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An optimal incentive contract to avert firm relocation under unilateral environmental regulation

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Abstract

The unilateral introduction of an emissions price can induce firms to relocate to other countries with less stringent environmental regulation. However, firms may be able to reduce the emissions costs in their home country by investing into low-carbon technologies or equipment (abatement capital). Using a two-period model with asymmetric information, we study the optimal design of contracts offered by a regulator who seeks to avert the relocation of a polluting firm to another country. The transfers are contingent on the firm's emissions that are observable to the regulator, and terminate if the firm relocates. We show that under limited commitment, the regulator implements more stringent policies in the first period to induce higher abatement capital investments. This creates a 'lock-in effect' that prevents relocation even in the absence of transfers in period 2. We also show that types are not separated if relocation is sufficiently attractive. In practice, the transfers may be implemented via a free allocation of permits if the emissions price arises within an emissions trading scheme.

Keywords: environmental regulation; contract theory; limited commitment; firm mobility; abatement capital

JEL classification: D82, H23, L51, Q58

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1 Introduction

The unilateral introduction of an emissions price (e.g., on greenhouse gases) may negatively affect the international competitiveness of emission-intensive industries located in a country. If the emissions price is sufficiently high, firms may be induced to relocate to other countries with less stringent environmental policy. Firm relocation is an important channel of ‘emissions leakage’ (or ‘carbon leakage’ in case of CO₂-emissions). Other channels are price-reductions in fossil fuels due to a lower demand by countries that reduce their emissions, and changes in trade patterns. Firm relocation, however, may be perceived by policy makers as particularly harmful, because it is often associated with a direct loss of employment in the country that imposes the environmental regulation. This may explain why certain industries are exempted from environmental charges in the European Union.¹ The fear of a loss of competitiveness may also help to explain why many countries are reluctant to introduce emissions prices.²

In some industries, however, firms are able to lower their emissions costs when they stay in their home country, by investing into low-carbon technologies or equipment (‘abatement capital’) that reduces their emissions intensity of output. In this paper, we analyze how in a country that introduces an emissions price, a regulator can design incentive contracts to avert the relocation of a firm to another country, taking into consideration the firm’s possibilities to invest in abatement capital. To this end, we introduce a simple two-period model with asymmetric information about the firm’s investment costs. The firm’s ability to invest in abatement capital makes it possible to design transfer schemes that terminate after one period, but avert the firm’s relocation in both periods. This holds if the investment in abatement capital renders the relocation option unprofitable, and, thus, creates a ‘lock-in effect’ that the regulator can exploit in the design of an incentive scheme to avert relocation.

Estimating abatement cost curves at the country-level is a difficult task, as becomes apparent by observing that such estimates for a single country are often rather divergent across different studies that one can find in the literature. Assessing the abatement costs at the *firm level* is, then, probably even harder, because a firm’s overall abatement costs are the result of an optimal portfolio of investment decisions into different abatement options (e.g., machinery, technology, fuel-switching etc.). The informational asymmetries between a regulator who seeks to avert a firm’s relocation and the regulated firm may, therefore, be significant. To take this into consideration, we assume in our model that the cost of an abatement capital investment depends on a parameter that is private knowledge

¹E.g., in Germany, energy-intensive sectors are exempted from the “ecotax” introduced in 1998.

²Another explanation is the freerider effect, which states that countries benefit when other countries reduce their emissions, but prefer not to reduce their own emissions substantially when emissions are transboundary (as in the case of greenhouse gases). This makes effective climate agreements hard to achieve. See Barrett (2005) for an overview over this strand of literature.

of the firm. We apply the tools of contract theory to characterize optimal incentive schemes designed to avert relocation with a minimum of transfers (in expectation), given the informational asymmetry between the regulator and the firm. We assume that the regulator can observe the firm's emissions and its location, while the firm's investment in abatement capital as well as its other operative decisions (e.g., input and output levels) that may allow the regulator to infer the abatement capital investment, are also private knowledge or not contractible.

In our benchmark model, the regulator offers contracts to the firm at the beginning of period 1 that fully specify emissions levels and transfers in both periods (full commitment case). However, it is widely acknowledged that regulators often cannot fully commit to their actions in future periods. E.g., majorities may change, and legislation may, therefore, also change over time. In the future, the regulator may, therefore, be able to renege on the original contract, or even to terminate the contract unilaterally and offer a new set of contracts. To take this into consideration, in the main part of the paper we focus on the optimal design of incentive contracts under *limited commitment*. More specifically, we assume that the regulator offers in each period a new set of short-term contracts. Given that the firm's investment in abatement capital is private knowledge, this leads to a hold-up problem. Namely, if the firm invests more in abatement capital, relocation becomes less profitable in period 2, so the regulator has an incentive to reduce the transfers to the firm. Anticipating this, the firm lowers its investment in abatement capital, planning to relocate after period 1.

As is well-known from the literature, optimal contracts under limited commitment are often difficult to derive. However, we introduce an additional assumption, namely that the firm always has the possibility to continue to produce in its home country, without accepting any of the contracts it is offered. In that case, it does not receive any transfers, but it also becomes impossible for the regulator to tax the firm. The possibility to reject all contracts and nevertheless continue to produce in the home country, improves the firm's outside options. Furthermore, it conveys some commitment power to the regulator. Namely, the regulator is committed not to tax the firm. We show that as a result of this, the regulator often imposes more stringent emissions targets in the first period than under full commitment. Intuitively, by imposing lower emissions in the first period, the firm is induced to invest more in abatement capital. If the investment is sufficiently large, relocation becomes unprofitable even in the absence of transfers in period 2 (lock-in effect). Relocation can, thus, be averted in both periods, even though transfers take place only in period 1.

Furthermore, we show that when relocation is sufficiently attractive, then under limited commitment the regulator does not separate between the types. Hence, a pooling contract is offered in period 1. The reason for this is that in order to circumvent the

hold-up problem under limited commitment, the regulator needs to distort the emissions downwards in the first period. If the relocation option is sufficiently attractive (compared to the option to stay in the home country), these distortions are significant so that it becomes too costly for the regulator to separate the types, as this would require further distortions.

In practice, an emissions price may, e.g., arise due to the introduction of an emissions trading scheme. Transfers to firms can, then, simply be implemented via a free allocation of permits. However, while a free allocation of permits is sometimes used when emissions trading schemes are introduced, it seems unrealistic to assume that such ‘grandfathering’ of permits can be maintained indefinitely.³ Therefore, our result that transfers can be phased-out after period 1 without triggering relocation in period 2 may be relevant for policy makers. The result indicates that *temporary* allocation schemes of free permits can have a *permanent* effect on location decisions of firms. This finding may help to rationalize a free allocation of permits at the early stage of an emissions trading scheme. Our results also indicate that such implicit transfers should be made contingent on a firm’s current emissions (or other indicators of its productive activity), rather than to allocate free permits on the basis of a firm’s past emissions (‘grandfathering’). And finally, if a regulator cannot fully commit to future transfers, then more stringent emissions targets should be imposed early on, in order to induce firms to invest more in abatement capital. This way, the regulator can exploit the lock-in effect of abatement capital investments in the design of an optimal incentive scheme to circumvent the hold-up problem that arises under imperfect commitment.

1.1 Related Literature

The impact of unilateral environmental regulation on firms’ location decisions has first been analyzed formally by Markusen, Morey, and Olewiler (1993).⁴ 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. Motta and Thisse (1994) analyze the delocation of firms already established in their home country in response to a unilateral anti-pollution policy pursued by the government in their home country. Similarly, Petrakis and Xepapadeas (2003) analyze the location decisions of a monopolist initially located in a country that introduces an emissions tax, focusing on time consistency issues of environmental regulation. Ulph and Valentini (1997) analyze strategic environmental policy in a setting where different sectors are linked via an input-

³E.g., in phase II of the EU-ETS (2008–2012), governments could auction at most 10% of their allowances, the remaining permits were allocated for free.

⁴See also Markusen et al. (1995).

output relation. Firms in different sectors, thus, have an incentive to agglomerate in a single country.

From a technical point of view, our model is based on and contributes to the literature on contract theory and mechanism design. A systematic application of mechanism design to environmental policy is, e.g., given in Laffont (1994), who treats both moral hazard and adverse selection in environmental regulation.⁵ Jebjerg and Lando (1997) analyze optimal regulation of a firm that can exert non-observable effort on pollution reduction and has private information on marginal abatement costs. The choice of instruments for pollution control under asymmetric information is studied in more detail for instance in Baron (1985b) or Thomas (1995). For unobservable emissions, Laffont (1994) and Lewis (1996) show how environmental regulation can be exerted via output distortion. Thomas (1995) suggests a combination of a uniform tax and a contract scheme which is offered only to some types. Freixas, Guesnerie and Tirole (1985) propose a simplified algorithm for finite types applying linear schemes.

A modification widely studied in regulation theory is the assumption of multiple principals (Baron 1985a, van Egteren 2002, Martimort 1999). Such common agency problems arise when political authorities are endorsed with different fields of competence and commonly affect the regulation of a single firm. A prominent example in pollution control policy is the regulation of coal-fired power plants in the US, which are both regulated by the Public Utility Commission (PUC) in terms of electricity prices and by the Environmental Protection Agency (EPA) in terms of emissions standards.

In our model, we assume that the firm faces an emissions price (e.g. an emissions tax or a permit price under emissions trading). In addition to that, the firm is offered transfers by a regulator who can condition the transfers on emissions targets that the firm must fulfill (in addition to paying the emissions price). Under emissions trading, the transfers could, e.g., be implemented via a free allocation of permits, combined with firm-specific emissions or reduction targets.⁶ However, while we explicitly analyze the behavior of a (local) regulator who can set firm-specific emissions targets, we treat the emissions price (e.g., set by the government) as exogenous in our model.

Our model is closely related to the theory of incentives under *limited commitment*, and offers a specific application of this theory to environmental regulation. Whereas for two-period models where types are perfectly correlated over time the optimal strategy for the principal is simply to offer the static contract twice (Baron and Besanko 1984), things become more complicated when the regulator cannot fully commit. E.g., with every new

⁵Baron and Myerson (1982) first used the revelation principle in a detailed analysis of a principal-agent relationship. Together with the contributions from Laffont and Tirole, they laid the grounds for the theory of incentives or theory of contracts. For an introduction, see Laffont and Martimort (2002) or Salanié (2005).

⁶Allocation schemes of free permits and rebates of environmental levies are analyzed, e.g., by Ahman and Zetterberg (2005), Bernard, Fischer, Fox (2007), Fischer (2010), and Hepburn, Quah, Ritz (2012).

election period, regulations by environmental authorities are subject to policy revisions. If we assume contracts to be carried out over a longer period of time (as is the case for pollution control), there is no reason to believe that the majority in power feels bound by the promises of their predecessors (see, e.g., Freixas et al. 1985). This holds especially true if interest groups hold different stakes in the regulated firms (see Boyer and Laffont 1999 for a formal analysis of this problem).

If the regulator cannot commit to the initially announced contract, it is reasonable to assume that the firm can break the contract too, i.e. with the start of each period it can leave the relationship if its utility falls below a certain reservation utility (Laffont and Tirole, 1987). We also adopt this approach, by assuming that the regulated firm may continue to produce in its home country without accepting any of the contracts it is offered. In that case, it still faces the emissions price in that country, but does not receive any transfers. Alternatively, the firm may relocate to the other country. The firm's exit option leads to a 'take-the-money-and-run problem', which complicates the analysis because the inefficient type may have an incentive to pick the contract designed for the efficient type in the first period.

The remainder of this paper is organized as follows. In Section 2, we introduce the model and identify the lock-in effect of abatement capital investments that plays a crucial role for our results. Section 3 characterizes the full commitment case and demonstrates that a sufficient amount of transfers must be postponed until period 2 if the firm's relocation is to be averted with minimal transfers. Section 4 is devoted to the limited commitment problem and derives the main results of the paper. Section 5 concludes. All formal proofs are relegated to the Appendix.

2 Model

There are two countries (A and B), and one regulated firm initially located in country A. Due to the introduction of an emissions price (e.g., as a result of the implementation of an emissions trading scheme), the firm may find it profitable to relocate to country B, where no (or a lower) emissions price is implemented. Using incentive contracts with transfers, the regulator in A will try to avert the firm's relocation for reasons not specified in this model (e.g., to avoid a loss of employment).

There are two time periods, and the firm is free to relocate from A to B in each period. If the firm relocates, it shifts its entire production once and for all to country B. If the firm plans to stay in country A in both periods, we say that it has the 'location plan AA'. If the firm relocates from A to B immediately, it has the 'location plan BB'. If the firm produces in A in period 1, and relocates to B in period 2, then it follows the 'location plan AB'.

If the firm plans to stay in A for at least one period, it may invest in *abatement capital* to reduce its emissions costs (in light of the emissions price in A). The firm determines its location plan and its abatement capital investment simultaneously in period 1. If the firm produces in A in both periods, then its abatement capital stock installed in period 1 is available also in period 2 (which creates the potential for a lock-in effect, see below). We assume that any abatement capital investment takes place in period 1, and we neglect depreciation of the abatement capital stock (for simplicity).⁷

If the firm produces in country B, it incurs a fixed profit per period of π_B . If it produces in country A, it has a profit per period of $\pi_A(e, a)$, where e are the firm's emissions and a is the firm's abatement capital stock that is installed at the beginning of period 1 and used in period 1 and period 2. $\pi_A(e, a)$ is a reduced profit function, implicitly determined by optimizing all other decision variables of the firm. E.g., the firm's emissions may depend also on the firm's output, and on other short-term abatement activities that are not related to the firm's abatement capital stock a . What is important is that the regulator can only observe the firm's emissions, and not a , nor the firm's other decision variables (for otherwise, the regulator could infer the level of a by observing the other variables). It is important to highlight that the function $\pi_A(e, a)$ encompasses not only the firm's revenues and production costs, but also the firm's emissions costs that are induced by the carbon price in country A. Below, we illustrate the derivation of $\pi_A(e, a)$ for a specific example in which the firm can reduce its emissions by output contraction and by abatement capital investments.

