Department of Economics

# Essays on optimal environmental regulation and information economics

Topi Hokkanen

Aalto University

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# Essays on optimal environmental regulation and information economics

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# Abstract

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**Abstract**
This monograph studies optimal environmental regulation under asymmetric information and carbon leakage risk. I use tools from the fields of mechanism design and microeconomic theory to study how the possibility of firms' relocation to less regulated countries as a result of domestic regulation, i.e. carbon leakage affects incentive-compatible environmental regulation. To address this question, I build a stylized model of a single country which regulates global externality-producing firms by way of incentive-compatible regulatory schemes, i.e. mechanisms. I allow the firms to possess private information on their costs of abatement and carbon leakage risk as type-dependent outside options.

In the first chapter of this monograph, I introduce my main model and derive the optimal second-best regulatory mechanism for the monopolist country. I find that novel regulatory distortions arise from relocation risk and that the optimal second-best mechanism sometimes implements stricter regulation that would be socially optimal. Interestingly, I find that carbon leakage is also not necessarily an indication of a failed regulatory policy, but rather an optimally induced result of it.

The second chapter of this monograph extends the basic model by relaxing the assumption that the domestic regulator cannot commit to cross-border transfers. I show that conditional cross-border transfers rectify the major drawback of the simple mechanisms discussed previously: the fact that the regulator is losing socially valuable firms and therefore also abatement. With cross-border transfers, the regulator is able to buy the otherwise leaked abatement directly from the relocating firms themselves, essentially outsourcing both the firms and their abatement. The second extension considers exogenous regulatory policies implemented in the other country. I show that the regulator benefits from any such policies - be they price or quantity-based, since they serve to decrease the outside options of the firms, thus making the firms more captive in the home country at the outset.

The third and final chapter of this monograph analyzes a situation where two countries compete for externality-producing firms by way of incentive-compatible regulatory mechanisms. Using a simplified version of my main model, I show that a Bertrand-like race to the bottom results, where both countries' social welfare dissipates fully in the resulting equilibrium. The main cause of this is the lack of relocation frictions for the firm, pitting the countries against one another as Bertrand competitors. I extend the model to account for a fixed preference of a firm in favor of the other country and show that in this case, the preferred country reaps this preference for its own benefit in every resulting equilibrium.

**Keywords** carbon leakage, mechanism design, externalities, asymmetric information

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Topi Hokkanen

# Contents

# Chapter 1

# Introduction

Market failures and externalities have been a topic exhaustively studied in economics. Some of the most substantial externalities affecting all of us on the planet are climate externalities, such as pollution and carbon emissions. While these externalities cause global damages, the costs of regulating such emissions are still to a great degree private. This misalignment of the social costs of emissions and the private costs of regulating them implies a tragedy of the commons when it comes to abatement, since property rights to a clean environment are not well-defined enough to allow for a Coasian, free-market solution[1]. Therefore, it behooves a regulator to step in and try to rectify this problem, if possible. In this monograph, I assume that the regulator in question cannot perfectly observe all the relevant private information of the agents involved in creating these externalities, i.e. the polluting firms, thus setting up a principal-agent problem between the regulator and the firms. This problem of asymmetric information then requires the regulator to use an incentive-compatible mechanism to elicit the firms' private information truthfully and to regulate their pollution externalities.

This monograph studies optimal environmental regulation under asymmetric information and carbon leakage risk. I use tools from the fields of

[1] cf. Coase (1960)

mechanism design and microeconomic theory to study how the possibility of firms' relocation to less regulated countries as a result of domestic regulation, i.e. *carbon leakage* affects incentive-compatible environmental regulation mechanisms and the additional regulatory distortions that arise out of it. To address this question, I build a stylized model of a single country regulating global externality-producing firms by way of incentive-compatible regulatory schemes, i.e. mechanisms. I allow the firms to possess private information on their costs of abatement and model relocation or carbon leakage risk as type-dependent outside options.

Furthermore, I assume throughout this monograph that the most straightforward solution to the externality problem - i.e. a Pigouvian carbon tax (Pigou, 1932) - cannot be implemented globally, due to e.g. a coordination failure between different countries owing to the well-known free-riding incentives that arise from unilateral carbon pricing. In addition to the private information held by the firms on their abatement costs, I assume that firms can relocate to some other country, which does not have any regulation in place and that these relocation costs are type-dependent, creating an incentive regulation problem with type-dependent outside options. This sets up the main research question addressed in this monograph as how to regulate externality-producing firms, when the regulator is facing asymmetric information on *both* the firms' abatement costs and relocation costs, or the risk of carbon leakage (i.e. the country faces an asymmetric information problem on both the intensive and extensive margin).

The European Commission (EC) defines carbon leakage as: "[a] situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints. This could lead to an increase in their total emissions"[2]. In this monograph, I define carbon leakage specifically as *firm relocation to lesser regulated countries due to domestic regulation*. In the economics literature, car-

[2]See https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage

bon leakage may occur through many channels (Timilsina (2022), Ahlvik and Liski (2021)), of which firm relocation is but one. However, I use it as my main definition throughout.

The key contribution of this monograph is to highlight the effect of carbon leakage risk on the optimal regulatory mechanisms under asymmetric information. My key findings are the following: first, the association between abatement costs and relocation costs (the firms' outside options) matters a great deal. In other words, even more important than relocation itself is the question of *who relocates*. I show that distortions in the optimal regulatory policy will depend crucially on whether the low-cost firms or high-cost firms are the most mobile.

Moreover, I find that some carbon leakage is always optimal in the second-best mechanism, similar to Ahlvik and Liski (2022). This insight implies that carbon leakage, rather than being a sign of a failed regulatory policy, is in fact *the induced equilibrium outcome of an optimal regulatory mechanism*.

Finally, I show that when regulators compete for the firms directly by way of offering mechanisms, the resulting equilibrium and degree of rent dissipation is determined by the degree of firm mobility between the countries. If firms can move costlessly between countries, regulatory competition results in pure Bertrand competition between the regulators and full rent (and thus welfare) dissipation. However, when firms face small but constant moving costs, the domestic regulator can reap these costs for themselves.

## 1.1 Type-dependent outside options and countervailing incentives in mechanism design

Formally, the model used in this monograph makes use of type-dependent outside options in an otherwise relatively standard mechanism design problem with externalities. Type-dependent outside options have received relatively little attention in the theoretical mechanism design literature, likely due to the additional difficulties they cause for the standard method of solving mechanism design problems.

In standard models of mechanism design or incentive regulation (see Laffont and Tirole (1993)), incentive compatibility, the requirement that the agents reveal their private information truthfully implies monotonicity of allocation (cf. e.g., Börgers (2015), Laffont and Martimort (2002) or Bolton and Dewatripont (2004)). In standard models, this monotonicity, coupled with quasi-linear payoffs allows for the elegant use of the envelope theorem (see e.g. Milgrom and Segal (2002)) to rewrite the problem in terms of the allocation and a constant, which typically is the reservation utility of the lowest participating type. Together these two basic results in mechanism design imply that checking the individual rationality, or participation constraints of all types typically only requires checking that the induced equilibrium payoff of the mechanism is at least as great as the non-type dependent outside option for the lowest participating type. When the outside option is type-dependent, however, this procedure does not always work or yield the uniquely optimal IC mechanism. On the contrary, the optimal mechanism under type-dependent outside options may imply a non-monotonic allocation, which then requires that advanced optimal control techniques, such as ironing (see Fudenberg and Tirole (1991)) or bunching need to be used to characterize the optimal mechanism.

Jullien (2000) covers the general theory of type-dependent outside options in a standard adverse selection model, and shows that advanced optimal control techniques are necessary to characterize the optimal solution, and the optimal mechanism may include non-monotonicities, or bunching, where a certain measure of types is restricted to the same payoff. Laffont and Martimort (2002), on the other hand cover specific applications of type-dependent outside options in a more applied, textbook context. In this monograph, I assume a very particular form of type-dependence, namely the most straight-forward and simplest specification I can use to illustrate my results and my model, a *linear relationship.* This assumption allows me to sidestep much of the technical hurdles mentioned previously.

Moreover, in standard mechanism design problems[3] with a fixed outside option for all types, the agent's incentive compatibility constraints to be taken into account by the mechanism designer boil down to designing a mechanism where the agent has no incentive to either overstate or understate their private information, yielding an incentive-compatible mechanism that elicits the true information from the agent. This requirement formally is that the true type report should be the maximizer (resp. minimizer)[4] of the agent's expected payoff, given the mechanism. When the outside option is type-dependent, the situation is slightly different, as the agent may simultaneously have incentives to *both understate and overstate* their type, which is the key point in the *countervailing incentives* literature, pioneered by Lewis and Sappington (1989)[5].

Lewis and Sappington (1989) consider an extension of the monopoly regulation model of Baron and Myerson (1982), extending it to an environment where the regulated firms privately known cost type affects not only its marginal cost of production, but its fixed cost as well. Assuming the fixed cost of the firm (which determines the extensive marginal shut-down decision) varies in firm type, with higher marginal costs affiliated with a lower

[3] See e.g. Börgers (2015) or Fudenberg and Tirole (1991).

[4] Whenever the maximizer isn't a singleton, the requirement naturally is that the true type belongs to the set of maximizers or minimizers (argmax/argmin sets).

[5] See also Laffont and Martimort (2002), Chapter 3.4.

fixed cost, they find that the optimal mechanism exhibits countervailing incentives, and therefore the incentives of the firm are not any more to either over- or understate their cost parameter, but a mixture of the two, where for a certain measure of types, the incentive is to overstate their costs in hopes of a higher compensation (allocation) but for a second measure of types, these incentives reverse themselves, and they prefer to understate their costs. This non-monotonicity results in a non-monotonic expected payoff for the firm in type, and in contrast to standard mechanism design, the optimal allocation (price) is distorted above first-best for the first measure of types and below it for the second measure.

A previous application of type-dependent outside options interpreted as the relocation costs of firms to be regulated was done by Vislie (2000), but unlike in this monograph he only considers the case where the *relocation costs* of firms are negatively correlated with their abatement costs[6] and where, moreover, the externalities produced by the firms are purely local and he includes foreing ownership of the firms in the model. Nonetheless, he finds the same downwards distortions in the optimal regulatory policy as I do later on, arising out of incentive compatibility. His results moreover, also imply that the optimal second-best mechanism induces some firms to relocate, which while not stated as such, can be interpreted as carbon leakage. Jebjerg and Lando (1997) consider a standard mocel of incentive regulation in the vein of Laffont and Tirole (1993) while extending it to cover firm relocation. In their model the regulator has asymmetric information about the (single) firm's abatement costs, like in this monograph. However, they constrain the regulator to ensure the firm's survival (which, in their model amounts to firm relocation) and they limit the amount of transfers/subsidies the regulator may give the firm. They find the classic rent-efficiency trade-off, since the regulator is forced to ensure firm survival (allow no leakage), leading to low-cost firms reaping rents due to incentive compatibility.

[6]This is a very similar setup as the $k < 0$ case in the next chapter.

In the carbon leakage model considered in this monograph, I find similar results for the regulatory distortions in the abatement threshold under different association regimes, although countervailing incentives do not arise in my model as they do in Lewis and Sappington (1989) (or as defined by Aguirre and Beitia (2017)), even with type-dependent outside options.

## 1.2 Mechanism design and environmental externalities

While environmental regulation is a topic often covered in mechanism design (see, e.g Montero (2008), Kim and Chang (1993), Dasgupta, Hammond, and Maskin (1980), Baliga and Maskin (2003) or Lewis and Sappington (1995)), and a separate literature (for instance Martin, Muûls, De Preux, and Wagner (2014), Meunier, Ponssard, and Quirion (2014)) has addressed the optimal regulatory responses to carbon leakage, the combination of these two - i.e. the mechanism design approach to carbon leakage is quite novel, having previously been considered only by Ahlvik and Liski (2022). The model primarily used in this monograph shares many of the same features as the models in Ahlvik and Liski (2017) and Ahlvik and Liski (2022), who consider firm relocation (carbon leakage) issue in a mechanism design framework with global externality-producing firms, but in a more general setup without explicitly specifying the mapping between relocation costs and abatement costs. By applying the random participation mechanism of Rochet and Stole (2002) to make the model tractable, they arrive at the same novel upwards distortion in the abatement threshold as I do in my more stylized model. My first and second chapters benefit greatly from this same model setup, but allow for cleaner results due to the additional - but more restrictive - assumption of a one-to-one mapping between the abatement costs and the relocation costs[7]. However, what the more streamlined set-up loses in generality, it makes up for in cleaner intuition.

The first two chapters of this monograph deal with the problem of a single regulator, when facing asymmetric information and carbon leakage risk, while the third chapter addresses the question of two competing regulators competing for firms. In the third chapter, I streamline the setup of the previous chapters' leakage model and present a stylized model of regulatory competition. I show that in this instance, the key issue that determines the resulting regulatory equilibrium is the level of firm mobility. When firms are free to costlessly locate in either country, this sets the regulators up as Bertrand competitors, resulting in full welfare dissipation with the locating firm reaping all the rents that the mechanism provides. I show that introducing frictions to the model, i.e. a slight preference of the firm for one country over the other leads to a separating equilibrium where countries both receive different types of firms in equilibrium, and moreover that not all welfare is then dissipated as firm rents.

## 1.3 Theoretical and empirical results on carbon leakage

Carbon leakage itself is a topic frequently addressed in theoretical literature, however the majority of approaches use general equilibrium models in a macroeconomic context (i.e. CGE or DSGE models). (see Misch and Wingender (2021)). Addressing the problem of carbon leakage in a mechanism design context is quite novel, however, with Ahlvik and Liski (2022) being one of the first papers to do this.

[7]Without this mapping, the problem would essentially be a multidimensional screening problem, which are notoriously difficult to solve generally. A brief survey of these problems can be found in, e.g. Armstrong and Rochet (1999).

More generally, the carbon leakage problem analyzed in this monograph is closely related to the literature on tax competition between jurisdictions, where mechanism design has been used extensively. In this vein Lehmann, Simula, and Trannoy (2014) apply the random participation mechanism of Rochet and Stole (2002) and analyze a situation of tax competition between countries for citizens (workers), when the citizens' are free to relocate to the other country, and both their productivity (or skill) and migration costs are private information. They derive both the intensive margin tax rate, which is distorted by the asymmetric information, and the *semi-elasticity* of migration, which essentially characterizes the extensive margin equilibrium outcome when both countries play Nash equilibrium strategies, which they dub the "leakage of taxpayers". Their setup is different, as they derive their results to address tax competition, but in the broad strokes this paper is very similar to the model used in this monograph, in that it contains the two major components integral to my analysis as well, namely an asymmetrically informed regulator and mobile agents.

Focusing on the EU-ETS, Martin, Muûls, De Preux, and Wagner (2014) investigate the relation between regulatory stringency and carbon leakage risk, and show that in a simple optimization model, the free allocation of permits inherent in the EU-ETS in fact leads to significant overcompensation, and that similar reductions of carbon leakage risk could be achieved simply by equalizing the weighted marginal leakage probabilities. Meunier, Ponssard, and Quirion (2014) find broadly similar results in that the optimal instrument to deter carbon leakage in the EU-ETS would be a hybrid instrument, combining both output-based allocation and free allocation of permits.

The majority of empirical literature has focused on either estimating carbon leakage rates within specific industries under unilateral regulation (such as the EU-ETS), often assessing its effects on (different measures) of competitiveness, as this is a highly relevant topic in empirical literature. While this literature in its entirety is much too vast for me to parse in this introduction, I will highlight some recent papers that are relevant to the model used in this monograph. For a comprehensive survey of the empirical literature related to the competitiveness effects of the EU-ETS, I refer the reader to Verde (2020) or Dechezleprêtre and Sato (2017), whereas Venmans, Ellis, and Nachtigall (2020) survey the empirical literature on carbon leakage in the G20 and OECD countries. A similar treatise focusing broadly on carbon taxes is Köppl and Schratzenstaller (2023).

To the best of my knowledge, there have been very few empirical papers that have tried to estimate the association between the abatement (or compliance) costs and relocation costs (or, alternatively, relocation propensities) of firms under regulation, which is a key parameter used in this monograph[8]. One such paper is Ederington, Levinson, and Minier (2005) who find evidence of a positive association between abatement and relocation costs, whereas Levinson and Taylor (2008) find that industries whose abatement costs increased the most increased their net imports the most.

Focusing on trade flows, Naegele and Zaklan (2019) find no evidence of EU ETS causing carbon leakage in European manufacturing, whereas recent estimates by Misch and Wingender (2021) generally show high leakage rates across the European Union caused by the EU ETS. In contrast to the other leakage literature, Eskeland and Harrison (2003) test the pollution haven hypothesis and find that firms relocating to lesser regulated countries tended to be cleaner than their counterparts, polluting less.

[8] Ahlvik, Liski, and Martin (2017) provide an estimate of this correlaction using the survey data from Martin, Muûls, De Preux, and Wagner (2014)

## 1.4 Summaries of the chapters

### Optimal leakage mechanism under correlated costs

In the first chapter of this monograph, I derive the optimal second-best regulatory mechanism for a regulator under asymmetric information about externality-producing firms' abatement costs and type-dependent outside options. The type-dependent outside options represent the firms' relocation propensities to an unregulated country. I posit a simple linear relationship between a firm's abatement costs and relocation costs and analyze the resulting optimal regulation in each of the different association regimes. I find novel distortions in the regulatory mechanism arising from relocation. i.e. that the optimal second-best mechanism sometimes implements stricter regulation that would be socially optimal. I find that carbon leakage, quite strikingly, is not necessarily an indication of a failed regulatory policy, but rather a result of it. The second key takeaway of this stylized model is to highlight the crucial importance of the association (positive/negative) between abatement and relocation costs and its effect on the second-best mechanism.

### Extensions of the simple leakage model

The second chapter of this monograph extends the basic leakage model of the first chapter in two ways. First, I relax the assumption that the domestic regulator cannot commit to *cross-border transfers*. I show that conditional cross-border transfers rectify the one major drawback of the simple leakage mechanisms discussed previously: the fact that the regulator is losing socially valuable firms and therefore also abatement. With cross-border transfers, the regulator is able to buy the otherwise leaked abatement from the relocating firms themselves, essentially outsourcing the firms alongside their abatement. Moreover, I show that in any association regime, the foreign carbon price is unique and differs from the domestic carbon price, creating carbon price dispersion in the market.

In a second extension I consider exogenous regulatory policies implemented in the other country. I show that the regulator benefits from these exogenous policies - be they price or quantity-based - since they serve to *decrease* the outside options of the firms. In the context of my model these policies increase firm relocation costs, thus having the effect of making the firms more captive to the home country at the outset. Hence the domestic regulator is able to benefit from these policies in two ways: i) by receiving an abatement benefit they do not need to subsidize themselves using costly public funds and ii) by being able to decrease the transfers paid out to the staying firms, since the exogenous regulation makes firms more tolerant of higher domestic compliance costs.

### Regulatory competition with multilateral externalities

The third and final chapter of this monograph analyzes a situation where two countries compete for externality-producing firms by way of incentive-compatible regulatory mechanisms. Using a simplified version of my main model, I show that a Bertrand-like race to the bottom results, where both countries' social welfare dissipates fully in the resulting equilibrium. The main cause of this is the lack of relocation frictions for the firm, pitting the countries against one another as Bertrand competitors. I extend the model to account for a fixed preference of a firm in favor of the other country and show that in this case, the preferred country reaps this preference for its own benefit in every resulting equilibrium. A separating equilibrium does not obtain, even with a high frictions, since it is payoff-dominated by the pooling equilibria.

# Chapter 2

# Optimal leakage mechanism under correlated costs

## 2.1 Introduction

This chapter introduces the model of carbon leakage and competing regulation under asymmetric information that I will work with throughout this monograph. The main focus is on analyzing the effects of firm relocation on the optimal regulatory mechanism under asymmetric information, when firms create global externalities by way of pollution emissions. In this chapter I set up a model of optimal environmental regulation under asymmetric information and carbon leakage risk that will be used for the bulk of this monograph.

A common argument from firms and policymakers alike when new regulation (such as environmental regulation, higher corporate tax rates, etc.) is to be introduced in the home country, is that this regulation will only serve to drive domestic firms to relocate somewhere with less stringent regulation. With environmental externalities such as carbon dioxide, this threat is called *carbon leakage*. In this chapter I show, that in a simple mechanism design problem with global externalities, the key question isn't just *if firms relocate*, it's *who relocates*, and that in fact carbon leakage is not necessarily a signal of a failed environmental policy, it may actually be optimally induced by the regulatory mechanism to save on socially costly public funds. I analyze how carbon leakage risk affects the stringency of climate policy, and find a novel upward distortion in the abatement threshold (or, alternatively, carbon price) alongside the more commonly found downward distortions due to information rents and incentive compatibility.

In some environments, the optimal second-best mechanism distorts the abatement threshold below first-best, but in others, the threshold is distorted above first-best. The key parameter driving the size and direction of these distortions is how the firms' abatement costs associate with their relocation propensities. Partly due to the ambiguity of the received empirical literature with regards to the correlation between these two cost parameters[1], I take no stance in this monograph as to the most likely sign of this correlation, but instead set up an agnostic model that allows for a wide range of associations between the two. While this necessarily makes the model more cumbersome, it paints the most complete picture of the problem at hand.

This workhorse model is based on the model of Ahlvik and Liski (2022) and the preceding papers Ahlvik and Liski (2017) and Ahlvik and Liski (2019). These papers to my knowledge pioneered the mechanism design approach to carbon leakage, considering a similar scenario. Ahlvik and Liski (2022) also consider type-dependent relocation costs alongside a privately known abatement cost, but use a more general set-up without specifying a the relationship between the two costs explicitly. This allows them to use the limited participation mechanism of Rochet and Stole (2002) to arrive at a two-part tariff characterization for their optimal mechanism and get similar results with regards to the upwards distortion in the abatement threshold. However, their main interest is in addressing firm selection policies, while I try to characterize carbon leakage. Moreover, my more streamlined

[1] cf. the Introduction for a parsing of this literature.

model allows me to incorporate, in Chapter 2, exogenous price or quantity regulation implemented in the other country, and show that the domestic regulator benefits from such policies. The streamlining does come at the cost of generality, as I posit a simple linear relationship between the two parameters of private information. However, as I cover a wide range of affiliation regimes, the model is still sufficiently agnostic as to allow for the types of correlations or affiliations suggested by the empirical literature to be analyzed in an analytic, simple fashion.

## 2.2 The model

Consider a continuum of firms with unit mass, each characterized by a privately known abatement cost, $c \in [\underline{c}, \bar{c}]$ (with $\underline{c} \geqslant 0$) of reducing one unit of emissions. A single unit of emissions causes a global externality of size $D > 0$ that firms impose on the country where they reside, absent any abatement. Aside from negative externalities, each firm generates $\gamma > 0$ of social welfare with their activities, hence the need for the regulator to balance the gains and losses of regulating the firms. We assume that the abatement costs c are distributed according to a continuously differentiable density function $f(c)$, strictly positive on $(\underline{c}, \bar{c})$, with cumulative distribution function $F(c)$ satisfying the monotone hazard rate assumption. The shadow cost of public funds is positive and equal to $\lambda$.

**Assumption 1** *Monotone Hazard Rate (regularity of* $F$*): We assume that the distribution of types* $F(\cdot)$ *satisfies the monotone hazard rate assumption, i.e.*

$$\frac{d}{dc}\left(\frac{f(c)}{1-F(c)}\right) \geqslant 0 \quad \textit{and} \quad \frac{d}{dc}\left(\frac{F(c)}{f(c)}\right) \geqslant 0 \tag{2.1}$$

The initial location for each firm is the home country, i.e. country $i$. Each firm also has the opportunity to relocate to another country, the cost of which is given by a linear function

$$\theta := \overline{\theta} + kc \tag{2.2}$$

with $k, \overline{\theta} \in \mathbb{R}$. This *relocation cost* is a type-dependent outside option for the firm. The key parameter in this linear relationship is the association parameter $k \in \mathbb{R}$. If $k < 0$, then the abatement costs c and relocation costs $\theta$ are negatively associated, meaning that the highest cost abaters (those with the highest c) face the smallest relocation costs, or are the most mobile. Under positive association, i.e. when $k > 1$, we have the opposite, so that the lowest cost abaters are the most mobile, and the highest cost firms are the most immobile. In the intermediate case, when $0 < k < 1$, relocation costs are weakly positively associated with the relocation costs, with the lowest cost firms being the most mobile.

