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School of Business & Economics
Discussion Paper
Economics
2016/25

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Abstract

The allocation of free allowances for firms belonging to the carbon leakage list of the European Union Emissions Trading Scheme (EU ETS) was found to lead to substantial overcompensation, which is why some stakeholders recently have called for a phasing out of free allowances in the near term. This paper analyzes the consequences of phasing out free allowances in a dynamic two-period model when one group of countries unilaterally implements climate policies such as an emissions trading scheme. A carbon price induces firms to invest in abatement capital, but may also lead to the relocation of some firms. The social planner addresses the relocation problem by offering firms transfers, i.e. free allowances, conditional on maintaining the production in the regulating country.

If transfers are unrestricted in both periods, then the social planner can implement the first best by setting the carbon price equal to the marginal environmental damage and using transfers to prevent any relocation. However, if transfers in the future period are restricted, it is optimal to implement a declining carbon price path with the first period price exceeding the marginal environmental damage. A high carbon price triggers investments in abatement capital and thus creates a lock-in effect. With a larger abatement capital stock, firms are less affected by carbon prices in the future and therefore less prone to relocate in the second period where transfers are restricted.

Keywords: unilateral climate policy, relocation, lock-in effect, rebating
JEL Classification Numbers: Q54, Q56, Q58, H23.

*I thank Clemens Hetschko, Fabian Lange, Robert Schmidt, Ronnie Schöb, Mark Schopf, Roland Strausz and participants of the AURÖ workshop 2015 in Hamburg, the research seminar at Fudan University in Shanghai, the EAERE 2015 conference in Helsinki, the IIPF 2015 conference in Dublin and the FiWi workshop 2016 in Berlin for helpful comments and suggestions. I am grateful for the financial assistance of the Research Training Group 1659.

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1. Introduction

In a globalized world with mobile capital, unilateral climate policy by a group of countries may have adverse effects known as carbon leakage. As the pricing of carbon dioxide (CO_2) raises the production costs of firms in the cooperating countries, these firms lose competitiveness relative to their foreign competitors and may relocate to countries with laxer environmental regulations. The relocation involves severe welfare losses to the regulating countries and is associated with a loss of employment, which is why the design of climate policy should account for the relocation problem.

In practice, several instruments have been implemented to address the adverse effects of unilateral climate policy out of which the allocation of free emission allowances is the most prominent one. For instance, the European Union Emissions Trading System (EU ETS), the largest trading scheme for CO_2 emission allowances in the world, allocates a specified amount of allowances free of charge to firms that are deemed to be exposed to relocation. However, Martin et al. (2014) find that the current practice leads to windfall profits and substantial overcompensation for the regulated firms. That is why some stakeholders have called for a phasing out of free allowances at the latest stakeholder consultation of the EU.[1] This paper analyzes in a stylized dynamic model the consequences of free allowances to be phased out in the near term and derives the implications for the optimal inter-temporal carbon price structure.

At the 21st meeting of the Conference of the Parties in December 2015 in Paris, the representatives of 195 countries agreed on a worldwide treaty that aims to reduce CO_2 emissions substantially as suggested by the IPCC (2014). In particular, the Paris Agreement calls for 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (UNFCCC 2015: Art. 2a). In order to achieve this worldwide goal, each country individually has put forward its emissions reduction target known as nationally determined contribution (NDC). However, according to Jeffery et al. (2015), these pledges vary substantially across countries. While only 5 out of 32 analyzed countries made pledges that are in line with the 2°C target, the pledges of 16 countries are rated as inadequate, meaning that global warming is likely to exceed 3-4°C if all governments had committed to similar efforts. When implementing the NDCs by national policies, it can be expected that the heterogeneity of efforts translates into dif-

[1] During the stakeholder consultation regarding the carbon leakage list organized by the EU in 2014, 61 % of civil stakeholders consider the allocation of free allowances as problematic. In particular, environmental NGOs such as Climate Action Network, Greenpeace and Worldwide Fund for Nature would like to replace free allowances by full auctioning in the next trading period.

ferent carbon prices across countries, implying the relocation problem to persist despite the Paris Agreement.