We assume that the function $\pi_A(e, a)$ is twice continuously differentiable w.r.t. e and a . We also assume that $\partial^2 \pi_A(e, a) / \partial e^2 < 0$, $\partial^2 \pi_A(e, a) / \partial a^2 < 0$, and $\text{argmax}_e \pi_A(e, a) < \infty$ for all $0 \leq a < \infty$. Furthermore: $\frac{\partial^2 \pi_A(e, a)}{\partial e \partial a} < 0$, which implies that the firm's optimal emissions are lower when the firm has installed a larger abatement capital stock. And finally, we assume that $\max_e \pi_A(e, a)$ is strictly increasing in a . Intuitively, the firm is strictly better off with a larger abatement capital stock when it chooses the emissions e optimally (given a), because a larger a implies that the firm can implement the same production plan (e.g., output) at lower emissions costs.⁸

The firm's investment cost in abatement capital is given by $K(a, \theta)$, where $\theta > 0$ is a cost parameter. We assume $\partial K(a, \theta) / \partial \theta > 0$, $\partial K(a, \theta) / \partial a > 0$, $\partial^2 K(a, \theta) / \partial a \partial \theta > 0$, and $\partial^2 K(a, \theta) / \partial a^2 \geq 0$. θ is private information of the firm, and revealed to the firm before period 1. It is randomly drawn from $\{\underline{\theta}, \bar{\theta}\}$, with $\bar{\theta} > \underline{\theta}$ and $\text{Pr}[\theta = \underline{\theta}] = \nu$.

Let $V_{AA}(e_1, e_2, a, \theta)$ be the firm's discounted profit, *given* that the firm plans to stay in A in both periods, emits e_1 (resp. e_2) in period 1 (period 2)⁹, and θ is the firm's type.

⁷Allowing for depreciation of abatement capital does not alter the basic trade-offs at work in our model, but would complicate the formal analysis.

⁸An alternative way to justify this is to assume that the firm can achieve a profit of $\pi_A(e, a)$ (for arbitrary e and a) also with any $a' > a$ by simply leaving $a' - a$ of its installed abatement capital idle.

⁹E.g., these emissions levels may be fixed in contracts offered by the regulator.

The discount factor for profits incurred in period 2 is denoted by δ . Using our above assumptions, we have:

$$V_{AA}(e_1, e_2, a, \theta) = \pi_A(e_1, a) - K(a, \theta) + \delta\pi_A(e_2, a). \quad (1)$$

Similarly, let

$$V_{AB}(e_1, a, \theta) = \pi_A(e_1, a) - K(a, \theta) + \delta\pi_B \quad (2)$$

be the firm's discounted profit when it plans to relocate to B in period 2. If the firm relocates from A to B immediately, we obtain:

$$V_{BB} = (1 + \delta)\pi_B,$$

in which case the firm does not invest in abatement capital.

The following definitions are useful for the formal analysis of this model. Let

$$V_{AA}^*(e_1, e_2, \theta) = \max_a V_{AA}(e_1, e_2, a, \theta) \quad (3)$$

be the firm's maximized value when a is chosen optimally under location plan AA, given e_1 , e_2 , and θ . The corresponding optimal investment in abatement capital is denoted by $a_{AA}^*(e_1, e_2, \theta)$. Similarly, let

$$V_{AB}^*(e_1, \theta) = \max_a V_{AB}(e_1, a, \theta) \quad (4)$$

be the firm's maximized value under location plan AB (given e_1 and θ). The corresponding investment in abatement capital is denoted by $a_{AB}^*(e_1, \theta)$.

In the following Lemma we collect some basic properties of the value functions V_{AA}^* and V_{AB}^* , as well as the induced abatement capital investments a_{AA}^* and a_{AB}^* .

Lemma 1. *The value function $V_{AA}^*(e_1, e_2, \theta)$ has the following properties*

$$(1.a) \quad \delta \cdot \frac{\partial}{\partial e_1} V_{AA}^*(e, e, \theta) = \frac{\partial}{\partial e_2} V_{AA}^*(e, e, \theta).$$

$$(1.b) \quad \frac{\partial^2}{\partial e_t \partial \theta} V_{AA}^*(e_1, e_2, \theta) > 0 \quad \text{for } t = 1, 2.$$

$$(1.c) \quad V_{AA}^*(e_1, e_2, \theta) \text{ is concave both in } e_1 \text{ and } e_2.$$

The value function $V_{AB}^(e_1, \theta)$ has the following properties*

$$(1.d) \quad \frac{\partial^2}{\partial e_1 \partial \theta} V_{AB}^*(e_1, \theta) > 0.$$

$$(1.e) \quad V_{AB}^*(e_1, \theta) \text{ is concave in } e_1.$$

For the (implicit) levels of optimal abatement capital investment we have

$$(1.f) \quad \frac{\partial}{\partial \theta} a_{AA}^*(e_1, e_2, \theta) < 0 \quad \text{and} \quad \frac{\partial}{\partial \theta} a_{AB}^*(e_1, \theta) < 0.$$

Now consider the firm's optimal choice of emissions. Since the firm produces with the same abatement capital stock in both periods, it is clear that in the absence of policy intervention, the optimal emissions are constant over time: $e_1 = e_2 \equiv e$. Let

$$V_{AA}^o(\theta) = \max_e V_{AA}^*(e, e, \theta) \quad (5)$$

be the firm's maximized value when both emissions and abatement capital are chosen optimally, given location plan AA. Denote by $a_{AA}^o(\theta)$ and $e_{AA}^o(\theta)$ the corresponding abatement capital stock and emissions level. Similarly, let

$$V_{AB}^o(\theta) = \max_{e_1} V_{AA}^*(e_1, \theta) \quad (6)$$

be the firm's maximized value under location plan AB, when a and e_1 are chosen optimally, and let $a_{AB}^o(\theta)$ and $e_{AB}^o(\theta)$ be the corresponding abatement capital stock and emissions.

The following result gives a first indication of the lock-in effect of abatement capital investments that plays a crucial role in later sections.

Lemma 2. *Due to the lock-in effect, in the absence of policy intervention, 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 that $V_{AB}^*(e, \theta) < \max\{V_{AA}^*(e, e, \theta), V_{BB}\}$.*

Note, that Lemma 2 implies that also the following inequality holds:¹⁰

$$V_{AB}^o(\theta) \leq \max\{V_{AA}^o(\theta), V_{BB}\}.$$

The intuition behind Lemma 2 is as follows. An investment in abatement capital involves sunk costs. Therefore, if a firm prefers to undertake such an investment in order to reduce its emissions costs during one period of production in country A (rather than to relocate immediately), then the firm is even better off staying in country A in both periods, raising its investment accordingly. Since the investment costs are incurred only in period 1, it may well be (given $a = a_{AA}^o(\theta)$) that the firm achieves a lower net profit in country A in period 1 than in country B. However, if the firm prefers to stay in country A in both periods ($V_{AA}^o(\theta) > V_{BB}$), then its profit in A in the second period must always be larger than π_B , and compensate the firm for a (possibly) low profit incurred in the first period. There is, thus, a positive 'rent' from the abatement capital investment, causing the lock-in effect. This rent will play an important role in later sections, when the regulator designs incentive schemes to avert the firm's relocation.

¹⁰To see this, set $e = e_{AB}^o(\theta)$, and note that $V_{AA}^o(\theta) \geq V_{AA}^*(e, e, \theta)$ holds for all e .

Given the informational constraints of the regulator, in each period, contracts will then be offered to the firm that specify some transfer t , contingent on the firm still being located in country A in that period, and a fixed emissions target e that the firm must reach (see the following sections). The regulator can also drop the fixed emissions target, but specifying a target is (weakly) dominant from the regulator's point of view.¹¹

Before we come to the analysis of (constrained) optimal incentive schemes under full and under limited commitment, let us first introduce a simple example to illustrate the basic assumptions of the model. This example will be referred to also in later sections.

2.1 Example

Suppose, the regulated firm is a monopolist, operating in a market with an inverse demand function given by: $P(q) = 2 - q/2$, where q is the firm's output. The marginal costs of production are constant and normalized to zero. The emissions price in A (following the introduction of a cap-and-trade scheme) is equal to 1. Let $\tilde{\pi}_A(e, q)$ be the firm's profit (per period) in country A, gross of abatement capital installation costs. Hence:

$$\tilde{\pi}_A(e, q) = (2 - q/2)q - e. \quad (7)$$

Emissions are a function of output and the firm's abatement capital stock: $e = e(q, a)$. In this example, we assume that the firm's emissions are additive in q and a and given by: $e(q, a) = q - a$. Solving $e = e(q, a)$ for q , we obtain an equivalent relation $q = q(e, a) = a + e$. Inserting this into (7), we obtain the *reduced profit function*:

$$\pi_A(e, a) = 2a + e - (a + e)^2/2. \quad (8)$$

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

Let the investment cost function in abatement capital be quadratic:

$$K(a, \theta) = \theta a^2/2. \quad (9)$$

Suppose, the firm plans to stay in country A in both periods (irrespective of whether this is optimal or not), and the regulator does not interfere with the firm's decisions. Then the firm solves:

$$\max_{e,a} V_{AA}(e, e, a, \theta) = (1 + \delta)(2a + e - (a + e)^2/2) - \theta a^2/2,$$

where $e = e_1 = e_2$ are the firm's emissions in each period. Maximizing the firm's dis-

¹¹To see this, note that any outcome that is implementable with a transfer that is contingent only on the firm's location, can be replicated also with a contract that (in addition) specifies also a fixed emissions target.

counted value (given the location plan AA) over e first, we obtain: $e = 1 - a$. Inserting this back into the target function, we obtain after maximizing over a :

$$a_{AA}^o(\theta) = \frac{1 + \delta}{\theta}, \text{ and } e_{AA}^o(\theta) = \frac{\theta - 1 - \delta}{\theta}. \quad (10)$$

Throughout the paper, we will allow the firm's emissions to be negative. This simplifies the exposition. The economic intuition is that the firm may build up more abatement capital (e.g., by generating electricity using renewable energies) than it actually needs for its own production. Assuming that the excess electricity can be fed into the grid, the firm becomes a seller of negative emissions. Requiring e to be non-negative would add another constraint to the maximization problem.

Now suppose, the firm plans to stay in country A only for one period, and relocates to B in period 2. In the absence of policy intervention, the firm then solves:

$$\max_{e_1, a} V_{AB}(e_1, a, \theta) = 2a + e_1 - (a + e_1)^2/2 - \theta a^2/2 + \delta \pi_B.$$

Using the same steps as before, we obtain:

$$a_{AB}^o(\theta) = 1/\theta, \text{ and } e_{AB}^o(\theta) = \frac{\theta - 1}{\theta}. \quad (11)$$

By comparison with (10), we observe that the firm's optimal emissions are higher, and the abatement capital stock is lower when it plans to relocate after one period.

3 Full commitment

In this section we assume the regulator is able to commit to contracts for both periods. Following the revelation principle the contract offer is $\gamma = \{(e_1, t_1, e_2, t_2), (\bar{e}_1, \bar{t}_1, \bar{e}_2, \bar{t}_2)\}$, where the first part is designed for type $\underline{\theta}$ and the second part for type $\bar{\theta}$. The firm is asked to report her type and is assigned the respective contract. Alternatively the firm can relocate to B immediately in period 1. In the former case, she has to fulfill the emissions target e_1 specified in the contract¹² and she receives a transfer t_1 . In the following period 2, the firm can stay in country A, in which case it has to reach the emissions target e_2 as specified in the chosen contract. Alternatively, the firm can decide to relocate to B. Hence, we assume that the firm has the possibility to terminate the contract at no cost after period 1. This *exit option* constrains the set of implementable contracts. In particular, as we will see below, it restricts the intertemporal allocation of transfers to the firm.

For the remainder of this section we assume $V_{BB} > V_{AA}^o(\underline{\theta})$, that is even for the efficient

¹²We assume the punishment for non-compliance is prohibitively high.

type immediate relocation would be more profitable than staying in country A in the absence of any transfers.

