Relocation in presence of polluting and heterogeneous technologies

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Abstract. This paper develops a simple partial equilibrium model with two regions, North and South, to fathom the effects of firms' relocation in a context of international and imperfect competition. Two different production technologies are considered, a relatively clean technology and a dirty one, and the effects of relocation according to the kind of technology used by the relocated firms are determined. We consider one immobile dirty firm located in the South and two mobile firms located in the North: one relatively clean and one dirty firm. This paper demonstrates that the offshoring of a dirty firm as compared to the offshoring of a clean firm is worse for the environment, better for northern consumers, and better for the domestic profits.

Keywords. Relocation; Emissions tax; Trade of polluting goods; Dirty and clean production technologies; Imperfect competition.

JEL codes. L13, Q53, Q58.

1 Introduction

The relocation of companies is a particularly sensitive and topical subject,[1] and encompasses different situations. The companies in a country may change location for the first time (offshoring), and these relocated companies can relocate to their country of origin (reshoring). These two concepts were discussed in particular during the Covid-19 crisis. On the one hand, offshoring was criticized as it partly explains the difficulties in supplying strategic goods such as medicines or face masks. Offshoring can be also detrimental to a country: it leads to job losses in specific sectors, especially low-skilled jobs,[2] and in specific regions,[3] and thus leads

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[1]According to Amiti (2005), 2,634 articles on offshoring were published in US newspapers in the first five months of 2004, about five times the amount of coverage found in a similar period in 2001.

[2] Many studies show that offshoring negatively affects demand for low-skilled workers (see for instance, Geishecker (2002), Wright (2014), or Feenstra and Hanson (1996)). However, Winkler (2009) reports that the effect of services offshoring in Germany was negative for the relative demand for high-skill German labour for the period 1995-2004.

[3]Using French data, Jennequin et al. (2018) shows that offshoring generates significant asymmetric shocks at the local level.

to the destruction of physical and human capital. Rising unemployment also generates costs such as unemployment benefits but also deficits in taxes and social contributions. On the other hand, reshoring is now one of the stated objectives of many developed countries. For instance, the recent 8 billion euros rescue plan for Renault requires the location of production and assembly in France for electric vehicles.[4] Reshoring makes it possible to reduce dependency on foreign countries and, conversely to offshoring, to increase the number of jobs and rebuild physical capital. This paper studies the effects of relocation.

More precisely, this study focuses on the effects of relocation on both environment and competition, and ignores the issue of strategic dependency. Many sectors using offshoring, such as cement or steel, are characterized by polluting production processes and are oligopolistic. Offshoring can be harmful for the environment since firms that relocate in countries implementing more lenient environmental regulations, may contribute to increase emissions by producing more (see for instance Taylor (2015) and the literature on pollution havens). Moreover, in the presence of international trade and imperfect competition, relocations alter market structures and competition, and changes the exercise of market power by firms. This paper takes into account technology heterogeneity among countries and firms. More precisely, we focus on emission intensity heterogeneity, which means that the production of one unit of the same good can generate different levels of emissions between companies. Indeed, according to Lyubich et al. (2018), to produce one dollar of output, a plant at the 10^{th} percentile of a typical industry's energy productivity distribution spends 580 percent more on energy than a plant at the 90^{th} percentile of the same industry. It therefore seems interesting to examine the effects of relocations (either offshoring or reshoring) on welfare depending on whether the technology used is environmentally-friendly or not. This study sheds some lights on the merits to retain or to attract a clean or a dirty firm on the territory.

We develop a simple partial equilibrium model with two regions (North and South) to fathom the effects of firms' relocation in a context of international and imperfect competition. Each region implements an emission tax, and firms produce an homogeneous polluting good consumed in each region. We consider that transporting goods from one region to another creates emissions and we consider two different production technologies, a relatively clean technology and a dirty one. The cleanliness of a firm is given by its emission intensity, that is the number of emissions per unit produced. The southern economy is assumed to be less advanced than the northern economy where the emissions tax and the production cost are higher. These assumptions reflect the facts that the environmental awareness increases with the development, and that labour is usually more expensive in advanced economies. To simplify the analysis, we consider three firms: one dirty firm in the South that is not mobile, and two mobile firms in the North, one clean firm and one dirty firm. We assume that first the mobile firms decide whether they relocate or not and second the three firms choose their production. By backward induction, we determine the necessary conditions for the emergence of each potential market structure and show that, by using individualized lump-sum taxes and subsidies, the regulator in the North can allow the emergence of each potential market

[4] Reshoring, is also a perennial subject in the US, as an illustration, on August 23 2019, Trump took to Twitter, ordering American companies to "immediately start looking for an alternative to China" and build more products in the U.S.

structure. By comparing the four potential market structures, we are able to study from a normative point of view the benefits and disadvantages of offshoring. More specifically, we study how relocation affects the price, the emissions, the profits and the production. The paper shows that the offshoring of a dirty firm as compared to the offshoring of a clean firm is worse for the environment, better for northern consumers, and better for the domestic profits.

This paper is related to the strand of literature which studies the determinants and the effects of relocation when there is pollution, trade and asymmetric environmental regulation such as Motta and Thisse (1994), Hoel (1997), Markusen et al. (1993), Greaker (2003), Petrakis and Xepapadeas (2003) and Sanna-Randaccio et al. (2017). Our paper departs from Markusen et al. (1993), Hoel (1997) and Greaker (2003) which examine how the optimal environmental policy depends on the possibility that firms may relocate. Like Motta and Thisse (1994), we consider environmental policy to be exogenous and study its effects. The closest paper to our article is Motta and Thisse (1994). The authors analyze in a context of two countries, global pollution and two firms (one in each country) how the implementation of an environmental policy in one country can lead to the relocation of the firm residing there or the opening by the latter of a subsidiary abroad. In addition, they study the welfare effects of offshoring. Our article is complementary to the latter and we consider two firms in the home country, one clean and one polluting, and we assume that pollution is global. This framework allows us to compare the effect of relocating a clean firm with the effect of relocating a polluting firm, which was impossible to study in the model developed by Motta and Thisse (1994). The other difference with this paper is that we do not consider the possibility of opening a subsidiary and only study the complete relocation of production activities. We also study the conditions under which firms relocate by considering that the two mobile firms simultaneously decide on their choice of location. Our paper also complements Petrakis and Xepapadeas (2003) and Sanna-Randaccio et al. (2017), which determine the conditions of relocation by considering that only one firm can relocate.

The paper is structured as follows. Section 2 presents the modelling assumptions. Section 3 describes the four potential market structures. Section 4 analyzes the location decisions while Section 5 discusses the effects of offshoring. Section 6 puts the results in perspectives and derives some policy implications.

2 The model

Starting from the observation that within a given sector, there is a great heterogeneity among firms production technologies in terms of greenhouse gas emissions, our study compares the effects of relocation according to the environmental quality, which we consider here to be given by the number of greenhouse gas emissions for a production unit. We wish to answer the following question. Is it better for a country, for its tax revenue, for its consumers, for the environment that the least polluting firm relocates or is it preferable that it is the most polluting firm that relocates?

Therefore, the model describes the production and the trade of an homogeneous good by two countries: Country N (N denotes North) and Country S (S denotes South). In each country, there are consumers and firms respectively purchasing and producing the homogeneous good. The demand function of the good in the country l is given by $p_l = a_l - Q_l$, where a_l is the market size in country l, and Q_l the quantity consumed in country l.

Three additional assumptions are made. Firms are assumed to compete "à la Cournot" in each market. We consider three firms: one dirty firm in the South that is not mobile, and two mobile firms in the North. The production of the good is polluting and generates emissions which are harmful. We consider pollution with global effects. The first assumption allows us to account for the market power of firms and the concentration of a market for products. The second is simplifying and is the simplest possible market structure to answer the questions presented above. However, such a structure can of course be explained by history dependency. The third is simply to consider greenhouse gases such as CO_2 that cause global pollution that affects all countries. Sectors such as steel and cement meet the assumptions made: homogeneous product, greenhouse gas emitting and concentrated sector. We will in Section 6 relax the assumptions about the homogeneity of the product and the specific market structure and we will show that these assumptions do not affect the robustness of our results.

In order to emphasize the role of technology, we consider two different production technologies: a so-called clean technology, denoted by c and a so-called dirty technology, denoted by d. Each production technology is defined by its emission intensity, which is the number of emission units generated by the production of one unit. Let μ^k be the emission intensity associated to technology k. Let us denote the emission intensity gap by $\Delta_\mu = \mu^d - \mu^c > 0$. We consider that one mobile firm is clean (it owns the clean technology) and the other mobile firm is dirty (it owns the dirty technology). Furthermore, the southern firm is also assumed to be dirty. Technological asymmetry can be explained by different research and development efforts or simply by different successes. We study in Section 6 other types of technologies and the effect of property rights on the technology diffusion.