We denote the alternative location by $j$ and for the most part, we assume that location $j$ has no regulatory policies in place. The home country can retain firms by means of offering them a mechanism denoted as $\mathcal{M} := \{X(c), T(c)\}$, consisting of:

> **Abatement** $X(c) \in [0, 1]$, ie. whether a c-type firm cuts emissions or not, and
>
> **The transfer** (subsidy) to the firm $T(c) \in \mathbb{R}$, given to the firm conditional on it staying in the home country.

Moreover, we require that the mechanism should be incentive compatible for the firms, meaning the firms should report their cost types truthfully. Firms are cost-minimizers, and choose to stay (i.e. report their cost type to the domestic mechanism) or relocate based on which action minimizes their compliance costs. Every firm has an option to relocate to the unregulated country, but this incurs a the relocation cost $\theta$ in (2.2).

The regulator wants to maximize the social surplus, ie. the surplus less firm compliance. The tools at its disposal are *incentive-compatible mechanisms* $\mathcal{M}$. The regulator has to take into account the type-dependent relocation cost $\theta$, which later on gives us three cases to consider as far as distortions go.

### 2.2.1 The social welfare function and preliminaries

We define the compliance cost of a firm in a given mechanism $\mathcal{M}$ as a linear function of their own private type, the abatement $X$ and the subsidy $T$. When reporting a type $c'$ , the compliance cost $C(c, c')$ of a firm of (privately known) type $c$ is defined as

$$C(c, c') := cX(c') - T(c') \tag{2.3}$$

The firms' cost-minimization implies that the mechanism on offer should satisfy an incentive-compatibility constraint of the following type: reporting truthfully must minimize the compliance costs of the firm, given the mechanism. Therefore we have the following IC constraint:

$$c \in \arg \min_{c' \in [\underline{c}, \overline{c}]} C(c, c') \tag{2.4}$$

This constraint implies that in any incentive-compatible mechanism, the abatement $X(c)$ is a non-increasing function of c.

**Lemma 1** *An allocation* $X(c)$ *is incentive compatible iff it is a non-increasing function.*

**Proof.** Take two types in $[\underline{c}, \overline{c}]$, say c and $c'$. Without loss of generality, let $c' > c$. Now the incentive compatibility constraints directly imply

$$cX(c) - T(c) \leqslant cX(c') - T(c') \tag{2.5}$$

$$c'X(c') - T(c') \leqslant c'X(c) - T(c) \tag{2.6}$$

Adding the constraints to one another and noting that we defined $c' > c$ yields $X(c') \leqslant X(c)$, which completes the proof. ■

The baseline for the model is that firms do not abate and stay in the country. Doing so, they impose a full negative externality of size D for the home country. If a firm abates their externality, it yields the home country a *climate surplus* of $(D - c)$. In addition to the possible climate surplus, the firm generates $\gamma$ if it stays. Noting the shadow cost of public funds $(\lambda)$, we can now define the social welfare function to be maximized by choice of mechanism, comprising of the benefit of retaining the firm less the firm compliance costs.

$$W(\mathcal{M}) := \int_{\underline{c}}^{\overline{c}} [\gamma + DX(c) - (1+\lambda)T(c) - cX(c) + T(c)]\, f(c)dc$$

$$= \int_{\underline{c}}^{\overline{c}} [\gamma + (D-c)X(c) - \lambda T(c)]\, f(c)dc \tag{2.7}$$

The integrand is linear in the allocation $X(c)$, which moreover belongs to the interval $[0, 1]$. Therefore the optimal $X(c)$ must be a bang-bang solution, i.e. $X(c) \in \{0, 1\}$ for all c. Together with Lemma (1), which states that incentive compatibility requires $X(c)$ to be decreasing in c, we get that the incentive compatible allocation must be a step function, specifying a threshold type $c^* \in [\underline{c}, \overline{c}]$, such that every firm below or at the threshold is allocated full abatement, i.e. $X(c) = 1$, and firms above the threshold are allocated zero abatement:

$$X(c) = \mathbf{1}_{\{c \leqslant c_i^*\}} \tag{2.8}$$

In order to satisfy incentive compatibility, whenever the allocation $X(c)$ is constant, the transfer that corresponds with that allocation must also be a constant. Otherwise there would exist firm types that would find it profitable to misreport their types, altering their compliance costs, while keeping the allocation the same. Since the requirement for truthfully reporting c to be minimizer of $C(c, \hat{c})$, this immediately implies that the transfers must be constant whenever the allocation is a constant as well.

**Lemma 2** *Whenever the allocation* $X(c)$ *is constant in an incentive compatible mechanism, the transfer* $T(c)$ *is constant.*

**Proof.** Suppose not. In this case there exist types $c, c' \in [\underline{c}, \overline{c}]$ for which

$$cX(c') - T(c') < cX(c) - T(c)$$

which contradicts incentive compatibility. ■

Therefore the optimal incentive compatible mechanism is fully characterized by a two part tariff with allocation $X(c)$ as defined above, and a transfer of $T(c) := T^* + \mathbf{1}_{\{c \leqslant c_i^*\}} c^*$. In other words, every firm gets a base transfer of $T^*$ , and a top-up of $c^*$ if they abate. Since we want to make the connection this stylized model has with Pigou taxation very clear, we rescale the mechanism $\mathcal{M}$ by altering the transfers from

$$T(c) = T^* + \mathbf{1}_{\{c \leqslant c_i^*\}} c^* \tag{2.9}$$

to a down-scaled transfer of

$$\hat{T}(c) := T^* - \left(1 - \mathbf{1}_{\{c \leqslant c_i^*\}}\right) c^* \tag{2.10}$$

and with the induced firm compliance cost of

$$\hat{C}(c) := \underbrace{c^*}_{\text{Carbon tax}} - \underbrace{T^*}_{\text{Base subsidy}} + \underbrace{X(c)(c - c^*)}_{\text{Incentive part}} \tag{2.11}$$

**Lemma 3** *The rescaled mechanism is incentive-compatible.*

**Proof.** Firm compliance with the transfer above is

$$\hat{C}(c) = c^* - T^* + X(c)(c - c^*)$$

With the allocation being a step function, the IC constraints reduce to preventing deviations that cross the threshold $c^*$:

$$c - T^* \leqslant c^* - T^* \tag{2.12}$$

$$c^* - T^* \leqslant \hat{c} - T^* \tag{2.13}$$

for $c \leqslant c^* < \hat{c}$. These hold trivially for every $T^*$ so the new mechanism is incentive-compatible. ■

This has the direct market interpretation so that $c^*$ is both the threshold type, and *the price of carbon*. To see why, let us take a look at the compliance costs for abating and non-abating firms. Abating firms, for which $X(c) = 1$ have a compliance cost of $c - T^*$. That is, they abate fully, pay their private cost of that abatement and get a $T^*$ base subsidy for this action. Non-abating firms face a compliance cost of $c^* - T^*$, likewise receiving the base subsidy of $T^*$, but now pay up front the *carbon tax* $c^*$ due to their one unit of pollution (or zero units of abatement, respectively). Next, we take a look at the *relocation constraint* and formulate the optimization problem of the regulator.

### 2.2.2 The relocation constraint and regulator's problem

The regulator's objective function, given the two-part tariff implied by incentive compatibility and the re-scaled transfer can now be written as

$$\max_{c^*, T^*} \underbrace{\int_{\underline{c}}^{c^*} \{\gamma + (D - c)X(c) - \lambda T^*\} f(c) dc}_{\text{Welfare from abating firms}} + \underbrace{\int_{c^*}^{\overline{c}} (\gamma + \lambda(c^* - T^*)) f(c) dc}_{\text{Welfare from non-abating firms}} \tag{2.14}$$

subject to the individual rationality, or relocation constraint induced by (2.2). Non-abating firms yield an additional[2] $\lambda c^*$ of welfare, on top of $\gamma$, since they are taxed by the regulator for their emissions with a carbon price of $c^*$. Firms choose to relocate to the alternative location whenever their

[2]That is, we consider the shadow cost of public funds to be symmetric wrt. transfers. A tax from the firm to the regulator of $c^*$ is worth $(1 + \lambda)c^*$ to the regulator.

cost of compliance in the home country exceeds their relocation cost $\theta$. That is, firms leave when

$$\hat{C}(c) > \overline{\theta} + kc \tag{2.15}$$

$$\tag{2.16}$$

Therefore, the optimization problem of the regulator is to jointly decide $\{c^*, T^*\}$, given parameters $\left(D, \gamma, k, \overline{\theta}\right)$ and the distribution of costs $F(c)$. However, the relocation constraint above induces a partition on the type space $[\underline{c}, \overline{c}]$, where some measure of firms will stay and abate, some measure will stay but not abate, and some measure leaves. The crucial parameter that induces this partition is the dependence parameter $k$.

### 2.2.3 The first-best benchmark

As a starting-off point, we will solve the regulator's problem when the regulator has perfect information, i.e. can simply optimize type-by-type. This will give us the efficient, or *first-best* outcome, to which we will later on compare our optimal mechanisms to. In this case, the regulator can disregard the incentive compatibility constraints, and reduce every type $c$ to its outside option payoff - in this case given by the relocation constraint in (2.2). Since incentive compatibility can be disregarded due to the firm's type being observable, the optimization problem of the regulator is to choose the allocation $X(c)$ to maximize

$$\max_{X(c)} \left[\gamma + DX(c) - (1+\lambda)T(c) - \hat{C}(c)\right] \tag{2.17}$$

such that $\hat{C}(c) = \overline{\theta} + kc$ for all $c$. After inserting the compliance cost and simplifying, we have

$$\max_{X(c)} \left[\gamma + (D - (1+\lambda)c)\, X(c) + \lambda(\overline{\theta} + kc)\right] \tag{2.18}$$

where $X(c)$ is set to $X(c) = 1$ if $(D - (1+\lambda)c) \geqslant 0$, yielding *the first-best* abatement threshold which we denote:

$$c^{FB} = \frac{D}{1+\lambda}. \tag{2.19}$$

So we see that the abatement threshold is set at the socially optimal level, given that the regulator has a positive shadow cost for public funds[3]. The entire transfer schedule then is set such that it renders every type, regardless of abatement, at their outside option payoff. The transfer that implements this is

$$T(c) := \mathbf{1}_{\{c \leqslant c^{FB}\}} c - \left(\overline{\theta} + kc\right) \tag{2.20}$$

**Lemma 4** *The perfect information mechanism is*

$$X(c) = \mathbf{1}_{\{c \leqslant \frac{D}{1+\lambda}\}}$$
$$T(c) = \mathbf{1}_{\{c \leqslant c^{FB}\}} c - \left(\overline{\theta} + kc\right)$$

**Proof.** Noting that the only constraint relevant for the regulator's problem is the relocation constraint, simple inspection yields that the induced compliance cost for a firm of type $c$ in the above mechanism is indeed $\hat{C}(c) = \overline{\theta} + kc$. ■

The perfect information mechanism retains all of the types, or alterna-

[3] If the transfers to the firms would be costless, i.e. $\lambda = 0$, then we see that the threshold would be set at the full level of the externality, D. As we see later, this would also negate the asymmetric information problem as well.

tively induces full participation and hence implies no carbon leakage. This contrasts with the asymmetric information mechanisms soon to be derived, which generally induce limited participation, i.e. carbon leakage[4].

## 2.3 Local regulatory policies

When the regulator cannot observe firm types, and can only offer transfers conditional on firms locating in the country, the mechanism design problem amounts to solving an optimization problem, where the objective function is (2.14), subject to a specific partition of the type space, given by the relocation constraints in (2.15). We write out the relocation constraints explicitly below, and split the range of the association parameter $k$ into three regimes, solving each separately. The relocation constraints with the induced compliance cost $\hat{C}(c)$ are, for a given $c^*$:

Assuming that firms above the threshold (non-abaters) relocate, i.e. **if** $c > c^*$ **leave**, then the partition[5] is determined by:

$$c^* - T^* \geqslant \overline{\theta} + kc \tag{2.21}$$

$$-kc \geqslant \overline{\theta} + T^* - c^* \tag{2.22}$$

from where we get as the cut-off type

$$c \leqslant -\left(\frac{\overline{\theta} + T^* - c^*}{k}\right), \quad \text{for } k > 0 \tag{2.23}$$

$$c \geqslant -\left(\frac{\overline{\theta} + T^* - c^*}{k}\right), \quad \text{for } k < 0 \tag{2.24}$$

[4] see Vislie (2000) for carbon leakage and Laffont and Tirole (1993) and Jullien (2000) for limited participation

[5] Alternatively, you may think of this as defining the sets of types that leave and stay, respectively.

However, **if** $c < c^*$ **leave**, then the relocation constraint is

$$c - T^* \geqslant \overline{\theta} + kc$$
$$(1-k)c \geqslant \overline{\theta} + T^*$$

giving us cut-off types of

$$c \leqslant \frac{\overline{\theta} + T^*}{1-k}, \quad \text{for } k > 1 \tag{2.25}$$
$$c \geqslant \frac{\overline{\theta} + T^*}{1-k}, \quad \text{for } k < 1 \tag{2.26}$$

For convenience, let us denote

$$c' := -\left(\frac{\overline{\theta} + T^* - c^*}{k}\right) \tag{2.27}$$
$$c'' := \frac{\overline{\theta} + T^*}{1-k}. \tag{2.28}$$

These relocation constraints now induce the partition of types that stay or relocate, depending on $k$. For clarity, we will analyze each regime for the association parameter $k$ as a separate subsection. In the following, we focus on interior solutions, while corner solutions to the optimization problems are relegated to the appendix.[6]

### 2.3.1 $k < 0$: Negative association

**When** $k < 0$, then we have a situation in which the firms with the highest relocation costs are ones with low abatement costs and thus ones who are the most immobile. We assume that $c' < \overline{c}$, so that we have an interior

[6] Since $\theta$ is a linear function, cases where $k = -1, k = 0$ or $k = 1$ are essentially corner solutions.

solution for the optimization problem, and conjecture that the partition in this case is the following: firms with $c \leqslant c^*$ stay and abate, firms with $c^* < c \leqslant c'$ stay, but don't abate, and firms with $c > c'$ leave. The only relocation constraint that is relevant with this partition is (2.24), pinning down the marginal relocating type of firm above the abatement threshold $c^*$. We can now write the the social welfare function to be optimized as:

$$\max_{c^*,T^*} W = \int_{\underline{c}}^{c^*} (\gamma + (D - c) - \lambda T^*) f(c)dc + \int_{c^*}^{c'} (\gamma + \lambda(c^* - T^*)) f(c)dc \tag{2.29}$$

And the optimal mechanism in this case is summarized in the following proposition:

**Proposition 1** *Whenever* $k < 0$*, the low-cost firms are the most immobile in the home country, and the abatement threshold in the mechanism under global externalities is distorted lower than first-best, to*

$$c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)}$$

This means that we have a result of the threshold being distorted downwards from the first-best ($c^{FB}$), meaning the country sets a less strict regime than would be socially optimal. We illustrate the result below in Figure 1. At the outset, one might not expect this to happen, since in this association regime the best firm types for the regulator (low-cost types) are the most immobile in the country, and hence it might seem that the optimal mechanism should exploit this. This distortion arises due to the dual role of $c^*$ alluded to earlier, as in this stylized model it functions as both the abatement threshold *and* the carbon price. So, while this association regime has the low-cost firms face the highest relocation costs (since $k < 0$), this friction cannot be fully exploited in the optimal mechanism (by increasing $c^*$ to the socially optimal level), since this action would at the same time increase the compliance costs for all non-abaters (holding $T^*$ constant), leading to more relocation (and loss of $\gamma$ for that measure of firms).

Therefore, this is a restatement of a very classic result in mechanism design, namely the efficiency-rent extraction trade-off. Similar results in incentive regulation can be found in Baron (1985), Laffont and Tirole (1996) or Laffont and Tirole (1993), where the optimal regulation falls short of the first-best level due to the requirement of maintaining incentive compatibility. Indeed, the result of downwards distortion in abatement arises also in Vislie (2000), where net abatement is below first-best levels (or net emissions are distorted upwards) in order to reduce information rents flowing to the most efficient abaters, who otherwise all would have incentives to report a higher type.

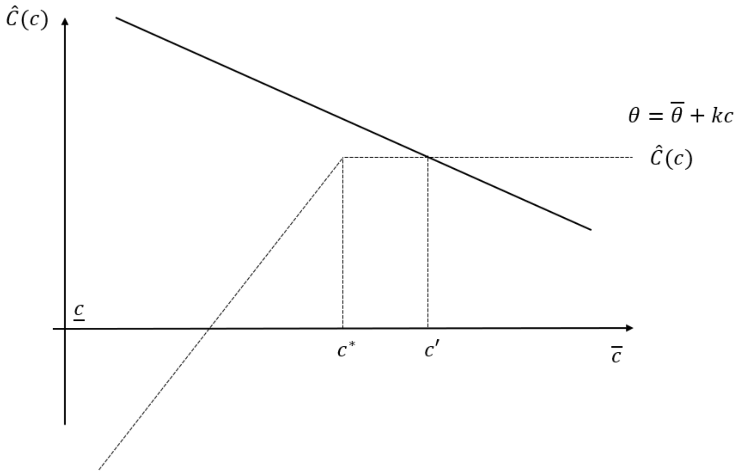


FIGURE 2.1. WHEN $k < 0$, THE THRESHOLD IS DISTORTED DOWNWARDS TO RETAIN SOME OF THE HIGH TYPES AS WELL.

**Proof.** Given the social welfare function in (2.29) the first-order condition for the abatement threshold, ie. carbon price is:

$$\frac{\partial W}{\partial c^*} = (\gamma + D - c^* - \lambda T^*)\, f(c^*) + \frac{1}{k}(\gamma + \lambda(c^* - T^*))f(c') \\ -(\gamma + \lambda(c^* - T^*))f(c^*) + \int_{c^*}^{c'} \lambda f(c)dc = 0$$

and the first-order condition for the base transfer $T^*$:

$$\frac{\partial W}{\partial T^*} = \int_{\underline{c}}^{c^*} (-\lambda)f(c)dc - \frac{1}{k}(\gamma + \lambda(c^* - T^*))f(c') + \int_{c^*}^{c'} (-\lambda)f(c)dc = 0$$

From which we get the optimal $\{c^*, T^*\}$:

$$c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)} < \frac{D}{1+\lambda} \tag{2.30}$$

and

$$
\begin{aligned}
T^* &= \frac{\gamma}{\lambda} + c^* - \frac{kF(c')}{f(c')} \\
&= \frac{\gamma}{\lambda} + \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)} - \frac{kF(c')}{f(c')}
\end{aligned}
$$

Since we have found an optimal solution that is a two-part tariff, we can conclude by Lemmas (1) & (2) that the resulting mechanism is the optimal IC mechanism. ■

### 2.3.2 $k > 1$: Strong positive association

**When** $k > 1$, then the situation is reversed from before. The high-cost firms now face the highest relocation costs, or are the most immobile. We assume that $c'' > \underline{c}$, so that we have an interior solution for the optimization, and conjecture that the partition of types in this case is the following: types $c < c''$ relocate, types $c'' \leqslant c \leqslant c^*$ stay and abate, and types $c > c^*$ stay without abating. Since with our conjecture, the only relocation constraint that is relevant is (2.25), that pins down the marginal relocating type below the abatement threshold $c^*$. The social welfare function to be optimized can be written as:

$$
\max_{c^*,T^*} W = \int_{\frac{\overline{\theta}+T^*}{1-k}}^{c^*} \left(\gamma + (D-c) - \lambda T^*\right) f(c)dc + \int_{c^*}^{\overline{c}} \left(\gamma + \lambda(c^* - T^*)\right) f(c)dc \tag{2.31}
$$

We summarize the optimal mechanism in this case in the following proposition.

**Proposition 2** *Whenever $k > 1$, the high-cost firms are the most immobile, i.e. face the highest relocation costs, and the abatement threshold in the mechanism* *under global externalities is distorted higher than first-best, to*

$$c^* = \frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1-F(c^*))}{f(c^*)}$$

In this case we find that the threshold is now, surprisingly *distorted above* the first-best level, meaning that the country actually implements stricter regulation than would be socially optimal. We illustrate this below in Figure 2.

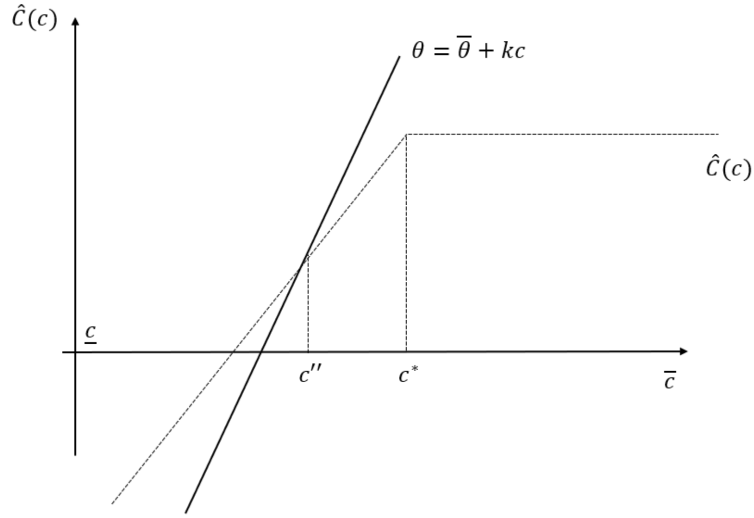


FIGURE 2.2. WHEN $k > 1$, THE THRESHOLD IS DISTORTED UPWARDS TO EXTRACT HIGHER RENTS FROM THE NON-ABATING TYPES ABOVE THE THRESHOLD.

This distortion arises due to the fact that with this association regime, the high-cost firms face the highest relocation costs, and now the regulator has more leeway in designing the optimal $c^*$. Since the secondary role of $c^*$ is a carbon tax for non-abaters, then increasing the threshold above the social optimum allows extracting more rents from the most immobile firms at the high end of the cost spectrum, while sacrificing relatively little abatement[7]. This is similar to the upward distortion in Ahlvik and Liski (2021), which

[7]Note that there exists also a corner solution to the optimization problem, where only non-abaters are retained.

to my knowledge is a relatively non-standard result in the incentive regulation literature (although arising here perhaps in a slightly mechanistic way).

**Proof.** The first-order condition for $c^*$ is:

$$\frac{\partial W}{\partial c^*} = (\gamma + D - c^* - \lambda T^*)\, f(c^*) - (\gamma + \lambda(c^* - T^*))f(c^*) + \int_{c^*}^{\overline{c}} \lambda f(c) dc = 0$$

and

$$c^* = \frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1-F(c^*))}{f(c^*)} > \frac{D}{1+\lambda} \tag{2.32}$$

the first-order condition for the base transfer is

$$\frac{\partial W}{\partial T^*} = -\frac{1}{1-k}\left(\gamma + D - \left(\frac{\overline{\theta} + T^*}{1-k}\right) - \lambda T^*\right) f(c'') + \int_{c''}^{c^*} (-\lambda) f(c) dc + \int_{c^*}^{\overline{c}} (-\lambda) f(c) dc = 0$$

from which

$$T^* = \frac{1-k}{\lambda(1-k)+1}(\gamma + D) + \frac{\lambda(1-k)^2(1-F(c''))}{(\lambda(1-k)+1)f(c'')} - \frac{\overline{\theta}}{\lambda(1-k)+1} \tag{2.33}$$

Since the solution is a two-part tariff, based on the previous lemmata we conclude that we have found the optimal mechanism for $k > 1$.