Let $t \equiv t_1 + \delta t_2$ be the discounted transfers to the firm when the firm stays in A in both periods, assuming that the regulator discounts future payments at the same rate as the firm. The regulator's problem can be stated as

$$\min_{\underline{e}_1, \underline{e}_2, \bar{e}_1, \bar{e}_2, \underline{t}_1, \bar{t}_1, \underline{t}, \bar{t}} \nu \cdot \underline{t} + (1 - \nu) \cdot \bar{t}, \quad (12)$$

subject to the following constraints. First of all each type of firm must prefer participation to immediate relocation, i.e.

$$V_{AA}^*(\underline{e}_1, \underline{e}_2, \underline{\theta}) + \underline{t} \geq V_{BB}, \quad (\text{PC-}\underline{1})$$

$$V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta}) + \bar{t} \geq V_{BB}. \quad (\text{PC-}\bar{1})$$

Second, planned relocation at period 2 must be inferior for each type:

$$V_{AA}^*(\underline{e}_1, \underline{e}_2, \underline{\theta}) + \underline{t} \geq V_{AB}^*(\underline{e}_1, \underline{\theta}) + \underline{t}_1, \quad (\text{PC-}\underline{2})$$

$$V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta}) + \bar{t} \geq V_{AB}^*(\bar{e}_1, \bar{\theta}) + \bar{t}_1. \quad (\text{PC-}\bar{2})$$

Third, the firm must be incentivized to report her type truthfully:

$$V_{AA}^*(\underline{e}_1, \underline{e}_2, \underline{\theta}) + \underline{t} \geq V_{AA}^*(\bar{e}_1, \bar{e}_2, \underline{\theta}) + \bar{t}, \quad (\text{IC-}\underline{1})$$

$$V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta}) + \bar{t} \geq V_{AA}^*(\underline{e}_1, \underline{e}_2, \bar{\theta}) + \underline{t}. \quad (\text{IC-}\bar{1})$$

Lastly, the firm must not find it optimal to misreport her type and plan to relocate in period 2:

$$V_{AA}^*(\underline{e}_1, \underline{e}_2, \underline{\theta}) + \underline{t} \geq V_{AB}^*(\bar{e}_1, \underline{\theta}) + \bar{t}_1, \quad (\text{IC-}\underline{2})$$

$$V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta}) + \bar{t} \geq V_{AB}^*(\underline{e}_1, \bar{\theta}) + \underline{t}_1. \quad (\text{IC-}\bar{2})$$

Define \mathcal{P} the problem of maximizing (23) with respect to all eight constraints. At least at a first glance it is not immediate which of the eight constraints will be binding when solving problem \mathcal{P} . We adopt the procedure of solving a relaxed problem first, in which we ignore the inter-temporal constraints (PC- $\underline{2}$), (PC- $\bar{2}$), (IC- $\underline{2}$) and (IC- $\bar{2}$). We then show that for any solution to this relaxed problem, transfers in each period can be chosen such that the solution also satisfies the omitted constraints.

Consider the relaxed problem

$$\begin{aligned} \min_{\underline{e}_1, \underline{e}_2, \bar{e}_1, \bar{e}_2, \underline{t}, \bar{t}} \quad & \nu \cdot \underline{t} + (1 - \nu) \cdot \bar{t} \\ \text{subject to} \quad & (\text{IC-}\underline{1}), (\text{IC-}\bar{1}), (\text{PC-}\bar{1}), (\text{PC-}\underline{1}). \end{aligned} \tag{\mathcal{P}'}$$

Note that for this problem only \underline{t} and \bar{t} matter, i.e. the distribution of transfers across periods is irrelevant. Problem \mathcal{P}' is similar to a standard adverse-selection contracting problem, only that the profit function of the firm has two arguments. The solution to this problem is given in the following Lemma.

Lemma 3. *The solution to the relaxed problem \mathcal{P}' is given by $\underline{e}_1 = \underline{e}_2 = \underline{e}^o$ and $\bar{e}_1 = \bar{e}_2 =: \bar{e}^{sb}$, where $\bar{e}^{sb} > \bar{e}^o$ solves*

$$\frac{\partial}{\partial e} \pi_A(\bar{e}^{sb}, a_{AA}(\bar{e}^{sb}, \bar{e}^{sb}, \bar{\theta})) = \frac{\nu}{1-\nu} \left(\frac{\partial}{\partial e} \pi_A(\bar{e}^{sb}, a_{AA}(\bar{e}^{sb}, \bar{e}^{sb}, \underline{\theta})) - \frac{\partial}{\partial e} \pi_A(\bar{e}^{sb}, a_{AA}(\bar{e}^{sb}, \bar{e}^{sb}, \bar{\theta})) \right). \tag{13}$$

Additionally transfers are given by

$$\bar{t} = V_{BB} - V_{AA}^*(\bar{e}_1^{sb}, \bar{e}_2^{sb}, \bar{\theta}), \quad \underline{t} = V_{BB} + V_{AA}^*(\bar{e}_1^{sb}, \bar{e}_2^{sb}, \underline{\theta}) - V_{AA}^*(\bar{e}_1^{sb}, \bar{e}_2^{sb}, \bar{\theta}) - V_{AA}^*(\underline{e}^o, \underline{e}^o, \underline{\theta}).$$

The basic properties of the solution of problem \mathcal{P}' are familiar. The efficient firm is required to produce only the efficient level of emissions. For the inefficient firm however the emissions level is distorted upwards. Furthermore only the efficient firm receives an information rent, that is a transfer that is larger than what is required to keep her just in country A . No rent is paid to the inefficient firm. A transfer payment is required, since for both types of firm it is not profitable to stay in country A without additional payments. However, the transfer is minimal, whenever the firm produces optimally in A , i.e. with the first-best emissions level and the optimal investment in abatement capital. The regulator can therefore reduce the transfer payments in allowing the firm to use these optimal values for emissions and abatement capital investment. However, the efficient firm would be better off pretending to be inefficient in order to be allowed larger emissions and consequently reduce the investment in abatement capital. To prevent this, the regulator must distort the emissions level of the inefficient firm which also leads to an inefficiently low investment in abatement capital.

Lemma 3 leaves open the distribution of transfers across periods. This is due to the neglect of the firm's exit option and is not true anymore, when also the omitted constraints have to be satisfied. To see this, assume the whole transfer is paid in period 1. Then it may be optimal for a firm to take the whole transfer payment but underinvest in abatement capital in period 1 and relocate at the beginning of period 2. To prevent this from happening, the regulator may be forced to shift a large part of the entire transfer to period 2, i.e. the firm may only receive the entire transfer when she stays in country A

for both periods. In the following Proposition we show that it is always possible for the regulator to split transfers in such a way, that the firm neither plans to relocate in period 2 nor to misreport her type and then relocate in period 2. Furthermore this is possible without imposing negative transfer on the firms in period 1.

Proposition 1. *The solution to problem \mathcal{P}' given in Lemma 3 together with $\underline{t}_1 = \bar{t}_1 = 0$ also solves problem \mathcal{P} . On the other hand, the solution of problem \mathcal{P}' together with $\underline{t}_1 = \underline{t}$ and $\bar{t}_1 = \bar{t}$ always violates one of the omitted constraints.*

The first part of Proposition 1 is positive, the solution to the relaxed problem \mathcal{P}' also solves problem \mathcal{P} with the appropriate choice of transfers. In particular it can be done paying all transfers only in period 2, i.e. with a maximal delay of transfer payments. Having no transfer in period 1, a firm would only choose location plan AB when this is superior to location plan BB , given the required level of emissions. But the lock-in effect then implies, that the respective firm type would prefer staying in country A for both periods, even absent any transfers – a contradiction. The second part of Proposition 1 however is rather negative. The regulator is never entirely free to allocate transfers in the second period. In particular there must always be strictly positive transfer payment in period 2 to avoid firms taking advantage of their exit option. This requires commitment power on the side of the regulator, not to deny the firm a transfer payment in period 2 which was promised in period 1. A firm anticipating that this might happen will then make use its exit option in order to maximize profits. We will discuss the consequences of limited commitment by the regulator in the next section, but before that we illustrate the above findings in our example.

3.1 Example

To illustrate the above findings, we reconsider the example introduced in Section 2.1. For simplicity, we set the discount factor δ equal to 1, and assume that the ex-ante probability that the firm is of the low-cost type ($\theta = \underline{\theta}$) is $\nu = \frac{1}{2}$. Using (30) and (31), we obtain under the specifications of the example:

$$\underline{e} = \frac{\underline{\theta} - 2}{\underline{\theta}} = e_{AA}^o(\underline{\theta}), \text{ and } \bar{e} = \frac{6(\bar{\theta} - \underline{\theta}) - 4 + \underline{\theta}}{\bar{\theta}(4 + \underline{\theta}) - 2\underline{\theta}}.$$

According to Lemma 3, the regulator sets the efficient type's emissions target optimally (given location plan AA), whereas \bar{e} is distorted upwards. It is easy to verify that $\bar{e} > e_{AA}^o(\bar{\theta}) = \frac{\bar{\theta} - 2}{\bar{\theta}}$ is indeed fulfilled.

Computing the total transfers \underline{t} and \bar{t} , it is easy to verify that $\bar{t} > \underline{t}$ holds. We can furthermore verify that constraint (PC- $\bar{2}$) is binding, i.e. the regulator must delay a sufficient amount of the transfer \bar{t} to period 2 in order to prevent the inefficient type from

relocating in period 2. The efficient type's inter-temporal incentive constraint (IC-2), which also involves \bar{t}_1 , however is never binding. Within this example we cannot draw a general conclusion on the requirement for the efficient type's first period transfer t_1 . Each of the constraints (IC- $\bar{2}$) and (PC-2) may be binding, such that each of the two may limit the amount of transfer that can be paid to the efficient type in the first period. Either the regulator has to prevent the efficient type from relocation in period 2 or he has to prevent the inefficient type from misreporting and then relocating in period 2.

4 Limited commitment

We now assume that the regulator cannot commit to a contract that specifies emissions and transfers for both periods, and that a new set of short-term contracts is offered in each period. The firm anticipates the contracts that will be offered in period 2, which restricts the set of implementable outcomes in period 1.

In each period, the regulator's goal is to avert the firm's relocation permanently, with a minimum of (expected) discounted transfers. In the absence of informational constraints, relocation can be averted with a minimum of transfers if a firm of type θ chooses an abatement capital stock of $a_{AA}^o(\theta)$ in period 1. However, having built up this amount of abatement capital in period 1, relocation may be strictly unprofitable, and the regulator may, thus, be tempted to tax the firm in period 2. This renders the investment unprofitable from the perspective of period 1, and, therefore, creates a *hold-up problem*. Given the regulator's inability to commit to a contract that covers both periods, the firm would rather relocate immediately than invest and stay in country A in both periods if it expects to be taxed in period 2.

The hold-up problem can be alleviated if the regulator is unable to tax the firm. This allows the firm to maintain a positive rent generated by the lock-in effect if the abatement capital investment is sufficiently large. We assume that, apart from relocating to country B, the firm has the possibility in each period to reject all contracts offered by the regulator, but nevertheless continue to produce in country A. In this case, it cannot obtain transfers offered by the regulator (in case positive transfers are offered), but it also avoids any negative transfers. Furthermore, the firm is then free to choose its own emissions target, and is not constrained by an emissions target set by the regulator. As we will show below, this makes it impossible for the regulator to tax the firm in period 2. Furthermore, the fact that it is not possible to implement negative transfers in period 2, gives some commitment power to the regulator (not to tax the firm), which helps to overcome the hold-up problem.

Under limited commitment, the regulator may distort the firm's emissions in the first period, but as we will show below, emissions in the second period are generally optimal,

given a . To take this into account in a simple way, it is useful to introduce some further notation, that will be used extensively in this Section. In particular, denote the maximum profit that the firm can achieve in country A in a single period by choosing the emissions e optimally, *given* that an abatement capital stock of a is implemented, by

$$\pi_A^*(a) = \max_e \pi_A(e, a), \quad (14)$$

and let $e^*(a)$ be the corresponding emissions choice.¹³ By our earlier assumptions (see Section 2), we know that $d\pi_A^*(a)/da > 0$. Furthermore, the following definition is useful:

$$V_{AA}^{**}(e_1, \theta) = \max_a V_{AA}(e_1, e^*(a), a, \theta). \quad (15)$$

The corresponding abatement level is denoted by $a_{AA}^{**}(e_1, \theta)$. Intuitively, $a_{AA}^{**}(e_1, \theta)$ is the firm's optimal investment in abatement capital given a (potentially distorted) emissions level e_1 in period 1 (that may be fixed by a short-term contract), when the firm can nevertheless choose the emissions e_2 in the second period optimally (for any given a). Note, that $a_{AA}^{**}(e_1, \theta)$ fulfills the following condition (using (3), and suppressing the functional dependency of a_{AA}^{**} from e_1 and θ for an ease of notation):

$$a_{AA}^{**} = a_{AA}^*(e_1, e^*(a_{AA}^{**}), \theta). \quad (16)$$

Recall, that $a_{AA}^*(e_1, e_2, \theta)$ is the firm's optimal abatement capital choice when it is constrained to emit e_1 (resp. e_2) in period 1 (period 2). The superscript “**” in a_{AA}^{**} (resp. V_{AA}^{**}) indicates that – in addition to choosing its abatement capital stock a optimally – the firm also optimizes its emissions in period 2 (for any given a). This, of course, affects the firm's optimal abatement capital investment.

Lemma 4. $a_{AA}^{**}(e_1, \theta)$ and $a_{AB}^*(e_1, \theta)$ are decreasing in e_1 :

$$\frac{\partial a_{AA}^{**}(e_1, \theta)}{\partial e_1} < 0, \text{ and } \frac{\partial a_{AB}^*(e_1, \theta)}{\partial e_1} < 0.$$

The result of Lemma 4 is intuitive. If the regulator allows for higher emissions in the first period, then the firm benefits less from a large abatement capital stock and, thus, invests less. However, it also implies that the regulator can stimulate additional abatement capital investments by imposing a *lower* emissions target in the first period. In the absence of ex-ante commitment power for the second period, this will turn out to be a crucial feature of the optimal incentive scheme offered in the first period, when the option to relocate is attractive (sufficiently large π_B).