In each country, an emissions tax is introduced to reduce the emissions generated by the production of the goods. Let us denote $\tau_l > 0$ the emissions tax in country l. We assume that the emissions tax in the North is higher than the one in the South that is $\Delta_\tau = \tau_N - \tau_S > 0$. Indeed, developed countries are currently doing larger efforts than developing countries. For instance, the carbon tax in France, Sweden and Switzerland is respectively 52, 137 and 101 dollars per ton, while there is no carbon tax in Africa, with the exception of South Africa (9 dollars), the tax is 5 dollars in Chile and Argentina and 3.18 dollars in Mexico. Moreover, the price of the permit on the European market was 90 euros per ton in January 2022. The price of the pilot markets in China (Beinjing, Hubei, Chongking, Shanghai and Tianjin) is less than 6 dollars. We also discuss the implementation of a market of pollution rights instead of a tax in Section 6.

Each firm is assumed to sell on the two markets. Transportation from one country to another generates emissions with global effect and is costly. Let us assume that each unit of good transported, either from North to South or from South to North, induces γ unit of pollution emissions. Transportation-related emissions depend on the type of transportation mode which in turn depends on the type of traded goods. If we focus on trade between China and the EU, EU's main imports from China are industrial and consumer goods, machinery and equipment, and clothing, while EU's main exports to China are machinery and equipment, motor vehicles, aircraft, and chemicals. Despite, this variety of traded goods, according to the United Nations Economic Commission for Europe 62% of China-EU trade is done using maritime transport, 23% using flights, and only 7% using road. It should be noted that maritime transport generates greenhouse gas emissions but also sulphur dioxide (SO2), nitrogen oxides (NOx) and fine particles. For this reason, we treat production emissions and transport emissions differently. The γ parameter could be used as a conversion rate from one gas to another.

Let us also assume that transportation cost does not depend on the cleanliness of the production technology. We consider a symmetric and constant unit transportation cost t in the two regions. This transportation cost may include a pollution tax for transport-related emissions. However, there are currently no market instruments to regulate carbon emissions from shipping. Nevertheless, in the framework of the European Green Deal, it is discussed to include European maritime transport in the European Union Emissions Trading Scheme. In addition, the International Maritime Organization committed in 2018 to peak GHG emissions from international shipping as soon as possible and to reduce total annual GHG emissions by at least 50% by 2050, compared to 2008. For all these reasons we do not consider any market instrument reducing transport emissions, but the model can easily be adapted to the introduction of such instruments.

Production of the northern clean (dirty) firm i sold in the North and in the South is respectively denoted by $r^c_{NN_i}$ and $r^c_{NS_i}$ ($r^d_{NN_i}$ and $r^d_{NS_i}$). Let us also denote $r^d_{SN_i}$ and $r^d_{SS_i}$ ($r^c_{SN_i}$ and $r^c_{SS_i}$), the production of the southern dirty (clean) firm i, sold respectively in the northern and in the southern market. Thus, we make the assumption that a firm has only one plant. We relax in Section 6 this assumption and consider companies with plants in different countries. We also take into account that production costs differ between the North and the South. Let us also denote c_l the unit production cost in country l. We assume that the unit production cost is higher in the northern economy than in the southern one, that is the unit production cost differential $\Delta_c = c_N - c_S$ is strictly positive.

The two mobile firms can relocate. Let us assume that clean and dirty firms have the same relocation costs denoted by C^O. Moreover, we assume that the two mobile firms decide simultaneously whether they change their location. We will study in Section 6 how firms' sequential relocation decision affects our results.

The timing of the game is as follows:

Stage 1: Each mobile firm chooses its location.

Stage 2: Each firm chooses its production level given its location.

Indeed, we consider that offshoring decisions are long-term decisions while production decisions are short-term decisions. Solving by backward-induction, we will first study the second stage of the game in the Section 3 then the first stage in the Section 4. Since both firms in the North can relocate to the South, there are four possible market structures: both firms stay in the North, only one relocates, either the clean or the dirty one, or both relocate to the South.

3 The potential market structures (Stage 2)

We analyze the four potential market structures: the two mobile firms are located in the North, only one clean (or one dirty) firm is located in the North, and all firms are in the South.

Market structure 1. North: one dirty and one clean firm - South: one dirty firm. The two northern firms sell in the North and in the South. In the North, one dirty firm and one clean firm coexist. They respectively solve the following problems:

$$\max_{r^d_{NS}, r^d_{NN}} \pi^d_N = (p_S - c_N - \tau_N \, \mu^d - t) \, r^d_{NS} + (p_N - c_N - \tau_N \, \mu^d) \, r^d_{NN}, \tag{1}$$

$$\max_{r^c_{NS}, r^c_{NN}} \pi^c_N = (p_S - c_N - \tau_N \, \mu^c - t) \, r^c_{NS} + (p_N - c_N - \tau_N \, \mu^c) \, r^c_{NN}. \tag{2}$$

The two northern firms have to pay the emissions tax in the North, their effective marginal cost is $c_N + \tau_N \, \mu^c$ for the clean firm and $c_N + \tau_N \, \mu^d$ for the dirty one, respectively. Each unit exported induces an additional transportation cost t.

The southern firm solves the following problem:

$$\max_{r^d_{SS}, r^d_{SN}} \pi^d_S = (p_S - c_S - \tau_S \, \mu^d) \, r^d_{SS} + (p_N - c_S - \tau_S \, \mu^d - t) \, r^d_{SN}. \tag{3}$$

The effective marginal cost for a southern firm is $c_S + \tau_S \, \mu^d$, which consists of the unit production cost c_S and the cost related to the environmental tax $\tau_S \, \mu^d$. As previously, each unit exported induces an additional transportation cost t.

By calculating the first-order conditions and solving the system of equations, we obtain the productions at equilibrium, which are given by:

$$\begin{aligned}
r_{SN}^{d_1} &= \frac{a_N - 3\,c_S + \mu^d\,\tau_N + \mu^c\,\tau_N - 3\,\mu^d\,\tau_S - 3\,t + 2\,c_N}{4},\\
r_{NN}^{c_1} &= \frac{a_N - 2\,c_N + \mu^d\,\tau_N - 3\,\mu^c\,\tau_N + \mu^d\,\tau_S + t + c_S}{4},\\
r_{NN}^{d_1} &= \frac{a_N - 2\,c_N + \mu^c\,\tau_N - 3\,\mu^d\,\tau_N + \mu^d\,\tau_S + t + c_S}{4},\\
r_{SS}^{d_1} &= \frac{a_S - 3\,c_S + \mu^d\,\tau_N + \mu^c\,\tau_N - 3\,\mu^d\,\tau_S + 2\,t + 2\,c_N}{4},\\
r_{NS}^{d_1} &= \frac{a_S - 2\,c_N + \mu^c\,\tau_N - 3\,\mu^d\,\tau_N + \mu^d\,\tau_S - 2\,t + c_S}{4},\\
r_{NS}^{c_1} &= \frac{a_S - 2\,c_N + \mu^d\,\tau_N - 3\,\mu^c\,\tau_N + \mu^d\,\tau_S - 2\,t + c_S}{4}.
\end{aligned}$$

On each market, the northern clean firm produces more than the northern dirty firm. A dirty firm always produces more on its domestic market than the dirty firm exporting on this market. Finally, depending on the transportation cost, taxes, and unit production costs, the clean firm may produce on each market more or less than the dirty southern firm. Indeed, the clean firm uses a more efficient technology but faces a higher tax and a higher unit production cost c_N. Moreover, firms have an advantage on their domestic market since they do not pay the transportation cost when they supply their local market.

The equilibrium prices are then deduced and are as follows:

$$\begin{aligned}
p_N^1 &= \frac{\mu^d\,\tau_N + \mu^c\,\tau_N + \mu^d\,\tau_S + t + 2\,c_N + c_S + a_N}{4},\\
p_S^1 &= \frac{\mu^d\,\tau_N + \mu^c\,\tau_N + \mu^d\,\tau_S + 2\,t + 2\,c_N + c_S + a_S}{4}.
\end{aligned}$$

It should be noted that a reduction in emission intensity for both clean and dirty firms leads to lower product prices. In addition, a tightening of environmental policy in one of the two countries leads to higher product prices in both markets. Lower transport costs lead to lower product prices in each market. An increase in a firm's production cost leads to higher prices in both markets. An increase in the market size of a country leads to an increase in the price of products sold in that country.