■

### 2.3.3 $0 < k < 1$: Mild positive association

In the intermediate case **when** $0 < k < 1$ we have two relocation constraints that affect the partition of types, so both constraints (2.26) and (2.23) are relevant, pinning down both the lower and higher marginal relocating type. We assume that both $c' < \overline{c}$ and $c'' > \underline{c}$ so that we have an interior solution to the optimization problem. We conjecture that the partition in this case is the following: types $c \leqslant c'' = \frac{\overline{\theta}+T^*}{1-k}$ stay and abate, types in the middle, i.e. $c'' < c < c' := -\left(\frac{\overline{\theta}+T^*-c^*}{k}\right)$ leave, and types $c > c'$ stay without abating. Therefore the social welfare function is:

$$\max_{c^*,T^*} W = \int_{\underline{c}}^{\frac{\overline{\theta}+T^*}{1-k}} (\gamma + (D-c) - \lambda T^*)\, f(c)dc + \int_{-\left(\frac{\overline{\theta}+T^*-c^*}{k}\right)}^{\overline{c}} (\gamma + \lambda(c^* - T^*))\, f(c)dc \tag{2.34}$$

**Proposition 3** *Whenever $0 < k < 1$, both the lowest-cost and highest-cost firms are the most immobile, and the abatement threshold in the mechanism under global externalities lies between the thresholds of the previous mechanisms:*

$$c^* \in \left(\frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)}, \frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1-F(c^*))}{f(c^*)}\right)$$

When the association between the abatement and relocation costs is mildly positive, we have a situation in which there are two marginal relocating types. One below the abatement threshold $(c'')$, and one above $(c')$. In this case, surprisingly, the threshold is set above the marginal relocating type $(c'')$, even though the types in $(c'', c')$ all relocate. The reason this happens is that the threshold $c^*$ is now used in its secondary role as a carbon price to tax the staying non-abaters optimally[8]. I note that interestingly, the first-

[8] I focus only on the interior solution in this proposition, the corner solutions to this problem are relegated to the Appendix.

best abatement threshold $c^{FB} = \frac{D}{1+\lambda}$ is contained in the interval, implying that in this association regime, the optimal mechanism even under asymmetric information may implement the first-best level of abatement.

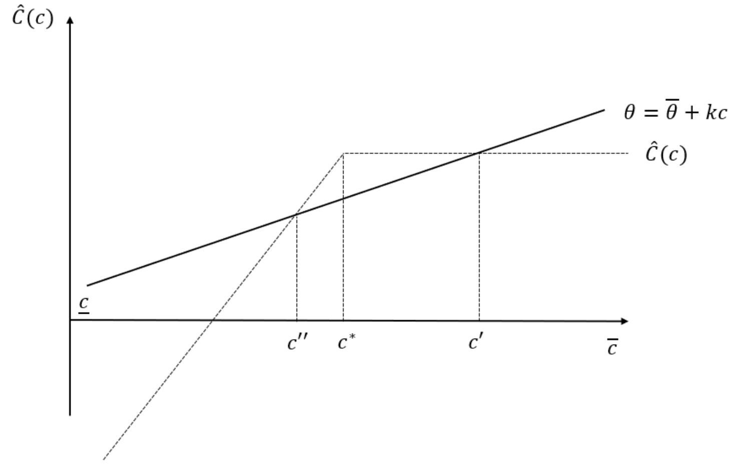


FIGURE 2.3. THE OPTIMAL MECHANISM EXPLOITS THE THRESHOLD $c^*$ TO TAX THE HIGH TYPES, WHEN $0 < k < 1$.

In each of the association regimes considered, the higher the shadow costs of public funds, the larger the distortions from the first-best solution are. A somewhat less savory, but regardless immediate consequence of my chosen streamlined model is that whenever public funds have no shadow costs (in social welfare terms), the entire problem of asymmetric information disappears altogether.

**Proof.** the first-order condition for the carbon price is

$$\frac{\partial W}{\partial c^*} = -\frac{1}{k}\left(\gamma + \lambda(c^* - T^*)\right) f(c') + \int_{c'}^{\overline{c}} \lambda f(c)dc = 0$$

and the first-order condition for the base transfer is

$$\begin{aligned}\frac{\partial W}{\partial T^*} = \frac{1}{1-k}\left(\gamma + D - \left(\frac{\overline{\theta} + T^*}{1-k}\right) - \lambda T^*\right) f(c'') + \int_{\underline{c}}^{c''} (-\lambda) f(c)dc \\ + \frac{1}{k}\left(\gamma + \lambda(c^* - T^*)\right) f(c') + \int_{c'}^{\overline{c}} (-\lambda) f(c)dc = 0\end{aligned}$$

which yield, after some manipulations

$$c^* = T^* - \frac{\gamma}{\lambda} + \frac{k(1 - F(c'))}{f(c')} \tag{2.35}$$

and

$$T^* = \frac{1-k}{1+\lambda(1-k)}(\gamma + D) - \frac{\lambda(1-k)^2 F(c'')}{(1+\lambda(1-k))f(c'')} - \frac{\overline{\theta}}{1+\lambda(1-k)} \tag{2.36}$$

From the first-order condition for $c^*$:

$$\begin{aligned}\frac{\partial W}{\partial c^*} &= -\frac{1}{k}\underbrace{\left(\gamma + \lambda(c^* - T^*)\right)}_{:=-\Delta(c')} f(c') + \int_{c'}^{\overline{c}} \lambda f(c)dc = 0 \\ \frac{\partial W}{\partial c^*} &= 0 \Leftrightarrow \Delta(c')f(c') = k(1 - F(c'))\end{aligned}$$

And the foc for $T^*$:

$$\frac{\partial W}{\partial T^*} = \frac{1}{1-k}\underbrace{\left(\gamma + D - c'' - \lambda T^*\right)}_{:=-\Delta(c'')} f(c'') + \int_{\underline{c}}^{c''} (-\lambda) f(c) dc$$

$$+ \underbrace{\frac{1}{k}\left(\gamma + \lambda(c^* - T^*)\right) f(c') + \int_{c'}^{\overline{c}} (-\lambda) f(c) dc}_{=\partial W/\partial c^*} = 0$$

$$\frac{\partial W}{\partial T^*} = 0 \Leftrightarrow \Delta(c'') f(c'') = -(1-k)\lambda F(c'')$$

Then, noting that $\Delta(c'') = \Delta(c') - (D - c'' + \lambda c^*)$ we can write

$$\Delta(c'') f(c'') = -(1-k)\lambda F(c'') \Leftrightarrow \Delta(c'') = -\frac{(1-k)\lambda F(c'')}{f(c'')}$$

$$\Delta(c') - (D - c'' + \lambda c^*) = -\frac{(1-k)\lambda F(c'')}{f(c'')}$$

$$\frac{k\lambda(1 - F(c'))}{f(c')} + D - c'' - \lambda c^* = \frac{(1-k)\lambda F(c'')}{f(c'')}$$

$$D - c'' - \lambda c^* = \frac{(1-k)\lambda F(c'')}{f(c'')} - \frac{k\lambda(1 - F(c'))}{f(c')}$$

And, since by assumption $c'' = \left(\frac{\overline{\theta} + T^*}{1-k}\right) < c^*$, it follows that

$$D - (1+\lambda)c^* < \frac{(1-k)\lambda F(c'')}{f(c'')} - \frac{k\lambda(1 - F(c'))}{f(c')}$$

And taking a look at the RHS, we have

$$\frac{\lambda F(c'')}{f(c'')} - k\lambda\left(\frac{F(c')}{f(c')} - \frac{F(c'')}{f(c'')} + \frac{1}{f(c')}\right)$$

Where we know that $\frac{F(c')}{f(c')} - \frac{F(c'')}{f(c'')} \geqslant 0$, by regularity of $F(\cdot)$ in c, and that $\frac{1}{f(c')} > 0$. Therefore the bracketed term is strictly positive and hence the second term strictly negative. Regularity of $F(\cdot)$ again implies that $\frac{\lambda F(c'')}{f(c'')} \leqslant$

$\frac{\lambda F(c^*)}{f(c^*)}$, and so we have that

$$D - (1+\lambda)c^* < \frac{\lambda F(c^*)}{f(c^*)} \Leftrightarrow c^* > \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)}$$

meaning that the threshold in this intermediate regime is strictly above the threshold found in the negative association regime. We have again arrived at a two-part tariff as our optimal solution, so by our previous lemmata we conclude this to be the optimal IC mechanism in this case.

■

## 2.4 Conclusions

I confirm, in a streamlined and stylized model of optimal environmental regulation under both informational asymmetry and firm relocation risk the main insights of Ahlvik and Liski (2022), i.e. that carbon leakage, or firm relocation does not indicate a failed regulatory policy. Indeed, as highlighted above, carbon leakage in the form of firm relocation is, in fact, an equilibrium outcome in the *optimal second-best mechanism*. My model posits firm relocation risk as a type-dependent outside option, affiliated with the abatement costs of the firm in either a positive or negative way. This affiliation plays a key role in optimal policy design, essentially setting up multiple different affiliation regimes where the regulator is facing carbon leakage as a result of their regulatory policy, either by inefficient firms (negative association), or by efficient firms (strong positive association). The optimal regulatory policy is distorted either below or above first-best, where the upwards distortion is novel.

In a wider context, the results of this model imply that optimal regulatory policies under relocation risk have additional distortions beyond the simple ones caused by incentive compatibility, with both the size and sign of those distortions depending on the affiliation between the firm's cost type and it's outside option. Therefore, my model formalizes one argument for regulating different industries separately, as one could easily think that different industries may well have different affiliations and hence face differing relocation, or carbon leakage risk. Industry-specific policies arise also in Hoel (1996) and in Martin, Muûls, De Preux, and Wagner (2014), where industry-specific leakage risk is one of the motivating factors behind the model.

## 2.5 APPENDIX: corner solutions to the leakage mechanism

If we have a corner solution in any of the cases, i.e. if $c' \geqslant \overline{c}$ when $k < 0$, $c'' \leqslant \underline{c}$ when $k > 1$, or $c' \geqslant \overline{c}$ and $c'' \leqslant \underline{c}$ when $0 < k < 1$, the problem reduces to designing the optimal mechanism while no subset of types relocates. The objective function in every case and hence first-order condition for the threshold $c^*$ is therefore

$$W = \int_{\underline{c}}^{c^*} (\gamma + (D - c) - \lambda T^*)\, f(c) dc + \int_{c^*}^{\overline{c}} (\gamma + \lambda(c^* - T^*))\, f(c) dc$$
$$\frac{\partial W}{\partial c^*} = (\gamma + D - c^* - \lambda T^*) f(c^*) - (\gamma + \lambda(c^* - T^*)) f(c^*) + (1 - F(c^*))\lambda = 0$$

which yields $c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{(1-F(c^*))}{f(c^*)}$. The first-order conditions for the transfer $T^*$ coincide as well in each case, and therefore we have the same optimal mechanism on offer in any regime of $k$.

Moreover, whenever there is weak positive association, i.e. $0 < k < 1$, one corner solution then is for the regulator to exploit the optimality of the two-part tariff characterization of all IC mechanisms by designing the mechanism such that $\theta \geqslant \hat{C}(c)$ for all $c$. This is done by requiring that the only indifferent marginal type is type $c^*$, therefore pinning down the transfer $T^*$, since:

$$\begin{aligned} c^* - T^* &= \theta \\ &= \overline{\theta} + kc^* \\ T^*(c^*) &= (1 - k)c^* - \overline{\theta} \end{aligned}$$

with this in hand, we can now express the SWF and optimize with regard to $c^*$ alone, leading to:

$$W = \int_{\underline{c}}^{c^*} \left(\gamma + (D - c) - \lambda T^*\right) f(c) dc + \int_{c^*}^{\overline{c}} \left(\gamma + \lambda(c^* - T^*)\right) f(c) dc$$
$$= \int_{\underline{c}}^{c^*} \left(\gamma + (D - c) - \lambda \left[(1-k)c^* - \overline{\theta}\right]\right) f(c) dc + \int_{c^*}^{\overline{c}} \left(\gamma + \lambda c^* - \lambda \left[(1-k)c^* - \overline{\theta}\right]\right) f(c)$$

and

$$\frac{\partial W}{\partial c^*} = \left(\gamma + D - c^* - \lambda(1-k)c^* + \lambda\overline{\theta}\right) - \lambda(1-k) \int_{\underline{c}}^{c^*} f(c^*) dc$$
$$- \left(\gamma + \lambda c^* - \lambda(1-k)c^* + \lambda\overline{\theta}\right) f(c^*) + \lambda k \int_{c^*}^{\overline{c}} f(c) dc = 0$$

from which we get

$$c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda} \frac{1}{f(c^*)} \left[k - F(c^*)\right]$$

and the transfer is then computed as previously. As before with the actual leakage model, we immediately get a result that the threshold $c^*$ may lie below or above the first-best level of $\frac{D}{1+\lambda}$. Interestingly, if it happens that

$$k = F(c^*)$$

this mechanism actually implements the first-best level of abatement.

**Optimal mechanisms for $k = 0$, $k = 1$:**

If we have no association between the abatement and relocation costs, i.e. $k = 0$, then the relocation cost $\theta$ is constant at $\overline{\theta}$ for all firm types. Moreover, we restrict ourselves to relocation costs $\overline{\theta} \geqslant 0$, so that our model does not become non-sensical. The optimization problem now reduces to a standard mechanism design problem with a fixed outside option, since type-dependence is now ruled out. In this case, Lemmas 2 and 3 still imply the uniquely optimal IC mechanism to be a two-part tariff. Now, however, firms relocate when

$$\hat{C}(c) \geqslant \overline{\theta}$$

**Proposition 4** *When $k = 0$, the optimal mechanism is:*

$$c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)}$$
$$T^* = c^* - \overline{\theta}$$

**Proof.** It is immediate that the regulator can retain the highest measure of firms (i.e. receive the highest welfare possible) by reducing the non-abating firms to their outside option payoff. This is now possible, since the outside option is a constant. This then implies that we can solve for the base transfer using the compliance cost of a non-abating firm:

$$c^* - T^* = \overline{\theta} \Leftrightarrow T^* = c^* - \overline{\theta}$$

This scheme retains all the types, and therefore the social welfare function is:

$$W(c^*) = \int_{\underline{c}}^{c^*} \left(\gamma + (D - c) - \lambda \left(c^* - \overline{\theta}\right)\right) f(c)dc + \int_{c^*}^{\overline{c}} \left(\gamma + \lambda\overline{\theta}\right) f(c)dc$$

The first-order condition for the threshold is:

$$\frac{\partial W}{\partial c^*} = \left(\gamma + D - c^* - \lambda(c^* - \overline{\theta})\right) f(c^*) - \lambda F(c^*) - \left(\gamma + \lambda\overline{\theta}\right) f(c^*) = 0$$

from which

$$c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)}$$

Since the mechanism we have derived is a two-part tariff, by our previous lemmata (1) and (2) we conclude it to be uniquely optimal in this case.

■

**When** $k = 1$**, then the relocation cost is an affine function of the abatement cost of the firm**, i.e.

$$\theta = c + \overline{\theta}$$

Now, unlike in the previous case, here the regulator will optimally use a mechanism that reduces *the abating types* to their outside option payoffs, while leaving information rents to the non-abaters. Due to our assumption of linear abatement costs, where the cost of abating a single unit of pollution for a firm is just c, we see immediately that the relocation cost $\theta$ now has the same slope as the abatement cost for any firm type. This now means that the regulator can essentially use a mechanism that lines these two functions up (by clever design of the base transfer, $T^*$), and therefore guarantee that every abater will be reduced to their outside option payoff.

For this to be the case, we must then have that the compliance for the abating firms leaves them at their outside option payoff, i.e.

$$c - T^* = c + \overline{\theta} \tag{2.37}$$

from which we get that $T^* = -\overline{\theta}$. At an interior solution, the objective function becomes (after inserting $T^*$ from before):

$$W = \int_{\underline{c}}^{c^*} \left(\gamma + (D - c) + \lambda\overline{\theta}\right) f(c)dc + \int_{c^*}^{\overline{c}} \left(\gamma + \lambda(c^* - \overline{\theta})\right) f(c)dc$$

The first-order condition for the threshold gives us the same upwards-distorted threshold as in the $k > 1$ association regime, i.e. we have that:

$$c^* = \frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1 - F(c^*))}{f(c^*)}$$

However, we have one other candidate for an equilibrium mechanism in this case. As previously mentioned, when $k = 1$ the regulator reduces the abating types to their outside option payoffs. This also means that the regulator has at their disposal an IC mechanism, where *all the types abate*. To see how this is constructed, note that if the regulator sets a threshold of $\hat{c} = \overline{c}$, then every firm will face a compliance cost as in (2.37), since all of them are abating if they stay. As in the previous section, this induced compliance also pins down the base transfer, such that $T^* = -\overline{\theta}$. Incentive compatibility is trivially satisfied, since no deviation by any firm type to any report will change neither their allocation nor their transfer. Therefore we have a second candidate mechanism in this case, one consisting of

$$\hat{\mathcal{M}} = \{\overline{c}, -\overline{\theta}\} \tag{2.38}$$

The expected welfare from this mechanism is

$$\hat{W} = \int_{\underline{c}}^{\overline{c}} \left(\gamma + D - c + \lambda\overline{\theta}\right) f(c)dc$$
$$= D + \gamma + \lambda\overline{\theta} - \underbrace{\int_{\underline{c}}^{\overline{c}} cf(c)dc}_{=E[c]}$$

While the first mechanism yields an expected welfare of:

$$W = \int_{\underline{c}}^{\overline{c}} \left(\gamma + \lambda\overline{\theta}\right) f(c)dc + \int_{\underline{c}}^{c^*} (D - c)\, f(c)dc + \int_{c^*}^{\overline{c}} \lambda c^* f(c)dc$$
$$= \gamma + \lambda\overline{\theta} + \int_{\underline{c}}^{c^*} (D - c)\, f(c)dc + \int_{c^*}^{\overline{c}} \lambda c^* f(c)dc$$

computing the difference in welfare between the two, we have

$$\hat{W} - W = D - \left(\int_{\underline{c}}^{c^*} (D - c)\, f(c)dc + \int_{c^*}^{\overline{c}} \lambda c^* f(c)dc\right) - \int_{\underline{c}}^{\overline{c}} cf(c)dc$$
$$= D - \int_{\underline{c}}^{c^*} (D - 2c)\, f(c)dc - \int_{c^*}^{\overline{c}} (\lambda c^* - c) f(c)dc$$

and from this expression, it is possible to define a range for the parameters $(D, \lambda)$ such that the integrands are negative and hence the difference $\hat{W} - W > 0$. In this parameter range then, the *optimal* mechanism under $k = 0$ is therefore the one specified in (2.38). Outside this range, the optimal mechanism is

$$\mathcal{M} = \left\{\frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1 - F(c^*))}{f(c^*)}, -\overline{\theta}\right\} \tag{2.39}$$

Figures 2.4 and 2.5 capture the situation graphically. Essentially, in these two separate cases the optimal mechanism either sets the threshold lower than first-best to leverage welfare from the non-abating types, who are in that regime kept to their outside option payoff, or alternatively the threshold is set higher than first-best in order to leverage additional welfare out of the abating types, who are being kept at their participation constraint.

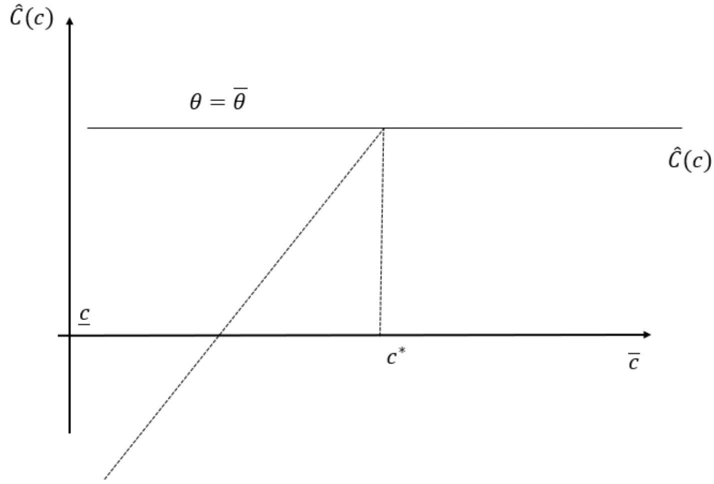


FIGURE 2.4. THE OPTIMAL MECHANISM KEEPS THE NON-ABATERS AT THEIR OUTSIDE OPTION PAYOFF WHEN $k = 0$.

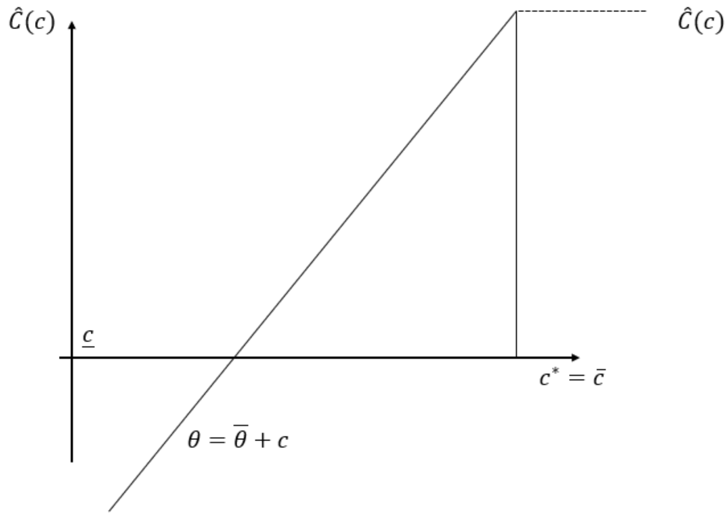


FIGURE 2.5. THE OPTIMAL MECHANISM KEEPS THE ABATERS AT THEIR OUTSIDE OPTION PAYOFF WHEN $k = 1$.

# Chapter 3

# Extensions to the leakage mechanism

## 3.1 Introduction

In this chapter I extend the previous model of carbon leakage by firstly allowing the domestic regulator to make *cross-border transfers*, i.e. to pay the relocating firms for their abatement abroad. When optimally designed, I show that this addition rectifies one major source of distortion in the previous leakage mechanisms, the fact that in some association regimes the regulator was losing firms which are efficient enough to yield positive social welfare if they could be incentivized to abate. Cross-border transfers now allow the regulator to create these incentives. Moreover, I show that in each association regime the regulator has a uniquely optimal cross-border transfer, differing from the domestic carbon price, creating market-wide carbon price dispersion.

In a second extension I consider the foreign country having in place either a fixed carbon tax (price-based regulation) or a fixed emission cap via a cap-and-trade scheme (quantity-based regulation) and derive the domestic regulator's best-response. I show that the domestic regulator benefits from such policies, as they serve to increase the induced firm compliance and relocation costs, hence allowing the regulator to uniformly alter transfers it gives to staying firms and costlessly reap additional abatement benefits from abroad.

## 3.2 Recap of the basic leakage model in Chapter 1

The basic leakage model of the previous chapter dealt with a regulator facing a unit measure of externality-producing firms, who have private information on both their abatement costs and their relocation costs to an alternative country, which I assumed to have no regulation in place.

The optimal policy is distorted from first-best, with the sign of this distortion depending on the association between firm abatement costs and relocation costs. Each separate association regime has a different distortion and its own unique economic insights that arise out of it.

1. In the negative association regime, where $k < 0$, the low-cost firms are captive in the country and in this regime I find that the optimal mechanism is distorted below the socially optimal first-best level (Proposition 1).

2. In the strong positive association regime, where $k > 1$, the situation is reversed and the high-cost firms are now the ones that are captive in the home country. In this regime I find a novel distortion that the optimal mechanism distorts the regulation *above* first-best levels (Proposition 2).

3. Finally, in the intermediate or weak positive association regime, where $0 < k < 1$, I bound the optimal mechanism to lie between the two extremes considered previously (Proposition 3).

## 3.3 Global regulatory policies

We continue using the same model we set up earlier in the first chapter. Previously, relocating firms were assumed to take no action in country j. We extend the basic model considered previously by now allowing the regulator to pay the relocating firms a price $p_F \geqslant 0$ for their voluntary abatement abroad, or in other words we allow the regulator to make cross-border transfers. Therefore the regulatory mechanism, previously consisting only of the domestic carbon price $c^*$ and a base transfer or subsidy, $T^*$ now becomes a triple, which we define as:

$$\mathcal{M} = \{c^*, p_F, T^*\}. \tag{3.1}$$

where $p_F \geqslant 0$ is the price paid to a relocating firm in exhange for their voluntary abatement abroad, which I will call the *foreign carbon price*. We assume that the abatement action by relocating firms is perfectly verifiable by the home country at zero cost. We assume that a relocating firm will voluntarily abate abroad iff $c \leqslant p_F$, since the firm can always reject the offer and simply relocate without accepting $p_F$.

