contract entails $e_2 = e^*(a)$ and $t_2 = \max\{0, \pi_B - \pi_A^*(a)\}$, unless the stated t_2 exceeds L (in this case no second-period contract is offered and the firm relocates). Let $\overline{a}$ be the investment level that is just sufficiently large to create a lock-in situation in period 2. Hence, it is implicitly defined by the condition $\pi_A^*(\overline{a}) = \pi_B$.[26] For $a \geq \overline{a}$ no second-period transfer is required to avert relocation and the firm's second-period profit is $\pi_A^*(a)$. Otherwise (for $a < \overline{a}$), the firm is either offered a contract and does not relocate, or there is no second-period contract offer and the firm relocates; in both cases, the firm's profit in period 2 is π_B. Overall, the firm's discounted profit at the investment stage is

$$t_1 + \pi_A(e_1, a) - K(a) + \delta \begin{cases} \pi_A^*(a), & a \geq \bar{a}, \\ \pi_B, & a < \bar{a}. \end{cases} \tag{12}$$

After having accepted the first-period contract, the firm chooses its investment to maximize (12). The corresponding investment level depends only on e_1. For low values of e_1, namely $e_1 \leq e^\sharp$, the firm invests $a_A(e_1)$. Intuitively, the optimal investment when the firm plans to stay for only one period in country A is, then, already fairly large. The firm then prefers to invest even more, planning to stay also in period 2, even without a second-period transfer. This leads to an optimal investment of $a = a_A(e_1)$. On the other hand, less stringent first-period emission levels $e_1 > e^\sharp$ render large investments unprofitable, so that the firm ends up requiring a transfer in period 2. But in that case its second-period profit is always π_B, so that the firm optimally chooses $a = a_{AB}(e_1)$ even when it does not plan relocate.

Plugging the optimal investment level back into the firm's discounted profit, (12), its profit is $t_1 + V_A(e_1)$ whenever $e_1 \leq e^\sharp$, and $t_1 + V_{AB}(e_1)$ whenever $e_1 > e^\sharp$. The first-period transfer that is necessary to implement some first-period emission level e_1 is thus given by $t_1 = V_B - V_A(e_1)$ if $e_1 \leq e^\sharp$, and $t_1 = V_B - V_{AB}(e_1)$ if $e_1 > e^\sharp$. In the latter case, also a positive second-period transfer of $t_2 = \pi_B - \pi_A^*(a_{AB}(e_1))$ is paid. The total (discounted) transfer needed to implement a first-period emission level of $e_1 > e^\sharp$ is

[26] Existence of $\overline{a}$ follows from Lemma 1, result (2).

$V_B - V_{AB}(e_1) + \delta\big(\pi_B - \pi_A^*(a_{AB}(e_1))\big)$.

Minimizing the total transfer needed to permanently avert relocation leads us to the following result.

Proposition 4. *Assume $a_{AB}(e)$ is concave in e.*[27] *With observable investment, the optimal first-period contract is*

- $(t_1, e_1) = (t^o, e_A^o)$, *if* $\pi_B \leq \pi_B^\sharp$ *and* $L \geq t^o$;
- $(t_1, e_1) = (t^\sharp, e^\sharp)$, *if* $\pi_B^\sharp < \pi_B \leq \pi_B^{tr}$ *and* $L \geq t^\sharp$;
- $(t_1, e_1) = (V_B - V_{AB}(e_A^{tr}), e_A^{tr})$, *if* $\pi_B > \pi_B^{tr}$ *and* $L \geq t^{tr}$;
- *the null contract otherwise.*

$\pi_B^{tr} > \pi_B^\sharp$ *is the critical value for* π_B *for which* $t^\sharp = t^{tr}$. *The second-period contract in the third case is* $(t_2, e_2) = (\pi_B - \pi_A^*(a_{AB}(e_A^{tr})), e^*(a_{AB}(e_A^{tr})))$.

Hence, in contrast to the case with unobservable investment, the regulator now has an alternative way to avert relocation, using the possibility to implement a positive second-period transfer. To this end, the regulator adjusts the emissions target in period 1 to the level e_A^{tr}, which induces a sufficiently *small* investment by the firm. In period 2, the regulator then pays a transfer that just averts relocation. However, this option creates a (potential) double inefficiency. Namely, the firm's investment is inefficiently small (given e_1), and in addition the emissions in period 1 are, in general, also distorted.[28] Since the actions implemented by the firm in this case do *not* depend on the value of π_B, whereas the distortions in the case with a lock-in (second case in Proposition 4) are increasing in π_B, the regulator implements e_A^{tr} whenever π_B is sufficiently large (larger than π_B^{tr}).

5.2 Alternative objective function

In our model as presented so far the regulator's preference only varies in the location of the firm and not directly in the firm's productive choices. Adding a preference over the contractible productive choices of the firm slightly complicates the analysis, but does not reverse the major result of the paper concerning the implementability of outcomes. In addition, we will also allow for positive benefits of averting relocation only in period 1. We will show that also this modification does not alter the main results. Unlike in the previous subsection, we again assume that a is *not* observable to the regulator.

[27] This assumption is sufficient to establish existence and uniqueness of the value e_A^{tr}. Only mild assumptions are required to establish concavity of a_{AB}. E.g., in our illustrative example, $a_{AB}(e)$ is always concave.