We also determine the emissions generated by the production, which are denoted by E_1^p and are equal to:

$$E_1^p = \frac{2\left(2\,\mu^d - \mu^c\right)\left(\mu^c\,\tau_N - \mu^d\,(\tau_N + \tau_S) - c_S\right) - 4\,\mu^c\,(\mu^c\,\tau_N + c_N) + \left(2\,\mu^d + \mu^c\right)(a_N + a_S - t)}{4}.$$

An increase in the market size of a country leads to an increase in emissions generated by production. An increase in production costs leads to a decrease in emissions generated by production. Note that emissions are not monotonic with emission intensities.

Similarly, we determine the emissions from the transport of goods which are denoted by E_1^t and equal to:

$$E_1^t = \gamma \frac{a_N + 2\,a_S - \mu^d\,\tau_N - \mu^c\,\tau_N - \mu^d\,\tau_S - 7\,t - 2c_N - c_S}{4}.$$

Transport-related emissions increase with market size and decrease with transport costs, production costs, emission taxes and emission intensities.

Market structure 2. North: one clean firm - South: two dirty firms. The northern firm uses the clean technology, while the two southern firms own the dirty technology. The three firms sell in the North and in the South. The superscript 2 refers to this market structure and the calculations are detailed in Appendix A.1. We show that the clean firm may produce more or less than the dirty southern firms. Indeed, the clean firm uses a more efficient technology but faces a higher tax and unit production costs. Moreover, if the southern firms produce individually more than the northern firm in the northern market, then they produce also more on the southern market.

The equilibrium prices in this market structure are equal to:

$$p_N^2 = \frac{\mu^c\,\tau_N + 2\,\mu^d\,\tau_S + 2\,t + c_N + 2\,c_S + a_N}{4},$$
$$p_S^2 = \frac{\mu^c\,\tau_N + 2\,\mu^d\,\tau_S + t + c_N + 2\,c_S + a_S}{4}.$$

The emissions generated by the production, denoted by E_2^p, and the emissions from the transport of goods, denoted by E_2^t, are equal to:

$$E_2^p = \frac{2\,(2\,\mu^d - 3\,\mu^c)\,(\mu^c\,\tau_N + c_N) - 4\,(2\,\mu^d - \mu^c)\,(\mu^d\,\tau_S + c_S) - (2\,\mu^d + \mu^c)\,(t - a_N - a_S)}{4},$$
$$E_2^t = \gamma \frac{2\,a_N + a_S - \mu^c\,\tau_N - 2\mu^d\,\tau_S - 7\,t - c_N - 2\,c_S}{4}.$$

Market structure 3. North: one dirty firm - South: one dirty and one clean firm. The northern firm uses the dirty technology, while in the South the two technologies coexist. The superscript 3 refers to this market structure and the calculations are detailed in Appendix A.2. On each market, the southern clean firm produces more than the southern dirty firm. Each southern firm produces more than the northern dirty firm on the southern market. The northern dirty firm may produce more or less than the southern firms in the northern market since it does not pay for the transportation cost.

The equilibrium prices are:

$$p_N^3 = \frac{\mu^d\,\tau_N + \mu^d\,\tau_S + \mu^c\,\tau_S + 2\,t + c_N + 2\,c_S + a_N}{4},$$
$$p_S^3 = \frac{\mu^d\,\tau_N + \mu^d\,\tau_S + \mu^c\,\tau_S + t + c_N + 2\,c_S + a_S}{4}.$$

The emissions generated by the production, denoted by E_3^p, and the emissions from the transport of goods, denoted by E_3^t, are equal to:

$$E_3^p = \frac{2\,(\mu^c - 2\,\mu^d)\,\mu^d\,\tau_N - 2\,(2\,{\mu^d}^2 - 3\,\mu^c\,\Delta_\mu)\,\tau_S + (2\,\mu^d + \mu^c)\,(a_N + a_S - t - 2\,c_N)}{4} + \Delta_c\,\mu^c,$$
$$E_3^t = \gamma\frac{2\,a_N + a_S - \mu^d\,\tau_N - \mu^d\,\tau_S - \mu^c\,\tau_S - 7\,t - c_N - 2\,c_S}{4}.$$

Market structure 4. North: no firm - South: two dirty firms and one clean firm. The three firms produce in the South. One firm uses the clean technology, while the two others own the dirty technology. The superscript 4 refers to this market structure and the calculations are detailed in Appendix A.3. The effective marginal cost of producing and selling in the South is $c_S + \tau_S\,\mu^c$ for the clean firm and $c_S + \tau_S\,\mu^d$ for the dirty one. The two dirty firms produce the same, while the clean firm produces more since its effective marginal cost is lower. The productions obviously do not depend on the northern environmental tax and on the northern marginal production cost.

The equilibrium prices are:

$$p_N^4 = \frac{2\,\mu^d\,\tau_S + \mu^c\,\tau_S + 3\,t + 3\,c_S + a_N}{4},$$
$$p_S^4 = \frac{2\,\mu^d\,\tau_S + \mu^c\,\tau_S + 3\,c_S + a_S}{4}.$$

The emissions generated by the production, denoted by E_4^p, and the emissions from the transport of goods, denoted by E_4^t, are equal to:

$$E_4^p = \frac{\left(2\,\mu^d + \mu^c\right)\,(a_N + a_S - t - 2\,c_S) - 2\left(4\,\mu^d\,\Delta_\mu + 3\,\mu^{c2}\right)\,\tau_S}{4},$$
$$E_4^t = \gamma\frac{3\,a_N - 2\,\mu^d\,\tau_S - \mu^c\,\tau_S - 3\,t - 3\,c_S}{4}.$$

4 The location decisions (Stage 1)

Once we have described the four potential market structures, let us study the location decisions. We solve this game using backward induction: each mobile firm chooses its location given that in the second stage firms will compete in quantity. Firms play simultaneously. The decision to relocate depends on the expected gains, the cost of relocation and the decision of the other mobile firm. Table 1 represents the normal form of the game. From the latter, we determine the conditions under which each market structure is a Nash equilibrium. These results will allow us to deduce how the regulator can use them to implement the market structure that seems most favourable to her.

		Dirty firm	
		Stay	Offshore
Clean firm	Stay	$(\pi_N^{c_1}, \pi_N^{d_1})$	$(\pi_N^{c_2}, \pi_S^{d_2} - C^O)$
	Offshore	$(\pi_S^{c_3} - C^O, \pi_N^{d_3})$	$(\pi_S^{c_4} - C^O, \pi_S^{d_4} - C^O)$

Table 1: The normal form of the game.

We derive two main messages from the analysis of these conditions. First, the equilibrium market structure (or the number and identity of offshoring) depends on the value of the cost of offshoring and on the profits comparison, and there may be multiple equilibria. Second, by using individualized lump-sum taxes and subsidies, the regulator in the North can allow the emergence of each potential market structure.

Whether one or both firms relocate or stay in the North depends on the cost of offshoring. Moreover depending on the value of the offshoring cost and the parameters, there may be multiple equilibria. Indeed, the comparison of the profits of each market structure depends on the parameters of the model, i.e. the unit production cost differential, the tax differential, the emission intensities and the transportation cost. Since firms play simultaneously, it is possible to have the coexistence of two equilibria at the same time.

Before presenting the results, let us define the concept of incentive to relocate. The incentive to relocate is the gain to relocate, i.e, the comparison between the profit made after relocation minus the offshoring cost and the profit before relocation. The clean firm's incentive to relocate when the dirty firm stays in the North is given by $IC_N^c = \pi_S^{c_3} - C^O - \pi_N^{c_1}$, while the incentive is $IC_S^c = \pi_S^{c_4} - C^O - \pi_N^{c_2}$ when the dirty firm also relocates. Likewise, the dirty firm's incentive to relocate when the clean firm stays in the North is given by $IC_N^d = \pi_S^{d_2} - C^O - \pi_N^{d_1}$, while the incentive is $IC_S^d = \pi_S^{d_4} - C^O - \pi_N^{d_3}$ when the clean firm also relocates.

We can easily show that:

$$\begin{aligned}(\pi_S^{d_2} - \pi_N^{d_1}) - \left(\pi_S^{d_4} - \pi_N^{d_3}\right) &= (\pi_S^{c_3} - \pi_N^{c_1}) - (\pi_S^{c_4} - \pi_N^{c_2}) \\ &= \frac{3}{4}\,(\mu^c\,\Delta\tau + \Delta\,c)\,\left(\mu^d\,\Delta\tau + \Delta\,c\right) + \frac{3}{4}\,t^2 > 0. \end{aligned} \tag{4}$$

From equation (4), we deduce that $IC_N^c > IC_S^c$ and $IC_N^d > IC_S^d$, meaning that a firm has more incentive to relocate when the other mobile firm stays in the North. This means that as the offshoring cost decreases, a firm may have the incentive to relocate only if the other mobile firm stays in the North, and as the offshoring cost decreases further, a firm may have the incentive to relocate even if the other mobile firm relocates.