In the EU ETS, the major instrument to address relocation is the allocation of free allowances. Allocating allowances free of charge attenuates the negative impact of carbon pricing on firms' profits, reducing the incentive to relocate. In the third trading phase from 2013 to 2020, the EU ETS switched from allocating free allowances according to historical emissions (grandfathering) to output-based allocation (benchmarking according to best-available technology), where firms get a specified share of a sector-specific benchmark. The benchmark reflects the emissions of the 90% most efficient installation within each sub-sector that is necessary to produce one unit of the respective final good. While in 2013, firms got 80% of this benchmark, this share is going to drop to zero by 2027.[2]

The EU ETS addresses carbon leakage explicitly by the carbon leakage list which includes 'energy-intensive sectors or sub-sectors that have been determined to be exposed to significant risks of carbon leakage' (EU 2009: Directive 2009/29/EC, Article 10b, 1). Sectors qualify for this list if the EU ETS raises the production costs by at least 5% *and* if the trade intensity with third countries exceeds 10%.[3] In addition, sectors belong to the carbon leakage list when either the production costs increase by more than 30% due to the EU ETS or the trade intensity is above 30%.[4] The carbon leakage list is to be updated every five years starting in 2009.[5] In contrast to all other firms, firms in sectors belonging to the carbon leakage list receive 100% of the benchmark emissions free of charge until the end of the third phase in 2020.[6] There is an ongoing debate concerning the rules applying for these sectors beyond 2020. While representatives of the industry have expressed their wish to continue the allocation free of charge in a first stakeholder meeting, the majority of civil society respondents prefers phasing out or restricting the amount of free allowances.[7] This paper contrasts both scenarios and derives implications for the optimal carbon price path.

The research question has been partially addressed in the scientific literature by Mæstad (2001) and Schmidt and Heitzig (2014). Mæstad (2001) derives the optimal levels of a set of policy instruments, which includes import tariffs, emissions taxes and local-

[2]EU (2009): Directive 2009/29/EC, Article 10a, 11.
[3]Ibid, Article 10a, 15.
[4]Ibid, Article 10a, 16.
[5]Ibid, Article 10a, 13.
[6]Ibid, Article 10a, 12.
[7]In the first stakeholder consultation 'some 29% of civil society respondents expressed their preference for no more free allocation after 2020, while 25% believe the share of allowances dedicated to carbon leakage and competitiveness should be lower than in 2013-2020' (EC 2014, p.9).

ization subsidies (formally equivalent to free allowances) when firms may relocate to a non-regulating country. Schmidt and Heitzig (2014) show in a dynamic setting that the temporary allocation of free allowances is sufficient to induce firms to produce in the regulating country permanently. While Mæstad (2001) uses a static setting, Schmidt and Heitzig (2014) focus on the analysis of the cost-minimal inter-temporal allocation of free allowances for a given carbon price. The present paper fills in the research gap by analyzing the implications for the optimal climate policy in a dynamic setting when free allowances may or may not be restricted in the future.

In a two-period model with two countries, one country unilaterally implements carbon prices in both periods to account for the damage from global warming. Carbon pricing induces domestic firms to invest in abatement capital at the beginning of the first period to reduce their actual emissions. However, in order to avoid carbon pricing, some firms may relocate to the other country before or after the first period at a fixed and firm specific relocation cost. The social planner addresses the relocation problem by a second policy instrument, namely by offering transfers, i.e. free allowances, to the firms contingent on the firm producing in the regulating country in the respective period. Depending on the carbon prices and transfers in the two periods, firms choose the profit maximizing location plan already at the beginning of the first period, meaning that firms choose to either relocate immediately, after the first period or never.

If transfers are unrestricted in both periods, then the social planner can implement the first best by setting carbon prices equal to the marginal environmental damage and averting relocation entirely through transfer payments. This is equivalent to the result of Mæstad (2001) in a static setting.

When the regulator has committed to restrict the allocation of free allowances in the second period, the first best may not be feasible anymore. In the second best, the social planner can avert any immediate relocation by offering sufficiently high first period transfers. However, this entices some firms to play a 'take the money and run'-strategy, collecting transfers in the first period, but relocating thereafter. In order to prevent delayed relocation, the social planner increases the first period carbon price above the marginal environmental damage. This induces firms to invest more in abatement capital, thereby creating a lock-in effect. A high abatement capital stock attenuates the negative impact of the carbon price in the future on firms' profits, making relocation less likely. Thus, by raising the first period carbon price above and lowering the second period price below the marginal environmental damage, the social planner increases the number of firms that permanently produce in the regulating country.