[28] Whether emissions in period 1 are distorted depends on the specified functions. It turns out that in our illustrative example we have $e_A^{tr} = e_A^o$.

Suppose, the regulator's payoff can be written as follows:

$$-\chi_1 (t_1 + D(e_1)) - (1-\chi_1) L_1 - \chi_2 \delta(t_2 + D(e_2)) - (1-\chi_2)\delta L_2, \tag{13}$$

where $\chi_\tau = 1$ if the firm operates in country A in period τ (and accepts the contract offered in that period), and $\chi_\tau = 0$ otherwise. If the firm relocates in the second period the regulator incurs a loss of L_2 in that period, and if it relocates already in period 1 the regulator incurs an additional loss of $L_1 \geq 0$. Hence, L_1 is the regulator's *benefit* of averting relocation only in period 1. We assume $L_2 \geq L_1$, so that the same payoff structure as in (5) is obtained when $L_1 = 0$, while the regulator has an identical interest in averting relocation in each of the two periods when $L_1 = L_2$. $D(e)$ is a penalty function, capturing the domestic damages from the firm's emissions.[29] We assume that $D(e)$ is weakly increasing in e, and that $D(e) = 0$ if $e \leq 0$.

With this payoff structure it is not obvious that the regulator always prefers either immediate relocation or no relocation, because the regulator benefits also from averting relocation only in period 1. However, we argue in the following that due to the sunk costs associated with abatement capital investments, such an outcome is less preferable to either immediate relocation or no relocation and, hence, cannot arise in equilibrium.

Lemma 5. *Under the optimal sequence of short-term contracts the firm either relocates immediately or stays for both periods.*

The intuition is straightforward. If the firm stays for one period, it has to receive a transfer that compensates it for not relocating in that period. Because investments are made in the first period, this transfer has to take the investment cost into account. Because these costs are sunk, in period 2 a lower transfer is sufficient to discourage the firm from relocating. This implies that whenever the regulator prefers to avert the firm's relocation in period 1, then he strictly prefers to avert it also in period 2.

Under limited commitment, the regulator thus seeks to find the optimal sequence of short-term contracts that permanently avert relocation with minimal total transfers, taking into consideration also the damages of emissions. If this is too costly, the regulator offers no contract and implements the outcome where the firm relocates immediately.

In the following we derive necessary and sufficient conditions for the implementability of such an outcome, that parallel the results in Section 4.2.

To form an equilibrium where the firm does not relocate, the quintuple (t_1, e_1, t_2, e_2, a) again has to satisfy the constraints (PC), (MH-1), and (MH-2). The constraint of se-

[29] When the firm relocates, it may increase its emissions abroad. If pollution is trans-boundary, the regulator will take these emissions into account as well. However, they effectively only raise the fixed welfare loss of relocation and, hence, can be embedded in the parameters L_1 and L_2.

quential optimality now reads as follows

$$(t_2, e_2) \in \arg\min_{\tilde{t}_2, \tilde{e}_2} \tilde{t}_2 + D(\tilde{e}_2), \quad \text{s.t. } \tilde{t}_2 + \pi_A(\tilde{e}_2, a) \geq \max\{\pi_B, \pi_A^*(a)\}. \tag{SO'}$$

Because the regulator may now prefer a different level of emissions than the firm also in period 2, a further constraint emerges. Namely, the firm should not choose a different investment and thereafter stay in country A also in period 2 without accepting the second-period contract. This leads us to the following additional moral hazard constraint:[30]

$$t_1 + \pi_A(e_1, a) - K(a) + \delta(t_2 + \pi_A(e_2, a)) \geq t_1 + V_A(e_1). \tag{MH-3}$$

We can now extend the central result regarding the implementability of outcomes under short-term contracting (see Proposition 2) to the generalized payoff structure.

Proposition 5. *For a first-period emission level e_1, there exists a second-period contract* (t_2, e_2) *and an investment level a such that constraints* (MH-1)*,* (MH-2)*,* (SO')*, and* (MH-3) *are satisfied if and only if $V_A(e_1) \geq V_{AB}(e_1)$ and $D'(e^*(a_A(e_1))) = 0$.*

Hence, our result on implementability, which is the central result of this paper, carries over to the more general payoff function of the regulator. However, the implementation of outcomes becomes even harder. The second condition in Proposition 5 requires that given the firm's equilibrium investment a, the regulator's and the firm's interests in the second period are fully aligned. Hence, the regulator must have no incentive to distort the firm's emissions e_2 away from the level that the firm would optimally choose (given a) in the absence of regulation in that period.

The underlying reason for this result is similar as before. Namely, whenever the regulator has an incentive to distort the firm's emissions in period 2, this is anticipated by the firm, and leads to an adjustment in the firm's investment in abatement capital. The regulator, in turn, anticipates this adjustment, and is only willing to compensate the firm for the distortion in second-period emissions, taking this adjustment into account. This shifts the reference point for transfers in the second period, so that the firm is always better off when it plans to reject the second-period contract offer from the start, and invests in abatement capital accordingly (i.e., $a = a_A(e_1)$).[31]

The only way to escape this dilemma is for the regulator to implement an emission level e_1 that preempts the conflict between the regulator's and the firm's interests in period 2.