Before we move on to the analysis of the full model, let us first consider a simpler

¹³Applying our definitions from Section 2, we can also write: $V_{AA}^o(\theta) = \max_a (1 + \delta)\pi_A^*(a) - K(a, \theta)$.

special case of the model, without adverse selection. The firm's investment cost function in abatement capital is, thus, common knowledge: $\underline{\theta} = \bar{\theta} \equiv \theta$. Analyzing this special case first, we will illustrate how the regulator can exploit his inability to tax the firm in period 2 in order to design incentive schemes that avert the firm's relocation in both periods, despite the fact that the firm's abatement capital investment in period 1 is private knowledge, which creates the potential hold-up problem. Then, we will analyze the full model with adverse selection.

4.1 Special case: no adverse selection

In the spirit of subgame perfection, we first analyze the outcome of period 2. Assuming that the firm has not relocated to B in period 1, in the second period, the firm's abatement capital stock a is fixed but not observable to the regulator. Hence, the regulator forms a belief about a , and we denote the regulator's anticipated value of a by a^R .¹⁴ In equilibrium, it will hold that $a = a^R$ (otherwise, the regulator would form irrational beliefs).

The regulator's problem in period 2 can be written as follows:

$$\min_{e_2, t_2} t_2 \text{ s.t. } \pi_A(e_2, a^R) + t_2 \geq \max\{\pi_B, \pi_A^*(a^R)\}. \quad (17)$$

The constraint assures that the firm does not find it profitable to relocate to country B in period 2, given that an abatement capital stock of $a = a^R$ has been implemented in period 1, and that the firm indeed chooses the contract it is offered. This latter condition explains the second expression in the max-operator. Namely, if the firm rejects the contract (e_2, t_2) it is offered in period 2 but does not relocate, then it does not receive a transfer in period 2, but is free to choose its optimal emissions level (given $a = a^R$).

From the structure of this problem, it follows immediately that the regulator sets e_2 so as to $\max_{e_2} \pi_A(e_2, a^R)$, which yields $e_2 = e^*(a^R)$, and t_2 so that the above constraint is fulfilled with equality. Therefore, we obtain for the optimal transfer in period 2 (after subtracting $\pi_A^*(a^R)$ from both sides of the above constraint):

$$t_2(a^R) = \max\{\pi_B - \pi_A^*(a^R), 0\}. \quad (18)$$

The regulator, thus, does not distort the firm's emissions in period 2, and sets them in the same way as the firm chooses them if it chooses its own emissions optimally (given $a = a^R$). This is intuitive, as the regulator's and the firm's interests are to some extent aligned: the firm seeks to maximize its profits, and the regulator seeks to avert the firm's

¹⁴Since there is only one firm type, there is no loss of generality in assuming that the firm chooses a single value of a in period 1 with probability 1. In the case with adverse selection, this will become a probability distribution.

relocation with a minimum of transfers to the firm, which requires a profit-maximizing choice of the firm's emissions in period 2. The transfers are, then, just large enough to compensate the firm's disadvantage from not relocating when there remains such a disadvantage (given an abatement capital stock of a^R), which is the case if $\pi_B > \pi_A^*(a^R)$. Otherwise, the transfers in period 2 are zero, because the regulator is unable to implement negative transfers in period 2. This follows immediately from the firm's outside options. Namely, it can always reject the contract offered in period 2, in which case it does not receive any transfers, and is free to choose its own emissions.

Let us now analyze the first period. The regulator offers to the firm a contract (e_1, t_1) . Assuming that the firm chooses and fulfills this contract, from the firm's perspective, it is as if the regulator had already specified an emissions target $e_2 = e^*(a^R)$ along with the contract, because the regulator cannot condition his contract in period 2 upon the actual value of a , and (upon observing (e_1, t_1)), the firm immediately anticipates the contract that the regulator will offer in period 2. Therefore, neglecting the transfers, the firm expects a value of $V_{AA}(e_1, e^*(a^R), a, \theta)$ under location plan AA, respectively $V_{AB}(e_1, a, \theta)$ if the firm plans to relocate in period 2. Note, that the regulator's expected a^R does not change when the *actual* value of a changes. Therefore, the anticipated emissions target in period 2, $e^*(a^R)$, also remains fixed when the firm changes a (for any given e_1). However, as $e^*(a^R)$ is endogenous, it clearly depends on the regulator's choice of e_1 .

Suppose, the firm adopts the location plan AA. Given the emissions target e_1 specified in the contract offered in period 1, and assuming that the firm plans to accept the contract that it anticipates for period 2, it solves: $\max_a V_{AA}(e_1, e_2 = e^*(a^R), a, \theta)$. As in Section 2, this leads to an optimal abatement capital stock of $a_{AA}^*(e_1, e_2, \theta)$, and a resulting value of $V_{AA}^*(e_1, e_2, \theta)$. The main difference compared to Section 2 is, that not all combinations of e_1 and e_2 are implementable. In particular, it must hold that $e_2 = e^*(a^R)$, where a^R will depend on e_1 (see below). Under location plan AB, the corresponding results are $a_{AB}^*(e_1, \theta)$ and $V_{AB}^*(e_1, \theta)$ (as in Section 2).

Given these results, the regulator's problem in period 1 is to

$$\min_{e_1, t_1} t_1 + \delta t_2(a^R),$$

where $t_2(a^R)$ is given by (18), subject to the constraint:

$$V_{AA}^*(e_1, e^*(a^R), \theta) + t_1 + \delta t_2(a^R) \geq \max\{V_{BB}, V_{AB}^*(e_1, \theta) + t_1\},$$

where a^R solves

$$a^R = a_{AA}^*(e_1, e^*(a^R), \theta) \tag{19}$$

to assure consistency of the regulator's belief (a^R) in period 2 with the actual value of a

implemented by the firm in equilibrium. An alternative way to interpret (19) is to assume that the regulator does not specify any emissions target for the second period and instead offers the transfer t_2 conditional only on the firm still being located in A in period 2. The firm is, then, free to choose its own emissions level in that period. Choosing e_2 optimally (given a) implies $e_2 = e^*(a)$ (for any a), and the firm's optimal choice of a is determined by condition (16). The two interpretations are equivalent, because (16) coincides with (19) for $a^R = a_{AA}^{**}$. Therefore, $a^R(e_1, \theta) = a_{AA}^{**}(e_1, \theta)$ holds for all e_1 and θ , and we will write $a_{AA}^{**}(e_1, \theta)$ from now on.

The following Proposition summarizes the central result of this subsection.

Proposition 2. *There exists no solution to the regulator's optimization problem under no commitment and no adverse selection that entails $\pi_B \geq \pi_A^*(a_{AA}^{**})$. Hence, any solution to this problem fulfills $t_2 = 0$ (no transfers in the second period).*

Proposition 2 implies that as a consequence of the hold-up problem under no commitment, the regulator designs the contract (e_1, t_1) in period 1 always in such a way that the firm invests enough in abatement capital to render the option to relocate to B in period 2 unprofitable. Hence, a lock-in effect of abatement capital investments is induced, and (via his inability to tax the firm in period 2) exploited by the regulator to resolve the hold-up problem which would otherwise induce the firm to relocate. Note, that if abatement capital investments are fairly costly (large θ), the regulator may have to distort the firm's emissions in period 1 significantly in order to induce a sufficiently strong lock-in effect in period 2. The transfers in period 1 will, then, be much higher than the total discounted transfers needed to avert relocation under full commitment. Only if θ is sufficiently small, no distortion is needed. The discounted transfers are, then, the same as under full commitment.

Given the above results, let us now show that a solution to the regulator's problem exists, and characterize its properties. To this end, we first define a *critical emissions level* in period 1, denoted by e_1^\sharp , that fulfills:

$$V_{AA}^{**}(e_1^\sharp, \theta) = V_{AB}^*(e_1^\sharp, \theta). \quad (20)$$

The following Lemma collects properties related to the critical emissions level e_1^\sharp .

Lemma 5. *The critical emissions level e_1^\sharp is*

(5.a) *decreasing in π_B : $\frac{d}{d\pi_B} e_1^\sharp < 0$, and*

(5.b) *decreasing in θ : $\frac{d}{d\theta} e_1^\sharp < 0$.*

Furthermore:

(5.c) *The condition $V_{AA}^{**}(e_1, \theta) \geq V_{AB}^*(e_1, \theta)$ is equivalent to $e_1 \leq e_1^\sharp$.*

Intuitively, the critical emissions level e_1^\sharp is just low enough to make the firm indifferent between location plans AA and AB when it fulfills the emissions target e_1^\sharp imposed by the regulator in period 1. Note, that under location plan AA, the firm invests more in abatement capital than under AB. Hence, whenever the regulator imposes an emissions target e_1 lower than e_1^\sharp , the firm *strictly* prefers location plan AA to AB (given $t_2 = 0$), because the larger abatement capital investment induced by the low emissions target in period 1 makes the lock-in effect sufficiently strong to render the relocation option in period 2 unprofitable. Conversely, if $e_1 > e_1^\sharp$, the firm strictly prefers location plan AB to AA. In this case, it is impossible for the regulator to avert the firm's relocation in period 2 without offering a positive transfer in that period. However, as Proposition 2 has shown, such an outcome cannot be obtained in equilibrium. Therefore, a necessary requirement for an equilibrium to exist is that it fulfills: $e_1 \leq e_1^\sharp$.

Proposition 3. *A solution to the regulator's optimization problem in period 1 under no commitment and no adverse selection exists. It is given by $e_1 = \min\{e_{AA}^o, e_1^\sharp\}$ and $t_1 = V_{BB} - V_{AA}^{**}(e_1, \theta)$.*

Intuitively, if $e_1^\sharp \geq e_{AA}^o$, then the regulator only needs to assure that the firm stays for one period in country A. Setting an emissions target of $e_1 = e_{AA}^o$, the firm will then realize that even in the absence of transfers in period 2, it is more profitable to stay in country A also in the second period, investing in abatement capital accordingly, rather than to invest less in abatement capital ($a_{AB}(e_1, \theta)$) and to relocate in period 2. The transfer in period 1 is, then, identical to the discounted transfer t under full commitment. If $e_1^\sharp < e_{AA}^o$, the regulator needs to distort the emissions in period 1 downwards to induce a higher abatement capital investment, which implies a higher transfer than under full commitment. In order to avert relocation in the second period, the distortion has to be high enough to induce a sufficiently strong lock-in effect. The firm will then realize that in order to fulfill the emissions target e_1 in period 1, a high investment in abatement capital is needed even when the firm plans to relocate after one period. The condition $e_1 = e_1^\sharp$ assures that the firm still prefers to stay in country A in both periods, rather than to relocate after period 1.

4.1.1 No adverse selection – Example

Let us return to our example from Section 2.1, to illustrate the above findings under no commitment for the special case without adverse selection. For simplicity, we set the discount factor δ and the cost parameter θ equal to 1: $\delta = \theta = 1$.

Using (14), we obtain: $e^*(a) = 1 - a$. Now apply condition (32) to obtain:

$$a_{AA}^{**}(e_1, \theta = 1) = (3 - e_1)/2.$$

As indicated in Lemma 4, the firm's optimal investment in abatement capital is declining in e_1 . Applying condition (20), we obtain for the critical value of e_1 :

$$e_1^\sharp = 7/2 - 2\pi_B.$$

In line with Lemma 5, this is declining in π_B . By (10), the firm's optimal (undistorted) emissions under location plan AA are $e_{AA}^o = -1$. Hence, by Proposition 3, the solution to the regulator's optimization problem is given by:

$$e_1 = \min\{e_{AA}^o = -1, e_1^\sharp = 7/2 - 2\pi_B\}, \text{ and } e_2 = e^*(a_{AA}^{**}(e_1, \theta)) = (e_1 - 1)/2.$$

Equalizing e_{AA}^o and e_1^\sharp , we find that if $\pi_B \leq 9/4$, the regulator does not distort the firm's emissions. If $\pi_B > 9/4$, emissions in the first period are distorted downwards in order to induce a higher abatement capital investment. This strengthens the lock-in effect in period 2, which allows the regulator to avert the firm's relocation without transfers in period 2: $t_2 = 0$ (Proposition 2). The optimal transfer in period 1 is given by:

$$t_1 = V_{BB} - V_{AA}^{**}(e_1, \theta) = 2\pi_B - 11/4 + e_1(2 + e_1)/4.$$

This is larger than the transfer $t = t_1 + \delta t_2 = V_{BB} - V_{AA}^o(\theta)$ under full commitment (see (28)) if e_1 is distorted ($\pi_B > 9/4$).

4.2 Limited commitment – Full model

Let us now reintroduce asymmetric information about the firm's cost parameter θ into the model. Hence, the hold-up problem illustrated in the previous subsection is combined with an adverse selection problem.

Consider the regulator's problem in period 2. In general, we cannot restrict the set of implementable outcomes in period 1 without knowledge about the set of implementable outcomes in period 2, because both sets are related. However, relevant for the regulator's optimization problem in period 2 is only the firm's abatement capital stock that was installed in period 1.¹⁵ In period 2, the regulator, thus, forms some belief over the value of a that may have been implemented in period 1. We express this in terms of a probability distribution function $F(a)$, with a support S .¹⁶ Hence, a is the firm's *type* in period 2, and we can formulate the regulator's problem in period 2 using standard mechanism design tools. In particular, the revelation principle holds, so we can focus on truthful direct revelation mechanisms $(e(a), t(a))$ for all $a \in S$. The regulator commits

¹⁵Because of our focus on short-term contracts, all other decision variables from period 1 (emissions, transfers...) do not affect the interaction between the regulator and the firm in period 2.