This extension now allows the domestic regulator to mitigate some of the damages arising from carbon leakage, since it can buy abatement from the relocating firms. However, the addition of $p_F$ will, in general, affect the relocation constraints of the firms and therefore lead to a different partition of firms than the basic leakage modeland hence yield a different leakage rate than the basic leakage model of Chapter 1.

To see how the relocation incentives for firms change, let us express the relocation constraint of a firm, given an IC mechanism $\mathcal{M} = \{c^*, p_F, T^*\}$.

As before in Chapter 1, a type c -firm relocates if

$$\underbrace{\hat{C}(c)}_{\text{Domestic compliance}} > \overline{\theta} + kc + \underbrace{(c - p_f)}_{\text{Compensation for abatement abroad}} \tag{3.2}$$

and abates abroad when $p_F \geqslant c$. Furthermore, since relocating firms can choose to not accept the transfer and just relocate with no abatement, that implies that a moving firm of type c rejects any $p_F < c$, as such a price entails a loss should the firm abate abroad.

In the association regimes we have considered, the strongest incentive for the regulator to set such a price is when the most efficient abaters relocate. This happens because the regulator is then losing the most desirable firms in terms of abatement and hence social surplus, and is therefore keen to secure abatement from them if possible. The association regime that induces this scenario is strong positive association, i.e. when $k > 1$. Moreover, we note that securing abatement from abroad is only relevant for the regulator when the externality is global[1].

Therefore I begin with analyzing *strong positive association*, where $k > 1$.

**Strong positive association regime,** $k > 1$**:**
In this regime, the low-cost firms are the most mobile. The optimal simple mechanism is characterized in Proposition (2) and the associated Figure 2.2 illustrates the optimal mechanism and leakage.

As noted previously, the regulator is now able to offer a non-negative foreign carbon price, $p_F$ to relocating firms for their abatement. Since these firms are now the most efficient abaters, and since we are looking at inte-

[1]With local externalities, the relocating firms yield the maximum possible surplus obtainable from them ($\gamma$ notwithstanding) at no additional cost to the regulator. Therefore purely local externalities will have the regulator either not offer this price, or alternatively, set $p_F = 0$.

rior solutions to the optimization problem, the regulator will always wish to offer $p_F$ strictly higher than $\underline{c}$, which will secure a measure $F(p_F)$ of foreign abatement from the relocating firms.

The regulator optimally offers a foreign carbon price that is the minima of the monopsony price of foreign abatement (the regulator is the only buyer in the market) and the marginal relocating type.

**Proposition 5** *When,* $k > 1$*, the uniquely optimal foreign carbon price is characterized by the minimum of the monopsony price and the marginal relocating type:*

$$p_F = \min\left(c'', \frac{D}{1+\lambda} - \frac{F(p_F)}{f(p_F)}\right), \quad \textit{where } \; c'' := \frac{\overline{\theta} + T^*}{1-k}$$

**Proof.** when $k > 1$, the moving firms are ones with low abatement costs, so the regulator may wish to offer a positive price $p_F$ to secure their abatement even in the alternative location. In this case, we conjecture that the partition is such that types $c \leqslant p_F$ move and abate abroad, types $p_F < c \leqslant c''$ move and don't abate, types $c'' < c \leqslant c^*$ stay and abate, and types above $c^*$ stay without abating, so the social welfare function is:

$$W = \int_{\underline{c}}^{p_F} \left(D - (1+\lambda)p_F\right) f(c)dc + \int_{\frac{\overline{\theta}+T^*}{1-k}}^{c^*} \left(\gamma + (D - c) - \lambda T^*\right) f(c)dc$$
$$\int_{c^*}^{\overline{c}} \left(\gamma + \lambda(c^* - T^*)\right) f(c)dc$$

where the first term is the extra surplus attained from abatement abroad. Taking the first-order conditions with respect to $\{T^*, c^*\}$ we find that they are the same as in case (ii) in Proposition 2, therefore the domestic mechanism is unchanged. The first-order condition with regards to the foreign price $p_F$ is

$$\frac{\partial W}{\partial p_F} = 0 \Leftrightarrow (D - (1+\lambda)p_F)\, f(p_F) - (1+\lambda)F(p_F) = 0 \Leftrightarrow$$
$$p_F = \frac{D}{1+\lambda} - \frac{F(p_F)}{f(p_F)}$$

Whenever $p_F < c''$, the regulator buys abatement from the moving firms as well. However, since the marginal relocating firm is of type $c'' = \frac{\overline{\theta}+T^*}{1-k}$ the regulator may be able to do even better than $p_F$. To see why, note that by simply setting $p_F = c''$, the regulator is buying the entire measure $[\underline{c}, c'']$ of reductions, and moreover every firm in this interval strictly prefers this scheme to one where they relocate without abatement. Therefore, the optimal global mechanism in this case consists of:

$$\left\{ c^*, T^*, \min\left( c'', \frac{D}{1+\lambda} - \frac{F(p_F)}{f(p_F)} \right) \right\} \tag{3.3}$$

where $c^*$ and $T^*$ are the same as in Proposition 2 (ii). Since the compensation for abatement abroad is decreasing in the firm's type, and the marginal type abating abroad is pinned down by (3.3) the relocation constraints are unaffected in the domestic mechanism. ■

The addition of a foreign carbon price to the set of instruments available to the regulator essentially fixes the tradeoff facing the regulator in the simple leakage model; they are losing the most efficient firms that would yield the most social surplus when abating, which happens due to the strong positive association between abatement costs c and relocation costs $\theta$. By adding in an instrument for the regulator that allows them to purchase the abatement from relocating firms, the regulator is able to reverse some of the carbon leakage, while still keeping the same measure of firms in-country. Moreover, the foreign carbon price is always strictly lower than the domestic carbon price, since

$$p_F = \min\left(c'', \frac{D}{1+\lambda} - \frac{F(p_F)}{f(p_F)}\right) < c^* = \frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1-F(c^*))}{f(c^*)} \tag{3.4}$$

The base transfer rate is the same as in the simple leakage model (since the first-order condition is the same). This is due to the fact that the regulator has no need to adjust the base compensation or subsidies given to staying firms, since the relocation constraints are unaffected in this association regime. Instead, the regulator simply buys the abatement from the relocating firms at a price given above.

As both the threshold $c^*$ and the base transfer $T^*$ are unchanged from the simple mechanism, it then follows that this global mechanism must lead to strictly higher welfare than the simple model since the regulator is now receiving an additional flow of valuable abatement from the relocating firms.

**Negative association regime:**
Next let us consider the case of negative association, when $k < 0$. In this case, the situation is reversed from before, and the high-cost firms are the most mobile and relocate. Unlike in the previous association regime, the relocating firms now lie *above* the domestic abatement threshold, i.e. do not abate if they stay. Therefore, for the regulator to offer a positive foreign carbon price $p_F$, the relocating firms must not be too inefficient (in a sense I will make precise shortly). Since the welfare gain available from any firm relocating and abating abroad for a price $p_F$ is:

$$D - (1+\lambda)p_F$$

It follows that the maximal price that the regulator is willing to pay is $p_F^{MAX} = \frac{D}{1+\lambda}$, which coincides with the first-best abatement threshold $c^{FB}$. We can then note that whenever $c' = -\left(\frac{\overline{\theta}+T^*-c^*}{k}\right) > \frac{D}{1+\lambda}$, i.e. the marginal moving type lies above the first-best abatement threshold, the regulator is unwilling to buy abatement from the relocating firms, since they are too inefficient. Therefore I assume:

**Assumption 2** *The marginal relocating type lies below the first-best abatement threshold, i.e.*

$$c' < c^{FB} = \frac{D}{1+\lambda}, \ \textit{where} \ c' := -\left(\frac{\overline{\theta} + T^* - c^*}{k}\right)$$

This assumption guarantees that there exists a positive measure of relocating high-cost firms that could still be incentivized to abate abroad at such a cost as to yield strictly positive social welfare for the domestic regulator. I find that in comparison to the basic leakage model, in this association regime the equilibrium mechanism has the same abatement threshold, but the base transfer rate is different and the leakage rate is higher than in the basic model.

**Proposition 6** *When the low-cost firms are the most immobile, and high-cost firms relocate, i.e. when* $k < 0$ *and moreover, whenever assumption (2) holds, the equilibrium mechanism is:*

$$\begin{aligned}
c^* &= \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)} \\
p_F &= \frac{D}{1+\lambda} + \frac{1}{f(p_F)}\left[\frac{F(c^\Delta)}{1+\lambda} - F(p_F)\right] \\
T^* &= \frac{\gamma}{\lambda} + c^* + \frac{(k+1)F(c^\Delta)}{f(c^\Delta)} + \frac{F(c^\Delta)}{f(p_F)} - (1+\lambda)F(p_F)
\end{aligned}$$

*with the new induced marginal relocating type*

$$c^\Delta = \frac{1}{k+1}\left(p_F + c^* - T^* - \overline{\theta}\right). \tag{3.5}$$

Comparing the equilibrium mechanism here to the one outlined in Proposition (1), we find that the domestic carbon price is the same but with a different base transfer rate.

Moreover, the regulator is now optimally inducing *more* carbon leakage than in the basic leakage model of Chapter 1 (since $c^{\Delta} > c'$). Quite intuitively, this only happens since the regulator is able to buy abatement from these firms, so their relocation isn't as harmful to the regulator as in the basic model. The difference in base transfer rates between the global mechanism and the simple mechanism in Chapter 1 can be rewritten as

$$\Delta T^* = \frac{kF(c')}{f(c')} + \frac{(k+1)F(c^{\Delta})}{f(c^{\Delta})} + \frac{F(c^{\Delta})}{f(p_F)} - (1+\lambda)F(p_F) \tag{3.6}$$

$$= \frac{kF(c')}{f(c')} - (1+\lambda)F(p_F) + F(c^{\Delta})\left[\frac{k+1}{f(c^{\Delta})} + \frac{1}{f(p_F)}\right] \tag{3.7}$$

and the base transfer rate in the global mechanism to be lower than in the simple mechanism whenever $\frac{k+1}{f(c^{\Delta})} + \frac{1}{f(p_F)} < 0$ or whenever

$$k < -1 - \frac{f(c^{\Delta})}{f(p_F)}$$

hence, when the association is sufficiently negative, the base transfer rate in the global mechanism is uniformly lower than in the simple mechanism.

**Proof.** First, we must establish the new marginal type, since the optimal choice of $p_F$ will affect the relocation constraints of the staying non-abating firms. In particular, the old marginal type $c'$ that is indifferent between staying and relocating, i.e.

$$c^* - T^* = kc' + \overline{\theta}$$

now has a strict preference to relocate, when offered $p_F > 0$ since

$$c^* - T^* > kc' + \overline{\theta} + \underbrace{(c' - p_F)}_{<0}$$

and therefore $p_F$ induces the marginal relocating type to shift to the left, to type $c^\Delta$, defined by

$$c^* - T^* = kc^\Delta + \overline{\theta} + \left(c^\Delta - p_F\right) \Leftrightarrow c^\Delta = \frac{1}{k+1}\left(p_F + c^* - T^* - \overline{\theta}\right) \tag{3.8}$$

Now we can again form the social welfare function in a piecewise manner, with the following partition: $c \leqslant c^*$ stay and abate, $c^* < c < c^\Delta$ stay and don't abate, and types $c \in [c^\Delta, p_F]$ relocate and abate. Therefore the SWF is

$$\begin{aligned} W := \int_{\underline{c}}^{c^*} (\gamma + D - c - \lambda T^*) f(c) dc + \int_{c^*}^{c^\Delta} (\gamma + \lambda(c^* - T^*)) f(c) dc \\ + \int_{c^\Delta}^{p_F} (D - (1+\lambda)p_F) f(c) dc \end{aligned} \tag{3.9}$$

The first-order conditions are:

$$\begin{aligned} \frac{\partial W}{\partial c^*} = (\gamma + D - c^* - \lambda T^*) f(c^*) + \frac{1}{k+1}(\gamma + \lambda(c^* - T^*)) f(c^\Delta) \\ - (\gamma + \lambda(c^* - T^*)) f(c^*) + \lambda \int_{c^*}^{c^\Delta} f(c) dc \\ - \frac{1}{k+1}(D - (1+\lambda)p_F) f(c^\Delta) = 0 \end{aligned}$$

$$
\begin{aligned}
\frac{\partial W}{\partial p_F} &= \frac{1}{k+1}\left(\gamma+\lambda(c^*-T^*)\right) f(c^\Delta) + \left(D-(1+\lambda)p_F\right) f(p_F) \\
&\quad -\frac{1}{k+1}\left(D-(1+\lambda)p_F\right) c^\Delta - (1+\lambda)\int_{c^\Delta}^{p_F} f(c)dc = 0
\end{aligned}
$$

and

$$
\begin{aligned}
\frac{\partial W}{\partial T^*} &= -\lambda\int_{\underline{c}}^{c^\Delta} f(c)dc - \frac{1}{k+1}\left(\gamma+\lambda(c^*-T^*)\right) f(c^\Delta) - \lambda\int_{c^*}^{c^\Delta} f(c)dc \\
&\quad +\frac{1}{k+1}\left(D-(1+\lambda)p_F\right) f(c^\Delta) = 0
\end{aligned}
$$

Rewriting the condition for $T^*$, we get

$$
\frac{1}{k+1}\left(\gamma+\lambda(c^*-T^*)\right) f(c^\Delta) - \frac{1}{k+1}\left(D-(1+\lambda)p_F\right) f(c^\Delta) = -\lambda F(c^\Delta)
$$

inserting this into the condition for $p_F$ we have

$$
\begin{aligned}
&-\lambda F(c^\Delta) + \left(D-(1+\lambda)p_F\right) f(p_F) - (1+\lambda)\left[F(p_F)-F(c^\Delta)\right] = 0 \\
p_F &= \frac{D}{1+\lambda} + \frac{1}{f(p_F)}\left[\frac{F(c^\Delta)}{1+\lambda} - F(p_F)\right]
\end{aligned}
$$

Using the same substitution in the condition for $c^*$, we get

$$
\begin{aligned}
\frac{\partial W}{\partial c^*} &= \left(D-(1+\lambda)c^*\right) f(c^*) - \lambda F(c^\Delta) + \lambda\int_{c^*}^{c^\Delta} f(c)dc = 0 \Leftrightarrow \\
c^* &= \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)}
\end{aligned}
$$

which is the same threshold than in the previous domestic mechanism without the foreign price. The base transfer, however takes some more algebra to tease out, so start with rewriting the condition for $T^*$:

$$-\frac{1}{k+1}\left(\gamma+\lambda(c^*-T^*)\right)+\frac{1}{k+1}\left(D-(1+\lambda)p_F\right)=\frac{\lambda F(c^\Delta)}{f(c^\Delta)}$$

inserting $p_F$ and simplifying yields

$$T^*=\frac{\gamma}{\lambda}+c^*+\frac{(k+1)F(c^\Delta)}{f(c^\Delta)}+\frac{F(c^\Delta)}{f(p_F)}-(1+\lambda)F(p_F)$$

■

In this association regime, things look slightly different than in the previous one. Now the regulator is losing the more inefficient firms and this already puts bounds on when the regulator optimally buys abatement from abroad (Assumption 2). Whenever this assumption holds, then the regulator is optimally inducing *more* carbon leakage than in the basic leakage model. This follows from the fact that now the regulator is able to both buy valuable abatement abroad, and at the same time optimize the base transfer rate it offers to firms it retains, creating a push-pull dynamic of tightening the screw on the staying firms, while simultaneously shelling out cross-border transfers for relocating firms for their abatement abroad. The key thing to note here, is that this boils down to the regulator exploiting the association between the abatement and relocation costs to their benefit.

**Mild positive association,** $0 < k < 1$**:**
Finally, I consider the regime of mild positive association, where $0 < k < 1$. In this association regime, we have two marginal relocating types, $c'$ and $c''$, where every cost type between these two marginal types relocates. This creates a regime where the regulator retains only the low-cost types and the high-cost types, whereas types in the middle relocate. Our previous results imply that in this case, the abatement threshold will lie between the two other cases considered. That is

$$c^*_{[k<0]} < c^*_{[0<k<1]} < c^*_{[k>1]}$$

We note that $c^{FB} := \frac{D}{1+\lambda} \in \left[c^*_{[k<0]}, c^*_{[k>1]}\right]$ as well. Therefore in this case, we are essentially dealing with the same situation as when the high-cost firms were relocating. Whereas on the one hand, there are relocating firms that can abate and yield positive welfare in doing so (because the first-best threshold is in the interval considered), we must also compensate them according to the last marginal cost type that should be abating, due to the linear compensation scheme in (3.2). Like before, however, any choice of $p_F > c''$ will affect the relocation constraints of every type below $p_F$. Therefore we have a similar shift in the marginal relocating type to the left as we had in the previous regime.

**Proposition 7** *When both the lowest and highest-cost firms are relatively immobile and cost types in the middle relocate, with* $0 < k < 1$, *the optimal mechanism is*

$$p_F = \frac{D}{1+\lambda} + \frac{1}{f(p_F)}\left[\frac{F(c^\Delta)}{1+\lambda} - F(p_F)\right] \tag{3.10}$$

$$T^* = \frac{\lambda k^2 F(c^\Delta)}{(\lambda k - 1) f(c^\Delta)} + \frac{\gamma k}{\lambda k - 1} + \frac{(1+\lambda)k}{\lambda k - 1} p_F + \frac{\overline{\theta}}{\lambda k - 1} \tag{3.11}$$

$$c^* = \frac{k\,(1 - F(c'))}{f(c')} - \frac{\gamma}{\lambda} + T^* \tag{3.12}$$

*where*

$$c^{\Delta} = \frac{1}{k}\left(p_F - T^* - \overline{\theta}\right).$$

Note that counter to the case with negative association, the regulator now induces *less* carbon leakage by their choice of mechanism. This is established by noting that the high marginal relocating type stays constant at $c'$, while the new low marginal type is higher than in the simple leakage model, since

$$c^{\Delta} > c'' \quad \Leftrightarrow \frac{\overline{\theta} + T^*}{1-k} < p_F \tag{3.13}$$

which we assumed to hold. Therefore the new induced measure of leakage, $\int_{c^{\Delta}}^{c'} f(c)dc$ is less than the simple leakage of $\int_{c''}^{c'} f(c)dc$. Not only does the regulator now induce less leakage, but they can claw back some of the damages of that leakage as well with the optimal cross-border transfer.

**Proof.** We conjecture that the partition of types in this case will be such that types below $c^{\Delta}$ will stay and abate, types between $[c^{\Delta}, p_F]$ relocate and abate abroad, and types above $c'$ stay without abating. Therefore we can again express the social welfare function in a piecewise manner in the following way:

$$W := \int_{\underline{c}}^{c^{\Delta}} (\gamma + D - c - \lambda T^*) f(c)dc + \int_{c^{\Delta}}^{p_F} (D - (1+\lambda)p_F) f(c)dc + \int_{c'}^{\overline{c}} (\gamma + \lambda(c^* - T^*))$$

where the marginal relocating low type $c^{\Delta}$ is defined by the relocation constraint

$$c^{\Delta} - T^* = kc^{\Delta} + \overline{\theta} + \left(c^{\Delta} - p_F\right) \Leftrightarrow c^{\Delta} = \frac{1}{k}\left(p_F - T^* - \overline{\theta}\right)$$

The first-order conditions are:

$$\frac{\partial W}{\partial c^*} = -\frac{1}{k}\left(\gamma + \lambda(c^* - T^*)\right) f(c') + \lambda \int_{c'}^{\overline{c}} f(c)dc = 0$$

$$\begin{aligned}\frac{\partial W}{\partial p_F} = \frac{1}{k}\left(\gamma + D - c^{\Delta} - \lambda T^*\right) f(c^{\Delta}) - \frac{1}{k}\left(D - (1+\lambda)p_F\right) f(c^{\Delta}) \\ + \left(D - (1+\lambda)p_F\right) f(p_F) - (1+\lambda)\int_{c^{\Delta}}^{p_F} f(c)dc = 0\end{aligned}$$

$$\begin{aligned}\frac{\partial W}{\partial T^*} = -\frac{1}{k}\left(\gamma + D - c^{\Delta} - \lambda T^*\right) f(c^{\Delta}) - \lambda\int_{\underline{c}}^{c^{\Delta}} f(c)dc + \frac{1}{k}\left(D - (1+\lambda)p_F\right) f(c^{\Delta}) \\ + \frac{1}{k}\left(\gamma + \lambda(c^* - T^*)\right) f(c') - \lambda\int_{c'}^{\overline{c}} f(c)dc = 0\end{aligned}$$

using the condition for $c^*$, and inserting it into the condition for $T^*$, then plugging everything into our condition for $p_F$ we can solve for

$$p_F = \frac{D}{1+\lambda} + \frac{1}{f(p_F)}\left[\frac{F(c^{\Delta})}{1+\lambda} - F(p_F)\right] \tag{3.14}$$

which we can check to be below the first-best threshold of $\frac{D}{1+\lambda}$, since $c^{\Delta} < p_F$, $F(\cdot)$ is nondecreasing and $f(\cdot) > 0$. Simplifying further, we can solve for the optimal base transfer and domestic abatement threshold in this case, which are:

$$T^* = \frac{\lambda k^2 F(c^\Delta)}{(\lambda k - 1) f(c^\Delta)} + \frac{\gamma k}{\lambda k - 1} + \frac{(1+\lambda)k}{\lambda k - 1} p_F + \frac{\overline{\theta}}{\lambda k - 1} \tag{3.15}$$

$$c^* = \frac{k\,(1 - F(c'))}{f(c')} - \frac{\gamma}{\lambda} + T^* \tag{3.16}$$

■

In each association regime, the domestic carbon price is unaffected by the addition of the foreign carbon price to the regulatory mechanism.

## 3.4 Optimal regulation when the foreign country sets a fixed regime

A second natural extension - and a very interesting research question in its own right - is to think about what may happen when the foreign country (who, so far, only exists in the model as a passive participant) can also regulate the firms arriving there. While addressing the complete problem of competing mechanism design lies beyond the scope of this chapter, the extension we consider here is one where the foreign country is implementing a fixed regulation mechanism, by way of using an exogenous carbon tax rate, set at an exogenous, not necessarily Pigouvian level.

### 3.4.1 Price regulation

Let us assume that the foreign country implements a static carbon tax per unit of emissions of size $\tau \geqslant 0$. In this case, the firm's relocation choice becomes a comparison between compliance at home and compliance abroad, where we continue to treat the firms as cost-minimizers and assume that the firms choose optimally between abating and paying $\tau$ when relocating. Therefore, the firm relocates iff

$$\hat{C}(c) \geqslant \overline{\theta} + kc + \min(\tau, c) \tag{3.17}$$

where in constrast to the previous section, there is now a foreign carbon tax $\tau$ and not a foreign carbon price set by the home country.

In the following, I limit my analysis to exogenous carbon tax rates that have some bite in the sense that they induce some relocating firms to abate when they relocate. For tax rates $\tau$ that satisfy $\tau < \underline{c}$, i.e. $\min(\tau, c) = \tau$, for all $c \in [\underline{c}, \overline{c}]$, the carbon tax only has a level effect on the domestic mechanism, whereby no relocating firm is incentivized to abate due to it, but the regulator is able to decrease their base transfer rate $T^*$ by the amount $\tau$ in all regimes, thus reaping more rents from the firms themselves. This happens because at these low levels, the effect of the carbon tax is to uniformly shift the relocation costs of all firm types[2] by the amount $\tau$. Therefore, in the following analysis I assume that:

**Assumption 3** $\underline{c} < \tau < \overline{c}$.

So that the carbon tax is set at an intermediate level. This assumption guarantees that the tax itself has some bite (due to being higher than $\underline{c}$), but is not so excessively high so as to essentially trap the firms in the home country. With this in mind, let us analyze the different association regimes separately, as we did before:

### Most efficient firms move:

When $k > 1$, then the most efficient firms relocate (cf. Figure 2.2). Now when faced with the foreign carbon tax $\tau$, the relocation constraint of the firm is modified to (3.17). To clarify exposition, I modify the carbon tax assumption to

[2]This can be seen by noting that since $\min(\tau, c) = \tau$, for all $c \in [\underline{c}, \overline{c}]$, the relocation constraints are uniformly increased for all types, and thereby enter the optimization in Propositions 1-3 additively.