[30] For the sake of brevity we did not write down this constraint under the original payoff structure (see Section 4.2), because there it is automatically satisfied given the constraint (SO). This is no longer true under the modified constraint (SO').

[31] This reasoning also applies if the regulator has an incentive to distort the firm's emissions upwards (e.g., in order to trigger a higher choice of output). Anticipating this distortion in the second period, the firm reduces its investment, so that its optimal (un-distorted) emissions are higher in period 2. The regulator then only compensates the difference in the firm's profit when choosing its optimal emissions in period 2, given this investment, and the emission level preferred by the regulator.

Given the above specification of the regulator's payoff, this holds whenever $e^*(a_A(e_1)) \leq 0$, which implies $D'(e^*(a_A(e_1))) = 0$.[32] Hence, first-period emissions must be set at a sufficiently low level in order to induce a lock in, *and* fulfill the above constraint.[33]

6 Conclusion

This paper identifies a general implementation problem associated with persistent investments by an agent, that yield returns over more than one period. It arises when the principal cannot commit to contractual obligations for the full period of time in which the returns on the investments are incurred. The agent has an outside option, and realizes that in the future, the principal will compensate her only for forgone profits (due to not using the outside option) within a period, and not for her prior investment costs. Hence, the agent is unable to recover the full investment cost, and is better off when she plans to use the outside option in a future period from the start, which implies lower investment costs. We show that the principal is unable to implement outcomes where the agent never uses the outside option *and* requires a strictly positive transfer in a future period. To circumvent this implementation problem, the principal distorts the contract offered to the agent in the first period, where the investment takes place. In particular, by offering more high-powered incentives, the agent is induced to invest more. The outside option, then, becomes less attractive, so that the agent no longer requires a positive transfer in the future and yet refrains from using the outside option.

We frame this general idea in a more specific context. Namely, we analyze the problem of designing optimal incentive contracts that avert firm relocation. A local regulator aims to avert a firm's relocation in each of two periods. The firm, if staying for at least one period, undertakes some location-specific investment, which is not observable to the regulator. Contracts consist of transfers and targets for an observable productive activity, such as the firm's emissions, output, or employment.

If contracts are long-term, they specify simple subsidy payments, conditional on the firm's location. Optimal long-term contracts do not interfere directly with the firm's operative decisions. This simple structure results because the interests of the regulator and the firm are to some extent aligned. Averting relocation with minimal transfers

[32]Depending on the value of the outside option π_B, either the constraint $V_A(e_1) \geq V_{AB}(e_1)$, or the constraint $D'(e^*(a_A(e_1))) = 0$ is binding.

[33]There are other possible modifications of the model that can alleviate the implementation problem. E.g., suppose that in addition to the variable cost of installing an abatement capital stock of a, there is a fixed cost that arises only if a is strictly larger than zero. In that case, the regulator can always induce an investment of zero by setting a sufficiently high emission target for the first period, because this reduces the firm's benefit from investing in abatement capital. But as long as $a = 0$ holds, the local effects from a distortion in the second-period emission target upon the firm's investment vanish. This suggests that – similarly as in the case with an observable investment (see Section 5.1) – the regulator has an alternative way to circumvent the implementation problem, by setting a sufficiently loose emission target in the first period.

requires maximal profits of the firm. Therefore, the regulator has no incentive to distort the firm's operative decisions.

With limited commitment an implementation problem arises whenever relocation is sufficiently attractive. Optimal first-period contracts are then more stringent, and implement an inefficiently high investment in order to induce a 'lock-in'. The more attractive the relocation option is, the tougher the contract needs to be, which leads to larger first-period transfers. The distortions that arise due to the implementation problem can be so severe that higher transfers are required to avert the firm's relocation permanently than in a hypothetical situation where the firm cannot invest at all – although a positive investment would be required to avert relocation with minimal transfers.

Our model has an important application in the area of climate policy. When some countries unilaterally introduce prices for emissions, the competitiveness of their energy-intensive industries is harmed. In response, firms may be tempted to relocate to other countries with less stringent environmental regulation. This may be one of the reasons why the EU initially decided to allocate allowances for free in the EU-ETS. Our results indicate that such simple subsidies may not prevent relocation on a *permanent* basis. In order to be effective in this respect, subsidies should be conditioned upon the fulfillment of binding criteria such as firm-specific emission levels, output or employment targets. Such policies are needed whenever policy makers cannot make binding commitments that last for a sufficiently long period of time.

A Proofs

A.1 Proofs of Section 3

Proof of Lemma 1. Claim (1): $e^*(a)$ is implicitly defined by $\partial\pi_A/\partial e = 0$. By Assumption (A1) this value exists and is unique. Differentiating $\partial\pi_A/\partial e = 0$ w.r.t. a and rearranging yields

$$\frac{\partial e^*}{\partial a} = -\frac{\frac{\partial^2\pi_A}{\partial e\partial a}}{\frac{\partial^2\pi_A}{\partial e^2}} < 0. \tag{14}$$

Claim (2): π_A^* is strictly increasing by assumption (A5). To prove concavity of π_A^* differentiate twice, using the envelope-theorem, to get

$$\frac{\partial^2\pi_A^*}{\partial a^2} = \frac{\partial^2\pi_A}{\partial a\partial e}\cdot\frac{\partial e^*}{\partial a} + \frac{\partial^2\pi_A}{\partial a^2}.$$