¹⁶ $F(\cdot)$ and S depend on the policies implemented in period 1, but this dependency is still unknown and irrelevant for what follows.

to offer the transfer $t(\tilde{a})$ and the emissions level $e(\tilde{a})$ if the agent announces the value $\tilde{a} \in S$. Given $t(\cdot)$, the firm (with an abatement capital stock of a) solves:

$$\max_{\tilde{a}} \pi_A(e(\tilde{a}), a) + t(\tilde{a}).$$

Suppose first that $t(\cdot)$ is differentiable.¹⁷ Then we obtain the following condition:

$$\dot{t}(\tilde{a}) + \frac{\partial \pi_A(e(\tilde{a}), a)}{\partial e} \dot{e}(\tilde{a}) = 0,$$

which under truth-telling yields the following local incentive constraint:

$$\dot{t}(a) + \frac{\partial \pi_A(e(a), a)}{\partial e} \dot{e}(a) = 0. \quad (21)$$

The local second-order condition:

$$\ddot{t}(\tilde{a})|_{\tilde{a}=a} + \frac{\partial^2 \pi_A(e(\tilde{a}), a)}{\partial e^2} \dot{e}(\tilde{a})|_{\tilde{a}=a} + \frac{\partial \pi_A(e(\tilde{a}), a)}{\partial e} \ddot{e}(\tilde{a})|_{\tilde{a}=a} \leq 0$$

can be rewritten as (using (21)):

$$\frac{\partial^2 \pi_A(e(a), a)}{\partial e \partial a} \dot{e}(a) \geq 0.$$

By our earlier assumptions (see Section 2), we have: $\partial^2 \pi_A(e, a) / \partial e \partial a < 0$. Hence, the local second-order condition simplifies to:

$$\dot{e}(a) \leq 0.$$

Let

$$U(a) = t(a) + \pi_A(e(a), a)$$

be the firm's payoff in period 2, including transfers. Differentiating this condition, the local incentive constraint (21) can be rewritten as:

$$\dot{U}(a) = \frac{\partial \pi_A(e(a), a)}{\partial a}.$$

The regulator, thus, solves the following problem in period 2:

$$\max_{\{(U(\cdot), e(\cdot))\}} \int_{a \in S} (\pi_A(e(a), a) - U(a)) dF(a), \quad (22)$$

¹⁷The following analysis can be extended in a straight-forward manner to the case where $t(\cdot)$ is piecewise differentiable.

subject to the constraints:

$$\dot{U}(a) = \frac{\partial \pi_A(e(a), a)}{\partial a}, \dot{e}(a) \leq 0, U(a) \geq \max\{\pi_B, \pi_A^*(a)\}.$$

We cannot solve this optimization problem in general without knowledge about $F(\cdot)$ and S . However, as a result of the hold-up problem, we are able to rule out certain outcomes in period 2. The following result extends Proposition 2 to the general case with adverse selection under no commitment:

Proposition 4. *As a result of the hold-up problem under no commitment, the regulator cannot implement any outcome that entails positive transfers to some a -types in the second period and where the transfer $t_2 = t(a)$ is (locally) differentiable in a at the lowest value of $a \in S$. Hence, either the transfers to all a -types are zero ($t_2 = 0$), or S is a disconnected set with a mass point located at the minimum of S and $F'(a) = 0$ over some non-zero interval located next to the mass point.*

As a result of Proposition 4, in what follows, we will restrict our attention on two possible types of equilibrium. The first type entails zero transfers ($t_2 = 0$) in the second period for all possible values of a . This implies that the regulator must design contracts in the first period in such a way that sufficient investment incentives are triggered for both θ -types to render the relocation-option unprofitable, once the investment costs are sunk. Hence, no transfers are needed in the second period in order to avert relocation. This equilibrium type corresponds to our results of Section 4.1, where we analyzed the simpler special case without adverse selection under no commitment.

The second equilibrium type is more subtle, and can exist *only* in the presence of adverse selection. This equilibrium is constructed in such a way that the hold-up problem vanishes for the lowest a -type, although this firm receives positive transfers in the second period. This is possible only if this type's investment in abatement capital is optimal for a permanent stay in country A, and at the same time optimal also when the firm plans to relocate from A to B in period 2. Such outcome can exist if the regulator distorts the lowest a -type's emissions upwards in the second period in order to reduce the information rent of the more efficient type(s), and this distortion is so high that the lowest a -type would not benefit from a rise in a in the second period, even if the additional abatement capital were obtained for free. This equilibrium type requires an information rent to the higher a -type(s) in the second period, which implies that the outcome of period 1 must not be (fully) revealing. Due to its special properties, we will analyze this type of outcome in a separate subsection.

Let us now focus on the first equilibrium type that extends our results from Section 4.1 in a straight-forward fashion. Given $t_2 = 0$, it remains to analyze what contracts the regulator offers in the first period under adverse selection. In line with Bester and Strausz

(2001), we will assume that the regulator offers at most two contracts in the first period, as there are two θ -types in the model.

Proposition 5. *Given $t_2 = 0$, the results of Bester and Strausz (2001) can be applied to the analysis of the regulator's problem in period 1.*

Given $t_2 = 0$, it is clear that the regulator can not distort the firm's choice of emissions in the second period, because to distort them, a positive transfer would be needed in order to compensate the firm for the reduced profit in that period (given the firm's outside option to stay in country A without accepting any contract in period 2). Therefore, the firm always chooses e_2 optimally in period 2 (given any value of a chosen in period 1). In period 1, the regulator's problem can, thus, be stated as

$$\min_{\underline{e}_1, \bar{e}_1, \underline{t}_1, \bar{t}_1} \nu \cdot \underline{t}_1 + (1 - \nu) \cdot \bar{t}_1, \quad (23)$$

subject to the following constraints.¹⁸ Each type of firm must prefer participation to immediate relocation, i.e.

$$V_{AA}^{**}(\underline{e}_1, \underline{\theta}) + \underline{t}_1 \geq V_{BB}, \quad (\text{PC-lc-1})$$

$$V_{AA}^{**}(\bar{e}_1, \bar{\theta}) + \bar{t}_1 \geq V_{BB}. \quad (\text{PC-lc-}\bar{1})$$

Furthermore, planned relocation at period 2 must be inferior for each type:

$$V_{AA}^{**}(\underline{e}_1, \underline{\theta}) + \underline{t}_1 \geq V_{AB}^*(\underline{e}_1, \underline{\theta}) + \underline{t}_1, \quad (\text{PC-lc-2})$$

$$V_{AA}^{**}(\bar{e}_1, \bar{\theta}) + \bar{t}_1 \geq V_{AB}^*(\bar{e}_1, \bar{\theta}) + \bar{t}_1. \quad (\text{PC-lc-}\bar{2})$$

The firm must be also incentivized to report her type truthfully:

$$V_{AA}^{**}(\underline{e}_1, \underline{\theta}) + \underline{t}_1 \geq V_{AA}^{**}(\bar{e}_1, \underline{\theta}) + \bar{t}_1, \quad (\text{IC-lc-1})$$

$$V_{AA}^{**}(\bar{e}_1, \bar{\theta}) + \bar{t}_1 \geq V_{AA}^{**}(\underline{e}_1, \bar{\theta}) + \underline{t}_1. \quad (\text{IC-lc-}\bar{1})$$

And finally, the firm must not find it optimal to misreport her type, planning to relocate in period 2:

$$V_{AA}^{**}(\underline{e}_1, \underline{\theta}) + \underline{t}_1 \geq V_{AB}^*(\bar{e}_1, \underline{\theta}) + \bar{t}_1, \quad (\text{IC-lc-2})$$

$$V_{AA}^{**}(\bar{e}_1, \bar{\theta}) + \bar{t}_1 \geq V_{AB}^*(\underline{e}_1, \bar{\theta}) + \underline{t}_1. \quad (\text{IC-lc-}\bar{2})$$

Before we characterize the equilibrium outcome in period 1, let us first state an important intermediate result. Let $\underline{e}_1^\#$ ($\bar{e}_1^\#$) be the solution to (20) when $\theta = \underline{\theta}$ (respectively

¹⁸See also Section 3.

$\theta = \bar{\theta}$). Recall, that e_1^\sharp is the critical emissions level in period 1 that makes the firm indifferent between location plans AA and AB when the emissions in period 2 are chosen optimally under location plan AA. Hence, in order to avert relocation permanently, a necessary condition is that $\underline{e}_1 \leq e_1^\sharp$ holds for the $\underline{\theta}$ -type, respectively $\bar{e}_1 \leq \bar{e}_1^\sharp$ for the $\bar{\theta}$ -type, for otherwise, relocation in period 2 would be profitable (given $t_2 = 0$). Now it follows immediately from Lemma 5 that:

$$\underline{e}_1^\sharp > \bar{e}_1^\sharp.$$

The intuition behind this result is quite simple. Given an identical emissions level e_1 imposed by the regulator for both types, the $\bar{\theta}$ -type is more tempted to relocate to B in period 2 than the $\underline{\theta}$ -type, because it is more costly for the $\bar{\theta}$ -type to invest in abatement capital, which leads to a lower profit in period 2 under the optimal investment (given location plan AA). Therefore, when π_B is raised in a comparative statics sense (see below), the constraint $\bar{e}_1 \leq \bar{e}_1^\sharp$ will be binding first, before $\underline{e}_1 \leq e_1^\sharp$ may become binding as well.

Let us now proceed to characterize the solution to the regulator's optimization problem in period 1. We start with an informal discussion of some basic properties, before we come to a full characterization of equilibrium properties (Proposition 6). It is clear that when π_B is small, the regulator does not need to distort the firm's emissions in period 1. If π_B is sufficiently small so that $V_{AA}^o(\bar{\theta}) \geq V_{BB}$, then no policy intervention is needed to prevent both types from relocating. Note, that $V_{AA}^o(\underline{\theta}) > V_{AA}^o(\bar{\theta})$ holds for any $\bar{\theta} > \underline{\theta}$, and $V_{AB}^o(\theta) \leq \max\{V_{AA}^o(\theta), V_{BB}\}$ holds by Lemma 2. Hence, if the inefficient θ -type prefers to stay permanently in A to immediate relocation, then the efficient type does, too, and relocation after one period is less profitable than staying permanently in A for both of them. Furthermore, we will show below that also when π_B is larger so that $V_{AA}^o(\bar{\theta}) < V_{BB}$, the regulator has no incentive to distort the firm's emissions in the first period as long as π_B is not too large.

On the other hand, it is clear that when π_B is large, so that $\bar{e}_1^\sharp < e_{AA}^o(\bar{\theta})$, the constraint $\bar{e}_1 \leq \bar{e}_1^\sharp$ will be binding in equilibrium, because it is impossible for the regulator to avert this type's relocation without transfers in period 2 when $\bar{e}_1 > \bar{e}_1^\sharp$ (by Lemma 5). Hence, the regulator needs to distort the inefficient type's emissions downwards in period 1, even when it would be desirable to distort them upwards in order to reduce the information rent to the efficient type (see Lemma 3 for the full commitment case). Furthermore, if π_B is sufficiently large so that $\underline{e}_1^\sharp < e_{AA}^o(\underline{\theta})$ holds even for the efficient type, then also this type's emissions will be distorted downwards in equilibrium. (Note, that the constraint $\bar{e}_1 \leq \bar{e}_1^\sharp$ becomes binding first when π_B is raised.)

These considerations give us a first idea of what the equilibrium will look like for extreme values of π_B (more details are shown below). Now suppose, π_B is in an interme-

diate range, where $V_{AA}^o(\underline{\theta}) < V_{BB}$ and $\bar{e}_1^\sharp > e_{AA}^o(\bar{\theta})$ are both satisfied. Hence, transfers are needed for both types in order to prevent their relocation to B, and it is possible to distort the inefficient type's emissions in period 1 upwards without inducing this type to relocate in period 2. Similarly as in Section 3, we will show that in the optimum, the participation constraint (PC-lc- $\bar{1}$) will be binding for the inefficient type (see below), which implies:

$$\bar{t}_1 = V_{BB} - V_{AA}^{**}(\bar{e}_1, \bar{\theta}), \quad (24)$$

whereas for the efficient type, the incentive constraint is binding. By Lemma 2, we can neglect conditions (PC-lc- $\underline{2}$) and (PC-lc- $\bar{2}$) if \underline{t}_1 resp. \bar{t}_1 are sufficiently large so that immediate relocation is not profitable, which obviously holds in any equilibrium. Therefore, the incentive constraint for the efficient type reduces to the following condition:

$$V_{AA}^{**}(\underline{e}_1, \underline{\theta}) + \underline{t}_1 = \bar{t}_1 + \max \{V_{AA}^{**}(\bar{e}_1, \underline{\theta}), V_{AB}^*(\bar{e}_1, \underline{\theta})\}. \quad (25)$$

Lemma 6. *If $\bar{e}_1 < \bar{e}_1^\sharp$, then $V_{AA}^{**}(\bar{e}_1, \underline{\theta}) > V_{AB}^*(\bar{e}_1, \underline{\theta})$.*

Lemma 6 implies that if $\bar{e}_1 \leq \bar{e}_1^\sharp$ (which must hold in equilibrium by Lemma 5), then the incentive constraint for the efficient type, (25), reduces further to the following condition:

$$\underline{t}_1 = \bar{t}_1 + V_{AA}^{**}(\bar{e}_1, \underline{\theta}) - V_{AA}^{**}(\underline{e}_1, \underline{\theta}), \quad (26)$$

which determines \underline{t}_1 as a function of \bar{t}_1 .