From equation (4), $IC_N^d - IC_N^c = IC_S^d - IC_S^c$. This equality implies that $IC_N^d - IC_N^c$ has the same sign as $IC_S^d - IC_S^c$, meaning that, a type of firm (clean or dirty) has a stronger incentive to relocate than the other type regardless of the strategy (relocate or stay) of the other mobile firm. Figures 1 and 2, study the case in which the dirty firm has more incentives to relocate, while Figures 3 and 4, study the opposite case.

By denoting $IC^d - IC^c = IC^d_N - IC^c_N = IC^d_S - IC^c_S$, and using the profits, we can show that:

$$IC^d - IC^c = \frac{3\,\Delta_\mu\,\Delta_\tau\,(a_N + a_S - 3\,\mu^d\,\tau_N - 3\,\mu^c\,\tau_N - \mu^d\,\tau_S - 3\,\mu^c\,\tau_S - t)}{8} - \frac{3\,\Delta_\mu\,\left(2\,c_N\,\left(3\,\tau_N + \tau_S\right) - 4\,c_S\,\left(\tau_N + \tau_S\right)\right)}{8}.$$

The dirty firm has more incentive to relocate than the clean firm when the market sizes are large, when the unit production cost differential Δ_c and the transportation cost t are small, and when the emission intensity parameters are also small. The effect of taxes are non monotonic.

Let us now return to the study of the equilibrium. Depending on the incentive to relocate and on the value of the offshoring cost, different equilibria occur. More precisely, the profit gains from relocation $\pi^{d_2}_S - \pi^{d_1}_N$, $\pi^{c_3}_S - \pi^{c_1}_N$, $\pi^{d_4}_S - \pi^{d_3}_N$ and $\pi^{c_4}_S - \pi^{c_2}_N$ can be classified in four different manners as represented in Figures 1, 2, 3 and 4. Depending on the offshoring cost, we determine for each case which potential market structures will be an equilibrium. The four cases are represented below:

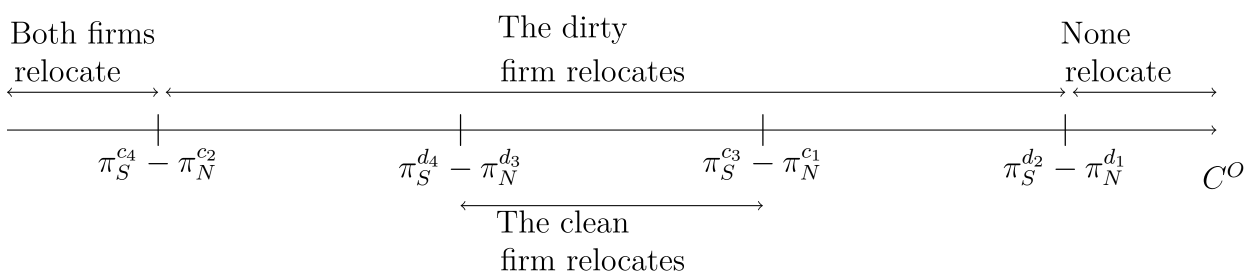

Figure 1: $\pi^{d_4}_S - \pi^{d_3}_N > \pi^{c_3}_S - \pi^{c_1}_N$

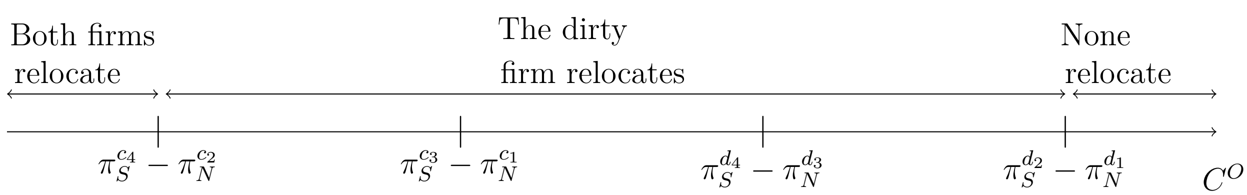

Figure 2: $\pi^{d_4}_S - \pi^{d_3}_N < \pi^{c_3}_S - \pi^{c_1}_N$

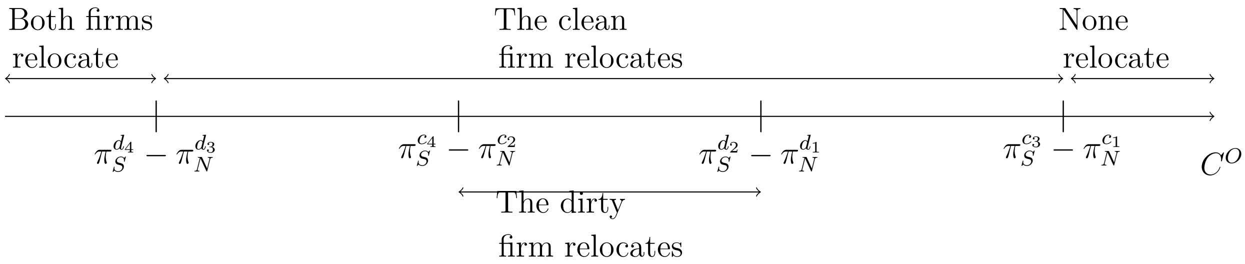

Figure 3: $\pi_S^{d_2} - \pi_N^{d_1} < \pi_S^{c_4} - \pi_N^{c_2}$

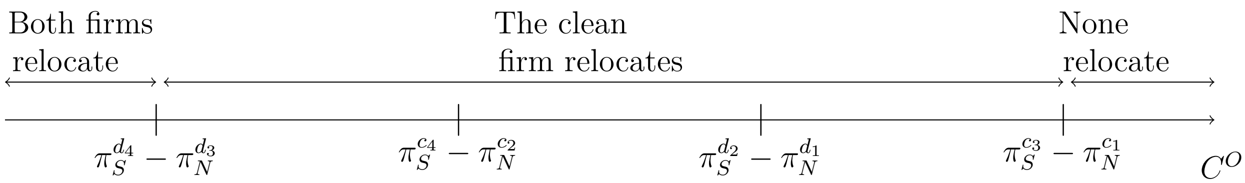

Figure 4: $\pi_S^{d_2} - \pi_N^{d_1} > \pi_S^{c_4} - \pi_N^{c_2}$

The four figures represent all the potential cases. Note, in any case, when the cost of relocation is high, both firms stay in the North, when the cost is low, both firms relocate to the South. These results are particularly obvious. However, when the cost is between the two previous bounds (the one for a low cost and the one for a high cost), the problem becomes more complicated. There will always be at least one equilibrium characterized by the firm with the highest incentive to relocate and potentially in a lower interval (included in the previous one) an equilibrium characterized by the relocation of the other firm. In other words, if the dirty firm has more incentive to relocate, then the clean firm may have the incentive to relocate for intermediate values of offshoring costs (Figure 1) or it may have no incentive to relocate (Figure 2). Likewise, if the clean firm has a higher incentive to relocate, then the dirty firm may have the incentive to relocate for intermediate values of offshoring costs (Figure 3) or it may have no incentive to relocate (Figure 4).

To finish the analysis, we must not forget that we have made the assumption that firms choose their location simultaneously. It is well known that in coordination games, multiple equilibria can appear. For this reason, in some cases (Figures 1 and 3), there may be two possible equilibria, where each mobile firm relocates. We will discuss in Section 6 the case where firms decide on their location sequentially.

The second important message we can deduce from this study is that by individualizing the costs of offshoring (i.e., by making the costs of each firm different through lump-sum taxes or even lump-sum subsidies) it is possible to have the clean firm offshoring instead of the dirty firm or the reverse. To show this result properly, we would have to individualize the offshoring costs of the two mobile firms and re-perform the equilibrium analysis in Stage 1. However, the result is obvious and for this reason we do not do this study. To convince oneself that this is the case, it is sufficient to see that incentives to relocate can be affected by changing the offshoring cost of a firm. Therefore, in the next section we will study the effect of offshoring and in particular compare the offshoring of the clean firm with that of the dirty firm.

5 The effects of offshoring

The purpose of this section is to compare the different market structures. We analyze the effects of offshoring on the four components of welfare, which are the environmental damage, the consumer surplus, the profits and the regulator's revenue.

The following proposition compares the effects of offshoring on the global emissions.

Proposition 1 *The effect of offshoring on global emissions depends on the type of relocated firm:*

- *Emissions generated by production increases when a dirty firm relocates or when both firms relocate, whereas they only increase when a clean firm relocates if the emission intensity gap is small, i.e, if* $\mu^c > \frac{2}{3}\,\mu^d$.