Using (14), this can be written as

$$\frac{\partial^2\pi_A^*}{\partial a^2} = -\frac{\left(\frac{\partial^2\pi_A}{\partial e\partial a}\right)^2}{\frac{\partial^2\pi_A}{\partial e^2}} + \frac{\partial^2\pi_A}{\partial a^2} = \frac{\frac{\partial^2\pi_A}{\partial a^2}\cdot\frac{\partial^2\pi_A}{\partial e^2} - \left(\frac{\partial^2\pi_A}{\partial e\partial a}\right)^2}{\frac{\partial^2\pi_A}{\partial e^2}} \leq 0.$$

The numerator is non-negative by (A3), while the denominator is negative by (A1). Hence the entire expression is negative. Furthermore, (A5) implies $\partial\pi_A^*/\partial a > \varepsilon > 0$ for all a, which yields $\lim_{a\to\infty}\pi_A^*(a) = +\infty$.
Claim (3): $a_A(e)$ is implicitly defined by the first-order condition

$$\frac{\partial\pi_A}{\partial a} - \frac{\partial K}{\partial a} + \delta\frac{\partial\pi_A^*}{\partial a} = 0. \tag{15}$$

At $a = 0$ the expression one the left-hand side is strictly positive, by (A2), $K'(0) = 0$, and (A5). Furthermore, boundedness of $\partial\pi_A/\partial a$ by (A2) and strict concavity of K imply that this expression turns negative for large values of a. Existence of $a_A(e)$ then follows from continuity. Furthermore, $\pi_A(e,a) - K(a) + \delta\pi_A^*(a)$ is strictly concave in a, because its components are concave and some even strictly concave, which proves uniqueness of $a_A(e)$. Differentiating (15) w.r.t. e and rearranging yields

$$\frac{\partial a_A}{\partial e} = \frac{\frac{\partial^2\pi_A}{\partial e\partial a}}{\frac{\partial^2 K}{\partial a^2} - \frac{\partial^2\pi_A}{\partial a^2} - \delta\frac{\partial^2\pi_A^*}{\partial a^2}} < 0. \tag{16}$$

For $a_{AB}(e)$ just repeat the above steps.
Claim (4): By claim (4) both $V_A(e)$ and $V_{AB}(e)$ are well defined. Differentiating $V_A(e)$ twice, using the envelope-theorem, yields

$$\begin{aligned}\frac{\partial^2 V_A}{\partial e^2} &= \frac{\partial^2\pi_A}{\partial e^2} + \frac{\partial^2\pi_A}{\partial e\partial a}\cdot\frac{\partial a_A}{\partial e} = \frac{\partial^2\pi_A}{\partial e^2} + \frac{\left(\frac{\partial^2\pi_A}{\partial e\partial a}\right)^2}{\frac{\partial^2 K}{\partial a^2} - \frac{\partial^2\pi_A}{\partial a^2} - \delta\frac{\partial^2\pi_A^*}{\partial a^2}}\\ &= \frac{\frac{\partial^2 K}{\partial a^2}\cdot\frac{\partial^2\pi_A}{\partial e^2} - \left[\frac{\partial^2\pi_A}{\partial a^2}\cdot\frac{\partial^2\pi_A}{\partial e^2} - \left(\frac{\partial^2\pi_A}{\partial e\partial a}\right)^2\right] - \delta\frac{\partial^2\pi_A^*}{\partial a^2}\cdot\frac{\partial^2\pi_A}{\partial e^2}}{\frac{\partial^2 K}{\partial a^2} - \frac{\partial^2\pi_A}{\partial a^2} - \delta\frac{\partial^2\pi_A^*}{\partial a^2}} < 0.\end{aligned}$$

Concavity of $V_{AB}(e)$ is proven in the same way (not shown). Using the envelope-theorem, the first-order condition for maximizing $V_A(e)$ is $\frac{\partial\pi_A}{\partial e}(e, a_A(e)) = 0$. By (A1) and continuity there exits some value e that satisfies this equation. Uniqueness follows from strict concavity of $V_A(e)$. Similarly, maximizing $V_{AB}(e)$ yields the first-order condition $\frac{\partial\pi_A}{\partial e}(e, a_{AB}(e)) = 0$, existence and uniqueness follow as before.
Claim (5): $a_{AB}(e)$ is defined by the first-order condition

$$\frac{\partial\pi_A}{\partial a} - \frac{\partial K}{\partial a} = 0. \tag{17}$$

Comparing this to (15), noticing that π_A^* is strictly increasing and by concavity of the respective objectives, we find that $a_A(e) > a_{AB}(e)$ for all e. □

Proof of Lemma 2. Assume $V_{AB}(e_1) \geq V_B$, which can be written as

$$V_{AB}(e_1) = \pi_A(e_1, a_{AB}(e_1)) - K(a_{AB}(e_1)) + \delta\pi_B \geq \pi_B + \delta\pi_B = V_B.$$