Replacing \bar{t}_1 and \underline{t}_1 (using (24) and (26)), the regulator seeks to minimize the expected transfer $\underline{v} \cdot \underline{t}_1 + (1 - \underline{v}) \cdot \bar{t}_1$ over \underline{e}_1 and \bar{e}_1 . We will show below that – as in the full commitment case (Proposition 3) – the regulator does not distort the efficient type's emissions ($\underline{e}_1 = e_{AA}^o(\underline{\theta})$), but distorts the inefficient type's emissions upwards to reduce the information rent of the efficient type. For later reference, denote the value of \bar{e}_1 obtained by solving the above optimization problem by \bar{e}_1^d ("d" for *distorted*).

If π_B is smaller, so that $V_{AA}^o(\bar{\theta}) < V_{BB}$ but $V_{AA}^o(\underline{\theta}) > V_{BB}$, the regulator may not want to distort \bar{e}_1 up to the level of \bar{e}_1^d . This is because the distortion makes the contract designed for the inefficient type less attractive for the efficient type. Since $V_{AA}^o(\underline{\theta}) > V_{BB}$, it may well be that – given the distortion – the $\underline{\theta}$ -type prefers to stay in A without accepting any contract, rather than to choose the inefficient type's contract. This holds if the transfer to the efficient type (\underline{t}_1) obtained under the above optimization problem is negative. Since the firm has the freedom not to choose any contract and yet to continue to produce in A, a negative transfer cannot be implemented in a short-term contract. Therefore, the regulator prefers to distort \bar{e}_1 by less, and can still offer the efficient type a transfer of zero without inducing this type to choose the contract designed for the inefficient type. \bar{e}_1 is, then, determined as part of a *corner solution*, and we denote its resulting value by \bar{e}_1^c (for later reference). Formally, \bar{e}_1^c is determined by the following

condition (inserting (24) into (26), setting $t_1 = 0$ and $e_1 = e^o(\underline{\theta})$):

$$V_{AA}^o(\underline{\theta}) = V_{BB} - V_{AA}^{**}(\bar{e}_1^c, \bar{\theta}) + V_{AA}^{**}(\bar{e}_1^c, \underline{\theta}). \quad (27)$$

We are now ready to state the main result of this section.

Proposition 6. *Raising the value of π_B , the solution to the regulator's problem in period 1 passes through the following intervals characterized by:*

- (i) $e_1 = e^o(\underline{\theta})$, $\bar{e}_1 = e^o(\bar{\theta})$, and $\underline{t}_1 = \bar{t}_1 = 0$ if π_B is sufficiently small so $V_{AA}^o(\bar{\theta}) \geq V_{BB}$ (no policy intervention)
- (ii) $e_1 = e^o(\underline{\theta})$, $\bar{e}_1 = e^o(\bar{\theta})$, $\underline{t}_1 = 0$, and $\bar{t}_1 = V_{BB} - V_{AA}^o(\bar{\theta})$ if $V_{AA}^o(\bar{\theta}) < V_{BB}$, $V_{AA}^o(\underline{\theta}) \geq V_{BB}$, and $\bar{e}_1^c \leq e^o(\bar{\theta})$
- (iii) $e_1 = e^o(\underline{\theta})$, $\bar{e}_1 = \bar{e}_1^c$, $\underline{t}_1 = 0$, and $\bar{t}_1 = V_{BB} - V_{AA}^{**}(\bar{e}_1^c, \bar{\theta})$ if $e^o(\bar{\theta}) < \bar{e}_1^c \leq \min\{\bar{e}_1^d, \bar{e}_1^\#\}$
- (iv) $e_1 = e^o(\underline{\theta})$, $\bar{e}_1 = \bar{e}_1^d$, $\bar{t}_1 = V_{BB} - V_{AA}^{**}(\bar{e}_1^d, \bar{\theta})$, and \underline{t}_1 given by (25) if $\bar{e}_1^d < \min\{\bar{e}_1^c, \bar{e}_1^\#\}$
- (v) $e_1 = e^o(\underline{\theta})$, $\bar{e}_1 = \bar{e}_1^\#$, $\bar{t}_1 = V_{BB} - V_{AA}^{**}(\bar{e}_1^\#, \bar{\theta})$, and \underline{t}_1 given by (25) if $e^o(\underline{\theta}) \leq \bar{e}_1^\# < \bar{e}_1^d$
- (vi) $e_1 = \bar{e}_1 = \bar{e}_1^\#$, and $\underline{t}_1 = \bar{t}_1 = V_{BB} - V_{AA}^{**}(\bar{e}_1^\#, \bar{\theta})$ if $\bar{e}_1^\# < e^o(\underline{\theta})$ (pooling).

Remark: If the upper boundary of interval (iii) is defined by the condition $\bar{e}_1^c = \bar{e}_1^\#$ rather than $\bar{e}_1^c = \bar{e}_1^d$, then interval (iv) is an empty set. Hence, in this case, the equilibrium moves from interval (iii) directly to interval (v). Otherwise, the results remain unchanged.

In order to get an intuition for Proposition 6, let us illustrate the results using our example of Section 2.1. Note, that for the moment, we are still excluding the second equilibrium type (see Proposition 4) that involves positive transfers in period 2, which is analyzed in a separate subsection. There, it will be shown that the outcome under this equilibrium is generally highly distorted and, thus, typically inferior to the above outcome from the regulator's perspective, unless π_B is very large.

4.2.1 Full model – Example

Let us apply these results to our example. Maximizing the profit function in (8) over e , we obtain $e^*(a) = 1 - a$ for the firm's optimal emissions (given a), and $\pi_A^*(a) = \frac{1}{2} + a$. Inserting this into $V_{AA}(e_1, e_2, a, \theta)$ ((1)), we obtain by maximizing over a :

$$a_{AA}^{**}(e_1, \theta) = \frac{2 - e_1 + \delta}{1 + \theta},$$

whereas a_{AB}^* is given by:

$$a_{AB}^*(e_1, \theta) = \frac{2 - e_1}{1 + \theta}.$$

Equalizing the resulting value functions $V_{AA}^{**}(e_1, \theta)$ and $V_{AB}^*(e_1, \theta)$, and solving for e_1 , we obtain the critical emissions level:

$$e_1^\# = \frac{1}{2}(5 + \delta + \theta) - (1 + \theta)\pi_B.$$

Imposing an emissions target for type θ not larger than $e_1^\#$, the regulator induces the firm to invest enough in abatement capital to render the option to relocate in period 2 unprofitable, whenever the firm plans to stay for at least one period. Transfers in period 2 are, then, not needed to avert relocation, while transfers in period 1 assure that the firm does not relocate immediately.

Let us now specify the parameter values to illustrate the outcome of the regulator's optimization problem under limited commitment. We choose values for which all intervals in Proposition 6 are visible. Let $\underline{\theta} = 5$, $\bar{\theta} = 7.5$, and $\delta = 1$. Figure 1 shows how the regulator sets the emissions targets for the two types in period 1, depending on π_B .

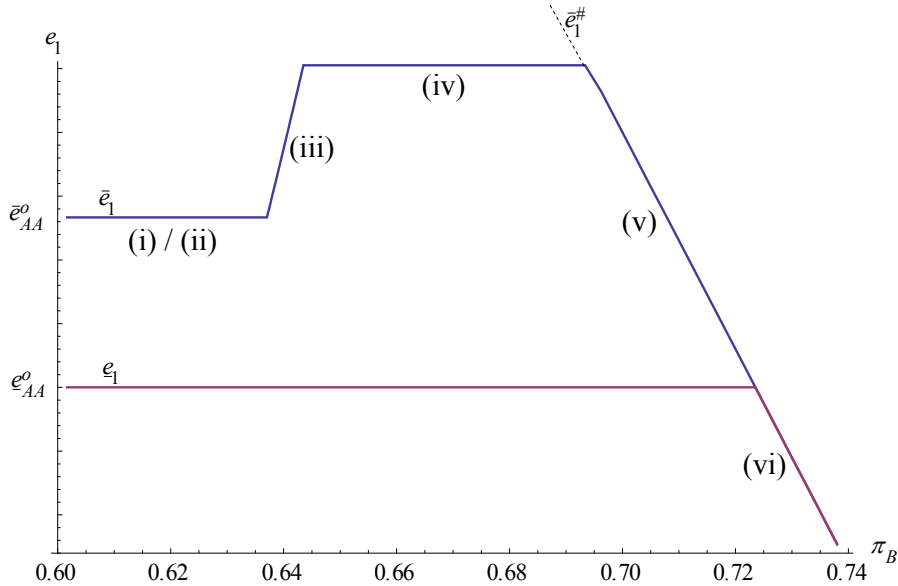


Figure 1: Emissions levels in period 1 under limited commitment

The figure illustrates that when π_B is sufficiently small, then the regulator does not distort the firm's emissions. The optimal emissions (under full information and no relocation) are given by $e_{AA}^o(\underline{\theta}) = 0.6$ and $e_{AA}^o(\bar{\theta}) = 0.733$. If $\pi_B < 0.633$ then $V_{AA}^o(\bar{\theta}) \geq V_{BB}$, so no policy intervention is needed to avert relocation of both types (interval (i)). If $0.633 \leq \pi_B \leq 0.637$, the regulator offers a transfer only to the inefficient type in period 1, while emissions remain undistorted (interval (ii)). In interval (iii), the regulator distorts the inefficient type's emissions upwards. Given this distortion, transfers to the efficient type are, however, not needed to avert relocation of both types (corner solution: $\bar{e}_1 = \bar{e}_1^c$). In interval (iv), positive transfers are paid to both types in period 1, and the inefficient

type's emissions are distorted to reduce the information rent of the efficient type. In this example, the optimal distortion (\bar{e}_1^d) is independent of π_B , so \bar{e}_1 reaches a plateau. In interval (v), it holds that $\bar{e}_1^d > e_1^\#(\bar{\theta})$, which cannot be implemented, so the regulator needs to reduce the emissions assigned to the inefficient type again, for otherwise, this firm relocates in period 2. Finally, in interval (vi), the regulator sets $\underline{e}_1 = \bar{e}_1 = \bar{e}_1^\#$ (pooling), because $e^o(\underline{\theta}) > \bar{e}_1^\#$, so in order to separate the types, even higher distortions would be needed, requiring higher transfers.

5 Conclusion

Firm relocation is one of the main channels of carbon leakage. If some countries introduce higher emissions prices in an attempt to curb global emissions, while other countries remain largely inactive in the area of climate protection, relocation of firms in emission-intensive industries can become a serious problem for countries that actively try to reduce their emissions, especially when relocation is associated with a loss of jobs in the active country. The fear of a loss of employment may explain partly why countries are often reluctant to introduce emissions prices in the first place.

The free allocation of emissions permits may help to cushion the negative impact upon firms' profitability in case the emissions price arises in the context of emissions trading. Such "grandfathering" of emissions may also be used by politicians as an instrument to reduce pressure from lobbyist groups against environmental regulation (Sterner and Isaksson, 2006). Assuming that such implicit subsidies to firms cannot be maintained indefinitely, they would clearly be socially wasteful if firms relocate after the transfers terminate. This may explain why environmental interest groups often argue in favor of auctioning the permits, rather than allocating them to the polluting firms for free.

Our analysis, however, shows that a free allocation of permits at the initial phase of an emissions trading scheme, or direct transfers to firms in case of an emissions tax, can be rationalized on economic grounds, if firms are able to reduce their emissions in the regulating country via technology improvements or abatement capital investments. Furthermore, the impact upon firms' location decision may be a *permanent* one even if the transfers terminate in finite time (after one period in our model). Behind this central result of our analysis lies a 'lock-in effect' of abatement capital investments. Namely, when the investment is sufficiently large, then the negative impact of the emissions price in the home country upon the profitability of a polluting firm can be mitigated, to an extent that relocation to the foreign country becomes unprofitable.

Our model applies methods developed in the theory of contracts to a specific environmental economic problem. Using a model with asymmetric information and imperfect commitment, we have shown in this paper that the regulator can exploit the lock-in effect

of abatement capital investments in order to design effective incentive contracts that avert a firm's relocation permanently with a minimum of (expected) transfers. Assuming that the regulator cannot observe (nor infer) the firm's abatement capital investment, transfers to the firm are conditioned on its emissions. Pure location-based transfer schemes (grandfathering) can also be effective, but the regulator can generally avert a firm's relocation more cost-effectively by regulating also the firm's emissions.

As a result of the limited commitment problem, in our model the regulator often imposes lower emissions in the first period, in order to induce the firm to invest more in abatement capital. This strengthens the lock-in effect, and makes further transfers in period 2 unnecessary. When relocation is very attractive (hence, when the emissions price in the home country is sufficiently high), the regulator no longer separates between types, and instead offers a pooling contract in the first period. Our results can guide policy-makers towards a more effective design of transfer schemes, such as for instance allocation schemes of free permits.

A Appendix: Proofs

Proof of Lemma 1. For the first three claims recall

$$V_{AA}^*(e_1, e_2, \theta) = \max_a \pi_A(e_1, a) - K(a, \theta) + \delta \pi_A(e_2, a).$$

By the envelope theorem we have

$$\frac{\partial}{\partial e_2} V_{AA}^*(e, e, \theta) = \delta \cdot \frac{\partial}{\partial e} \pi_A(e, a_{AA}^*) = \delta \cdot \frac{\partial}{\partial e_1} V_{AA}^*(e, e, \theta).$$

which proves the first claim. For the second claim, we further differentiate with respect to θ , which yields

$$\frac{\partial^2}{\partial e_t \partial \theta} V_{AA}^*(e_1, e_2, \theta) = \delta^{t-1} \frac{\partial^2}{\partial e_t \partial a} \pi_A(e_t, a_{AA}^*) \cdot \frac{\partial}{\partial \theta} a_{AA}^* > 0.$$

The derived expression is positive since both $\frac{\partial^2 \pi_A}{\partial e \partial a} < 0$ and, as we shall show at the end of this proof, $\frac{\partial a_{AA}^*}{\partial \theta} < 0$. The cross-partial of V_{AB}^* can be derived in the same manner and thus also claim (1.d) is proven.