- *Emissions generated by transport increases when a clean firm (respectively a dirty firm) relocates if the southern market size is sufficiently small, i.e, if* $a_S < a_N + \Delta_\tau\,\mu^d + \Delta_c$ *(respectively if* $a_S < a_N + \Delta_\tau\,\mu^c + \Delta_c$*).*

- *Total emissions increase when a dirty firm relocates if the southern market size is sufficiently small, if not, they decrease.*

- *Total emissions increase when a clean firm relocates if the southern market size and the technology gap are sufficiently small, if not, they decrease.*

- *Total emissions are higher when the dirty firm relocates than when the clean firm relocates to the South.*

proof 1 *The proof, Appendix B.1.*

Offshoring affects both the emissions generated by production and those induced by the transport. The comparison between the effects on transport-related and production-related emissions depends of course on the level of emission intensity of transport γ.

Offshoring affects the production-related emissions through a change in the production of the relocated firm (direct effect), and also through the response of the other firms (indirect effect). By offshoring, the firm benefits from a low emissions tax and a low unit production cost, hence, it increases its production and emissions. On the opposite, the other firms decrease their production and emissions since they now face a more competitive firm.

Production-related emissions always increase with the offshoring of a dirty firm. Indeed, the direct effect dominates the indirect one. In other words, the increase in emissions from the dirty relocated firm outweighs the decrease in emissions from its competitors. On the opposite, production-related emissions only increase with the offshoring of a clean firm if $\mu^c > \frac{2}{3}\mu^d$, hence the indirect effect may dominate the direct one. Since dirty firms react to the offshoring of a clean one by decreasing their production, offshoring reduces production-related emissions when μ^d is relatively large. On the opposite, since the relocated clean firm increases its production, offshoring increases production-related emissions when μ^c is relatively large. Hence, the offshoring of a clean firm increases the production-related emissions when the technological gap is relatively small.

Production-related emissions are higher when the dirty firm relocates than when the clean firm relocates. Indeed, a dirty relocated firm increases more its production than a clean relocated firm since a dirty firm benefits more from the low emissions tax. In addition, since it uses a dirtier technology, the increase in production-related emissions from the relocated firm is higher when a dirty firm relocates. Moreover, the southern firm decreases more its production (and emissions) when a dirty firm relocates than when a clean firm relocates.

Let us now focus on transport-related emissions. These depend on the total volume of trade between North and South. If the market size in the South is large enough, the relocation of a firm (dirty or clean) will reduce transport-related emissions because the relocation reduces the total volume of trade between North and South. Moreover, the relocation of a clean firm to the South will increase more substantially exports and the transport-related emissions than the relocation of a dirty firm. Hence, offshoring can decrease global emissions. This result goes against the pollution heaven hypothesis. This result is mainly driven by the fact that we account for emissions from transport and holds when the market size is large in the South. To conclude the offshoring of a clean firm is better for the environment than the offshoring of a dirty firm.

Let us focus on the northern consumer surplus, which is equal to $\frac{1}{2}(a_N - p_N)^2$. The following proposition compares the effects of offshoring on the northern consumer surplus.

Proposition 2 *Offshoring increases the northern consumer surplus when the transportation cost is relatively low:*

- *the offshoring of a dirty (respectively a clean firm) increases the northern consumer surplus if $t < \mu^d \Delta_\tau + \Delta_c$ (respectively if $t < \mu^c \Delta_\tau + \Delta_c$).*

- *The offshoring of both firms increases the northern consumer surplus if $t < \frac{(\mu^d+\mu^c)}{2} \Delta_\tau + \Delta_c$.*

- *The northern consumer surplus is higher when a dirty firm relocates than when a clean firm relocates.*

proof 2 *The proof, Appendix B.2.*

If the transportation cost is low, offshoring induces a decrease in the northern price. Indeed, the relocated firm is more efficient as it benefits from a lower unit production cost, a lower emissions tax, and only pays for a low transportation cost to export the good. Therefore, the relocated firm produces more than before relocating and the northern price will be lower. When the transportation cost is large, efficiency gains do not offset transportation cost and sales in the North will be lower than before relocation. Moreover, the northern price is lower when a dirty firm relocates than when a clean one relocates. Indeed, the efficiency gains are higher when the relocated firm is dirty than when it is clean.

Offshoring clearly decreases the price in the South. Relocated firms benefit from low unit production costs, a low tax and save on transportation costs when they supply the market locally. Hence, the lowest southern price occurs when both firms relocate. Moreover, the price is lower when a dirty firm relocates than when a clean firm relocates. Hence, the southern consumers benefit from having more firms producing in the South, and they benefit even more if the firm is dirty.

Let us focus on the northern tax revenue, which is equal to the northern emissions times the emission tax in the North. Let us recall that we assume that only production-related emissions are taxed. The following proposition determines the effects of offshoring on the northern tax revenue.

Proposition 3 *The offshoring of either a dirty or a clean firm decreases the northern tax revenue. The loss in tax revenue is higher when a clean firm relocates than when a dirty firm relocates if the market sizes are sufficiently small that is if* $a_N + a_S < 6\,\tau_N\,(\mu^d + \mu^c) - 2\,\mu^d\,\tau_S + t + 6\,c_N - 4\,c_S$.

proof 3 *The proof, Appendix B.3.*

The offshoring of either a dirty or a clean firm decreases the northern tax revenue since the remaining firm produces and pollutes less as it faces fiercer competition, and the relocated firm will stop paying for the tax. Nevertheless, the tax revenue may be either higher or lower in the dirty firm offshoring case than in the clean firm offshoring case. Indeed, a clean firm produces more (high tax revenue) but it pollutes less by units produced (low tax revenue). The tax revenue tends to be larger when a dirty firm relocates than when a clean firm relocates if the transportation cost, the unit production cost differential, and the tax differential are large, and when the market sizes are low. In other words, the government is able to capture more tax revenue from clean firms when southern firms are highly competitive.

The following proposition determines the effects of offshoring on the sum of northern profits.

Proposition 4 *The effect of offshoring on the sum of northern profits depends on the type of relocated firm:*

- *offshoring always decreases northern profits if the transportation cost is relatively low (if* $t < \mu^c\,\Delta_\tau + \Delta_c$*),*

- *offshoring may increase northern profits if the transportation cost is relatively large and if the profits on the northern market are sufficiently large (necessary condition* $a_N > a_S - 4\,t$*),*

- *the northern profits are higher when the dirty firm relocates (and the clean firm stays) than when the clean firm relocates (and the dirty firm stays).*

proof 4 *The proof, Appendix B.4.*

The effect of offshoring on northern profits is threefold. (i) The profits of the relocated firm disappear. (ii) The profits of the remaining firm on the southern market decrease since the relocated firm is more productive on the southern market. (iii) Finally, the profits of the remaining firm on the northern market increase if the transportation cost is high enough and decrease otherwise. Hence, if the transportation cost is low, offshoring always decreases northern profits. Northern profits can only increase with offshoring if the market size in the North is larger than the one in the South and if transportation costs are large. This necessary condition implies that the third effect is sufficiently large: the remaining firm has a strong advantage on the domestic market.[5] This result is counter intuitive. As we have seen, for a given location, the clean firm produces at a lower cost than a dirty firm since it uses a cleaner technology. As a result, for a given location, clean firms make higher profits than dirty firms. Hence, the northern profits are higher when both the dirty firm relocates and the clean firm remains in the North than when both the clean firm relocates and the dirty firm remains in the North.

To conclude this section, it is important to note that a government is characterised by its environmental preferences (in other words, its valuation of environmental damage), the weight it will give to consumers and companies in its decisions, and its financial constraints (need to raise tax revenues to finance public policies or public debt). Our model shows that depending on its preferences, a government is able to rank the different market structures and it may be willing to prevent relocations. For instance, a government with substantial needs for tax revenue will prefer the market structure 1 to the market structure 4. On the opposite, a government that cares about companies and profits, will prefer the market structure 4 to the market structure 1 only if the transportation cost and the northern market size are relatively large. Moreover, a government that cares about prices and consumers will prefer the market structure 2 to the market structure 1.

However, countries may be limited in choosing the market structures they want to implement. Countries are particularly heavily indebted and they can be forced to choose the type of firm (clean or dirty) they want to keep in their territory. Our model shows that if the marginal environmental damage is particularly significant, the regulator has an interest in preventing dirty firms from offshoring. Moreover, when the technological gap is sufficiently low and the marginal environmental damage is sufficiently large, the regulator has incentive to restrain clean firms from offshoring. Finally, if the government cares more about the economic activities than about consumers, it may be more willing to stop clean firms from offshoring.

The government's choice of a particular market structure also depends on the costs to reach this given market structure. The costs are in fact the subsidies given to a firm to affect

[5] The sufficient condition is given and studied in Appendix B.4.

its location decision. Hence, the means to implement the chosen market structure is related to the equilibrium conditions studied in Section 4. Indeed, one possibility is to impact the relocation costs of the dirty firm and the clean firm differently in order to obtain the desired market structure at equilibrium.