But this implies $\pi_A(e_1, a_{AB}(e_1)) > \pi_B$ and therefore

$$\begin{aligned} V_A(e_1) &= \max_a \; \pi_A(e_1, a) - K(a) + \delta\pi_A^*(a) \\ &\geq \pi_A(e_1, a_{AB}(e_1)) - K(a_{AB}(e_1)) + \delta\pi_A(e_1, a_{AB}(e_1)) \\ &> \pi_A(e_1, a_{AB}(e_1)) - K(a_{AB}(e_1)) + \delta\pi_B \\ &= V_{AB}(e_1). \end{aligned}$$

This proves our claim. □

Proof of Lemma 3. As is discussed in the main text, the optimal profit from not relocating is V_A^o. The profit from immediate relocation is V_B. As a consequence of Lemma 2 we have $V_{AB}(e_1) < \max\{V_A^o, V_B\}$ for all e_1. Therefore, the firm prefers immediate relocation whenever $V_B > V_A^o$ and no relocation otherwise. Solving $V_A^o = V_B$ for π_B leads to the definition of π_B^o. □

A.2 Proofs of Section 4

Proof of Proposition 1. As is argued in the main text, the regulator's problem is to minimize (11) over e_1 and e_2. This is equivalent to maximizing $\pi_A(e_1, a) - K(a) + \delta\pi_A(e_2, a)$ over a, e_1, and e_2. Maximizing first over e_2 and a yields $V_A(e_1)$. Maximizing this over e_1 yields $e_1 = e_A^o$. By comparing the respective first-order conditions we get $e_2 = e_1$. The total transfer required is $t^o = V_B - V_A^o$. The regulator offers this contract whenever $t^o \leq L$. □

Proof of Proposition 2. When (SO) is satisfied, the firm's second-period profit is $t_2 + \pi_A^*(a)$. By the envelope-theorem, (MH-1) then implies that the firm's total profit is $t_1 + \delta t_2 + V_A(e_1)$. This justifies constraint (MH-2′), as a replacement for (MH-2).
Now first assume $V_A(e_1) \geq V_{AB}(e_1)$, which can be stated as

$$\max_a \; \pi_A(e_1, a) - K(a) + \delta\pi_A^*(a) \geq \max_a \; \pi_A(e_1, a) - K(a) + \delta\pi_B. \tag{18}$$

This implies $\pi_A^*(a_A(e_1)) > \pi_B$, where $a_A(e_1)$ denotes the maximizer of the left-hand side. Hence, the second-period contract $(t_2, e_2) = (0, e^*(a_A(e_1)))$ satisfies (SO), given $a = a_A(e_1)$. By construction, (MH-1) and (MH-2) are satisfied, given (t_2, e_2).
Next assume $V_A(e_1) < V_{AB}(e_1)$. Constraints (MH-1) and (SO) imply $a = a_A(e_1)$ and the

second-period contract offer entails $t_2 = \max\{0, \pi_B - \pi_A^*(a_A(e_1))\}$ and $e_2 = e^*(a_A(e_1))$. As indicated above, (MH-2) can be replaced by (MH-2′). Therefore, necessary for all three constraints to hold is $\delta t_2 \geq V_{AB}(e_1) - V_A(e_1) > 0$. Further, note that

$$\begin{aligned}
\delta t_2 &\geq V_{AB}(e_1) - V_A(e_1) \\
&= \max_a \left\{\pi_A(e_1, a) - K(a) + \delta\pi_B\right\} - \max_a \left\{\pi_A(e_1, a) - K(a) + \delta\pi_A^*(a)\right\} \\
&> \delta\big(\pi_B - \pi_A^*(a_A(e_1))\big).
\end{aligned}$$

Therefore $t_2 > \pi_B - \pi_A^*(a_A)$ and together with $t_2 > 0$, as shown above, we get $t_2 > \max\{0, \pi_B - \pi_A^*(a_A)\}$ – this contradicts (SO). $\square$

Proof of Corollary 1. The result on implementability follows from Proposition 2. Regarding $\pi_B^\sharp$ notice that $V_A^o > V_{AB}(e_A^o)$ for $\pi_B = \pi_B^o$ by Lemma 2. Because $V_{AB}(e_A^o)$ strictly increases with π_B, while V_A^o is independent of π_B, we get $\pi_B^\sharp > \pi_B^o$. $\square$

Proof of Lemma 4. By the envelope-theorem $\partial V_A/\partial\pi_B = 0 < \delta = \partial V_{AB}/\partial\pi_B$. Furthermore, using $a_A(e) > a_{AB}(e)$, it holds that

$$\frac{\partial V_A}{\partial e} = \frac{\partial \pi_A}{\partial e}(e, a_A(e)) < \frac{\partial \pi_A}{\partial e}(e, a_{AB}(e)) = \frac{\partial V_{AB}}{\partial e}. \tag{19}$$

Together with $V_A(e_A^o) = V_{AB}(e_A^o)$ for $\pi_B = \pi_B^\sharp$ (from Corollary 1) this yields $e^\sharp < e_A^o$ and $e^\sharp$ strictly decreases with π_B.