To proof concavity we proceed as follows:

$$\begin{aligned} & V_{AA}^*(\lambda e_1 + (1 - \lambda)\tilde{e}_1, e_2, \theta) \\ &= \max_a \pi_A(\lambda e_1 + (1 - \lambda)\tilde{e}_1, a) - K(a, \theta) + \delta \pi_A(e_2, a) \\ &= \max_{a, \tilde{a}} \pi_A(\lambda e_1 + (1 - \lambda)\tilde{e}_1, \lambda a + (1 - \lambda)\tilde{a}) - K(\lambda a + (1 - \lambda)\tilde{a}, \theta) + \delta \pi_A(e_2, \lambda a + (1 - \lambda)\tilde{a}) \\ &\geq \max_{a, \tilde{a}} \left\{ \lambda \pi_A(e_1, a) + (1 - \lambda) \pi_A(\tilde{e}_1, \tilde{a}) - \lambda K(a, \theta) - (1 - \lambda) K(\tilde{a}, \theta) \right. \\ &\quad \left. + \lambda \delta \pi_A(e_2, a) + (1 - \lambda) \delta \pi_A(e_2, \tilde{a}) \right\} \\ &= \lambda \max_a \left\{ \pi_A(e_1, a) - K(a, \theta) + \delta \pi_A(e_2, a) \right\} + (1 - \lambda) \max_{\tilde{a}} \left\{ \pi_A(\tilde{e}_1, \tilde{a}) - K(\tilde{a}, \theta) + \delta \pi_A(e_2, \tilde{a}) \right\} \\ &= \lambda V_{AA}^*(e_1, e_2, \theta) + (1 - \lambda) V_{AA}^*(\tilde{e}_1, e_2, \theta) \end{aligned}$$

The inequality holds, since both $-K(a, \theta)$ and $\pi_A(e, a)$ are concave in a and the function $\pi_A(e, a)$ is jointly concave in e, a .¹⁹ Proving concavity in e_2 and concavity of V_{AB}^* uses the same line of arguments and is omitted here.

Last, consider $a_{AA}^*(e_1, e_2, \theta)$ which is implicitly defined by the first-order condition

$$\frac{\partial \pi_A(e_1, a)}{\partial a} + \delta \frac{\partial \pi_A(e_2, a)}{\partial a} = \frac{\partial K(a, \theta)}{\partial a}.$$

¹⁹This is true since all partial second derivatives are negative by assumptions and therefore the Hessian is negative semi-definite which is a sufficient condition for joint-concavity.

Differentiating the above condition w.r.t. θ , we obtain after rearranging:

$$\frac{\partial a_{AA}^*(e_1, e_2, \theta)}{\partial \theta} = \frac{\partial K(a, \theta)}{\partial a \partial \theta} / \left(\frac{\partial^2 \pi_A(e_1, a)}{\partial a^2} + \frac{\partial^2 \pi_A(e_2, a)}{\partial a^2} - \frac{\partial^2 K(a, \theta)}{\partial a^2} \right).$$

By our earlier assumptions, we have: $\partial^2 \pi_A(e, a) / \partial a^2 < 0$, $\partial^2 K(a, \theta) / \partial a \partial \theta > 0$, and $\partial^2 K(a, \theta) / \partial a^2 \geq 0$. Hence, $\partial a_{AA}^*(e_1, e_2, \theta) / \partial \theta < 0$. To show that $\partial a_{AB}^*(e_1, \theta) / \partial \theta < 0$, use the same steps as above, but replace $\partial \pi_A(e_2, a) / \partial a$ by $\partial \pi_B / \partial a = 0$. \square

Proof of Lemma 2. Assume $V_{AB}^*(e, \theta) \geq V_{BB}$. Using $a_{AB} = a_{AB}(e, \theta)$ for short, this can be written as

$$\pi_A(e, a_{AB}) - K(a_{AB}, \theta) + \delta \pi_B \geq \pi_B + \delta \pi_B.$$

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

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

Hence, we have shown the claimed for $V_{AB}^*(e, \theta) \geq V_{BB}$. On the other hand, the claimed is trivially true whenever $V_{BB} > V_{AB}^*(e, \theta)$. \square

Proof of Lemma 3. We adopt the standard procedure of considering only the local downward constraints, i.e. (PC- $\bar{1}$) and (IC- $\underline{1}$). When considering the problem with only these two constraints it is straightforward that both will be binding at the optimum. Solving both binding constraints for the transfers yields

$$\bar{t} = V_{BB} - V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta}), \quad (28)$$

$$\underline{t} = V_{BB} + V_{AA}^*(\bar{e}_1, \bar{e}_2, \underline{\theta}) - V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta}) - V_{AA}^*(\underline{e}_1, \underline{e}_2, \underline{\theta}). \quad (29)$$

Replacing transfers in the regulator's objective function leads us to the following first-order conditions

$$\frac{\partial}{\partial e_t} V_{AA}^*(\underline{e}_1, \underline{e}_2, \underline{\theta}) = 0, \quad t = 1, 2 \quad (30)$$

$$\frac{\partial}{\partial e_t} V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta}) = \frac{\nu}{1-\nu} \frac{\partial}{\partial e_t} (V_{AA}^*(\bar{e}_1, \bar{e}_2, \underline{\theta}) - V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta})) \quad t = 1, 2. \quad (31)$$

Clearly (30) implies $\underline{e}_1 = \underline{e}_2 = \underline{e}^o$. We next derive (13). Recall by Lemma 1 we have $\delta \frac{\partial}{\partial e_1} V_{AA}^*(e_1, e_2, \theta) = \frac{\partial}{\partial e_2} V_{AA}^*(e_1, e_2, \theta)$ and therefore the first-order conditions given by (31)

coincide for $t = 1, 2$, which proves $\bar{e}_1 = \bar{e}_2$ and the validity of (13).

We now prove that $\bar{e}^{sb} > \bar{e}^o$. To see this, first recall that \bar{e}^o is given by

$$\frac{\partial}{\partial e_t} V_{AA}^*(\bar{e}^o, \bar{e}^o, \bar{\theta}) = 0, \quad t = 1, 2.$$

Second, by Lemma 1 the right-hand side of (31) is strictly negative. This yields

$$\frac{\partial}{\partial e_t} V_{AA}^*(\bar{e}_1^{sb}, \bar{e}_2^{sb}, \bar{\theta}) < 0 = \frac{\partial}{\partial e_t} V_{AA}^*(\bar{e}^o, \bar{e}^o, \bar{\theta}).$$

Again, by Lemma 1 the function V_{AA}^* is concave both in e_1 and e_2 and therefore it must hold that $\bar{e}^{sb} > \bar{e}^o$.

It remains to show that the derived solution satisfies the omitted constraints. We begin with the efficient firm's participation constraint (PC-1):

$$V_{AA}^*(\underline{e}_1, \underline{e}_2, \underline{\theta}) + \underline{t} \stackrel{\text{(IC-1)}}{\geq} V_{AA}^*(\bar{e}_1, \bar{e}_2, \underline{\theta}) + \bar{t} > V_{AA}^*(\bar{e}_1, \bar{e}_2, \bar{\theta}) + \bar{t} \stackrel{\text{(PC-}\bar{1})}{\geq} V_{BB}.$$

Thus (PC-1) is satisfied. For (IC- $\bar{1}$) it is sufficient to show that the right-hand side is not larger than V_{BB} , since the left-hand side equals V_{BB} (from (PC- $\bar{1}$)). We have

$$V_{AA}^*(\underline{e}^o, \underline{e}^o, \bar{\theta}) + \underline{t} = V_{BB} + V_{AA}^*(\bar{e}^{sb}, \bar{e}^{sb}, \underline{\theta}) - V_{AA}^*(\bar{e}^{sb}, \bar{e}^{sb}, \bar{\theta}) - (V_{AA}^*(\underline{e}^o, \underline{e}^o, \underline{\theta}) - V_{AA}^*(\underline{e}^o, \underline{e}^o, \bar{\theta})).$$

Now the right-hand side of this expression is strictly smaller than V_{BB} since $\frac{\partial^2}{\partial e \partial \theta} V_{AA}^* > 0$. \square

Proof of Proposition 1. The first claim follows immediately from Lemma 2: By our assumption, that $V_{BB} > V_{AA}^o(\underline{\theta})$ we also have $V_{BB} \geq V_{AB}(e, \theta)$ for all e and all $\theta \in \{\underline{\theta}, \bar{\theta}\}$. When the transfer in period 1 is zero, the firm will therefore only get $V_{AB}(e, \theta)$ when planning to relocate in period 2, which is always less compared to immediate relocation. But the contract is designed such, that each type of firm prefers accepting the contract to immediate relocation and consequently to any kind of misreporting and/or delayed relocation. \square

Proof of Lemma 4. Applying condition (16) to the first-order condition that defines the function $a_{AA}^*(e_1, e_2, \theta)$ (see the proof of Lemma 1), we obtain:

$$\frac{\partial \pi_A(e_1, a_{AA}^{**})}{\partial a} + \delta \frac{\partial \pi_A(e^*(a_{AA}^{**}), a_{AA}^{**})}{\partial a} = \frac{\partial K(a_{AA}^{**}, \theta)}{\partial a}. \quad (32)$$

$e^*(a)$ is defined by the condition $\partial \pi_A(e, a) / \partial e = 0$. Therefore, applying the Envelope

Theorem, we observe that

$$\frac{d}{da} \left(\frac{\partial \pi_A(e^*(a), a)}{\partial e} \right) = 0.$$

Differentiating condition (32) w.r.t. e_1 , we obtain after rearranging and using the Envelope Theorem:

$$\frac{\partial a_{AA}^{**}(e_1, \theta)}{\partial e} = \frac{\partial^2 \pi_A(e_1, a_{AA}^{**})}{\partial a \partial e} / \left(\frac{\partial^2 K(a_{AA}^{**}, \theta)}{\partial a^2} - \frac{\partial^2 \pi_A(e_1, a_{AA}^{**})}{\partial a^2} \right).$$

Furthermore, by our basic assumptions from Section 2, we have: $\partial^2 \pi_A(e, a) / \partial a \partial e < 0$, $\partial^2 \pi_A(e, a) / \partial a^2 < 0$, and $\partial^2 K(a, \theta) / \partial a^2 > 0$. Therefore, $\partial a_{AA}^{**}(e_1, \theta) / \partial e_1 < 0$. To show that $a_{AB}^*(e_1, \theta)$ is decreasing in e_1 , follow the same steps as above, replacing the profit in period 2 by π_B . \square

Proof of Proposition 2. Suppose to the contrary that a solution to the regulator's problem exists that fulfills $\pi_B \geq \pi_A^*(a_{AA}^{**})$, with $a_{AA}^{**} = a_{AA}^{**}(e_1, \theta)$ for short. By (18), this implies $t_2 \geq 0$, and $\pi_A^*(a_{AA}^{**}) + t_2 = \pi_B$ (the firm is indifferent in period 2 between relocating and staying in A, given $a = a_{AA}^{**}$). By our basic assumptions (see Section 2), we know that $\pi_A(e_1, a) - K(a, \theta)$ is concave in a (for any given e_1), and that $\pi_A^*(a)$ is increasing in a . Since $a_{AA}^{**}(e_1, \theta)$ maximizes

$$\pi_A(e_1, a) - K(a, \theta) + \delta \pi_A^*(a), \quad (33)$$

whereas $a_{AB}^*(e_1, \theta)$ maximizes

$$\pi_A(e_1, a) - K(a, \theta) + \delta \pi_B,$$

it follows immediately that $a_{AA}^{**}(e_1, \theta) > a_{AB}^*(e_1, \theta)$, and

$$\pi_A(e_1, a_{AB}^*) - K(a_{AB}^*, \theta) > \pi_A(e_1, a_{AA}^{**}) - K(a_{AA}^{**}, \theta).$$

This inequality implies:²⁰

$$V_{AB}(e_1, a_{AB}^*, \theta) + t_1 > V_{AB}(e_1, a_{AA}^{**}, \theta) + t_1 = V_{AA}^{**}(e_1, \theta) + t_1 + \delta t_2,$$

where the equality follows from (18) (the firm is indifferent between relocating in period 2 and staying in A, given $a = a_{AA}^{**}$). Hence, relocation in period 2 is profitable, which completes the proof. \square

²⁰Note, that $V_{AA}^{**}(e_1, \theta) = V_{AA}^*(e_1, e^*(a_{AA}^{**}), \theta)$ by (15) and (3).