6 Discussion, policy implications and concluding remarks

Let us study first the counterpart of the offshoring, the reshoring, and discuss the robustness and the policy implications of our results.

The model we have used makes it possible to deal with reshoring, but to do so it is necessary to consider a fixed cost of reshoring (which is not the same as the cost of relocation previously considered) and that at least one mobile firm is located in the South. In other words, in such a case, the initial market structure would be market structures 2, 3 or 4. First of all, the effects of reshoring are opposite to those of offshoring. Reshoring only increases the northern consumer surplus if the transportation cost is relatively high, that is, if producing in the North is less expensive than exporting. Then, reshoring always increases the tax revenue, however, this increase can be higher or lower when a dirty firm relocates than when a clean firm relocates. As with offshoring, there are two opposite effects: a dirty firm produces less but pollutes more per unit produced. If the southern market size is sufficiently large as compared to the northern market size, the reshoring of a dirty firm increases emissions. Otherwise, the reshoring of a dirty firm decreases emissions. If the southern market size is sufficiently large as compared to the northern market size and if the emission intensity of the clean technology is sufficiently lower than the emission intensity of the dirty technology, the reshoring of a clean firm increases emissions. Otherwise, the reshoring of a clean firm decreases emissions. Emissions are lower when the dirty firm relocates to the North than when the clean firm relocates. Finally, if there is no industry in the North, reshoring necessarily increases the northern profits, and the profits are higher if a clean firm relocates to the North.

Let us now discuss the robustness of our results. Until now we have not taken into account the fact that technology property rights are less protected in the South than in the North. This makes it easier to copy and imitate a technology in the South than in the North. Therefore, offshoring can lead to technological spillovers, and the offshoring of a clean firm can induce an improvement in the technology of the southern dirty firm. The spillovers strengthen the competition in both markets. As a result, with offshoring, the northern consumers will be better off, the profits of the remaining firm in the North will be lower, and the North will lose even more tax revenue. Nevertheless, the effect of spillovers on the environment is ambiguous. Indeed, on the one hand, spillovers decrease the production and the emissions of both the relocated firm and the northern dirty firm, and on the other hand, increase the production of the former-dirty firm.

In this paper, we have assumed that the technology used by the firm is only defined by the emission intensity factor μ and that the production cost is country specific. However, we could relax this assumption by assuming that the firm's technology is defined by a couple emission intensity and production cost. If we assume that a clean firm produces at a higher cost, then northern firms will have less incentives to offshore, consumers will benefit less from relocation, and relocation will less reinforce competition.

So far, we have considered that a firm, which relocates, closes its production site in the North and opens a new site in the South. However, multinational companies from the North can open subsidiaries in the South. We assume as in Motta and Thisse (1994) that the home firm and its subsidiary only supply the good locally. If the subsidiary is created from scratch, our results are qualitatively unchanged and on each market there is always the same number of sellers. However, if the subsidiary is created by acquiring a dirty firm in the South, the new market structure will be more concentrated in the South and firms can exercise a higher market-power.

We have assumed the implementation of taxes on emissions. However, as we have seen previously, many countries use markets for rights to pollute. Assuming that the markets for permits are not connected, offshoring leads to a decrease in the demand for permits in the country of origin and an increase in the demand for permits in the country of arrival. In other words, offshoring would cause the price of permits to rise in the destination country and fall in the origin country. However, a clean firm would not have the same effect on permit prices as a dirty firm because they do not have the same demand for permits.

We considered that mobile firms decided simultaneously on their location at stage 1. Assuming that they play sequentially affects the results related to location (Section 4) but not those related to the effects of offshoring (Section 5). Indeed, only the equilibrium in Stage 1 of the game will be affected. A firm has an incentive to relocate first because the incentive to relocate as seen in Section 4 is weaker when the other mobile firm has already relocated. As a result, by relocating first, a firm may prevent the other firm from relocating (first move advantage). For a given offshoring cost, the Nash equilibrium could be that both relocate, while the Stackelberg equilibrium would be that only one firm relocates. Of course, sequential decisions prevent the possibility of multiple equilibria. Nevertheless, regardless of the equilibrium concepts used, as mentioned previously, the regulator is able to implement any market structure by using lump sum transfers.

So far we have studied the case of offshoring between the North and the South. We can use our model to discuss North-to-North offshoring. We must then assume that the production cost differential and the tax differential are both small or even zero. For the transport cost, this will depend on the good and the mode of transport chosen. For example, transporting a ton of cement from New York to Le Havre by sea is as costly as transporting a ton of cement from Le Havre to Paris by road. If we consider similar regions in terms of economic development, and thus in terms of technologies and policies, then firms will have an incentive to locate in the region with the largest market in order to save transportation costs.

The results, such as the relocation of a dirty firm as compared to the relocation of a clean firm is worse for the environment, better for northern consumers, and better for the domestic profits, are also robust with the presence of several dirty and several clean firms. Increasing the number of firms will of course qualitatively affect the results of the Section 4 but not those of Section 5. It will be more complicated to determine the location decisions of firms but the effect of offshoring will be qualitatively the same.

We can now turn our attention to the policy implications of our paper. In our model, the government is able to rank the different market structures and it may be willing to prevent relocations. As we have said, a first important constraint faced by governments is that countries are particularly indebted and that budgetary choices must be made. However, other constraints exist. In particular, governments face informational problems related to the environmental quality of a firm. In addition, institutional constraints limit the differentiation of treatment of firms.

An important result of our paper is that in order to act on market structures the regulator can introduce differentiated subsidies according to environmental quality. Treating firms differently is, however, a sensitive issue from both an acceptability and a legal point of view. From a legal point of view, in Europe, it is imperative to be able to demonstrate that such a solution is proportionate, satisfies the general interest and does not create barriers to market access for firms from other European countries. We can now turn our attention to the problems of identifying a clean firm and a dirty firm. For instance, Lyubich et al. (2018) and Barrows and Ollivier (2018) showed that by using private company data it was feasible to determine the CO2 footprint of firms in the same sector and to compare them. A solution for the government to solve this informational problem would be to propose a mechanism whereby firms would apply for a specific lump sum grant. This would require an environmental performance audit. This would require an environmental performance audit. If companies relocated all or part of their business over a certain period of time, they would have to repay this amount. Another possibility would be to offer such a mechanism for firms wishing to resettle their activities in their country of origin.

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Appendixes

A The productions and the prices at equilibrium

A.1 North: one clean firm - South: two dirty firms

The clean firm solves the following problem:

$$\max_{r^c_{NS}, r^c_{NN}} \pi^c_N = (p_S - c_N - \tau_N\,\mu^c - t)\, r^c_{NS} + (p_N - c_N - \tau_N\,\mu^c)\, r^c_{NN}. \tag{5}$$

Each dirty firm solves the following problem:

$$\max_{r^d_{SS_i}, r^d_{SN_i}} \pi^d_S = (p_S - c_S - \tau_S\,\mu^d)\, r^d_{SS_i} + (p_N - c_S - \tau_S\,\mu^d - t)\, r^d_{SN_i}. \tag{6}$$

The production levels are:

$$\begin{aligned}
r^{d_2}_{SN} &= \frac{a_N - 2\,c_S + \mu^c\,\tau_N - 2\,\mu^d\,\tau_S - 2\,t + c_N}{4}, \\
r^{c_2}_{NN} &= \frac{a_N - 3\,c_N + 2\,\mu^d\,\tau_S - 3\,\mu^c\,\tau_N + 2\,t + 2\,c_S}{4}, \\
r^{d_2}_{SS} &= \frac{a_S - 2\,c_S + \mu^c\,\tau_N - 2\,\mu^d\,\tau_S + t + c_N}{4}, \\
r^{c_2}_{NS} &= \frac{a_S - 3\,c_N + 2\,\mu^d\,\tau_S - 3\,\mu^c\,\tau_N - 3\,t + 2\,c_S}{4}.
\end{aligned}$$

A.2 North: one dirty firm - South: one dirty and one clean firm

The dirty firm in the North solves the following problem:

$$\max_{r^d_{NS}, r^d_{NN}} \pi^d_N = (p_S - c_N - \tau_N\,\mu^d - t)\, r^d_{NS} + (p_N - c_N - \tau_N\,\mu^d)\, r^d_{NN}. \tag{7}$$

The clean firm in the South solves the following problem:

$$\max_{r^c_{SS}, r^c_{SN}} \pi^c_S = (p_S - c_S - \tau_S\,\mu^c)\, r^c_{SS} + (p_N - c_S - \tau_S\,\mu^c - t)\, r^c_{SN}. \tag{8}$$