It remains to prove that $e^\sharp > \underline{e}$ for all π_B. To see this, notice that $V_A(e) = V_{AB}(e)$ at $\delta = 0$ for all e. Also, $\partial V_A/\partial\delta = \pi_A^*(a)$ and $\partial V_{AB}/\partial\delta = \pi_B$. For $e \to \underline{e}$ we have by (A1) and strictly convex K that $a_A(e) \to \infty$. As this holds irrespective of δ, we have that $V_A(e) > V_{AB}(e)$ for $e \to \underline{e}$ which completes the proof. $\square$

Proof of Proposition 3. We determine the cost of implementing an equilibrium with no relocation. Recall from the proof of Proposition 2 that there is no second-period transfer. As long as $\pi_B \leq \pi_B^\sharp$, by Corollary 1, e_A^o is implementable and minimizes the cost over the set of implementable first-period emission levels; the required (total) transfer is $t^o = V_B - V_A^o$. If $\pi_B > \pi_B^\sharp$, we have $e_A^o > e^\sharp$. Therefore, the regulator cannot use e_A^o to implement an outcome with no relocation. By the concavity of V_A, implementing $e^\sharp$ requires the smallest transfer, which is equal to $t^\sharp = V_B - V_A(e^\sharp)$. $\square$

Proof of Corollary 2. Trivial for $\pi_B \leq \pi_B^\sharp$. For $\pi_B > \pi_B^\sharp$ recall that $a_A(e)$ decreases in e (Lemma 1), and $e^\sharp < e_A^o$. The result follows. $\square$

Proof of Corollary 3. Recall that $t^\sharp = V_B - V_A(e^\sharp)$. On the other hand, the transfer to avert relocation when $a = 0$ is given by $t^{a=0} = V_B - (1+\delta)\pi_A^*(0)$, and no implementation problem arises in this case as a is fixed. Therefore $t^\sharp - t^{a=0} = -V_A(e^\sharp) + (1+\delta)\pi_A^*(0)$. Now, from Lemma 4 we have $e^\sharp \to \underline{e}$ for $\pi_B \to \infty$ and by strict concavity of V_A this implies $V_A(e^\sharp) \to -\infty$. Consequently, $t^\sharp - t^{a=0} \to \infty$, which proves the claim. □

A.3 Proofs of Section 5

Proof of Proposition 4. We first characterize the firm's optimal investment decision, i.e. the maximizer of (12). We distinguish three cases:

i) $\bar{a} \leq a_{AB}(e_1)$. By concavity of $\pi_A(e, a) - K(a) + \delta\pi_B$ (see the proof of Lemma 1), we have for all $a \leq \overline{a}$:

$$\pi_A(e_1, a) - K(a) + \delta\pi_B \leq \pi_A(e_1, \overline{a}) - K(\overline{a}) + \delta\pi_B = \pi_A(e_1, \overline{a}) - K(\overline{a}) + \delta\pi_A^*(\overline{a}).$$

Furthermore, because $\bar{a} \leq a_{AB}(e_1) < a_A(e_1)$, we have $V_A(e_1) \geq \pi_A(e_1, a) - K(a) + \delta\pi_A^*(a)$ for all $a \geq \bar{a}$. Consequently, $a = a_A(e_1)$ maximizes the firm's profit in this case and this maximal profit is $V_A(e_1)$.

ii) $a_A(e_1) \leq \bar{a}$. Similar to the previous case we have for all $a \geq \overline{a}$:

$$\pi_A(e_1, a) - K(a) + \delta\pi_A^*(a) \leq \pi_A(e_1, \overline{a}) - K(\overline{a}) + \delta\pi_A^*(\overline{a}) = \pi_A(e_1, \overline{a}) - K(\overline{a}) + \delta\pi_B.$$

Furthermore, because $a_{AB}(e_1) < a_A(e_1) \leq \bar{a}$, we have $V_{AB}(e_1) \geq \pi_A(e_1, a) - K(a) + \delta\pi_B$ for all $a \leq \bar{a}$. Consequently, $a = a_{AB}(e_1)$ maximizes the firm's expected profit in this case and this maximal profit is $V_{AB}(e_1)$.

iii) $a_{AB}(e_1) < \bar{a} < a_A(e_1)$. By the above arguments the firm's profit has two local maxima: at $a = a_A(e_1)$ and at $a = a_{AB}(e_1)$, such that the maximal profit is either $V_A(e_1)$ or $V_{AB}(e_1)$. Because $V_A(e) > V_{AB}(e)$ holds if and only if $e < e^\sharp$, we find that the firm's maximal profit, given $a_{AB}(e_1) < \bar{a} < a_A(e_1)$, is thus $V_A(e_1)$ if $e_1 \leq e^\sharp$, and $V_{AB}(e_1)$ if $e_1 > e^\sharp$.

Therefore, the firm's profit after having accepted a first-period contract offer (t_1, e_1) is

$$t_1 + \begin{cases} V_A(e_1), & e_1 \leq e^\sharp, \\ V_{AB}(e_1), & e_1 > e^\sharp. \end{cases} \tag{20}$$

We here implicitly assume that the firm always chooses $a_A(e_1)$ when $e_1 = e^\sharp$, although it is indifferent. This is without loss of generality, because the regulator chooses the equilibrium, in case there are multiple, and it is obvious that the first-period transfer to implement $e_1 = e^\sharp$ is unaffected by the continuation, but in case the firm chooses $a_{AB}(e^\sharp)$ the regulator has to pay a strictly positive second-period transfer to avert relocation in period 2.