Proof of Lemma 5. To show the first claim, rewrite (20) as:

$$\pi_A(e_1^\sharp, a_{AA}^{**}) - K(a_{AA}^{**}, \theta) + \delta\pi_A^*(a_{AA}^{**}) = \pi_A(e_1^\sharp, a_{AB}^*) - K(a_{AB}^*, \theta) + \delta\pi_B,$$

where $a_{AA}^{**} = a_{AA}^{**}(e_1, \theta)$ and $a_{AB}^* = a_{AB}^*(e_1, \theta)$ for short. To analyze the comparative statics with respect to changes in the parameter π_B , differentiate both sides w.r.t. π_B to obtain after rearranging (note, that a_{AA}^{**} and a_{AB}^* are independent of π_B):

$$\frac{de_1^\sharp}{d\pi_B} = \delta \left(\frac{\partial\pi_A(e_1, a_{AA}^{**})}{\partial e} - \frac{\partial\pi_A(e_1, a_{AB}^*)}{\partial e} \right)^{-1}.$$

Since $a_{AA}^{**} > a_{AB}^*$ (see the proof of Proposition 2), and $\frac{\partial^2\pi_A(e, a)}{\partial e\partial a} < 0$, the right-hand side is negative.

To show the second claim, recall that condition (20) defines e_1^\sharp as a function of θ . Therefore, it holds for all θ that $V_{AA}^{**}(e_1^\sharp(\theta), \theta) = V_{AB}^*(e_1^\sharp(\theta), \theta)$, and we can differentiate this condition with respect to θ to obtain:

$$dV_{AA}^{**}(e_1^\sharp(\theta), \theta)/d\theta - dV_{AB}^*(e_1^\sharp(\theta), \theta)/d\theta = 0.$$

Let

$$\Delta(e_1, \theta) \equiv V_{AA}^{**}(e_1, \theta) - V_{AB}^*(e_1, \theta).$$

Hence, evaluating the derivatives, the above condition yields after rearranging:

$$\frac{de_1^\sharp(\theta)}{d\theta} = - \left(\frac{\partial\Delta(e_1^\sharp(\theta), \theta)}{\partial\theta} \right) / \left(\frac{\partial\Delta(e_1^\sharp(\theta), \theta)}{\partial e_1} \right). \quad (34)$$

Applying the Envelope Theorem, we find that:

$$\frac{\partial V_{AA}^{**}(e_1, \theta)}{\partial\theta} = - \frac{\partial K(a_{AA}^{**}, \theta)}{\partial\theta}, \text{ and } \frac{\partial V_{AB}^*(e_1, \theta)}{\partial\theta} = - \frac{\partial K(a_{AB}^*, \theta)}{\partial\theta}.$$

Therefore, we have:

$$\frac{\partial\Delta(e_1^\sharp(\theta), \theta)}{\partial\theta} = \frac{\partial K(a_{AB}^*, \theta)}{\partial\theta} - \frac{\partial K(a_{AA}^{**}, \theta)}{\partial\theta}.$$

Since $a_{AA}^{**} > a_{AB}^*$ (see the proof of Proposition 2), it follows immediately from our basic assumption $\partial^2 K(a, \theta)/\partial a\partial\theta > 0$ (see Section 2) that $\partial\Delta(e_1^\sharp(\theta), \theta)/\partial\theta < 0$, hence, the numerator in (34) is negative. Now consider the denominator. We will show below that $\partial\Delta(e_1, \theta)/\partial e_1 < 0$ for all e_1 . Therefore, the denominator in (34) is also negative. Hence, $de_1^\sharp(\theta)/d\theta < 0$, which completes the proof of the second statement.

To show the third claim, note first that the condition $V_{AA}^{**}(e_1, \theta) \geq V_{AB}^*(e_1, \theta)$ is

equivalent to: $\Delta(e_1, \theta) \geq 0$. We can now apply the definitions of V_{AA}^{**} and V_{AB}^* :

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

where $a_{AA}^{**} = a_{AA}^{**}(e_1, \theta)$ and $a_{AB}^* = a_{AB}^*(e_1, \theta)$ for short. By the Envelope Theorem, $dV_{AA}^{**}(e_1, \theta)/da = 0$, and $dV_{AB}^*(e_1, \theta)/da = 0$, or more explicitly:

$$\frac{dV_{AA}^{**}(e_1, \theta)}{da} = \frac{\partial\pi_A(e_1, a_{AA}^{**})}{\partial a} - \frac{\partial K(a_{AA}^{**}, \theta)}{\partial a} + \delta \frac{\partial\pi_A^*(a_{AA}^{**})}{\partial a} = 0,$$

and similarly for $dV_{AB}^*(e_1, \theta)/da$. Applying the Envelope Theorem, we, thus, find:

$$\frac{\partial\Delta(e_1, \theta)}{\partial e_1} = \frac{\partial\pi_A(e_1, a_{AA}^{**})}{\partial e_1} - \frac{\partial\pi_A(e_1, a_{AB}^*)}{\partial e_1}.$$

Since $a_{AA}^{**} > a_{AB}^*$ (see the proof of Proposition 2), it follows from $\partial^2\pi_A(e, a)/\partial e\partial a < 0$ (Section 2) that $\partial\Delta(e_1, \theta)/\partial e_1 < 0$. The claim now follows immediately by noting that $V_{AA}^{**}(e_1^\sharp, \theta) = V_{AB}^*(e_1^\sharp, \theta)$ holds by the definition of e_1^\sharp . \square

Proof of Proposition 3. We distinguish two cases, and show existence of the solution by construction.

Case 1: $e_1^\sharp \geq e_{AA}^o$. By Proposition 2, any solution to the regulator's problem must fulfill $t_2 = 0$. Therefore, all transfers to the firm take place in period 1. To avert relocation with minimal transfers, it must hold that $e_1 = e_{AA}^o$ (any other emissions level is distorted and, thus, requires higher transfers to compensate the firm for the reduced profits in country A). It remains to be shown that – given this emissions level in period 1 – the firm does not relocate in period 1 or period 2 when $t_1 = V_{BB} - V_{AA}^{**}(e_1, \theta)$. Clearly, as shown in the main text, relocation in period 2 is less profitable than staying in A in both periods, as $e_1^\sharp \geq e_{AA}^o$. Furthermore, given the transfer in period 1, we have: $V_{AA}^{**}(e_1, \theta) + t_1 = V_{BB}$, so the firm does not benefit from immediate relocation either.

Case 2: $e_1^\sharp < e_{AA}^o$. Given $t_2 = 0$, $t_1 = V_{BB} - V_{AA}^{**}(e_1, \theta)$ assures that the firm's relocation is averted with minimal transfers in period 1. It remains to be shown that $V_{AA}^{**}(e_1, \theta)$ is increasing in e_1 for all $e_1 < e_{AA}^o$. Since e_{AA}^o maximizes $V_{AA}^*(e_1, e_2, \theta)$, this follows immediately from the concavity of this function (see Section 2). \square

Proof of Proposition 4. The maximization problem (22) is a standard mechanism design problem. The single-crossing condition for this problem is: $\partial^2\pi_A(e, a)/\partial e\partial a < 0$, and it is fulfilled by our basic assumptions outlined in Section 2. Therefore, the participation constraint $U(a) \geq \pi_B$ is binding only for the lowest type a_{min} if this type receives a

positive transfer in period 2, which holds if $\pi_A^*(a_{min}) < \pi_B$, and for all other values of $a \in S$ that fulfill $\pi_A^*(a) < \pi_B$, the local incentive constraint $\dot{U}(a) = \partial\pi_A(e(a), a)/\partial a$ is binding. Therefore, the solution to the regulator's problem in period 2 clearly entails $U'(a) > 0$ for all $a \in S$.

Given this result, we can apply the proof of Proposition 2 to the lowest value of $a \in S$, a_{min} , replacing $\delta\pi_A^*(a)$ by $U(a)$ in (33). Hence, if the firm with the lowest value of a that occurs in equilibrium is offered a transfer in period 2 that makes this firm indifferent (given a) between staying in A and relocating to B, then this firm is better off adjusting its abatement capital stock in period 1 optimally for just one period in A ($a_{AB}^*(e_1, \theta)$), planning to relocate after period 1. The hold-up problem, thus, applies to the firm with the lowest value of a that can occur in equilibrium. To prevent this firm from relocating, the regulator would have to offer a higher transfer in period 2, but cannot commit to such an offer because ex-post (once a is chosen), the regulator benefits from reducing the transfers in period 2, such that the lowest type is just indifferent between relocating or not (given a). Therefore, any solution to the regulator's problem entails $t_2 = t(a) = 0$ for the lowest type when $t(a)$ is (locally) differentiable at a_{min} , which (by $U'(a) > 0$) implies that $t_2 = 0$ holds for all types. $t(a) > 0$ for some a , therefore, requires that S is a disconnected set with an isolated mass point located at the minimum of S . \square

Proof of Lemma 6. By Lemma 5, the condition $V_{AA}^{**}(\bar{e}_1, \underline{\theta}) > V_{AB}^*(\bar{e}_1, \underline{\theta})$ is equivalent to: $\bar{e}_1 < \underline{e}_1^\#$. Furthermore, we have $\bar{e}_1^\# < \underline{e}_1^\#$. Hence, the claim $\bar{e}_1 < \underline{e}_1^\#$ follows immediately from $\bar{e}_1 < \bar{e}_1^\#$. \square

References

- [1] Ahman, M. and L. Zetterberg (2005) Options for Emissions Allowance Allocation under the EU Emissions Trading Scheme, *Mitigation and Adaptation Strategies for Global Change*, 10, 597–645.
- [2] Baron, D.P. (1985a) Noncooperative Regulation of a Nonlocalized Externality, *RAND Journal of Economics*, 16, 553–568.
- [3] Baron, D.P. (1985b) Regulation of prices and pollution under incomplete information, *Journal of Public Economics*, 28, 211–231.
- [4] Baron, D.P. and R.B. Myerson (1982) Regulating a Monopolist with Unknown Costs, *Econometrica*, 50, 911–930.
- [5] Baron, D.P. and D. Besanko (1984) Regulation and information in a continuing relationship, *Information Economics and Policy*, 1, 267–302.
- [6] Bernard, A.L., Fischer, C. and A.K. Fox (2007) Is there a rationale for output-based rebating of environmental levies? *Resource and Energy Economics*, 29, 83–101.
- [7] Bester, H. and R. Strausz (2001) Contracting with Imperfect Commitment and the Revelation Principle: The Single-Agent Case, *Econometrica*, 69, 1077–1098.
- [8] Boyer, M. and J.-J. Laffont (1999) Toward a Political Theory of the Emergence of Environmental Incentive Regulation, *RAND Journal of Economics*, 30, 137–157.
- [9] Fischer, C. (2010) Market power and output-based refunding of environmental policy revenues, *Resource and Energy Economics*, 33, 212–230.
- [10] Freixas, X., Guesnerie, R. and J. Tirole (1985) Planning under Incomplete Information and the Ratchet Effect, *Review of Economic Studies*, 52, 173–191.
- [11] Hepburn, C.J., Quah, J. K.-H. and R.A. Ritz (2012) Emissions Trading with Profit-Neutral Permit Allocations, forthcoming in *Journal of Public Economics*, doi: 10.1016/j.jpubeco.2012.10.004
- [12] Jebjerg, L. and H.D. Lando (1997) Regulating a Polluting Firm Under Asymmetric Information, *Environmental and Resource Economics*, 10, 267–284.
- [13] Laffont, J.-J. (1994) Regulation of Pollution with Asymmetric Information. In: Dosi, C.; Tomasi, T. (eds.) (1994) *Nonpoint Source Pollution Regulation: Issues and Analysis*. Kluwer Academic Publishers.

- [14] Laffont, J.-J. and D. Martimort (2002) The theory of incentives: The Principal-Agent Model, Princeton University Press.
- [15] Laffont, J.-J. and J. Tirole (1987) Comparative Statics of the Optimal Dynamic Incentive Contract, *European Economic Review*, 31, 901–926.
- [16] Lewis, T.R. (1996) Protecting the Environment When Costs and Benefits are Privately Known, *The RAND Journal of Economics*, 27, 819–847.
- [17] Markusen, J.R., E.R. Morey, and N. Olewiler (1993) Environmental policy when market structure and plant locations are endogenous. *Journal of Environmental Economics and Management*, 24, 69–86.
- [18] Markusen, J.R., E.R. Morey, and N. Olewiler (1995) Competition in Regional Environmental Policies When Plant Locations Are Endogenous. *Journal of Public Economics*, 56, 55–77.
- [19] Martimort, D. (1999) Renegotiation Design with Multiple Regulators. *Journal of Economic Theory*, 88, 261–293.
- [20] Motta, M. and Thisse, J.-F. (1994) Does environmental dumping lead to delocation? *European Economic Review*, 38, 563–567.
- [21] Petrakis, E. and Xepapadeas, A. (2003) Location decisions of a polluting firm and the time consistency of environmental policy. *Resource and Energy Economics*, 25, 197–214.
- [22] Salanié, B. (2005) The economics of contracts: A primer. MIT Press.
- [23] Sterner, T. and Isaksson, L.H. (2006) Refunded emission payments – a hybrid instrument with some attractive properties. *Ecological Economics*, 57, 93–106.
- [24] Thomas, A. (1995) Regulating Pollution Under Asymmetric Information: The Case of Industrial Wastewater Treatment, *Journal of Environmental Economics and Management*, 28, 357–373.
- [25] Ulph, A. (1994) Environmental Policy, Plant Location and Government Protection, in: Carraro, C. ed. Trade, innovation, environment (Kluwer Academic Publishers, Dordrecht), 123–163.
- [26] Ulph, A. and Valentini, L. (1997) Plant location and strategic environmental policy with inter-sectoral linkages. *Resource and Energy Economics*, 19, 363–383.

- [27] van Egteren, H. (2002) Regulating an Externality-Generating Utility. Environmental Taxes Under Limited Information, *Environmental and Resource Economics*, 21, 107–133.