1.1. Related literature

The relocation problem forms one part of the literature on the strategic location decision of firms under asymmetric environmental regulation between countries known as the pollution haven effect (Copeland and Taylor (1994)).[8] While Brunnermeier and Levinson (2004) report that most papers in the empirical literature find no evidence for the pollution haven effect, more recent papers, that use more advanced estimation techniques and data sets, find some - though small - evidence (Xing and Kolstad (2002), List et al. (2003), Kellenberg (2009), Dong et al. (2012) and Naughton (2014)), concluding that unilateral environmental regulation shifts investment flows abroad. For the EU ETS, Martin et al. (2014) explicitly analyze the effect of allocating free allowances on relocation. Theoretically, efficient allocation of allowances requires the marginal relocation risk weighted by the damage of relocation to be equal across all firms. Using firm-level data that allows for eliciting the marginal relocation propensity of firms under the EU ETS, Martin et al. (2014) find that the current allocation of permits results in substantial overcompensation, which serves as the major argument to phase out the allocation of free allowances.

The theoretical literature on endogenous plant location can be broadly separated into three strands. While the first strand deals with the strategic interaction of governments when determining environmental regulation (Markusen et al. (1995), Rauscher (1995), Hoel (1997), Ulph and Valentini (2001) and Greaker (2003)), the second strand analyzes the impact of environmental regulation on the location decision of the firm (Motta and Thisse (1994), Ulph and Valentini (1997)). This paper is related to the third strand, that normatively derives the optimal level of a predetermined set of policy instruments (Markusen et al. (1993), Hoel (1996), Petrakis and Xepapadeas (2003), Pollrich and Schmidt (2014) and Ikefuji et al. (2015)). The papers closest to the present one are Mæstad (2001) and Schmidt and Heitzig (2014).

In a static setting with two countries, Mæstad (2001) analyzes three policy instruments, namely an import tariff or export subsidy on the final good, an emissions tax and a localization subsidy. He shows that the welfare maximum requires the emissions tax to be equal to the marginal environmental damage, the import tariff to be set such that the marginal social costs of production are equalized across both countries and the localization subsidy to be positive. Without taking import tariffs into consideration, the present paper derives the same result in a dynamic setting when localization subsidies

[8] Taylor (2005) distinguishes between the pollution haven effect according to which tightening environmental standards leads to a shift of investments towards countries with laxer environmental regulation and the pollution haven hypothesis where abolishing trade barriers causes the shift of capital flows.

or transfers are unrestricted in the future. In an extension, Mæstad (2001) derives the optimal emissions tax in the absence of transfers and finds that this tax should be below the marginal environmental damage. This reflects the trade-off between the relocation of some firms and the distortion of the abatement decisions of the remaining firms, which is also found in this paper. In contrast to his static setting, the present paper uses a dynamic model which allows for deriving the optimal tax and transfer levels when transfer, i.e. free allowances, are not phased out immediately, but in the middle term.

Schmidt and Heitzig (2014) use a dynamic model with infinite time horizon and show that also temporary grandfathering schemes can avert the relocation of one firm permanently. While the carbon price triggers investments in abatement capital, free allowances prevent instantaneous relocation. For a fixed carbon price, the social planner averts the relocation of the firm for a sufficiently long time horizon by allocating free allowances. This increases the investment in abatement capital and creates a lock-in effect. Thus, the firm will also not relocate in the long run after the provision of free permits has ceased because a large abatement capital stock reduces the negative impact of carbon pricing on the firm's profit. While Schmidt and Heitzig (2014) focus on the cost minimal inter-temporal allocation of free allowances to avert the relocation of the firm for a given carbon price, the present paper normatively derives the optimal dynamic carbon prices and transfers when free allowances may or may not be phased out in the future. In addition, Schmidt and Heitzig (2014) analyze a one-firm setting. This does not allow for identifying the basic trade-off of the present paper, i.e. the trade-off between the relocation of some firms and the efficiency of the abatement decisions of the remaining firms.