The total transfer to avert relocation is given by

$$t(e_1) = \begin{cases} V_B - V_A(e_1), & e_1 \leq e^\sharp, \\ V_B - V_{AB}(e_1) + \delta\big(\pi_B - \pi_A^*(a_{AB}(e_1))\big), & e_1 > e^\sharp. \end{cases} \tag{21}$$

In case $e_1 \leq e^\sharp$ this is trivial, because it implies $a = a_A(e_1) > \overline{a}$ and therefore a first-period transfer is sufficient (this already follows from Lemma 4). Now consider $e_1 > e^\sharp$, and suppose $\pi_A^*(a_{AB}(e_1)) \geq \pi_B$. This would imply

$$\begin{aligned} V_{AB}(e_1) &= \pi_A(e_1, a_{AB}(e_1)) - K(a_{AB}(e_1)) + \delta\pi_B \\ &\leq \pi_A(e_1, a_{AB}(e_1)) - K(a_{AB}(e_1)) + \delta\pi_A^*(a_{AB}(e_1)) < V_A(e_1), \end{aligned}$$

which yields $e_1 < e^\sharp$ – a contradiction. Thus, $\pi_A^*(a_{AB}(e_1)) < \pi_B$, so that the minimal second-period transfer required to implement an outcome with no relocation is $t_2 = \pi_B - \pi_A^*(a_{AB}(e_1))$.

The regulator now chooses e_1 in order to minimize (21). The first case ($\pi_B \leq \pi_B^\sharp \Leftrightarrow e_A^o \leq e^\sharp$) follows readily from Corollary 1. For the remainder, assume $e_A^o > e^\sharp$, i.e. $\pi_B > \pi_B^\sharp$. By strict concavity of $V_A(e)$ we have

$$t(e_1) = V_B - V_A(e_1) > V_B - V_A(e^\sharp) = t^\sharp \qquad \forall e_1 < e^\sharp.$$

So it cannot be optimal to implement some $e_1 < e^\sharp$. For $e_1 > e^\sharp$, the required transfer is $\widetilde{t}(e_1) = V_B - V_{AB}(e_1) + \delta\big(\pi_B - \pi_A^*(a_{AB}(e_1))\big)$. Denote e_A^{tr} the minimizer of $\widetilde{t}(e_1)$. By Lemma 1, the function $V_{AB}(e_1)$ is strictly concave. Furthermore, because π_A^* is concave and strictly increasing by Lemma 1, the composition with the concave function $a_{AB}(e_1)$ is also concave. Therefore, $\widetilde{t}(e_1)$ is strictly convex for *all* $e_1 \in (\underline{e}, \overline{e})$. Furthermore, by (A1) and Lemma 1 the minimizer is interior, i.e. $e_A^{tr} \in (\underline{e}, \overline{e})$ exists. Now suppose $e_A^{tr} \leq e^\sharp$. Then $t(e^\sharp) \geq \widetilde{t}(e^\sharp) > \widetilde{t}(e_1)$ for all $e_1 > e^\sharp$ so that $e_1 = e^\sharp$ leads to minimal (total) transfers. Hence the relevant cases are where $e_A^{tr} > e^\sharp$. Notice, that $\widetilde{t}(e_A^{tr})$ does not depend on π_B, and that for $\pi_B = \pi_B^\sharp$ we have $V_A^{tr}(e_A^{tr}) < V_A(e^\sharp)$. Because $t(e^\sharp)$ strictly increases with π_B and converges to $+\infty$, there exists a level π_B^{tr} such that $t(e_A^{tr}) < t(e^\sharp)$ if and only if $\pi_B > \pi_B^{tr}$. This completes the proof. □

Proof of Lemma 5. Suppose the regulator offers (t_1, e_1) in the first period, which is accepted by the firm and relocation in period 2 occurs. Denote $\hat{a}$ the equilibrium value of the firm's investment. Because the firm relocates in period 2, we must have $\pi_A^*(\hat{a}) \leq \pi_B$.

Regarding the first-period transfer, it has to hold that $t_1 \geq V_B - V_{AB}(e_1)$, in order to be accepted by the firm. Furthermore, we must have $L_1 \geq t_1 + D(e_1)$, otherwise the regulator prefers not to offer the contract at all. But then we have

$$\begin{aligned}0 \leq\ & L_1 - t_1 - D(e_1) \ \leq\ L_1 - V_B + V_{AB}(e_1) - D(e_1) \\ =\ & L_1 - \pi_B + \pi_A(e_1, \hat{a}) - K(\hat{a}) - D(e_1) \ <\ L_2 - \pi_B + \pi_A(e_1, \hat{a}) - D(e_1).\end{aligned}$$

Now, because $\pi_A^*(\hat{a}) \leq \pi_B$, the optimal contract to keep the firm in country A in period 2 is the solution to

$$\min_{t_2, e_2} t_2 + D(e_2) \quad \text{s.t.} \ \ t_2 + \pi_A(e_2, \hat{a}) \geq \pi_B. \tag{22}$$

Clearly, the solution to this is $e_2 = \arg\max_e \pi_A(e, \hat{a}) - D(e)$ and $t_2 = \pi_B - \pi_A(e_2, \hat{a})$. Together with the above, the regulator's benefit from offering this contract is

$$L_2 - t_2 - D(e_2) = L_2 - \pi_B + \pi_A(e_2, \hat{a}) - D(e_2) > L_2 - \pi_B + \pi_A(e_1, \hat{a}) - D(e_1) > 0,$$

where the first inequality holds because e_2 maximizes $\pi_A(e, \hat{a}) - D(e)$, and the second inequality was shown above to hold. Hence, the regulator strictly prefers offering a contract in period 2 that averts relocation.
Notice that the method of proof also rules out random relocation in period 2. Hence, either immediate relocation or no relocation can be optimal. □