The dirty firm in the South solves the following problem:

$$\max_{r^d_{SS}, r^d_{SN}} \pi^d_S = (p_S - c_S - \tau_S\,\mu^d)\, r^d_{SS} + (p_N - c_S - \tau_S\,\mu^d - t)\, r^d_{SN}. \tag{9}$$

The production levels are:

$$r_{SS}^{c_3} = \frac{a_S - 2\,c_S + \mu^d\,\tau_N + \mu^d\,\tau_S - 3\,\mu^c\,\tau_S + t + c_N}{4},$$
$$r_{SS}^{d_3} = \frac{a_S - 2\,c_S + \mu^d\,\tau_N - 3\,\mu^d\,\tau_S + \mu^c\,\tau_S + t + c_N}{4},$$
$$r_{NS}^{d_3} = \frac{a_S - 3\,c_N + \mu^d\,\tau_S - 3\,\mu^d\,\tau_N + \mu^c\,\tau_S - 3\,t + 2\,c_S}{4},$$
$$r_{SN}^{c_3} = \frac{a_N - 2\,c_S + \mu^d\,\tau_N + \mu^d\,\tau_S - 3\,\mu^c\,\tau_S - 2\,t + c_N}{4},$$
$$r_{SN}^{d_3} = \frac{a_N - 2\,c_S + \mu^d\,\tau_N - 3\,\mu^d\,\tau_S + \mu^c\,\tau_S - 2\,t + c_N}{4},$$
$$r_{NN}^{d_3} = \frac{a_N - 3\,c_N + \mu^d\,\tau_S - 3\,\mu^d\,\tau_N + \mu^c\,\tau_S + 2\,t + 2\,c_S}{4}.$$

A.3 North: no firm - South: two dirty firms and one clean firm

The clean firm solves the following problem:

$$\max_{r_{SS}^c, r_{SN}^c} \pi_S^c = (p_S - c_S - \tau_S\,\mu^c)\,r_{SS}^c + (p_N - c_S - \tau_S\,\mu^c - t)\,r_{SN}^c. \tag{10}$$

The two dirty firms solve the following problem:

$$\max_{r_{SS_i}^d, r_{SN_i}^d} \pi_{S_i}^d = (p_S - c_S - \tau_S\,\mu^d)\,r_{SS_i}^d + (p_N - c_S - \tau_S\,\mu^d - t)\,r_{SN_i}^d. \tag{11}$$

The production levels are:

$$r_{SN}^{c_4} = \frac{a_N - c_S + 2\,\mu^d\,\tau_S - 3\,\mu^c\,\tau_S - t}{4},$$
$$r_{SN}^{d_4} = \frac{a_N - c_S + \mu^c\,\tau_S - 2\,\mu^d\,\tau_S - t}{4},$$
$$r_{SS}^{c_4} = \frac{a_S - c_S + 2\,\mu^d\,\tau_S - 3\,\mu^c\,\tau_S}{4},$$
$$r_{SS}^{d_4} = \frac{a_S - c_S + \mu^c\,\tau_S - 2\,\mu^d\,\tau_S}{4}.$$

B Proof of Propositions 1-5

To determine the effects of the offshoring:

- of a dirty firm, we have to compare market structure 1 to market structure 2.
- of a clean firm, we have to compare market structure 1 to market structure 3.
- of both firms, we have to compare market structure 1 to market structure 4.

To compare the relocation of a clean and a dirty firm, we have to compare market structure 2 to market structure 3.

B.1 Proof of Proposition 1

We compare the emissions generated by production:
$E_1^p - E_2^p = -\frac{\left(2\,\mu^d - \mu^c\right)\left(\mu^d\,\Delta_\tau + \Delta_c\right)}{2} < 0$, $E_1^p - E_4^p = -\frac{\left(3\,\mu^c\,\Delta_\mu - 2\,{\mu^d}^2\right)\Delta_\tau - 2\,\Delta_c\,\mu^c}{2} < 0$,
$E_2^p - E_3^p = \frac{\Delta_\mu\left(\left(2\,\mu^d + 3\,\mu^c\right)\Delta_\tau + 4\,\Delta_c\right)}{2} > 0$, $E_1^p - E_3^p = \frac{\left(2\,\mu^d - 3\,\mu^c\right)\left(\mu^c\,\Delta_\tau + \Delta_c\right)}{2}$ which is positive if $2\,\mu^d - 3\,\mu^c > 0$.
Note that $E_1^p - E_2^p = E_3^p - E_4^p$ and $E_1^p - E_3^p = E_2^p - E_4^p$

We compare the emissions generated by transportation:
$E_1^t - E_2^t = \frac{a_S - a_N - \Delta_\tau\,\mu^d - \Delta_c}{4}$, $E_1^t - E_3^t = \frac{a_S - a_N - \Delta_\tau\,\mu^c - \Delta_c}{4}$, $E_1^t - E_4^t = \frac{2\,(a_S - a_N) - 4\,t - \Delta_\tau\left(\mu^d + \mu^c\right) - 2\Delta_c}{4}$,
$E_2^t - E_3^t = \frac{\Delta_\tau\,\Delta_\mu}{4} > 0$.
Note that $E_2^t - E_4^t = \frac{a_S - a_N - 4\,t - \Delta_\tau\,\mu^c - \Delta_c}{4}$ and $E_3^t - E_4^t = \frac{a_S - a_N - 4\,t - \Delta_\tau\,\mu^d - \Delta_c}{4}$.

We compare global emissions:
$E_1^p + E_1^t - E_3^p - E_3^t = \frac{\left(2\left(2\,\mu^d - 3\,\mu^c\right) - \gamma\right)\left(\mu^c\,\Delta_\tau + \Delta_c\right) + \gamma\,(a_S - a_N)}{4}$
$E_1^p + E_1^t - E_2^p - E_2^t = \frac{\left(-2\left(2\,\mu^d - \mu^c\right) - \gamma\right)\left(\mu^d\,\Delta_\tau + \Delta_c\right) + \gamma\,(a_S - a_N)}{4}$
$E_1^p + E_1^t - E_4^p - E_4^t = \frac{\left(6\,\mu^c\,\Delta_\mu - 4\,{\mu^d}^2 - \left(\mu^d + \mu^c\right)\gamma\right)\Delta_\tau - 4\,t\,\gamma - 2\Delta_c(\gamma + 2\,\mu^c) + 2\,\gamma\,(a_S - a_N)}{4}$

B.2 Proof of Proposition 2

We compare prices according to the various market structures:
${p_N}^1 - {p_N}^2 = \frac{\mu^d\,\Delta_\tau - t + \Delta_c}{4}$, ${p_N}^1 - {p_N}^3 = \frac{\mu^c\,\Delta_\tau - t + \Delta_c}{4}$, ${p_N}^1 - {p_N}^4 = \frac{(\mu^d + \mu^c)\,\Delta_\tau - 2\,t + 2\,\Delta_c}{4}$,
${p_N}^2 - {p_N}^3 = -\frac{\Delta_\mu\,\Delta_\tau}{4} < 0$, ${p_S}^1 - {p_S}^2 = \frac{\mu^d\,\Delta_\tau + t + \Delta_c}{4} > 0$, ${p_S}^1 - {p_S}^3 = \frac{\mu^c\,\Delta_\tau + t + \Delta_c}{4} > 0$,
${p_S}^1 - {p_S}^4 = \frac{(\mu^d + \mu^c)\,\Delta_\tau + 2\,t + 2\,\Delta_c}{4} > 0$.
Note that ${p_l}^1 - {p_l}^2 = {p_l}^3 - {p_l}^4$ and ${p_l}^1 - {p_l}^3 = {p_l}^2 - {p_l}^4$ and ${p_N}^2 - {p_N}^3 = {p_S}^2 - {p_S}^3$

B.3 Proof of Proposition 3

$TR^1 - TR^2 = \mu^c\,r_N^{c_1} + \mu^d\,r_N^{d_1} - \mu^c\,r_N^{c_2} = \mu^c\,\left(r_N^{c_1} - r_N^{c_2}\right) + \mu^d\,r_N^{d_1}$.
$TR^1 - TR^3 = \mu^c\,r_N^{c_1} + \mu^d\,r_N^{d_1} - \mu^d\,r_N^{d_3} = \mu^c\,r_N^{c_1} + \mu^d\,\left(r_N^{d_1} - r_N^{d_3}\right)$
From $r_N^{c_1} - r_N^{c_2} = \frac{\mu^d\,\Delta_\tau + \Delta_c}{2} > 0$ and from $r_N^{d_1} - r_N^{d_3} = \frac{\mu^c\,\Delta_\tau + \Delta_c}{2} > 0$, offshoring, decreases tax revenue.
We now compare the difference in tax revenue if a dirty or a clean firm relocates to the South:
$TR^2 - TR^3 = \mu^c\,r_N^{c_2} - \mu^d\,r_N^{d_3}$.
Using, $r_{NN}^{c_2} - r_{NN^{d_3} = r_{NS}^{c_2} - r_{NS}^{d_3} = \Delta_\mu\,\mu_d}\,\frac{3\,\tau_N + \tau_S}{4}$,

$$TR^2 - TR^3 = -\Delta_\mu\,r_N^{c_2} + \Delta_\mu\,\mu_d\,\frac{3\,\tau_N + \tau_S}{4}$$