The remainder of the paper is organized as follows. Section 2 describes the model and presents the objective functions of the firms and the social planner. Section 3 contrasts the case where free allowances are available in both periods to the case of phasing out free allowances in the second period and derives the optimal carbon prices for both cases. Section 4 extends the model by introducing a budget constraint for the government. Finally, Section 5 concludes and discusses the results.

2. The model

In a deterministic two-period model with two countries A and B, country A introduces a carbon price while country B does not. The model abstracts from discounting within and between the periods, setting the discount factor equal to one. All consumers permanently reside in country A and all firms are initially located in country A, but may relocate to country B. There is neither market entry nor market exit. In each period, each firm produces one unit of the final good whose price is normalized to 1.[9] The production of the good causes baseline emissions $\bar{\epsilon}$. Firms can reduce their actual emissions by short-term abatement as well as investments in abatement capital. Short-term abatement, e.g. the use of less carbon-intensive, but costlier fossil fuels, reduces emissions by the amount q in the respective period and is associated with time-invariant abatement costs $\gamma(q)$ with $\gamma'(q) > 0$ and $\gamma''(q) > 0$.[10] Investments in abatement capital take place before period 1 and include the adoption of less carbon-intensive production technologies that reduce actual emissions by the amount k in *both* periods. Investment costs $\kappa(k)$ are assumed to be convex with $\kappa'(k) > 0$ and $\kappa''(k) > 0$. Moreover, the investment cannot be transferred to country B when a firm relocates after having invested.[11] Short-term abatement and investments in abatement capital are assumed to be independent of each other, i.e. they are additively separable. Finally, it is assumed that $\gamma'(0) = 0$ and $\kappa'(0) = 0$ to avoid corner solutions and that baseline emissions are sufficiently large such that actual emissions $\bar{\epsilon} - q - k$ are always positive.[12]

Firms may evade carbon pricing by relocating to country B, which causes relocation costs θ. The cost parameter θ reflects the investments necessary to install the production capacities in country B. Since those investments vary across different industries, firms are assumed to be heterogeneous with respect to θ with $\theta \sim UNI[\underline{\theta}, \overline{\theta}]$. While the parameter θ is private information of the firm, the regulator knows the distribution of θ.

Since θ is private information, the regulator makes use of uniform policy instruments. These instruments include carbon prices in the first and second period (p and P)[13] and transfers (or localization subsidies) g and G that are conditional on the firm operating in country A. Amundsen and Schöb (1999) show that there is a one to one relationship between carbon taxes and caps in a cap-and-trade system, provided that firms are not

[9]Implicitly, each firm is a monopolist, facing an inverse demand function that is a step function, where the price equals 1 up to the quantity of 1 and drops to 0 afterward. By assuming this, it can be abstracted from any loss of competitiveness due to carbon taxation, which allows for focusing on the interaction between relocation and carbon pricing.

[10]In the following, $f'(\cdot)$ and $f''(\cdot)$ denote the first and second derivative of the function $f(\cdot)$ with respect to its argument.

[11]This assumption is not crucial for the results, but makes the subsequent analysis more tractable. Implicitly, it is assumed that the new technology cannot be transferred to country B at zero costs, implying the relocating firm to have no incentive to install the more efficient technology in country B.

[12]If actual emissions were negative, firms would benefit from carbon pricing and thus would never relocate to country B. Alternatively, I could assume that $\lim_{q \to (1/2)\bar{\epsilon}} \gamma'(q) = \infty$ and $\lim_{k \to (1/2)\bar{\epsilon}} \kappa'(k) = \infty$ in order to guarantee actual emissions to be positive.

[13]In the following, lower case letters always refer to variables in the first and capital letters to variables in the second period.

allowed to bank or borrow emission allowances between the periods.[14] Since all firms are assumed to produce exactly one unit of the final good, uniform lump-sum transfers are equivalent to allocating free allowances based on the best available technology standard in a cap-and-trade system.[15] In the analysis of Section 3, transfers are assumed to be unlimited while the government must respect a budget constraint in Section 4. The regulator determines all policy variables at the beginning of the first period and is assumed to be able to fully commit to them.