**Assumption 4** $\underline{c} < \tau < c^*$

Which states that the level of the foreign tax is high enough to induce some types to abate if they relocate, but is still below the domestic abatement threshold of $c^*$. Under this assumption, the marginal relocating type, $c^\Delta$, now decides between staying and abating and relocating and paying the foreign carbon tax and therefore the marginal type is pinned down by the following indifference condition:

$$c^\Delta - T^* = \overline{\theta} + kc^\Delta + \tau \tag{3.18}$$

$$c^\Delta = \frac{\overline{\theta} + T^*}{1-k} + \frac{\tau}{1-k} \tag{3.19}$$

$$= c'' + \underbrace{\frac{\tau}{1-k}}_{<0} < c'' \tag{3.20}$$

**Proposition 8** *Under a fixed foreign carbon tax* $\tau$*, the best response for the regulator under* $k > 1$ *is to offer the same threshold* $c^*$ *as in the simple model, but with a different base compensation rate* $T^*$*.*

**Proof.** We conjecture that the partition is such that firms $c \leqslant \tau$ relocate and abate, firms $\tau < c < c^\Delta$ relocate and pay the carbon tax, firms with $c^\Delta \leqslant c \leqslant c^*$ stay and abate, and firms above $c^*$ stay without abating. The objective function becomes:

$$W = \int_{\underline{c}}^{\tau} Df(c)dc + \int_{c^\Delta}^{c^*} (\gamma + (D - c) - \lambda T^*)\, f(c)dc + \int_{c^*}^{\overline{c}} (\gamma + \lambda(c^* - T^*))\, f(c)dc$$

The first-order condition for the abatement threshold is:

$$\frac{\partial W}{\partial c^*} = (\gamma + D - c^* - \lambda T^*)\, f(c^*) - (\gamma + \lambda(c^* - T^*))f(c^*) + \int_{c^*}^{\overline{c}} \lambda f(c)dc = 0$$

which is equivalent to the standard model, so the threshold is identical as well at

$$c^* = \frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1-F(c^*))}{f(c^*)}$$

The first-order condition for the base transfer is:

$$\frac{\partial W}{\partial T^*} = -\frac{1}{1-k}\left(\gamma + D - \left(\frac{\overline{\theta}+T^*}{1-k} - \frac{\tau}{1-k}\right) - \lambda T^*\right) f(c^{\Delta}) + \int_{c^{\Delta}}^{c^*}(-\lambda)f(c)dc + \int_{c^*}^{\overline{c}}(-\lambda)f(c)dc = 0$$

from which we can solve for the optimal transfer as:

$$T^* = \frac{\lambda(1-k)^2\left(1-F(c^{\Delta})\right)}{(\lambda(1-k)+1)f(c^{\Delta})} + \frac{(1-k)}{\lambda(1-k)+1}(\gamma + D) - \frac{1}{\lambda(1-k)+1}\left(\overline{\theta}+\tau\right) \quad (3.21)$$

■

In the figure below, I illustrate the effects of the foreign carbon tax. Under my assumptions, the tax is set at a level to induce some abatement abroad, but the main effect of the foreign policy is to shift out the relocation costs. This then allows the regulator to shift more compliance costs for the firms, as their outside options become worse.

The difference in the base compensation can be computed to be

$$\Delta T^* = \underbrace{\frac{\lambda(1-k)^2(1-F(c''))}{(\lambda(1-k)+1)f(c'')}}_{A} + \underbrace{\frac{\lambda(1-k)^2\left(1-F(c^{\Delta})\right)}{(\lambda(1-k)+1)f(c^{\Delta})}}_{B} - \frac{1}{\lambda(1-k)+1}(\tau)$$

And the base compensation is lower than in the simple mechanism

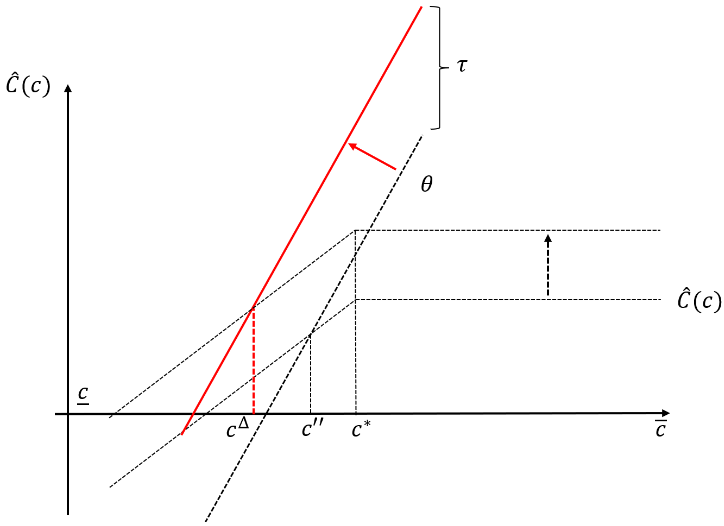


FIGURE 3.1. A FOREIGN CARBON TAX SHIFTS OUT THE OUTSIDE OPTIONS FOR THE FIRMS.

whenever

$$A + B < \frac{1}{\lambda(1-k)+1}(\tau)$$

**Most inefficient firms move:**

When $k < 0$, the most inefficient firms (high abatement cost firms) move. In this case, our assumption of $\tau < c^*$ implies that the foreign carbon price $\tau$ has a level effect on the relocation constraint. As in this case, the marginal relocating firm (which lies above the domestic abatement threshold of $c^*$) compares the compliance cost in the domestic mechanism with relocating and paying the foreign carbon tax, and the marginal firm must be indifferent between the two. This implies that the new marginal type $c^\Delta$ is pinned down by the following relocation constraint:

$$c^* - T^* = \overline{\theta} + kc^\Delta + \tau \Leftrightarrow c^\Delta = -\frac{1}{k}\left(\overline{\theta} + T^* + \tau - c^*\right) \tag{3.22}$$

and since $\tau > 0$, we have that $c^\Delta$ lies above the previous marginal type $c'$ in the original model, implying that the regulator can now retain a higher measure of firms.

**Proposition 9** *When $k < 0$, the best response of the regulator under a foreign carbon tax $\tau$ is to offer the same threshold $c^*$ as in the simple model, but a lower base compensation rate $T^*$.*

**Proof.** We conjecture that the partition of types is the following: $c \leqslant c^*$ stay and abate, $c < c^\Delta$ stay without abating, and firms above $c^\Delta$ relocate. With this partition, the social welfare function is:

$$W = \int_{\underline{c}}^{c^*} (\gamma + (D - c) - \lambda T^*)\, f(c)dc + \int_{c^*}^{c^\Delta} (\gamma + \lambda(c^* - T^*))\, f(c)dc$$

The first-order conditions are:

$$\frac{\partial W}{\partial c^*} = (\gamma + D - c^* - \lambda T^*) f(c^*) + \frac{1}{k}(\gamma + \lambda(c^* - T^*))f(c^\Delta)$$
$$-(\gamma + \lambda(c^* - T^*))f(c^*) + \int_{c^*}^{c^\Delta} \lambda f(c) dc = 0$$

and

$$\frac{\partial W}{\partial T^*} = -\lambda \int_{\underline{c}}^{c^*} f(c) dc - \frac{1}{k}(\gamma + \lambda(c^* - T^*))f(c^\Delta) - \lambda \int_{c^*}^{c^\Delta} f(c) dc = 0$$

inserting the condition for $T^*$ in the condition for $c^*$, we get that the optimal threshold is:

$$c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda} \frac{F(c^*)}{f(c^*)}$$

which is identical to the basic model in Chapter 1. The optimal base transfer can be computed to be

$$T^* = \frac{\gamma}{\lambda} + \frac{kF(c^\Delta)}{f(c^\Delta)} + c^*$$

with $c^\Delta = -\frac{1}{k}\left(\overline{\theta} + T^* + \tau - c^*\right)$. Computing the difference in base transfers with the simple mechanism, we have

$$\Delta T^* = k \left[ \frac{F(c^\Delta)}{f(c^\Delta)} + \frac{F(c')}{f(c')} \right]$$

Since the bracketed term is positive and $k < 0$, the difference is negative and the base transfer is lower than in the simple mechanism. ■

In the figure above, the foreign carbon tax serves only to shift out the

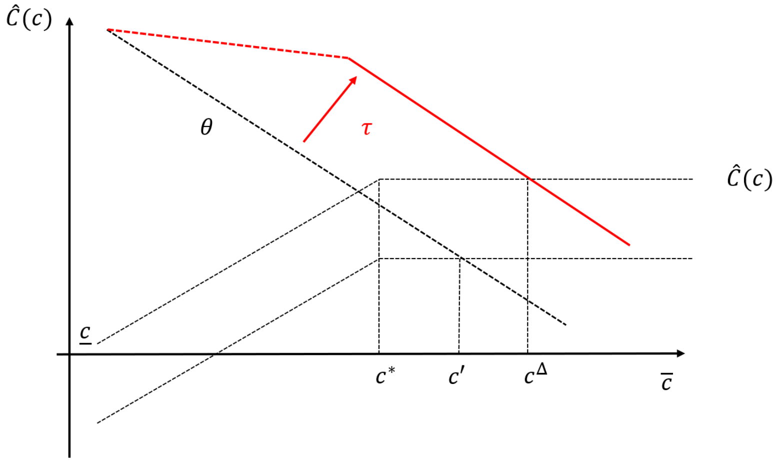


FIGURE 3.2. THE FOREIGN CARBON TAX $\tau$ SHIFTS THE OUTSIDE OPTION OUT WITH INDUCED SMALLER CARBON LEAKAGE.

relocation costs for the firms[3]. This has the effect that the regulator is able to decrease the base transfers it offers. No additional abatement happens, but carbon leakage decreases as the firm relocation costs increase, inducing a higher measure of firms to stay in the home country.

## Firms in the middle move

When $0 < k < 1$, then firms in the middle relocate, and we have two extensive margins and two marginal relocating types. Above the abatement threshold, we have the same marginal type as in the previous section, type $c^\Delta$. The second marginal type, below the threshold must be indifferent between relocating and paying the carbon tax, and staying and abating. Therefore, the relocation constraints yield a marginal type of

$$\tilde{c} - T^* = \overline{\theta} + k\tilde{c} + \tau \Leftrightarrow \tilde{c} = \frac{\overline{\theta} + T^* + \tau}{1 - k} \tag{3.23}$$

And we can verify, that in comparison to the marginal relocating type

[3]I cover the case of high carbon taxes in the Appendix, where Assumptions 3 (and hence also 4) are violated.

below the threshold in the basic model, $c''$, $\tilde{c} > c''$. Therefore the measure of relocating firms is smaller under a foreign carbon tax in this association regime.

**Proposition 10** *When* $0 < k < 1$*, the optimal best-response mechanism under a foreign carbon tax* $\tau$ *is:*

$$c^* = T^* - \frac{\gamma}{\lambda} + \frac{k(1 - F(c^\Delta))}{f(c^\Delta)} \tag{3.24}$$

$$T^* = \frac{1-k}{1+\lambda(1-k)}(\gamma + D) - \frac{\lambda(1-k)^2 F(\tilde{c})}{(1+\lambda(1-k))f(\tilde{c})} - \frac{\overline{\theta} + \tau}{1+\lambda(1-k)} \tag{3.25}$$

**Proof.** The social welfare function under our conjectured partition can be written as:

$$\max_{c^*, T^*} W = \int_{\underline{c}}^{\tilde{c}} (\gamma + (D - c) - \lambda T^*) f(c) dc + \int_{c^\Delta}^{\overline{c}} (\gamma + \lambda(c^* - T^*)) f(c) dc$$

with marginal relocating types $\tilde{c}, c^\Delta$ defined as previously. The first-order conditions are:

$$\frac{\partial W}{\partial c^*} = -\frac{1}{k}(\gamma + \lambda(c^* - T^*)) f(c^\Delta) + \lambda \int_{c^\Delta}^{\overline{c}} f(c) dc = 0$$

$$\frac{\partial W}{\partial T^*} = \frac{1}{1-k}(\gamma + D - \tilde{c} - \lambda T^*) f(\tilde{c}) - \lambda \int_{\underline{c}}^{\tilde{c}} f(c) dc$$
$$+ \frac{1}{k}(\gamma + \lambda(c^* - T^*)) f(c^\Delta) - \lambda \int_{c^\Delta}^{\overline{c}} f(c) dc = 0$$

which yield an optimal abatement threshold of

$$c^* = T^* - \frac{\gamma}{\lambda} + \frac{k(1 - F(c^\Delta))}{f(c^\Delta)}$$

and a base transfer of

$$T^* = \frac{1-k}{1+\lambda(1-k)}(\gamma + D) - \frac{\lambda(1-k)^2 F(\tilde{c})}{(1+\lambda(1-k))f(\tilde{c})} - \frac{\overline{\theta} + \tau}{1+\lambda(1-k)}$$

We have arrived at a two-part tariff, so therefore we can conclude that this is the uniquely optimal best-response mechanism.

■

### 3.4.2 Quantity regulation

To contrast the results under price regulation, where - in general - the price of the externality is set but where the abatement itself is endogenous, let us consider the other option of quantity regulation, where the total amount of pollution is capped. To this end, let us assume that location $j$ has a cap-and-trade scheme in place. In other words, there is an exogenous cap of $\bar{q} \in (0, 1]$ on emissions in country $j$, implemented by way of tradable emission permits, that are endogenously priced at a price $p$ in a way I will make clear soon.

The relocating firm now has to face the foreign regulation in the sense that it must decide whether to abate (and pay their private cost of said abatement), or not abate but purchase a permit for their emissions at price $p$. The cap-and-trade scheme modifies the relocation constraints of the firms in the following way: the relocation constraint for a type $c$ -firm now states, that the firm relocates iff compliance at home exceeds the foreign compliance cost $C_j(c)$, which now also includes the cap-and-trade scheme, i.e.

$$C_i(c) \geqslant \overline{\theta} + kc + \underbrace{C_j(c)}_{\text{Foreign compliance}} \tag{3.26}$$

$$\geqslant \overline{\theta} + kc + \min(p, c) \tag{3.27}$$

Where the minimization results from the firm abating abroad, whenever $p < c$, and buying a permit whenever $c \geqslant p$. In terms of the domestic mechanism, then, the new*feasibility constraint* that the regulator must satisfy is that in an IC mechanism $\{c^*, T^*\}$, the induced measure of carbon leakage must not exceed the foreign emission cap $\bar{q}$.

**The foreign permit market:**

The alternative country sets an emission cap of $\bar{q}$ that it implements by way of tradable permits. To illustrate how I model this market, let us assume that the domestic regulator implements a mechanism that result in all firms of types $c \in [\underline{c}, c_1]$ to relocate. Given my assumption of each firm polluting 1 unit, this yields a total of $\int_{\underline{c}}^{c_1} f(c)dc = F(c_1)$ of carbon leakage.

I assume that *whenever the cap is non-binding*, i.e. whenever $\bar{q}$ is large enough to absorb the full measure of carbon leakage, the resulting permit price is $p = 0$. Since $\underline{c} \geqslant 0$, this incentivizes at most the lowest type of firm to abate[4]. Continuing our example, I assume that whenever the cap is slack, i.e.

$$\int_{\underline{c}}^{c_1} f(c)dc = F(c_1) < \bar{q}$$

then the induced permit price is $p = 0$. In the following analysis I will assume that the cap *is always binding*, in each association regime. I do this since it is trivial to see that whenever the cap does not bind, the sim-

[4]Of course, yielding total foreign abatement of measure zero.

ple leakage mechanism remains uniquely optimal since the permit price is zero, implying that the relocation constraint in (3.26) is unchanged from the basic leakage model of Chapter 1. With these preliminaries out of the way, let us proceed to analyze the situation when the caps are binding. In the following analysis, I have limited my attention to analyzing the negative and strong positive affiliation regimes, with the intermediate regime being relegated to future work. The cleanest results arise in the negative association regime, so I start there.

### 3.4.3 $k < 0$: Negative association regime

In this regime, the low-cost firms are the most immobile and high-cost firms relocate. Keeping in mind the simple leakage model of Chapter 1 and the equilibrium mechanism characterized in Proposition (2), if the foreign emission cap is binding, this means that the induced carbon leakage from the simple mechanism is too large, i.e.

$$\int_{c'}^{\overline{c}} f(c)dc = \big(1 - F(c')\big) > \bar{q}$$

Therefore, the regulator must redesign the mechanism by taking into account the feasibility constraint of the foreign cap:

$$\int_{p}^{\overline{c}} f(c)dc \leqslant \bar{q} \tag{3.28}$$

where $p > c'$ is a permit price that must be set higher than the marginal relocating type in the simple mechanism to induce abatement and to satisfy the feasibility constraint. Since I assume the cap cannot be slack, this leads us to conclude that the cap (and the above feasibility constraint) must hold as an equality. Figure 3.3 illustrates the situation graphically below.

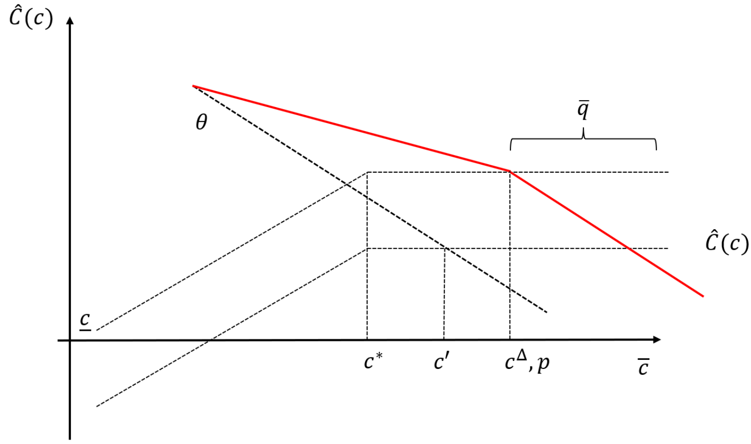


FIGURE 3.3. WHEN $k < 0$, A FOREIGN EMISSION CAP INDUCES THE REGULATOR TO INCREASE COMPLIANCE AND DECREASE LEAKAGE BUT NO ADDITIONAL ABATEMENT OCCURS.

In this figure, a permit price that is higher than the relocating type has the effect that it shifts out the relocation costs of the firms as in (3.26). The kink in the outside option occurs where the firm optimally switches from abating to purchasing a permit, i.e. at a point where $c = p$. However, since the feasibility constraint holds as an equality, we can solve for this price as follows:

$$\int_{\underline{p}}^{\overline{c}} f(c)dc = \bar{q}$$

$$(1 - F(p)) = \bar{q}$$

$$p = F^{-1}(1 - \bar{q})$$

where by continuity of F, this uniquely pins down the equilibrium permit price that induces exactly $\bar{q}$ leakage. Since (in the graph above) the regulator's welfare is maximized by moving the two-part tariff up as close to the firm's outside option function as possible, it follows that the regulator optimally sets the marginal relocating type equal to the permit price derived above. Therefore we have as the new marginal type:

$$\begin{aligned} c^* - T^* &= \overline{\theta} + kc^{\Delta} + p \\ &= \overline{\theta} + kc^{\Delta} + c^{\Delta} \\ &= \overline{\theta} + (k+1)\left[F^{-1}\left(1-\bar{q}\right)\right] \end{aligned}$$

Here, the RHS is a constant, so this pins down the base transfer $T^*$ in the two-part tariff, since

$$T^* = c^* - \overline{\theta} - (k+1)\left[F^{-1}\left(1-\bar{q}\right)\right] \tag{3.29}$$

Hence the social welfare to be optimized is

$$W = \int_{\underline{c}}^{c^*} \left(\gamma + D - c - \lambda T^*\right) f(c) dc + \int_{c^*}^{F^{-1}(1-\bar{q})} \left(\gamma + \lambda(c^* - T^*)\right)$$

inserting $T^*$ from (3.29) and taking the first-order condition yields the same abatement threshold as in the simple mechanism, i.e.

$$c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)} \tag{3.30}$$

whereas the transfers are lower than in the simple mechanism whenever

$$c^* - \overline{\theta} - (k+1)\left[F^{-1}\left(1-\bar{q}\right)\right] - \left[\frac{\gamma}{\lambda} + c^* - \frac{kF(c')}{f(c')}\right] < 0$$

and a sufficient condition for which is

$$(1+k)\left[F^{-1}\left(1-\bar{q}\right)\right] > \frac{kF(c')}{f(c')} \tag{3.31}$$

### 3.4.4 $k > 1$: Strong positive association regime

In the strong positive association regime, the high-cost firms are the most immobile and low-cost firms relocate. Again, since the emission cap is binding, we must have that the leakage induced by the simple mechanism of Chapter 1 exceeds the foreign cap, i.e. $\int_{\underline{c}}^{c''} f(c)dc = F(c'') > \bar{q}$. Therefore a positive amount of abatement needs to happen abroad, and in order to do this, the price of the emission permit must be $p > \underline{c}$. The relocation constraint of the firm is (from (3.26)):

$$c^* - T^* \leqslant \overline{\theta} + kc + \min\{c, p\}$$

Assuming that the required abatement is low enough so that a positive measure of relocating firms buy the permit, then the new marginal relocating type $c^{\Delta}$ is:

$$c^* - T^* = \overline{\theta} + kc^{\Delta} + p \Leftrightarrow c^{\Delta} = \frac{1}{1-k}\left(\overline{\theta} + T^* + p\right) \tag{3.32}$$

It is immediate that now, for any $p > 0$, the new marginal type is *lower* than the original marginal relocating type $c''$, since recall that

$$\begin{aligned} c^{\Delta} &= \frac{1}{1-k}\left(\overline{\theta} + T^* + p\right) \\ &= \frac{\overline{\theta} + T^*}{1-k} + \frac{p}{1-k} \\ &= c'' + \frac{p}{1-k} \end{aligned}$$

and since $\frac{p}{1-k} < 0$, this implies that $c^{\Delta} < c''$. So in this case, what happens is that the foreign emission cap *decreases* carbon leakage from the domestic country as more firms are retained.

The equilibrium permit price $p$ must satisfy the following, given the new marginal type:

$$\int_{p}^{c^{\Delta}} f(c)dc = \bar{q} \tag{3.33}$$

$$\Phi := F(c^{\Delta}) - F(p) - \bar{q} = 0 \tag{3.34}$$

Where the market clearing permit price is defined implicitly by function $\Phi$. I conjecture that the equilibrium partition of types is the following:

- Types $c \in [\underline{c}, p]$ relocate and abate,
- Types $c \in (p, c^{\Delta}]$ relocate and buy an emission permit
- Types $c \in (c^{\Delta}, c^{*})$ stay and abate, and finally
- Types $c > c^{*}$ stay without abating.