The LHS is a quantity effect: tax revenue decreases more when a clean firm relocates as it produces more. The RHS is an emission intensity effect: tax revenue decreases more when a dirty firm relocates as it pollutes more per unit. The quantity effect dominates when the market size is large.

$$TR^2 - TR^3 = \frac{\Delta_\mu \left(6\,\tau_N\,(\mu^d + \mu^c) - 2\,\mu^d\,\tau_S + t + 6\,c_N - 4\,c_S - a_N - a_S\right)}{4} \tag{12}$$

We study how this difference is affected by the parameters: $\frac{\partial\,(12)}{\partial\,t} = \frac{\Delta_\mu}{4}$; $\frac{\partial\,(12)}{\partial\,c_N} = \frac{3\,\Delta_\mu}{2}$; $\frac{\partial\,(12)}{\partial\,c_S} = -\Delta_\mu$; $\frac{\partial\,(12)}{\partial\,\tau_S} = -\frac{\mu^d\,\Delta_\mu}{2}$; $\frac{\partial\,(12)}{\partial\,a_N} = \frac{\partial\,(12)}{\partial\,a_S} = -\frac{\Delta_\mu}{4}$; $\frac{\partial\,(12)}{\partial\,\tau_N} = \frac{3\,\Delta_\mu\,(\mu^d+\mu^c)}{2}$.

Note that if only one firm is located in the North (market structures 2 and 3), if the firm relocates (market structure 4), tax revenue decreases and falls to zero.

B.4 Proof of Proposition 4

Let us first study the effect of the offshoring of a dirty firm:
The offshoring of a dirty firm decreases the northern profit if $\pi_N^1 = \pi_N^{c_1} + \pi_N^{d_1} > \pi_N^{c_2}$.

$$\pi_N^{c_1} - \pi_N^{c_2} = {r_{NN}^{c_1}}^2 - {r_{NN}^{c_2}}^2 + {r_{NS}^{c_1}}^2 - {r_{NS}^{c_2}}^2 = (r_{NN}^{c_1} - r_{NN}^{c_2})\,(r_{NN}^{c_1} + r_{NN}^{c_2}) + (r_{NS}^{c_1} - r_{NS}^{c_2})\,(r_{NS}^{c_1} + r_{NS}^{c_2})\,.$$

Using, $r_{NN}^{c_1} - r_{NN}^{c_2} = \frac{\mu^d\,\Delta_\tau + \Delta_c - t}{4}$ and $r_{NS}^{c_1} - r_{NS}^{c_2} = \frac{\mu^d\,\Delta_\tau + \Delta_c + t}{4}$, we obtain:

$$\pi_N^{c_1} - \pi_N^{c_2} = \frac{\mu^d\,\Delta_\tau + \Delta_c}{4}\,(r_{NN}^{c_1} + r_{NN}^{c_2} + r_{NS}^{c_1} + r_{NS}^{c_2}) + \frac{t}{4}\,(r_{NS}^{c_1} + r_{NS}^{c_2} - r_{NN}^{c_1} - r_{NN}^{c_2})\,.$$

Since $r_{NS}^{c_1} + r_{NS}^{c_2} - r_{NN}^{c_1} - r_{NN}^{c_2} = \frac{a_S - a_N - 4\,t}{2}$, if $a_N < a_S - 4\,t$, the northern profits decrease with offshoring. If $a_N > a_S - 4\,t$, the northern profits may increase with offshoring (necessary but not sufficient condition). It only increases if the following equation is negative:

$$\begin{aligned}\pi_N^{c_1} - \pi_N^{c_2} = {} & \frac{\left(\mu^d\,\Delta_\tau + \Delta_c\right)\,\left(\mu^d\,\tau_N - 6\,\mu^c\,\tau_N + 3\,\mu^d\,\tau_S - t - 5\,c_N + 3\,c_S + a_N + a_S\right)}{8} \\ & - \frac{t^2}{2} + \frac{(a_S - a_N)\,t}{8}\end{aligned} \tag{13}$$

$\frac{\partial\,(13)}{\partial\,a_N} = \mu^c\,\Delta_\tau + \Delta_c - t$; $\frac{\partial\,(13)}{\partial\,a_S} = \mu^c\,\Delta_\tau + \Delta_c + t$; $\frac{\partial\,(13)}{\partial\,t} = -\frac{\mu^c\,\Delta_\tau + \Delta_c + a_N - a_S + 8\,t}{8}$.

Let us now study the effect of the offshoring of a clean firm:
The offshoring of a clean firm decreases the northern profit if $\pi_N^1 = \pi_N^{c_1} + \pi_N^{d_1} > \pi_N^{d_3}$.

$$\pi_N^{d_1} - \pi_N^{d_3} = {r_{NN}^{d_1}}^2 - {r_{NN}^{d_3}}^2 + {r_{NS}^{d_1}}^2 - {r_{NS}^{d_3}}^2 = \left(r_{NN}^{d_1} - r_{NN}^{d_3}\right)\,\left(r_{NN}^{d_1} + r_{NN}^{d_3}\right) + \left(r_{NS}^{d_1} - r_{NS}^{d_3}\right)\,\left(r_{NS}^{d_1} + r_{NS}^{d_3}\right).$$

Using, $r_{NN}^{d_1} - r_{NN}^{d_3} = \frac{\mu^c\,\Delta_\tau + \Delta_c - t}{4}$ and $r_{NS}^{d_1} - r_{NS}^{d_3} = \frac{\mu^c\,\Delta_\tau + \Delta_c + t}{4}$, we obtain:

$$\pi_N^{d_1} - \pi_N^{d_3} = \frac{\mu^c\,\Delta_\tau + \Delta_c}{4}\,\left(r_{NN}^{d_1} + r_{NN}^{d_3} + r_{NS}^{d_1} + r_{NS}^{d_3}\right) + \frac{t}{4}\,\left(r_{NS}^{d_1} + r_{NS}^{d_3} - r_{NN}^{d_1} - r_{NN}^{d_3}\right).$$

Since $r_{NS}^{d_1} + r_{NS}^{d_3} - r_{NN}^{d_1} - r_{NN}^{d_3} = \frac{a_S - a_N - 4\,t}{2}$, if $a_N < a_S - 4\,t$, the northern profits decrease with offshoring. If $a_N > a_S - 4\,t$, the northern profits may increase with offshoring (necessary but not sufficient condition). It only increases if the following equation is negative:

$$\pi_N^{d_1} - \pi_N^{d_3} = \frac{\left(\mu^c\,\Delta_\tau + \Delta_c\right)\,\left(\mu^c\,\tau_N - 6\mu^d\,\tau_N + 2\,\mu^d\,\tau_N + \mu^c\,\tau_N - t - 5\,c_N + 3\,c_S + a_N + a_S\right)}{8} - \frac{t^2}{2} + \frac{\left(a_S - a_N\right)\,t}{8} \tag{14}$$

$\frac{\partial\,(14)}{\partial\,a_N} = \mu^c\,\Delta_\tau + \Delta_c - t$; $\frac{\partial\,(14)}{\partial\,a_S} = \mu^c\,\Delta_\tau + \Delta_c + t$; $\frac{\partial\,(14)}{\partial\,t} = -\frac{\mu^c\,\Delta_\tau + \Delta_c + a_N - a_S + 8\,t}{8}$.

Let us now compare the offshoring of a clean firm to the offshoring of a dirty firm in terms of northern profits:

$$\pi_N^{c_2} - \pi_N^{d_3} = {r_{NN}^{c_2}}^2 - {r_{NN}^{d_3}}^2 + {r_{NS}^{c_2}}^2 - {r_{NS}^{d_3}}^2 = \left(r_{NN}^{c_2} - r_{NN}^{d_3}\right)\,\left(r_{NN}^{c_2} + r_{NN}^{d_3}\right) + \left(r_{NS}^{c_2} - r_{NS}^{d_3}\right)\,\left(r_{NS}^{c_2} + r_{NS}^{d_3}\right)$$

which is strictly positive from $r_{NN}^{c_2} - r_{NN}^{d_3} = r_{NS}^{c_2} - r_{NS}^{d_3} = \frac{\Delta_\mu\,(3\,\tau_N + \tau_S)}{4}$.

It is clear if there is only one firm located in the North (market structures 2 and 3), if the firm relocates (market structure 4), northern profit decreases and falls to zero.