The model consists of two stages. In the first stage, the regulator sets the levels of all current and future policy instruments, whereas in the second stage, the firms simultaneously determine their abatement and location decisions. The model is solved by backwards induction.

2.1. Decisions of the firms

Depending on the policy instruments and the relocation cost parameter θ, firms either relocate never (AA), relocate later (AB) or relocate immediately (BB).[16] The respective profits for both periods read

$$\pi_{AA}(p,g,P,G,k,q,Q) = 1 - p\cdot(\bar{\epsilon}-k-q) - \kappa(k) - \gamma(q) + g + 1 - P\cdot(\bar{\epsilon}-k-Q) - \gamma(Q) + G \tag{1}$$

$$\pi_{AB}(p,g,k,q,\theta) = 1 - p\cdot(\bar{\epsilon}-k-q) - \kappa(k) - \gamma(q) + g + 1 - \theta \tag{2}$$

$$\pi_{BB}(\theta) = 1 - \theta + 1 \tag{3}$$

where 1 denotes the revenue of the firm from selling the good in each period. While AA-firms face carbon prices in both periods, AB-firms do so only in period 1 and relocate thereafter. For a given location plan, firms maximize their profits with respect to the short-term abatement, and the first-order conditions (FOC)s are given by

[14]If banking and borrowing was allowed, then carbon prices would equalize across the periods due to the arbitrage of firms, preventing the regulator from differentiating carbon prices across periods by setting the caps accordingly.

[15]In principle, the regulator may prevent firms from relocating by implementing an import tariff based on the carbon content of the final good. However, since this option requires to determine the carbon content of each final good, it seems to be hardly feasible to put into practice, which is why this model abstracts from the use of border carbon adjustment. In addition, there is an ongoing debate which questions the compatibility of border carbon adjustments with WTO law. See e.g. Fischer and Fox (2012).

[16]Relocation is assumed to be once and for all so that the location plan BA is excluded.

$$\begin{aligned}\frac{\partial \pi_{AA}(\cdot)}{\partial q} =& p - \gamma'(q) \overset{!}{=} 0 && (4)\\ \frac{\partial \pi_{AB}(\cdot)}{\partial q} =& p - \gamma'(q) \overset{!}{=} 0 && (5)\\ \frac{\partial \pi_{AA}(\cdot)}{\partial Q} =& P - \gamma'(Q) \overset{!}{=} 0. && (6)\end{aligned}$$

Firms choose their short-term abatement such that the marginal abatement costs equal the carbon price. The FOCs (4), (5) and (6) implicitly define the optimal short-term abatement quantities $q^*_{AA}(p) = q^*_{AB}(p) > 0$ as well as $Q^*_{AA}(P) > 0$ for strictly positive carbon taxes, where all quantities increase in their arguments.[17]Depending on the location plan, the FOCs for the investment in abatement capital read

$$\begin{aligned}\frac{\partial \pi_{AA}(\cdot)}{\partial k} =& p + P - \kappa'(k) \overset{!}{=} 0 && (7)\\ \frac{\partial \pi_{AB}(\cdot)}{\partial k} =& p - \kappa'(k) \overset{!}{=} 0. && (8)\end{aligned}$$

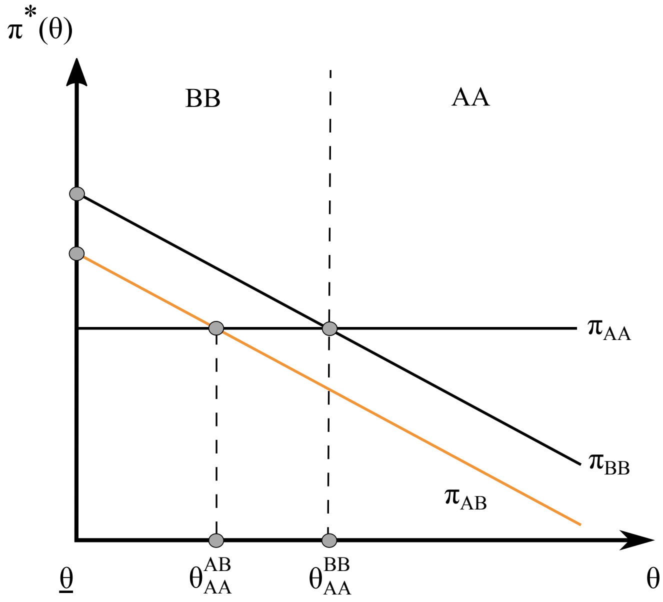
Equations (7) and (8) implicitly define the abatement capital stocks $k^*_{AB}(p) > 0$ and $k^*_{AA}(p + P) \geq k^*_{AB}(p)$ with strict inequality for $P > 0$. The capital stocks of both firm types are increasing in the carbon prices.[18] Even though an AB-firm plans to relocate after the first period, it invests some amount in abatement capital, thereby optimally responding to the first period carbon price. However, the investments of AA-firms are higher since they face the carbon price also in the second period. Note that for the investment decision of AA-firms, only the sum of the carbon prices over both periods is relevant, implying p and P to be perfect substitutes in triggering abatement capital investments.