With this partition, the Lagrangian function to be optimized is:

$$L = \int_{\underline{c}}^{p} Df(c)dc + \int_{c^{\Delta}}^{c^{*}} (\gamma + D - c - \lambda T^{*}) + \int_{c^{*}}^{\overline{c}} (\gamma + \lambda(c^{*} - T^{*}))\, f(c)dc + \mu\left[\bar{q} - \left(F(c^{\Delta}) - F(p)\right)\right] \tag{3.35}$$

where the first part is windfall abatement for the domestic regulator coming from relocating firms abating abroad, and the last part is the equality constraint that I have incorporated directly by integrating the constraint in (3.33). Taking the first-order condition for the abatement threshold, we find that:

$$\frac{\partial L}{\partial c^{*}} = (\gamma + D - c^{*} - \lambda T^{*})\, f(c^{*}) - (\gamma + \lambda(c^{*} - T^{*}))\, f(c^{*}) + \lambda(1 - F(c^{*})) = 0$$

which yields the same abatement threshold as in the simple leakage model,

$$c^* = \frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1-F(c^*))}{f(c^*)} \tag{3.36}$$

The first-order condition for the base transfer is trickier, but yields:

$$\begin{aligned}\frac{\partial L}{\partial T^*} = Df(p)\frac{dp}{dT^*} - \frac{1}{1-k}\left(\gamma + D - c^{\Delta} - \lambda T^*\right) f(c^{\Delta}) - \lambda \int_{c^{\Delta}}^{c^*} f(c)dc \\ - \lambda \int_{c^*}^{\overline{c}} f(c)dc - \mu f(c^{\Delta})\frac{1}{1-k} + \mu f(p)\frac{dp}{dT^*} = 0 \end{aligned} \tag{3.37}$$

**Signing the price derivative**

In the condition above, the derivative of the permit price with regards to the domestic mechanisms base transfer appears twice. I argue in the following that the sign of this derivative is negative. Differentiating $\Phi$ implicitly, one finds that

$$\begin{aligned}\frac{dp}{dT^*} &= -\frac{\Phi_T^*}{\Phi_p} \\ &= -\left[\frac{\frac{1}{1-k}f(c^{\Delta})}{\frac{1}{1-k}f(c^{\Delta}) - f(p)}\right] \\ &= -\left[1-(1-k)\frac{f(p)}{f(c^{\Delta})}\right]^{-1}\end{aligned}$$

From where we get that the derivative is negative whenever $\left[1-(1-k)\frac{f(p)}{f(c^{\Delta})}\right] > 0$. Simplifying further, one gets that

$$\left[1-(1-k)\frac{f(p)}{f(c^{\Delta})}\right] > 0 \Leftrightarrow$$
$$(1-k)\frac{f(p)}{f(c^{\Delta})} - 1 < 0 \Leftrightarrow$$
$$\frac{(1-k)f(p) - f(c^{\Delta})}{f(c^{\Delta})} < 0$$

where the nominator is strictly negative since $k > 1$.

Therefore the price derivative in the computation above is negative. One can see this from the graph below (Figure 3.4), in which increasing the transfer $T^*$ amounts to lowering the entire two-part tariff on the y-axis. As this amounts to the regulator paying every type of firm more subsidies, it incentivizes a higher measure of firms to stay in-country. Therefore the leakage rate decreases, and given an exogenous emission cap $\bar{q}$, the required measure of abatement - and hence the price of the emission permit also decreases. Alternatively, when the domestic transfers decrease, this now means every type of firm is compensated less for staying and hence the leakage rate increases. An increased leakage rate must (in this model) mean that the required measure of abatement also increases, and hence the permit price must also increase, and therefore

$$\frac{dp}{dT^*} < 0. \tag{3.38}$$

The situation is illustrated graphically below:

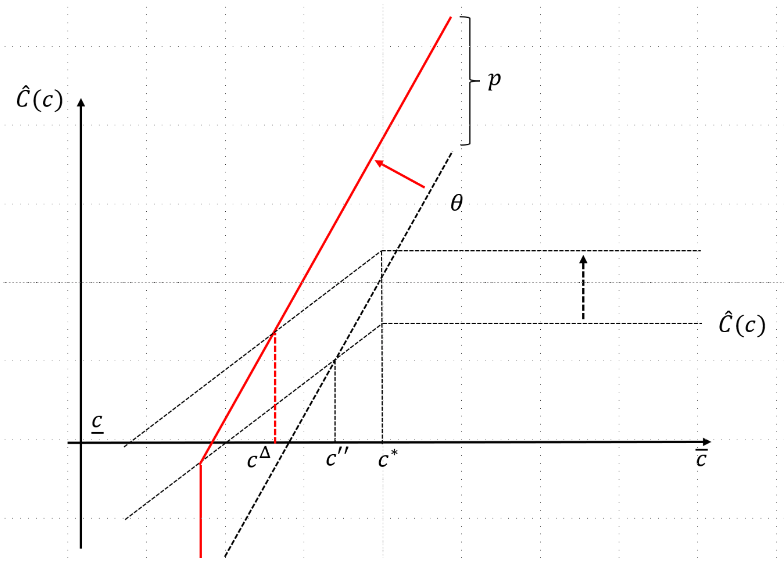


FIGURE 3.4. A BINDING FOREIGN EMISSION CAP SHIFTS THE RELOCATION COSTS FOR EVERY FIRM OUTWARD. THE REGULATOR BEST-RESPONDS BY INCREASING COMPLIANCE AND DECREASING LEAKAGE.

Continuing on and solving for the base transfer from (3.37) we have

$$T^* = \frac{(1-k)(\gamma + D)}{1+\lambda(1-k)} + \frac{\mu(1-k)}{1+\lambda(1-k)} + \frac{\lambda(1-k)^2\left(1-F(c^{\Delta})\right)}{[1+\lambda(1-k)]\,f(c^{\Delta})} - \frac{(1-k)^2\,(D-\mu)\,f(p)}{[1+\lambda(1-k)]\,f(c^{\Delta})}\frac{dp}{dT^*} - \left(\frac{\overline{\theta}+p}{1+\lambda(1-k)}\right) \tag{3.39}$$

and comparing this to the base transfer in the simple mechanism, the transfers with foreign regulation in place are lower whenever

$$\frac{1}{1+\lambda(1-k)}\left[\mu(1-k) - p - (1-k)^2\,[D-\mu]\,\frac{f(p)}{f(c^{\Delta})}\frac{dp}{dT^*}\right] < 0 \tag{3.40}$$

I find that quantity regulation implemented in the other country does not change the marginal incentives for the firms, and that the best-response mechanisms implement the same level of abatement than do the simple leakage mechanisms of Chapter 1. What changes, however, is the level of the base transfers that the regulator offers. This is intuitive, since foreign regulation effectively serves to shift out the relocation costs of the firms, hence making the firms uniformly worse off.

## 3.5 Conclusions and literature

I extend the basic leakage model by relaxing the assumption that the regulator cannot make (or commit to) cross-border transfers for the relocating firms. I show that conditional cross-border transfers rectify the one major drawback of the simple leakage mechanisms discussed previously: the fact that the regulator is losing socially valuable firms and therefore also abatement. With cross-border transfers, the regulator is able to buy the leaked abatement directly from the relocating firms themselves, essentially outsourcing not only the firms but their abatement as well. Moreover, I show that in any association regime, this foreign carbon price is both unique and differs from the domestic carbon price. I obtain similar results when considering exogenous regulatory policies set by the pollution haven country; the other country's policy works to the domestic regulator's advantage, since foreign regulation serves to decrease the outside options of relocating firms in a unilateral way, making each firm's compliance costs (at least weakly) higher than in the simple leakage model. This then allows the domestic regulator to cut back on its own compensation paid to the firms it does retain, while also providing windfall abatement benefits accrued from relocating firms who abate abroad.

I consider only exogenously given policies implemented in the alternative country. If indeed it is allowed to set its policy endogenously, we are in a situation where the two countries compete, and this requires a richer model than the one I have considered here (e.g. Mideksa (2022) or Landry (2021)). Moreover, multilateral linkages between quantity and price -based mechanisms such as an emissions trading system and a carbon tax may be very complex in reality (see, e.g. Metcalf and Weisbach (2012), Stavins (2022)). However, even these simple extensions serve to confirm much of the intuition and reasoning behind the interlinking (both proposed and actual) of various different regulatory mechanisms[5]. Whereas static linkage of emission trading schemes has been considered before by Doda, Quemin, and Taschini (2019) or Quemin and de Perthuis (2019) and dynamic linkage by Holtsmark and Midttømme (2021), to my knowledge the asymmetric information set-up here coupled with socially costly transfers makes my approach at least somewhat novel.

While I find similar results in both price and quantity regulation in the model I study, there is regardless an undercurrent of the classic prices vs quantities -theme here (see, e.g. Weitzman (1974)). The main difference between these two regulatory schemes is naturally what they endogenize. Price regulation (such as a carbon tax) endogenizes quantities, while quantity regulation (cap-and trade schemes) endogenizes prices. In a setup like mine, where the only uncertainty relates to the relocation costs of the firms and their private types, both types of regulation deliver broadly similar results[6]. This would not be the case when there is more uncertainty regarding the slope of the marginal costs and benefits of abatement.

[5] As an example, the EU ETS was linked to Switzerland's Emissions Trading Scheme in 2020, see https://ec.europa.eu/commission/presscorner/detail/en/IP196708, whereas California's cap-and-trade scheme was linked to Qubec's cap-and-trade system in 2014, see https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/program-linkage.

[6] Even a minuscule carbon tax, for instance, delivers some abatement in some association regime. If I were to concentrate on a single regime, the results would be cleaner and the comparisons easier.

## 3.6 APPENDIX: Equilibria under high carbon taxes

In the previous analysis, the exogenous foreign carbon taxes were assumed to be low, and in particular I assumed that $\tau < c^*$. When this assumption does not hold, then the foreign carbon tax is set at a higher level than the domestic carbon price, and this affects the relocation decisions of the firms, and hence also the marginal relocating type. Therefore we have the following additional results:

1. Under positive association, when $k > 1$ and the most efficient firms move, the marginal relocating firm now has to choose between relocating and abating abroad, and staying and abating. Therefore the marginal type is pinned down by

$$
\begin{aligned}
c^{\Delta} - T^* &= \overline{\theta} + kc^{\Delta} + c^{\Delta} \\
c^{\Delta} &= -\frac{1}{k}(\overline{\theta} + T^*)
\end{aligned}
$$

Again, we conjecture that the partition is such that firms below $c^{\Delta}$ relocate and abate abroad, firms between $c^{\Delta}$ and $c^*$ stay and abate, and firms above $c^*$ stay without abating. Therefore the SWF is:

$$
\int_{\underline{c}}^{c^{\Delta}} Df(c)dc + \int_{c^{\Delta}}^{c^*} (\gamma + (D - c) - \lambda T^*))\, f(c)dc + \int_{c^*}^{\overline{c}} (\gamma + \lambda(c^* - T^*))\, f(c)dc
$$

The first-order condition yields the same upwards-distorted domestic abatement threshold as in the standard model, i.e.

$$
c^* = \frac{D}{1+\lambda} + \frac{\lambda}{1+\lambda}\frac{(1 - F(c^*))}{f(c^*)} \tag{3.41}
$$

whereas the first-order condition for the base transfer yields (using the first-order condition for the threshold):

$$T^* = \frac{1}{\lambda k - 1}\frac{\left(1 - F(c^\Delta)\right)}{f(c^\Delta)} + \frac{1}{\lambda k - 1}\left(k\gamma + \overline{\theta}\right) \tag{3.42}$$

And we have the following:

2. Under negative association, when $k < 0$ and the most inefficient firms move, the marginal relocating firm now has to choose between relocating and abating abroad, and staying and not abating. The marginal relocating type is then pinned down by

$$\begin{aligned} c^* - T^* &= \overline{\theta} + kc^\Delta + c^\Delta \\ c^\Delta &= -\frac{1}{1-k}\left(\overline{\theta} + T^* - c^*\right) \end{aligned}$$

Again we conjecture that the partition is such that types below $c^*$ stay and abate, types above $c^*$ and below $c^\Delta$ stay without abating, and types above $c^\Delta$ but below $\tau$ relocate and abate abroad. Therefore the SWF is:

$$\int_{\underline{c}}^{c^*} (\gamma + (D - c) - \lambda T^*))\, f(c)dc + \int_{c^*}^{c^\Delta} (\gamma + \lambda(c^* - T^*))\, f(c)dc + \int_{c^\Delta}^{\tau} Df(c)dc$$

The first-order condition for the threshold is:

$$\begin{aligned} \frac{\partial W}{\partial c^*} = (\gamma + D - c^* - \lambda T^*)\, f(c^*) + \frac{1}{1-k}(\gamma + \lambda(c^* - T^*))f(c^\Delta) \\ -(\gamma + \lambda(c^* - T^*))f(c^*) + \int_{c^*}^{c^\Delta} \lambda f(c)dc - \frac{1}{1-k}Df(c^\Delta) = 0 \end{aligned}$$

and the condition for the transfer is:

$$\frac{\partial W}{\partial T^*} = -\lambda \int_{\underline{c}}^{c^*} f(c)dc - \frac{1}{1-k}\left(\gamma + \lambda(c^* - T^*)\right) f(c^\Delta) - \lambda \int_{c^*}^{c^\Delta} f(c)dc + \frac{1}{1-k} D f(c^\Delta) = 0$$

using the condition for $T^*$ and plugging it in to the condition for the threshold, we find that the domestic threshold is the same as in the standard model:

$$c^* = \frac{D}{1+\lambda} - \frac{\lambda}{1+\lambda}\frac{F(c^*)}{f(c^*)} \tag{3.43}$$

with a base transfer of

$$T^* = \frac{(1-k)F(c^\Delta)}{f(c^\Delta)} + \frac{\gamma + D}{\lambda} + c^* \tag{3.44}$$

where, interestingly the base transfer is wholly unaffected by the foreign carbon tax $\tau$.

# Chapter 4

# Regulatory competition with multilateral externalities

In this chapter I simplify the leakage model analyzed previously to allow for competition between two regulators for a single firm, that may be of a high or low type. As before, the firm produces a single unit of emissions if it locates in a country, causing local damages of size $D > 0$. I assume the countries compete for the firm by way of offering it incentive-compatible regulatory mechanisms. In contrast to the previous setup, where the firms resided initially in the domestic (home) country, however, I now assume that the firm's initial location is in neither of the two competing countries. This implies a non-trivial firm participation constraint that the mechanisms need to satisfy in equilibrium. As I assume the firm always has the option to not locate in either country, this constraint sets the countries up as Bertrand competitors.

When the firm can locate in either country costlessly, i.e. has no moving frictions, the participation constraint binds in equilibrium, leading to symmetric equilibria where both countries are forced to offer all surplus generated by the firm locating there to the firm itself. As I introduce moving (or relocation) frictions or a fixed preference for the firm to locate to either country over the other, I find that this friction always strictly benefits the preferred country, as it now has the option to offer a mechanism that has lower transfers than the competing country, yet still induces the firm to locate there. Due to the linearity of the model and the no-undercutting nature of the equilibria I consider, even a very high friction does not allow for type separation.

## 4.1 Introduction

In 2018 Amazon Web Services revealed publicly that it was considering locating a large installation in either the state of New York or neighboring New Jersey. This promptly set up the two states as direct competitors, and in the coming weeks unsurprisingly these two neighbors started to aggressively undercut each other with the benefits and tax exemptions they would provide for AWS to locate in the state. In 2019, Amazon withdrew its plans to locate in NY due to major public opposition to the exceptional incentive package extended to it by the state of New York[1]. This anecdote informally contains much of what my model tries to capture in a formal way. Namely that competition can sometimes lead to full social welfare dissipation for the participating countries (or states in the AWS example).

In the previous example, as in the model I consider in this chapter, the firm that is considering locating to either country or jurisdiction is free to pit the two competitors against one another in full-fledged Bertrand fashion, since my basic model assumes that the firm faces no specific relocation costs[2].

[1]https://www.nytimes.com/2018/01/18/nyregion/amazon-headquarters-finalists.html and https://edition.cnn.com/2019/02/14/tech/amazon-hq2-nyc/index.html.

[2]Analogously, one may interpret this as the firm having a search cost of zero.

## 4.2 Previous literature

Hoel (1997) sets up a model of two countries competing to attract local externality-producing firms by way of setting environmental policies and derives the Nash equilibria when the countries simultaneously set tax rates to attract the firm. He shows that the equlibria depend crucially on the size of the environmental externalities, and that competition has an ambiguous effect on the strictness of equilibrium tax rates (in comparison with first-best). With sufficiently low damages, a race to the bottom results, with countries setting too low environmental tax rates in equilibrium. In comparison, when the damages are high, the situation is reversed and the countries opt for too high tax rates in order to deter firm entry altogether. In a model with border carbon adjustments (BCAs), Elboghdadly and Finus (2022) find a similar, yet even more striking race to the bottom as the only Nash equilibrium in a simultaneous-move game when countries compete for firms and, importantly when BCAs cannot be used. They find that allowing BCAs induces both countries to impose higher regulation, leading to higher social welfare through higher abatement.

The endogeneity of firm location (or relocation) and environmental regulation in a competitive, two-country setup is investigated in Markusen, Morey, and Olewiler (1993), who note that firm relocation aspect amplifies the payoff consequences of even small changes in environmental regulation. The competition between two countries for firms in Markusen, Morey, and Olewiler (1995) leads to exceedingly high regulation and consequently firm shut-down, in a similar way as in Jebjerg and Lando (1997), whereas with lower pollution damages the competition results in a race to the bottom.

Mideksa (2022) considers competition in regulatory mechanisms, with his primary interest being the non-cooperative equilibria that arise when countries choose between price instruments (carbon taxes) and quantity instruments (emission caps). In his model, the countries compete against one another, but their firms do not relocate, so the additional competitive pressure brought on by firm mobility does not play a role. He shows that the Weitzman (1974) prices vs quantities -criterion remains optimal in this situation as well. In Landry (2021), atomistic countries compete against one another in quantity regulation of a global environmental externality by setting binding emission caps non-cooperatively. He shows that when trading of emission permits is allowed across the countries, the resulting Nash Equilibrium caps actually implement a first-best level of abatement due to the global nature of the externality and the allowance of inter-jurisdictional permit trading.

Competition in non-linear pricing has been considered previously in e.g. Stole (1995), Armstrong and Vickers (2010), or Attar, Mariotti, and Salanié (2019). McAfee (1993) considers competing mechanism designers, while Biais, Martimort, and Rochet (2000) consider common value environments. A similar setup than this model is used by Stole (1995), who considers competitive nonlinear pricing in a spatially differentiated oligopolistic market. In his model, the outside options of the two competing mechanisms relate to each other through the competitive model, as a type report by a consumer in one mechanism (i.e. the location of a consumer on the line in the Hotelling linear city model) allows the principal to also infer the type report given in the competing mechanism, and thus compute the consumer's outside option without need to observe the type report in the competing mechanism.

In general, modeling competition in mechanism design is a very difficult topic (see, e.g. Pai (2010)). The main difficulties in competing mechanism design may arise, for instance, out of the reporting and communication requirements of the mechanisms (Peters and Szentes (2012)), the failure of the standard revelation principle (Epstein and Peters (1999) , Peters (2001), Attar, Campioni, Mariotti, and Piaser (2021)) or multiplicity of equilibria (Peters and Troncoso-Valverde (2013)), with these being but a small taste of the various pitfalls inherent in expanding the scope of standard mechanism design to competing principals. The model considered in this chapter is a stylized version of the leakage model in the previous chapters, where I will make several assumptions that will allow me to produce clean results but do come at the cost of generality.

## 4.3 A model of regulatory competition with binary cost types

There are two countries, $\{i, j\}$ and a single firm considering locating in either country. I assume that the firm starts out at some other, third location, in which the firm will not be able to produce their good or service, and in which the firm is receiving its outside option payoff. The firm has a privately known abatement cost, $c \in \{c_L, c_H\}$ (with $c_H > c_L$) of reducing its one unit of emissions. A single unit of emissions causes a local externality of size $D > 0$ that the firm imposes on the country where it locates, absent any abatement[3]. The firm generates a social benefit of $\gamma > 0$ for the receiving country if it locates there, regardless of abatement[4]. Let the prior probability of a low type-firm be $\Pr(c = c_L) = \pi \in (0, 1)$.

The compliance costs of the firm are defined as

$$C_i(c) := cX_i(c) - T_i(c). \tag{4.1}$$

Consisting of the firm's abatement cost $c$, their allocated abatement $X_i(c)$, and the transfer or subsidy given to it, $T_i(c)$, with $i$ indexing the mechanism to which the firm reports. Moreover, firms only care about their location insofar as to minimize their compliance costs, and therefore the *sorting or*

[3] An alternative way of thinking of this model is that the firm is "created" in the country, but the regulator by their choice of mechanism can decide the type of firm it wants, i.e. clean or dirty (an abating or non-abating firm, respectively.)

[4] This is due to e.g. the employment they generate, or other firm- or industry-specific factors.

*location constraint* facing country $i$ is:

$$C_i(c) \leqslant C_j(c) \tag{4.2}$$

For some given, induced compliance cost in country $j$, $C_j(c)$. This constraint spells out that the firm will only locate in country $i$ over $j$ if the compliance is lower there. Moreover, the firm may choose to not arrive in either country, in which case it faces no compliance and receives an outside option payozz, normalized to zero. Therefore, I require that the countries mechanisms' on offer respect the firm's participation constraint, defined as:

$$C_i(c) \leqslant 0, \quad i \in \{i, j\} \tag{4.3}$$

For $c \in \{c_L, c_H\}$. This means that the countries are in direct competition with one another to attract the firm to themselves. I make the following additional assumptions to proceed with the analysis:

1. Firms only report to one mechanism, and
2. The countries (regulators) *cannot* condition their mechanism on the reports in the other mechanism, and
3. The firm sees both mechanisms offered by the countries before choosing where it locates to.

These assumptions render the mechanisms independent of one another in the sense of communication requirements (see, e.g. Peters and Szentes (2012)), which considerably simplifies the analysis. The countries compete for the firms by way of offering regulation schemes, or *mechanisms* of the following type:

$$\mathcal{M}_i := \{X_i(c), T_i(c)\}$$

Where $X_i(c) \in \{0, 1\}$ is the abatement allocated to a firm of type c, and $T_i(c) \in \mathbb{R}$ the transfer or subsidy given to the firm. I model the competition in mechanisms as as a simultaneous-move one-shot game, in which the countries simultaneously announce their mechanisms on offer, the firm locates to one country and reports their type there, whereupon payoffs realize for both countries and the firm. If the firm does not locate in either country, it stays at the third location and receives its outside option payoff, normalized to zero. The mechanisms on offer need to satisfy incentive compatibility, and therefore we must have that

$$c_L X_L - T_L \leqslant c_L X_H - T_H \tag{4.4}$$

$$c_H X_H - T_H \leqslant c_H X_L - T_L \tag{4.5}$$

**Proposition 11** *Incentive compatibility implies that the allocation* X *is monotonically decreasing.*

**Proof.** Adding the IC constraints yields

$$(c_L - c_H)(X_L - X_H) \leqslant 0$$

and since $c_H > c_L$ this implies that $X_L \geqslant X_H$. ■

Moreover, the mechanisms should satisfy the participation constraints for both types, i.e. constraint (4.2).

## 4.4 The monopolist's solution

We consider first the case of a local pollution externality and a monopolist country, acting alone with no competitor. The payoff accruing to a country from the firm locating there is then given by:

$$\Delta := \begin{cases} \gamma - (1+\lambda)T_i(c), & \text{for a firm of type c that arrives and abates} \\ \gamma - D, & \text{if a firm arrives but does not abate, and} \\ 0, & \text{if a firm stays out, or does not arrive in-country.} \end{cases}$$

Where $D > 0$ represents the local pollution damages caused by the firm. Note that since the monopolist cannot observe the firm's type, the firm must be paid a subsidy of $T_i(c)$ for it to abate. Given these payoffs we can now write the social welfare function of the monopolist as:

$$W_i(X_i, T_i) = \gamma - D + \pi X_L \left(D - (1+\lambda)T_L\right) + (1-\pi)X_H \left(D - (1+\lambda)T_H\right)$$

Since the monopolist is free to offer a mechanism that reduces the firm to it's outside option payoff, the optimal monopoly mechanism sets

$$X_i^* = \begin{cases} 1, & \text{if} \quad D - (1+\lambda)c_i \geqslant 0 \\ 0, & \text{otherwise} \end{cases} \tag{4.6}$$

The cut-off type for abatement (the type that generates zero surplus when abating) is found by setting the above expression to zero. Therefore this type is:

$$c^* = \frac{D}{1+\lambda} \tag{4.7}$$

with optimal abatement given as

$$X(c_i) = \mathbf{1}_{\{c_i \leqslant c^*\}}$$

With a transfer of $T_i(c) = c$. In other words, the monopolist allocates full abatement to cost types that generate more social surplus when abating then when not.

I denote a regulatory mechanism as a tuple $\{X_i, T_i\}, i \in \{L, H\}$ that specifies the abatement and transfer for the reported low and high-type firm, respectively. In the following analysis, I assume that an indifferent firm will arrive in the home country[5]. Note, that whenever an indifferent firm arrives in the home country, the *no abatement mechanism*:

$$\{X_i = 0, T_i = 0\}, \text{ for } i \in \{L, H\}$$

is always available. Noting the social welfare function we wrote down before, this yields the home country social welfare $W^0$:

$$W^0 = \gamma - D$$

These two parameters now give us several regimes or cases to consider, depending on whether this term is positive or negative. I proceed by solving the optimal monopoly mechanisms in each case, and tackle the competition setting later.