Proof of Proposition 5. Let (t_1, e_1, t_2, e_2, a) be the outcome to be implemented.
Assume first that $V_A(e_1) \geq V_{AB}(e_1)$ and the second-period contract entails $e_2 \neq e^*(a)$. Because $D' \geq 0$ this implies $e_2 < e^*(a)$ and thus (MH-1) implies $a > a_A(e_1)$. But then $\pi_A^*(a) > \pi_A^*(a_A(e_1)) > \pi_B$. The firm's second-period profit, including the transfer $t_2 = \pi_A^*(a) - \pi_A(e_2, a)$, is therefore $\pi_A^*(a)$, but then (MH-3) is clearly violated because $a \neq a_A(e_1)$ is not the maximizer of $\pi_A(e_1, \tilde{a}) - K(\tilde{a}) + \delta\pi_A^*(\tilde{a})$.
Next assume $V_A(e_1) \geq V_{AB}(e_1)$ and the second-period contract entails $e_2 = e^*(a)$. Then (MH-3) is trivially satisfied. Also (MH-2) holds, by the arguments used in proving Lemma 2. Constraint (SO') is only satisfied when the regulator indeed prefers to keep the firm without distorting its second-period emissions, for which the second condition from the Proposition is both necessary and sufficient.
Lastly, assume $V_A(e_1) < V_{AB}(e_1)$. If $\pi_A^*(a) \geq \pi_B$ the firm's equilibrium payoff is $t_1 + \pi_A(e_1, a) - K(a) + \delta\pi_A^*(a) \leq t_1 + V_A(e_1) < t_1 + V_{AB}(e_1)$, hence (MH-2) is violated. If on the other hand $\pi_A^*(a) < \pi_B$ the firm's equilibrium payoff is $t_1 + \pi_A(e_1, a) - K(a) + \delta\pi_B$. Because $D' \geq 0$ we must have $e_2 \leq e^*(a)$ and, therefore, $\partial\pi_A/\partial a \,|_{e_2, a} > 0$ by assumptions (A1) and (A5), which implies $a \neq a_{AB}(e_1)$. Consequently (MH-2) is violated because a is not the maximizer of $\pi_A(e_1, \tilde{a}) - K(\tilde{a}) + \delta\pi_B$. □

B Restriction to pure strategies

Here we argue that allowing for mixed strategies does not soften the regulator's implementation problem identified in Proposition 2. An equilibrium in mixed strategies is characterized by a randomized strategy of the firm, i.e. a distribution on a subset A of the real line, and a mechanism that the regulator offers in period 2. By the revelation principle, the latter mechanism can be assumed to be direct, incentive compatible and truth-telling.[34]

For simplicity we focus in our analysis on the discrete case, i.e. where the firm randomizes over the discrete set of investment levels $\mathcal{A} = \{a^1, \ldots, a^n\}$. Clearly, there must exist $\hat{a} \in \mathcal{A}$ which receives no positive rent. Denote the contract this types accepts in equilibrium as $(\hat{t}_2, \hat{e}_2)$. Then it must hold that

$$\hat{t}_2 + \pi_A(\hat{e}_2, \hat{a}) = \pi_B. \tag{23}$$

Now consider the firm's investment choice. First of all, $\hat{a}$ must maximize the following expression

$$t_1 + \pi_A(e_1, a) - K(a) + \delta(\hat{t}_2 + \pi_A(\hat{e}_2, a)). \tag{24}$$

Second, because of (23), $\hat{a}$ also maximizes

$$t_1 + \pi_A(e_1, a) - K(a) + \delta\pi_B. \tag{25}$$

Using the first order-conditions for (24) and (25), $\hat{a}$ has to satisfy

$$\frac{\partial \pi_A}{\partial a}(\hat{e}_2, \hat{a}) = 0. \tag{26}$$

Because the function π_A is strictly concave in a for any value e, we conclude that

$$\pi_A(\hat{e}_2, a) < \pi_A(\hat{e}_2, \hat{a}), \quad \forall a \neq \hat{a}. \tag{27}$$

Together with (23) this implies

$$\hat{t}_2 + \pi_A(\hat{e}_2, a) < \pi_B, \quad \forall a \in \mathcal{A} \setminus \{\hat{a}\}. \tag{28}$$

Thus, no other type has the incentive to mimic type $\hat{a}$, because any type is guaranteed a profit of at least π_B. But this implies that there exists a second type $a' \neq \hat{a}$ that also receives no rent, because otherwise we could reduce all transfers to types $a \neq \hat{a}$ without violating any incentive constraint. This type a' also has to maximize (25). Because (25)

[34] Because only allocations matter for providing investment incentives to the firm, replacing an arbitrary mechanism that leads to a particular allocation with its direct and incentive compatible counterpart is indeed without loss of generality.

has a unique maximizer, namely $a_{AB}(e_1)$, this leads to a contradiction.

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