Plugging $q^*_{AB}(p)$, $q^*_{AA}(p)$, $Q^*_{AA}(P)$ as well as $k^*_{AB}(p)$ and $k^*_{AA}(p+P)$ into equations (1) and (2) yields $\pi^*_{AA}(p, g, P, G)$ and $\pi^*_{AB}(p, g, \theta)$, which only depend on the heterogeneity parameter θ and the policy instruments. From equations (1) and (3) it follows immediately that $\pi^*_{AA}(p = 0, g = 0, P = 0, G = 0) \geq \pi_{BB}(\theta)$, meaning that firms keep producing permanently in country A in the absence of any climate policy. Otherwise, they would already have relocated before. Figure 1 depicts the profits of the firms with different location plans depending on their relocation costs θ for $g = G = 0$ and $p = P > 0$.

[17]Using the implicit functions theorem leads to $q^*_{AA}{}'(p) = q^*_{AB}{}'(p) = 1/\gamma''(q) > 0$ and $Q^*_{AA}{}'(P) = 1/\gamma''(Q) > 0$.

[18]Using the implicit functions theorem yields $k^*_{AB}{}'(p) = 1/\kappa''(k) > 0$ and $k^*_{AA}{}'(p + P) = 1/\kappa''(k) > 0$.

Figure 1: Profits of firms without transfers



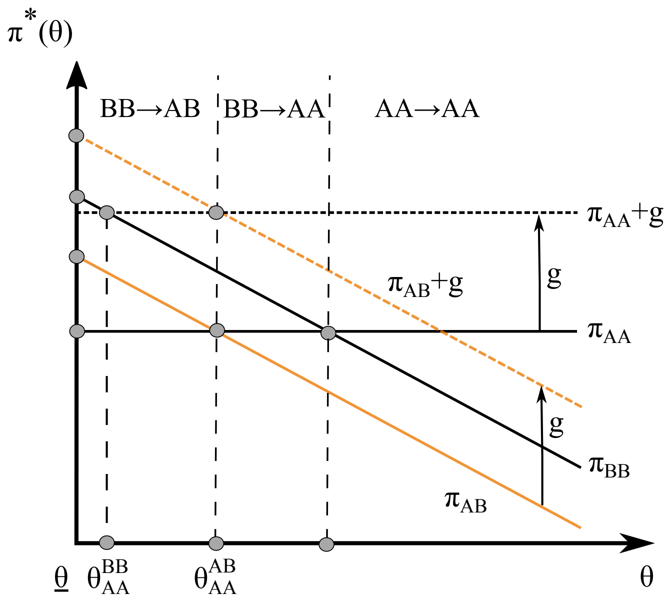
For positive carbon prices and low relocation costs ($\underline{\theta}$), the profit of BB-firms is the highest. However, this profit is declining in the relocation costs. Relative to BB-firms, the profit line of AB-firms is a parallel shift downwards because they incur the same relocation costs, but face carbon costs in the first period. The profit line of AA-firms is a horizontal line because they do not incur any relocation costs.

Firms choose the location plan which yields the highest profit. In Figure 1, all firms with $\theta \in [\underline{\theta}; \theta_{AA}^{BB})$ relocate immediately while all firms with $\theta \geq \theta_{AA}^{BB}$ produce permanently in country A.