- **If** $\gamma < D$**:**

Whenever $\gamma < D$, then an arriving non-abating firm yields *negative* social welfare for the monopolist home country. Therefore $W^0 < 0$. It follows that the monopolist would like to receive abating firms only. This is possible by offering a mechanism where both types of firms abate, i.e.

$$\{X_i = 1, T_i = c_H\}, \text{ for } i \in \{L, H\}$$

[5] This is commonly referred to in mechanism design as allowing the principal to pick their most preferred equilibrium to be played in case of the agent's indifference.

and the monopolist offers this if and only if $c_H \leqslant \frac{D}{1+\lambda}$, or when the high type is efficient enough.

In order to secure abatement from the high type, the monopolist must give both types a transfer of $c_H$, which leaves the high type with zero information rents, and the low type with rents $c_H - c_L > 0$. However, the monopolist may be able to do better than this candidate mechanism, if *the abating low type* by itself yields more expected surplus than the damages caused by the non-abating high type. The requirement for this is:

$$\underbrace{\gamma - (1+\lambda)c_H}_{\text{Welfare when both types abate}} \leqslant \underbrace{\gamma - D + \pi(D - (1+\lambda)c_L)}_{\text{Welfare when only } c_L \text{ abates}}$$

Which I call *the monopolist's condition (MC)*:

$$c_H - \pi c_L \geqslant \frac{(1-\pi)D}{1+\lambda} \tag{4.8}$$

Whenever this condition holds, the monopolist always prefers to have only the low type, $c_L$ abate. This is done to save on information rents, as when both types abate, the transfer that has to be paid (to both types) is $c_H$, yielding the efficient low type information rents $(c_H - c_L)$. Naturally, it is possible that both $c_H \leqslant \frac{D}{1+\lambda}$ and condition (4.8) hold simultaneously, meaning that although the high type is efficient enough to abate (and even yielding surplus when doing so), nevertheless the monopolist is willing to trade off the first-best, socially efficient abatement to save on rents flowing to the firm, reflecting the standard efficiency-revenue tradeoff of a monopolist.

**Proposition 12** *When $\gamma < D$, the monopoly mechanism consists of:*

$$\{X_L = 1, \quad X_H = 1\} \tag{4.9}$$

$$\{T_L = c_H, \quad T_H = c_H\} \tag{4.10}$$

*Moreover, whenever (4.8) holds, the monopoly mechanism is*

$$\{X_L = 1, \quad X_H = 0\} \tag{4.11}$$

$$\{T_L = c_L, \quad T_H = 0\} \tag{4.12}$$

**Proof.** The discreteness of X directly induces $X(c)$ to be a step function, $X(c_i) = \mathbf{1}_{\{c_i \leqslant c^*\}}$, or simply a threshold. Whenever both types abate, they are pooled to the same action and have to therefore receive the same transfer. This transfer must be set at $c_H$ to maintain incentives for the high type. Moreover, whenever (4.8) holds, then the expected welfare is higher by only having the low type abate, and therefore the types are separated and the transfer necessary to maintain abatement incentives for the low type only is $c_L$. ■

- **If** $\gamma = D$**.**

When $\gamma = D$, then the non-specific benefit of a firm arrival perfectly offsets its local pollution externality. Since the no-abatement mechanism is always available, this means that a monopolist can always secure $W^0 = \gamma - D = 0$ for itself by asking *no abatement and offering no transfers.* Since now the monopolist essentially does not have to worry (in social welfare terms) about the arriving non-abater, we have that:

**Proposition 13** *When* $\gamma = D$*, the monopoly mechanism is given in Proposition (12).*

(The proof is omitted, as it is the same as in the previous section).

- **If $\gamma > D$:**

Assuming that $\gamma > D$, then even a non-abating firm generates benefits in excess of their local damages. The cut-off is then

$$\begin{aligned} \gamma - (1+\lambda)c_i &\geqslant \gamma - D \\ c_i &\leqslant \frac{D}{1+\lambda} \end{aligned}$$

meaning that the abatement is at its first-best, socially optimal level. In this regime, a country has no incentive to deter either type of firm. Moreover, regardless of the efficiency of the cost types, the monopolist can always guarantee for itself a payoff of $W^0 = \gamma - D > 0$ by using the no-abatement mechanism. Therefore, the monopolist country will set the abatement cut-off at the efficient level:

$$c^* = \frac{D}{1+\lambda}$$

But now, unlike in the previous sections, both types of firms are valuable to the monopolist regardless of abatement. Therefore the candidate mechanisms for the monopolist in this case are to either ask for abatement from both types, only the low type, or neither type. In this case then, we have the most amount of equilibrium mechanisms, depending on the efficiency of the low and high types, respectively, vis-à-vis the threshold $c^*$. I summarize these results in the following proposition:

**Proposition 14** *When $\gamma > D$ (firm arrival is inherently valuable) and $c_H \leqslant \frac{D}{1+\lambda}$, the monopoly mechanism is*

$$\{X_L = 1, \quad X_H = 1\} \tag{4.13}$$

$$\{T_L = c_H, \quad T_H = c_H\} \tag{4.14}$$

*Moreover, whenever (4.8) holds, the monopoly mechanism is*

$$\{X_L = 1, \quad X_H = 0\} \tag{4.15}$$

$$\{T_L = c_L, \quad T_H = 0\} \tag{4.16}$$

(the proof is again the same as in the previous cases, and is therefore omitted).

If the high type is too inefficient to abate, i.e. when $c_H > \frac{D}{1+\lambda}$ then the only monopoly mechanism is the latter one, namely

$$\{X_L = 1, \quad X_H = 0\} \tag{4.17}$$

$$\{T_L = c_L, \quad T_H = 0\} \tag{4.18}$$

This occurs since now the high type would yield a negative social welfare contribution if it abates, and therefore the monopolist prefers to have the high type of firm enter with no abatement[6].

In other words: i) if both $c_L, c_H$ are efficient enough to abate, they do, and the low type reaps information rents. ii) If neither are efficient enough, neither abates and therefore reaps no information rents. iii) Whenever only the low type, $c_L$ is efficient enough to abate, it does and is compensated $c_L$ for it, and iv) Whenever the monopolist's condition in (4.8) holds, then only the low type is asked to abate even if the high type is efficient as well. The monopolist does this to save on the information rents provided to the low type.

[6]If we also have that the low type is too inefficient to abate, i.e. $c_L > \frac{D}{1+\lambda}$, then the equilibrium mechanism is the no-abate mechanism, with $X_i = 0, T_i = 0$, yielding welfare $W^0 = \gamma - D$.

## 4.5 Regulatory competition

Introducing the other country into the model, it acts as a Bertrand competitor to country $i$ by way of the relocation constraints. That is, we say that a firm chooses to locate in $i$ over $j$ if and only if their induced compliance cost (induced by the chosen mechanism in a country) is lower than in the alternative location $j$:

$$C_i(c) \leqslant C_j(c) \tag{4.19}$$

The countries are by assumption symmetric, so the key factors in determining the equilibria of this Bertrand-like game between the countries will be

1. The amount of friction the firm faces when relocating and
2. The social welfare contribution of the non-abating firm.

**The setup of the game:** The regulation game is played between two symmetric countries, both having the same shadow cost of public funds $\lambda > 0$. Both players (countries) share a common prior probability of a low-type firm $\pi \in (0, 1)$. I model the game as a simultaneous-move game, where both countries announce their mechanisms $\{\mathcal{M}_i, \mathcal{M}_j\}$ at the same time. Each mechanism consists of a 4-tuple, specifying the allocation $X_L^i, X_H^i$ and the transfers $T_L^i, T_H^i$ for the low and high type, respectively. After the mechanisms are announced, the firm(-s) makes a choice of whether to locate in either country or stays out altogether. After the firm's action, payoffs realize for both the countries and the firm(-s).

I maintain the assumption from before that the mechanisms are independent of one another in the sense that $i$'s mechanism *cannot depend* on the reports of a firm in $j$'s mechanism. The solution concept I'll be using is Nash equilibrium, where I will require that the equilibrium mechanisms offered must satisfy a *no profitable deviation* -requirement or allow for *no profitable* *undercutting from the other player*.

A direct consequence of the participation constraint of the firm is that the transfers are non-negative in any equilibrium mechanism, and therefore the firm cannot be taxed in equilibrium. In order to clarify exposition, I define a *configuration* as:

**Definition 1** *A configuration is a 4-tuple:*

$$\left\{X_L^k, X_H^k, T_L^k, T_H^k\right\}$$

*where* $X_j^n \in \{0,1\}$ *is the allocation of abatement for a firm of type* $j$ *in country* $n \in \{i,j\}$*, and* $T_j^n \in \mathbb{R}_+$ *the associated non-negative transfer.*

In the following analysis, I am searching for configurations that are symmetric and allow no profitable undercutting. With these preliminaries in hand, let us start with the case of having $\gamma < D$.

- **If** $\gamma < D$**:**

In this case an arriving firm yields negative social welfare if it does not abate. Therefore, either country when acting as a monopolist would offer a mechanism where either both types abate, or if the monopolist's condition in (4.8) holds, only the low type abates (Proposition 13). Let us start with assuming that $c_H \leqslant c^*$, where $c^* = \frac{D}{1+\lambda}$, so that the high type *is efficient*. From the monopolist's solution we know that a single country would now want to implement a full-abatement mechanism. We will start with this equilibrium candidate, i.e. one where both countries announce a mechanism of

$$X_i^k = 1$$
$$T_i^k = c_H$$

for $i \in \{L, H\}$, $k \in i, j$. This, however, is not an equilibrium as it allows for a profitable deviation. Let us fix $\mathcal{M}_j$ to the above monopolist mechanism. Now there exists a profitable deviation for country $i$, whereby it deviates to

$$\left\{\hat{T}_L^i, \hat{T}_H^i\right\} = \{c_H + \varepsilon, c_H + \varepsilon\}$$

while keeping the same allocation X. This means that $i$ is now offering an $\varepsilon$-better deal *uniformly to all types*. This yields expected welfare of

$$\hat{W}_i = \gamma - (1+\lambda)\hat{T}_H^i \tag{4.20}$$

The only deviation that allows for no undercuts from player $j$ is one where $\hat{W}_i = 0$, and therefore

$$\left\{\hat{T}_L^i, \hat{T}_H^i\right\} = \left\{\frac{\gamma}{1+\lambda}, \frac{\gamma}{1+\lambda}\right\}$$

For this to maintain incentives for the high type to abate, we must also have that $c_H \leqslant \frac{\gamma}{1+\lambda}$. So we note here that there is already a contrast to the monopolist's solution, where the requirement for the efficient high type to abate was that $c_H \leqslant \frac{D}{1+\lambda} > \frac{\gamma}{1+\lambda}$.

Whenever $c_H > \frac{\gamma}{1+\lambda}$ then the previous mechanism does not maintain incentives for the high type to abate anymore, and in this case we can apply the same logic and look for the no-undercutting equilibrium. Again fixing $\mathcal{M}_j$ to the monopolist mechanism, the profitable deviation now becomes

$$\{X_L^i = 1, \quad X_H^i = 0\}$$

and $T_L^i = \hat{T}_L^i$. This yields i an expected welfare of

$$\hat{W} = \gamma - D + \pi\left(D - (1+\lambda)\hat{T}_L^i\right)$$

And again the only deviation that allows no undercut from j is one where $\hat{W} = 0$, requiring

$$\hat{T}_L^i = \frac{\gamma}{\pi(1+\lambda)} - \frac{(1-\pi)D}{\pi(1+\lambda)}$$

The above has led us to the two unique equilibria of this setting, both of which are pure Bertrand equilibria in the sense that they leave no expected welfare for the countries.

**Proposition 15** *When $\gamma < D$, the symmetric equilibria of the regulation game are*

1. *The full abatement equilibrium, with configuration*

$$\left\{X_L^k = 1, \quad X_H^k = 1\right\}$$
$$\left\{T_L^k = \frac{\gamma}{1+\lambda}, \quad T_H^k = \frac{\gamma}{1+\lambda}\right\}$$

*for $k \in \{i, j\}$,* ***whenever*** $c_H \leqslant \frac{\gamma}{1+\lambda}$*, and*

2. *The partial abatement equilibrium, with configuration*

$$\left\{X_L^k = 1, \quad X_H^k = 0\right\}$$
$$\left\{T_L^k = \frac{\gamma}{\pi(1+\lambda)} - \frac{(1-\pi)D}{\pi(1+\lambda)}, \quad T_H^k = 0\right\}$$

*for $k \in i, j$, whenever $c_H > \frac{\gamma}{1+\lambda}$.*

**Proof.** In the text above. ■

In comparison to the monopolist's solution, where abatement is either set at the first-best level (Proposition 15), or distorted below it for the monopolist to extract more revenues by sacrificing efficiency, we have in this case that *abatement is distorted below first-best* even in the efficient high type's case. To see this, consider a high type $c_H$ such that

$$\frac{\gamma}{1+\lambda} < c_H \leqslant \frac{D}{1+\lambda}$$

A monopolist would ask for full abatement from such a high type (whenever condition (4.8) does not hold) but when competing with the other country for such a firm, the regulator no longer asks for abatement from this type of firm. So in this case I find that competition leads to less abatement than the monopolist's solution. (papereita!!!)

- **If** $\gamma = D$**:**

When $\gamma = D$, then the pollution damages are fully offset by firm arrival, and both countries can always secure a zero payoff for themselves by implementing the no-abatement mechanism. Let us then first assume that the high type is efficient, i.e. $c_H \leqslant \frac{D}{1+\lambda}$, in this case we know that a monopolist would ask for full abatement from both types (whenever (4.8) does not hold). Therefore let us fix $\mathcal{M}_j$ to the full-abatement mechanism with $X_i^k = 1, T_i^k = c_H$. By similar logic as before, we find that this cannot be an equilibrium, as it allows for a profitable deviation by the other country, by offering $X_L = X_H = 1$, but an increased transfer of $\hat{T}_i = c_H + \epsilon$. This yields a payoff of

$$\hat{W} = \gamma - (1+\lambda)\hat{T}_i$$

The only possible transfer that allows no undercutting from the other player is one that yields an expected welfare of zero, and therefore we have that the optimal transfer is

$$\hat{T}_i = \frac{\gamma}{1+\lambda}$$

And we have found one equilibrium configuration. If the high type is inefficient, i.e. $c_H > \frac{D}{1+\lambda}$, then the monopolist would ask for abatement from only the low type. So let us now fix $\mathcal{M}_j$ to the partial abatement mechanism with $X_L^k = 1, T_L^k = c_L$. By undercutting, this strategy cannot be an equilibrium, as it allows a profitable deviation by country $i$, which is to again offer the same abatement $X_L$, but now with a transfer of:

$$\hat{T}_L^i = \frac{\pi D}{1+\lambda}$$

and we have a second equilibrium configuration. The final equilibrium is found when we consider the trivial case of an inefficient low type, i.e. $c_L > \frac{D}{1+\lambda}$. In this case the only candidate equilibrium is the no-abatement equilbirium, where countries ask for no abatement from either firm, and give them no transfers. Therefore we have the following:

**Proposition 16** *When $\gamma = D$, the symmetric equilibria in the regulation game are*

1. *The full abatement equilibrium, with configuration*

$$\{X_L^k = 1, \quad X_H^k = 1\}$$
$$\left\{T_L^k = \frac{\gamma}{1+\lambda}, \quad T_H^k = \frac{\gamma}{1+\lambda}\right\}$$

   *for $k \in \{i, j\}$,* ***whenever*** $c_H \leqslant \frac{D}{1+\lambda}$.

2. *The partial abatement equilibrium, with configuration*

$$\{X_L^k = 1, \quad X_H^k = 0\}$$
$$\left\{T_L^k = \frac{\pi D}{1+\lambda}, \quad T_H^k = 0\right\}$$

*for* $k \in i, j$, *whenever* $c_H > \frac{D}{1+\lambda}$.

3. *And, finally the no-abatement equilibrium with configuration*

$$\{X_L^k = 0, \quad X_H^k = 0\}$$
$$\{T_L^k = 0, \quad T_H^k = 0\}$$

*for* $k \in \{i, j\}$, ***whenever*** $c_L > \frac{D}{1+\lambda}$.

So in this case I find that competitition does not distort abatement in a similar way as in the previous case (due to the assumption of $\gamma = D$), but does bring about total rent dissipation through the Bertrand competition and the no-undercutting equilibrium requirement. However, this case can be considered as a knife-edge result, as with these specific assumptions the non-specific benefit of firm arrival coincides with their pollution damages.

- **If** $\gamma > D$**:**

The next case we will consider is one where $\gamma > D$. Now firm entry is valuable regardless of their abatement, and therefore both countries will want to incentivize even the non-abaters to locate to their country. Let us once again turn to our previous monopolist results in this section and work towards the equilibria from there. The monopolist will set the allocation according to the first-best abatement threshold, i.e.

$$X(c) = \mathbf{1}_{\{c \leqslant c_i^*\}}$$

Whenever $c_H \leqslant c^*$, then the monopoly mechanism will ask from abatement from both, i.e. it sets $X_L = X_H = 1$ (we disregard the monopolist's condition for now). Therefore let us fix again $\mathcal{M}_j$ to a full-abatement monopolist mechanism, with transfer $T_L^j = T_H^j = c_H$. This mechanism is again not an equilibrium with competition, as it allows a profitable deviation for country $i$. By similar logic as we used before, country $i$ can uniformly increase its transfers by an $\varepsilon > 0$ and receive both types of firms. The welfare of country $i$ from deviating to a transfer of

$$T_H^{\hat{i}} > c_H$$

is the following, as doing so yields it both type of firm:

$$\hat{W} = \gamma - (1+\lambda)T_H^{\hat{i}}$$

and as before the only such transfer that allows no undercuts is one where this welfare is dissipated fully, i.e. where

$$T_H^{\hat{i}} = \frac{\gamma}{1+\lambda}$$

Therefore we have found one symmetric equilibrium configuration. Moreover, regardless of whether the monopolist's condition in (4.8) holds, we find that as long as $c_H \leqslant c^*$, the existence of a Bertrand competitor, and our equilibrium requirement of no profitable deviations precludes implementing the monopolist mechanism that asks for abatement from only the low type, $c_L$.

If we have a situation where $c_L > c^*$, then we are at the other end of the spectrum, where the only mechanism either will implement is the no-abatement mechanism. Now, in contrast to the monopolist, the welfare afforded by such a mechanism (i.e. one that asks for no abatement from either type), must still in the symmetric equilibrium yield both countries an expected social welfare of zero. Therefore we have as equilibrium configuration when $c_L > c*$,

$$\{X_L^k = 0, \quad X_H^k = 0\}$$
$$\{T_L^k = \gamma - D, \quad T_H^k = \gamma - D\}$$

for $k \in i, j$.

If $c_L \leqslant c^* < c_H$, then we have a situation where the types can be separated, since now the high type is inefficient and both countries strictly prefer the high type to arrive and not abate. Therefore let us fix $\mathcal{M}_j$ to a low-type only abates mechanism, i.e. one where $X_L = 1, T_L = c_L$, and zero abatement and transfers for the high type. Now there exists a profitable deviation for the other country, where they will match the high type allocation and transfers, but compete for the low type by offering them a higher transfer. The expected welfare from this is:

$$\hat{W} = \gamma - D + \pi(D - (1+\lambda)\hat{T}_i)$$

and once again, the no-undercuts transfer is one that makes this expected welfare zero, i.e.

$$\hat{T}_i = \frac{\gamma}{\pi(1+\lambda)} - \frac{D(1-\pi)}{\pi(1+\lambda)}$$

Therefore we have the following three equilibrium configurations:

**Proposition 17** *When $\gamma > D$, the symmetric equilibria of the regulation game are*

1. *The full abatement equilibrium, with configuration*

$$\{X_L^k = 1, \quad X_H^k = 1\}$$
$$\left\{T_L^k = \frac{\gamma}{1+\lambda}, \quad T_H^k = \frac{\gamma}{1+\lambda}\right\}$$

   *for $k \in \{i, j\}$,* ***whenever*** $c_H \leqslant \frac{D}{1+\lambda}$.

2. *The partial abatement equilibrium, with configuration*

$$\{X_L^k = 1, \quad X_H^k = 0\}$$
$$\left\{T_L^k = \frac{\gamma}{\pi(1+\lambda)} - \frac{D(1-\pi)}{\pi(1+\lambda)}, \quad T_H^k = 0\right\}$$

*for* $k \in i, j$, *whenever* $c_H > \frac{D}{1+\lambda}$.

3. *And, finally, the no-abatement equilibrium with configuration*

$$\{X_L^k = 0, \quad X_H^k = 0\}$$
$$\{T_L^k = \gamma - D, \quad T_H^k = \gamma - D\}$$

*for* $k \in \{i, j\}$, ***whenever*** $c_L > \frac{D}{1+\lambda}$.

**Proof.** In text above. ■

So we find that in this case, the actual abatement is not distorted away from first-best, like in the case where $\gamma < D$, but competition again results in full rent dissipation.

The main culprit for rent dissipation here is clearly the frictionless location of the firms. As firms face no costs in moving between the countries they act in a similar way to consumers in a standard model of Bertrand competition, disallowing any rents to be made by the countries themselves[7]. My next extension seeks to rectify this, and to this end I introduce a slight home bias or relocation cost for the firms.

## 4.6 Competition with relocation frictions

Let us now introduce frictions to the model. To this end, let us define an $\varepsilon$ -bias as a slight (but positive) preference for both types of firm in favor

[7] This is not dissimilar to a search model where consumers see the competing price offers at zero cost. In such models, the lack of any search frictions also leads to marginal cost pricing and perfect competition, although in a slightly different manner.

of the *home country*[8], or country $i$. In particular, this preference of the firm will enter the relocation constraints in the model in the following way:

**Definition 2** *A country* $i$ *is* $\varepsilon$*- preferred, or simply preferred to country* $j$ *whenever a type* $c$ *-firm chooses country* $i$ *over* $j$ *when facing the following location constraint:*

$$C_i(c) - \varepsilon \leqslant C_j(c) \tag{4.21}$$

*for some* $\varepsilon > 0$.

Which, in other words is stating that the home country has an absolute advantage over the other country at the outset of the game. This preference works as tie-breaker in the home country's favor, since now even when

$$C_i(c) = C_j(c), \text{ for } c \in \{c_L, c_H\}$$

both types of firm have a strict preference to locate in the home country. This allows the home country to benefit, since it now can uniformly reduce the transfers it offers while keeping the relocation constraints unchanged. In the analysis that follows, I analyze only the situation where $\gamma > D$, so that firms are valuable regardless of their abatement. I also assume that $c_H \leqslant \frac{D}{1+\lambda}$, so that the uniquely optimal equilibria without relocation frictions are given in Proposition (17). With relocation frictions, the home country has a profitable deviation from the full abatement equilibrium in which

$$\{X_L^k = 1, \quad X_H^k = 1\}$$
$$\left\{T_L^k = \frac{\gamma}{1+\lambda}, \quad T_H^k = \frac{\gamma}{1+\lambda}\right\}$$

[8] One may think of this parameter as home bias, or a non-negligible search cost.

to a mechanism that *extracts* a nonnegative amount of rents for the home country itself. To see this deviation, consider that country $i$ deviates to a mechanism

$$\left\{X_L^i = 1, \quad X_H^i = 1\right\}$$
$$\left\{\hat{T}_L^i = \frac{\gamma}{1+\lambda} - \varepsilon, \quad \hat{T}_H^i = \frac{\gamma}{1+\lambda} - \varepsilon\right\}$$

It is clear that the relocation constraints are unaffected, since the transfers offered by country $i$ are uniformly lower by $\varepsilon$ and therefore cancel out on the RHS of the constraint. To see whether this mechanism is individually rational, we must check the IR constraint of the high type, which holds whenever:

$$c_H - \left(\frac{\gamma}{1+\lambda} - \varepsilon\right) \leqslant 0 \Leftrightarrow \varepsilon \leqslant \frac{\gamma}{1+\lambda} - c_H \tag{4.22}$$

leading us to conclude that whenever the frictions (firm preferences) are sufficiently low, i.e. whenever $\varepsilon \leqslant \frac{\gamma}{1+\lambda} - c_H$, we have an equilibrium mechanism, since both IC and IR constraints are satisfied. Moreover, since the frictions introduce an asymmetry to the relocation constraints, we see that the competitor country cannot undercut the home country and offer anything less than the full welfare-dissipating transfer of $\frac{\gamma}{1+\lambda}$.

**Proposition 18** *When $\gamma > D$, and $c_H \leqslant \frac{D}{1+\lambda}$ and the relocation friction is low (4.22), the unique equilibrium mechanism with relocation frictions is one where*

$$\left\{X_L^j = 1, \quad X_H^j = 1\right\}$$
$$\left\{T_L^j = \frac{\gamma}{1+\lambda}, \quad T_H^j = \frac{\gamma}{1+\lambda}\right\}$$

*and*

$$\{X^i_L = 1, \quad X^i_H = 1\}$$
$$\left\{\hat{T}^i_L = \frac{\gamma}{1+\lambda} - \varepsilon, \quad \hat{T}^i_H = \frac{\gamma}{1+\lambda} - \varepsilon\right\}$$

*yielding country* $i$ *an expected welfare of* $W_i(\mathcal{M}_i, \mathcal{M}_j) = (1+\lambda)\varepsilon$*.*

**Proof.** The mechanism and equilibrium is derived in the text above. This equilibrium candidate yields the home country an expected welfare of:

$$\begin{aligned} W_i(\mathcal{M}_i, \mathcal{M}_j) &= \gamma - D + D - (1+\lambda)\left(\frac{\gamma}{1+\lambda} - \varepsilon\right) \\ &= (1+\lambda)\varepsilon \end{aligned}$$

■

Due to our assumption of a positive shadow cost of public funds, the home country nets higher social welfare than the relocation friction or home bias.

**Proposition 19** *With relocation frictions, every equilibrium configuration in the previous section survives unchanged, with the exception of the home country's transfers* $\{T^i_L, T^i_H\}$*. These transfers will be uniformly lower by* $\varepsilon$*, and therefore the preferred home country is able to extract* $(1+\lambda)\varepsilon > 0$ *of social welfare in every equilibrium for itself.*

**Proof.** In any equilibrium configuration, given the new relocation constraint (4.21) it is immediate that a uniformly lower transfer of $\varepsilon$ from the home country leaves the relocation constraints unchanged. Due to the asymmetry created by the friction or preference, the competitor country cannot undercut the lowered transfers of the home country, therefore establishing the first part. The second part follows from our assumption of a positive shadow cost of public funds of $\lambda$. This implies that any reduction in the transfer likewise is symmetrically valuable to the regulator, carrying a benefit of $(1+\lambda)$. ■

## 4.7 Conclusions and discussion

This simple model of regulatory competition with firm relocation and multilateral externalities highlights many interesting and relevant issues in the design of regulatory policies. I have tried to address an especially salient feature of real-world policy design - the fact that regulatory mechanisms are not designed in a void. It is typical for regulators or governments to be competing against one another. They may compete in tax policies to attract e.g. skilled immigrants (source) or firms (source), [examples], or as in this chapter they may compete in environmental regulation.

In this model, this competition manifests itself starkly as a race to the bottom, leading to full welfare dissipation when the firms can move frictionlessly between the two competing countries. This result conforms to basic intuition, as in this setting the situation is quite analogous to Bertrand competition with the countries undercutting their own rents until none remain in equilibrium. However, the mechanism at play behind the race to the bottom is a great deal more complex than in simple price competition[9].

I extend this result by introducing a relocation cost for the firms, which I model as a static preference for both types of firm to locate in the home country. I show that this results in higher welfare for the preferred country as it can now uniformly lower its equilibrium transfers but still attract the firm. Furthermore, since I model transfers as being socially costly, this decrease in equilibrium transfers nets the home country more welfare than the original preference. Extensions of this work to be pursued in the future include e.g. including the different association regimes of Chapter 2 and

[9] And, as pointed out to me, reaching this result in a more complex environment is anything but trivial.

extending this model to a continuous type space. Other possible avenues would be to investigate a sequential move game where the countries announce their mechanisms sequentially (as in Mideksa (2021) and Mideksa (2024)), which may lead to a first-mover advantage. A sequential-move structure would also allow analyzing the signaling aspects of policy commitments as in Miyaoka (2019) or Ambec and Coria (2021), but now within a setup that has carbon leakage added to it.

## 4.8 APPENDIX: Global pollution damages

If pollution damages are global, this serves as an equilibrium selection device compared to the local mechanisms discussed previously. Now we must modify the payoffs of a country from receiving (and not receiving) a firm to:

$$\Delta_G := \begin{cases} \gamma - (1+\lambda)c_i, & \text{for a firm of type } c_i \text{ that arrives and abates} \\ \gamma - D, & \text{if a firm arrives but does not abate, and} \\ 0, & \text{if a firm stays out} \\ -D, & \text{if a firm locates in country j but does not abate, and} \\ 0, & \text{if a firm locates in j and abates.} \end{cases}$$

For this example, let us assume that we are in the regime where firm arrival is valuable, i.e. $\gamma > D$, and that firms have no relocation frictions. Moreover, let us also assume that the high type is efficient $\left(c_H \leqslant \frac{D}{1+\lambda}\right)$. Denote

$$\mathbf{1}_{ij}^{L} := \mathbf{1}_{\{C_i^L \leqslant C_j^L\}}$$
$$\mathbf{1}_{ij}^{H} := \mathbf{1}_{\{C_i^H \leqslant C_j^H\}}$$

so these indicator variables represent the location constraints of the low and high-type firm, respectively. Now, given a candidate mechanism offered by country j, the expected welfare for i can be expressed as:

$$
\begin{aligned}
E\left[W_i|\mathcal{M}_j\right] = \pi \left[\mathbf{1}^L_{ij} \left(\gamma - D + (D - (1+\lambda)T^i_L)\right) X^i_L\right] \\
+ \left(1 - \mathbf{1}^L_{ij}\right) \left[(1 - X^j_L)(-D)\right] \\
+(1-\pi) \left[\mathbf{1}^H_{ij} \left(\gamma - D + (D - (1+\lambda)T^i_H)\right) X^i_H\right] \\
+(1-\pi)(1 - \mathbf{1}^H_{ij}) \left[(1 - X^j_H)(-D)\right]
\end{aligned}
$$

Recall that with local externalities, we had both a full-abatement equilibrium and a no-abatement equilibrium. However, with global externalities we now have a result that the no-abatement equilibrium is no longer a symmetric equilibrium of the game. To see why, let us fix country j's mechanism to the no abatement mechanism: $\mathcal{M}_j = (0,0), \gamma - D$. Now the expected welfare for i is:

$$
\begin{aligned}
E\left[W_i|\mathcal{M}_j\right] = \left[\pi \mathbf{1}^L_{ij} + (1-\pi)\mathbf{1}^H_{ij}\right](\gamma - D) - \pi D \\
+\mathbf{1}^L_{ij}\pi D - D + \mathbf{1}^H_{ij} D + \pi D - \pi D \mathbf{1}^H_{ij} + \pi \mathbf{1}^L_{ij} D \\
-\pi(1+\lambda)T^i_L \mathbf{1}^L_{ij} X^i_L + \mathbf{1}^H_{ij} D X^i_H - \pi \mathbf{1}^H_{ij} D X^i_H - (1+\lambda) T^i_H \mathbf{1}^H_{ij} X^i_H \\
+\pi(1+\lambda) T^i_H \mathbf{1}^H_{ij} X^i_H
\end{aligned}
$$

Our symmetric equilibrium candidate of $\mathcal{M}_i = \{(0,0), \gamma - D\}$ yields a welfare of $E\left[W_i|\mathcal{M}_j\right] = -D < 0$. Therefore country i has a profitable deviation to the *full-abatement equilibrium*, since playing $\mathcal{M}_i = \left\{(1,1), \frac{\gamma}{1+\lambda}\right\}$ yields $E\left[W_i|\mathcal{M}_j\right] = 0 > -D$. Therefore we have shown that in this particular case, global externalities imply that the no-abatement equilibrium is payoff-dominated by the full-abatement equilibrium and therefore is not an equilibrium anymore.

This type of result implies the existence of a first-mover advantage if the countries were to announce their mechanisms *sequentially*. The first-mover would be able to induce the second mover to best-respond with the full-abatement mechanism, essentially forcing the other country to pay for the common good of pollution abatement by credibly threatening to be a pollution haven. A similar conclusion arises in Bárcena-Ruiz (2006), whereas in Mideksa (2021) the first-mover's incentives work in the other direction, with policy choices serving as signals affecting both parties information. This allows the first-mover to induce *more abatement* by playing a high-abatement strategy, whereas in my model the overall level of abatement is fixed, and the leader's abatement fully crowds out the followers.

# Bibliography


AGUIRRE, I., AND A. BEITIA (2017): "Modelling countervailing incentives in adverse selection models: A synthesis," *Economic Modelling*, 62, 82–89.

AHLVIK, L., AND M. LISKI (2017): "Carbon leakage: a mechanism design approach," *Working paper*.

——— (2019): "Think global, act local! A mechanism for global commons and mobile firms," *CESifo Working Paper 7597*.

——— (2021): "Global Externalities, Local Policies and Firm Selection," *The Journal of the European Economic Association (forthcoming)*.

——— (2022): "Global externalities, local policies, and firm selection," *Journal of the European Economic Association*, 20(3), 1231–1275.

AHLVIK, L., M. LISKI, AND R. MARTIN (2017): "The association between the vulnerability score and compliance costs," *Mimeo*.

AMBEC, S., AND J. CORIA (2021): "The informational value of environmental taxes," *Journal of Public Economics*, 199, 104439.

ARMSTRONG, M. (1999): "Optimal regulation with unknown demand and cost functions," *Journal of Economic Theory*, 84(2), 196–215.

ARMSTRONG, M., AND J.-C. ROCHET (1999): "Multi-dimensional screening: A user's guide," *European Economic Review*, 43(4-6), 959–979.

ARMSTRONG, M., AND J. VICKERS (2001): "Competitive price discrimination," *The RAND Journal of Economics*, pp. 579–605.

——— (2010): "Competitive non-linear pricing and bundling," *The Review of Economic Studies*, 77(1), 30–60.

ATTAR, A., E. CAMPIONI, T. MARIOTTI, AND G. PIASER (2021): "Competing mechanisms and folk theorems: Two examples," *Games and Economic Behavior*, 125, 79–93.

ATTAR, A., T. MARIOTTI, AND F. SALANIÉ (2014): "Nonexclusive competition under adverse selection," *Theoretical Economics*, 9(1), 1–40.

——— (2019): "On competitive nonlinear pricing," *Theoretical Economics*, 14(1), 297–343.

BALIGA, S., AND E. MASKIN (2003): "Mechanism design for the environment," in *Handbook of environmental economics*, vol. 1, pp. 305–324. Elsevier.

BÁRCENA-RUIZ, J. C. (2006): "Environmental taxes and first-mover advantages," *Environmental and Resource Economics*, 35, 19–39.

BARON, D. P. (1985): "Regulation of prices and pollution under incomplete information," *Journal of Public Economics*, 28(2), 211–231.

BARON, D. P., AND R. B. MYERSON (1982): "Regulating a monopolist with unknown costs," *Econometrica*, pp. 911–930.

BERNHEIM, B. D., AND M. D. WHINSTON (1986): "Common agency," *Econometrica*, pp. 923–942.

BERTRAND, J. (1883): "Book review of theorie mathematique de la richesse social and of recherches sur les principes mathematiques de la theorie des richesses," *Journal des savants*.

BIAIS, B., D. MARTIMORT, AND J.-C. ROCHET (2000): "Competing mechanisms in a common value environment," *Econometrica*, 68(4), 799–837.

BIGLAISER, G., AND C. MEZZETTI (1993): "Principals competing for an agent in the presence of adverse selection and moral hazard," *Journal of Economic Theory*, 61(2), 302–330.

BOLTON, P., AND M. DEWATRIPONT (2004): *Contract Theory*. MIT Press.

BÖRGERS, T. (2015): *An introduction to the theory of mechanism design*. Oxford University Press, USA.

CALZOLARI, G., AND V. DENICOLÒ (2013): "Competition with exclusive contracts and market-share discounts," *American Economic Review*, 103(6), 2384–2411.

CHAMPSAUR, P., AND J.-C. ROCHET (1989): "Multiproduct duopolists," *Econometrica*, pp. 533–557.

CHIANG, A. (1992): *Elements of dynamic optimization.* McGraw-Hill.

COASE, R. H. (1960): "The problem of social cost," *The journal of Law and Economics*, 3(4), 1–44.

DASGUPTA, P., P. HAMMOND, AND E. MASKIN (1980): "On imperfect information and optimal pollution control," *The Review of Economic Studies*, 47(5), 857–860.

DECHEZLEPRÊTRE, A., AND M. SATO (2017): "The Impacts of Environmental Regulations on Competitiveness," *Review of Environmental Economics and Policy*, 11(2), 183–206.

DODA, B., S. QUEMIN, AND L. TASCHINI (2019): "Linking permit markets multilaterally," *Journal of Environmental Economics and Management*, 98, 102259.

EDERINGTON, J., A. LEVINSON, AND J. MINIER (2005): "Footloose and pollution-free," *Review of Economics and Statistics*, 87(1), 92–99.

EDGEWORTH, F. Y. (1925): "The pure theory of monopoly," *Papers relating to political economy*, 1(111), 42.

ELBOGHDADLY, N., AND M. FINUS (2022): "Strategic climate policy with endogenous plant location: The role of border carbon adjustments," *Journal of Public Economic Theory*, 24(6), 1266–1309.

EPSTEIN, L. G., AND M. PETERS (1999): "A revelation principle for competing mechanisms," *Journal of Economic Theory*, 88(1), 119–160.

ESKELAND, G. S., AND A. E. HARRISON (2003): "Moving to greener pastures? Multinationals and the pollution haven hypothesis," *Journal of development economics*, 70(1), 1–23.

FOWLIE, M., AND M. REGUANT (2018): "Challenges in the measurement of leakage risk," in *AEA Papers and Proceedings*, vol. 108, pp. 124–29.

FOWLIE, M., M. REGUANT, AND S. P. RYAN (2016): "Market-based emissions regulation and industry dynamics," *Journal of Political Economy*, 124(1), 249–302.

FOWLIE, M. L. (2009): "Incomplete environmental regulation, imperfect competition, and emissions leakage," *American Economic Journal: Economic Policy*, 1(2), 72–112.

FUDENBERG, D., AND J. TIROLE (1991): *Game theory*. MIT press.

HAAPARANTA, P. (1996): "Competition for foreign direct investments," *Journal of Public Economics*, 63(1), 141–153.

HELM, C., AND F. WIRL (2014): "The principal–agent model with multilateral externalities: An application to climate agreements," *Journal of Environmental Economics and Management*, 67(2), 141–154.

HOEL, M. (1996): "Should a carbon tax be differentiated across sectors?," *Journal of Public Economics*, 59(1), 17–32.

——— (1997): "Environmental policy with endogenous plant locations," *Scandinavian Journal of Economics*, 99(2), 241–259.

HOLTSMARK, K., AND K. MIDTTØMME (2021): "The dynamics of linking permit markets," *Journal of Public Economics*, 198, 104406.

IKEFUJI, M., J.-I. ITAYA, AND M. OKAMURA (2016): "Optimal emission tax with endogenous location choice of duopolistic firms," *Environmental and Resource Economics*, 65, 463–485.

JEBJERG, L., AND H. LANDO (1997): "Regulating a polluting firm under asymmetric information," *Environmental and Resource Economics*, 10, 267–284.

JULLIEN, B. (2000): "Participation constraints in adverse selection models," *Journal of Economic Theory*, 93(1), 1–47.

KAHN, C., AND J. SCHEINKMAN (1985): "Optimal employment contracts with bankruptcy constraints," *Journal of Economic Theory*, 35(2), 343–365.

KIM, J.-C., AND K.-B. CHANG (1993): "An optimal tax/subsidy for output and pollution control under asymmetric information in oligopoly markets," *Journal of Regulatory Economics*, 5(2), 183–197.

KÖPPL, A., AND M. SCHRATZENSTALLER (2023): "Carbon taxation: A review of the empirical literature," *Journal of Economic Surveys*, 37(4), 1353–1388.

KREPS, D. M. (2023): *Microeconomic Foundations II: Imperfect Competition, Information, and Strategic Interaction*. Princeton University Press.

LAFFONT, J.-J., AND D. MARTIMORT (2002): *The theory of incentives: the principal-agent model*. Princeton University Press.

LAFFONT, J.-J., AND J. TIROLE (1993): *A theory of incentives in procurement and regulation*. MIT Press.

——— (1996): "Pollution permits and compliance strategies," *Journal of Public Economics*, 62(1), 85–125.

LANDRY, J. R. (2021): "Think globally, cap locally, and trade widely: efficient decentralized policy making in the presence of spillovers," *Journal of the Association of Environmental and Resource Economists*, 8(1), 91–124.

LAPPI, P. (2016): "The welfare ranking of prices and quantities under noncompliance," *International Tax and Public Finance*, 23, 269–288.

LEHMANN, E., L. SIMULA, AND A. TRANNOY (2014): "Tax me if you can! Optimal nonlinear income tax between competing governments," *The Quarterly Journal of Economics*, 129(4), 1995–2030.

LEVINSON, A. (2023): "Are developed countries outsourcing pollution?," *Journal of Economic Perspectives*, 37(3), 87–110.

LEVINSON, A., AND M. S. TAYLOR (2008): "Unmasking the pollution haven effect," *International Economic Review*, 49(1), 223–254.

LEWIS, T. R., AND D. E. SAPPINGTON (1989): "Countervailing incentives in agency problems," *Journal of Economic Theory*, 49(2), 294–313.

——— (1995): "Using markets to allocate pollution permits and other scarce resource rights under limited information," *Journal of Public Economics*, 57(3), 431–455.

MAGGI, G., AND A. RODRIGUEZ-CLARE (1995): "On countervailing incentives," *Journal of Economic Theory*, 66(1), 238–263.

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(1), 55–77.

MARKUSEN, J. R., E. R. MOREY, AND N. D. OLEWILER (1993): "Environmental policy when market structure and plant locations are endogenous," *Journal of Environmental Economics and Management*, 24(1), 69–86.

MARTIMORT, D. (2006): "Multi-contracting mechanism design," *Econometric Society Monographs*, 41, 57.

MARTIMORT, D., AND L. STOLE (2002): "The revelation and delegation principles in common agency games," *Econometrica*, 70(4), 1659–1673.

——— (2009a): "Market participation in delegated and intrinsic common-agency games," *The RAND Journal of Economics*, 40(1), 78–102.

——— (2009b): "Selecting equilibria in common agency games," *Journal of Economic Theory*, 144(2), 604–634.

MARTIMORT, D., AND L. A. STOLE (2022): "Participation constraints in discontinuous adverse selection models," *Theoretical Economics*, 17(3), 1145–1181.

MARTIN, R., M. MUÛLS, L. B. DE PREUX, AND U. WAGNER (2014): "Industry compensation under relocation risk: A firm-level analysis of the EU emissions trading scheme," *The American Economic Review*, 104(8), 2482–2508.

MCAFEE, R. P. (1993): "Mechanism design by competing sellers," *Econometrica*, pp. 1281–1312.

METCALF, G. E., AND D. WEISBACH (2012): "Linking policies when tastes differ: Global climate policy in a heterogeneous world," *Review of Environmental Economics and Policy*.

MEUNIER, G., J.-P. PONSSARD, AND P. QUIRION (2014): "Carbon leakage and capacity-based allocations: Is the EU right?," *Journal of Environmental Economics and Management*, 68(2), 262–279.

MIDEKSA, T. (2022): "Pricing pollution in a non-cooperative world," *Journal of Public Economics Plus*, 3, 100014.

MIDEKSA, T. K. (2021): "Leadership and climate policy," *Working Paper*.

——— (2024): "Does Leadership Promote a Cleaner Climate?," *Working Paper*.

MIDEKSA, T. K., AND M. L. WEITZMAN (2019): "Prices versus quantities across jurisdictions," *Journal of the Association of Environmental and Resource Economists*, 6(5), 883–891.

MILGROM, P., AND I. SEGAL (2002): "Envelope theorems for arbitrary choice sets," *Econometrica*, 70(2), 583–601.

MISCH, F., AND P. WINGENDER (2021): "Revisiting Carbon Leakage," *IMF Working Paper 21/07*.

MIYAOKA, A. (2019): "The Signaling Effect of Emission Taxes Under International Duopoly," *Environmental and Resource Economics*, 72, 691–720.

MONTERO, J.-P. (2002): "Prices versus quantities with incomplete enforcement," *Journal of Public Economics*, 85(3), 435–454.

——— (2008): "A simple auction mechanism for the optimal allocation of the commons," *The American Economic Review*, 98(1), 496–518.

NAEGELE, H., AND A. ZAKLAN (2019): "Does the EU ETS cause carbon leakage in European manufacturing?," *Journal of Environmental Economics and Management*, 93, 125–147.

NEWELL, R. G., W. A. PIZER, AND D. RAIMI (2013): "Carbon markets 15 years after Kyoto: Lessons learned, new challenges," *Journal of Economic Perspectives*, 27(1), 123–146.

PAI, M. M. (2010): "Competition in mechanisms," *ACM SIGecom Exchanges*, 9(1), 1–5.

PETERS, M. (2001): "Common agency and the revelation principle," *Econometrica*, 69(5), 1349–1372.

PETERS, M., AND B. SZENTES (2012): "Definable and contractible contracts," *Econometrica*, 80(1), 363–411.

PETERS, M., AND C. TRONCOSO-VALVERDE (2013): "A folk theorem for competing mechanisms," *Journal of Economic Theory*, 148(3), 953–973.

PIGOU, A. C. (1932): *The Economics of Welfare*. MacMillan and Co.

QUEMIN, S., AND C. DE PERTHUIS (2019): "Transitional restricted linkage between emissions trading schemes," *Environmental and Resource Economics*, 74(1), 1–32.

ROCHET, J.-C., AND L. A. STOLE (2002): "Nonlinear pricing with random participation," *The Review of Economic Studies*, 69(1), 277–311.

RUDIN, W. (1973): *Functional Analysis*. McGraw-Hill Series in Higher Mathematics.

RYAN, S. P. (2012): "The costs of environmental regulation in a concentrated industry," *Econometrica*, 80(3), 1019–1061.

SHERIFF, G. (2008): "Optimal environmental regulation of politically influential sectors with asymmetric information," *Journal of Environmental Economics and Management*, 55(1), 72–89.

SLECHTEN, A. (2020): "Environmental agreements under asymmetric information," *Journal of the Association of Environmental and Resource Economists*, 7(3), 455–481.

STAVINS, R. N. (2022): "The relative merits of carbon pricing instruments: Taxes versus trading," *Review of Environmental Economics and Policy*, 16(1), 62–82.

STOLE, L. A. (1995): "Nonlinear pricing and oligopoly," *Journal of Economics & Management Strategy*, 4(4), 529–562.

TIMILSINA, G. R. (2022): "Carbon taxes," *Journal of Economic Literature*, 60(4), 1456–1502.

TWAIN, M. (1885): *The Adventures of Huckleberry Finn*.

VENMANS, F., J. ELLIS, AND D. NACHTIGALL (2020): "Carbon pricing and competitiveness: are they at odds?," *Climate Policy*, 20(9), 1070–1091.

VERDE, S. F. (2020): "The impact of the EU emissions trading system on competitiveness and carbon leakage: the econometric evidence," *Journal of economic surveys*, 34(2), 320–343.

VISLIE, J. (2000): "Environmental regulation under asymmetric information with type-dependent outside option," *Memorandum No. 2000, 18, University of Oslo*.

——— (2003): "Domestic Environmental Policy under Asymmetric Information: The role of foreign ownership, outside options and market power," Discussion paper.

WEITZMAN, M. L. (1974): "Prices vs. quantities," *The Review of Economic Studies*, 41(4), 477–491.

YU, B., Q. ZHAO, AND Y.-M. WEI (2021): "Review of carbon leakage under regionally differentiated climate policies," *Science of The Total Environment*, 782, 146765.

*"... and so there ain't nothing more to write about, and I am rotten glad of it, because if I'd a knowed what a trouble it was to make a book I wouldn't a tackled it and ain't agoing to no more."* (Twain, 1885)

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