The profit lines of AA- and AB-firms depend on the policy instruments. The policy instruments of the second period only affect the profits of AA-firms, i.e. their profit line shifts upwards when G increases or P decreases, implying the number of AA-firms to rise. Increasing p reduces the profits of both AA- and AB-firms. Higher transfers g shift both profit lines upwards by the same amount. This situation is depicted in Figure 2.

In Figure 2, increasing g induces some firms to switch from location plan BB to location plan AA so that all firms with $\theta \geq \theta_{AA}^{AB}$ prefer location plan AA. However, firms with $\theta \in [\underline{\theta}, \theta_{AA}^{AB}]$ relocate after the first period and are thus pursuing a 'take the money and run'-strategy. They benefit from transfers in the first period but relocate thereafter. Thus, first period transfers only induce firms to keep producing permanently

Figure 2: Profits of firms with positive transfers



in country A up to a certain point. Beyond this point, any further increase of g does not augment the number of AA-firms, but only replaces BB-firms by AB-firms. The indifference points θ_{AA}^{AB} and θ_{AA}^{BB} are given by

$$\theta_{AA}^{AB}(p,P,G) = p \cdot (k_{AB}^*(p) - k_{AA}^*(p+P)) - (\kappa(k_{AB}^*(p)) - \kappa(k_{AA}^*(p+P))) + \quad (9)$$
$$P \cdot (\bar{\epsilon} - Q_{AA}^*(P) - k_{AA}^*(p+P)) + \gamma(Q_{AA}^*(P)) + G$$
$$\theta_{AA}^{BB}(p,g,P,G) = p \cdot (\bar{\epsilon} - q_{AA}^*(p) - k_{AA}^*(p+P)) + \gamma(q_{AA}^*(p)) + \kappa(k_{AA}^*(p+P)) + g +$$
$$P \cdot (\bar{\epsilon} - Q_{AA}^*(P) - k_{AA}^*(p+P)) + \gamma(Q_{AA}^*(P)) + G. \quad (10)$$

Note that $\theta_{AA}^{AB}(p,P,G)$ does not depend on g because the first period transfer affects the profits of AA- and AB-firms by the same amount. Table 1 summarizes the properties of the indifference points by reporting the signs of the partial derivatives with respect to the policy instruments.

Table 1: Properties of Indifference Points

Indifference point	Condition	$\partial\theta(\cdot)/\partial p$	$\partial\theta(\cdot)/\partial g$	$\partial\theta(\cdot)/\partial P$	$\partial\theta(\cdot)/\partial G$
$\theta_{AA}^{AB}(p, P, G)$	$\pi_{AA}(\cdot) = \pi_{AB}(\cdot)$	-	0	+	-
$\theta_{AA}^{BB}(p, g, P, G)$	$\pi_{AA}(\cdot) = \pi_{BB}(\cdot)$	+	-	+	-

Note that, for instance, $\partial\theta_{AA}^{AB}(\cdot)/\partial p = k_{AB}^{*}(\cdot) - k_{AA}^{*}(\cdot) < 0$ implies the number of AA-firms to be increasing in p.

2.2. Social welfare

Welfare is based on the national concept of country A and is the sum of consumer surplus, producer surplus, environmental damage and the government budget. Since the price and quantity of the final good is constant, the consumer surplus is also constant and can be normalized to zero. The producer surplus is given by the profits of the firms, which are assumed to be entirely owned by citizens living in country A. Hence, carbon taxes cannot be used as an instrument to expropriate foreign firm owners.[19] Moreover, the model abstracts from any welfare losses that may arise due to the loss of jobs when firms relocate. Relaxing the ownership assumption or introducing welfare costs due to unemployment would only strengthen the results of this paper. Emissions are assumed to be a global public bad and a stock pollutant with constant marginal environmental damage ψ.[20] For simplicity, it is assumed that the damage occurs only in the long term, meaning in the second period, which adequately reflects the basic characteristics of global warming. Relaxing this assumption or assuming increasing instead of constant marginal environmental damages would not alter the qualitative results of this paper, but would complicate the analysis unnecessarily. Finally, the government budget consists of tax revenues minus transfers made to the firms, where both are assumed to be welfare-neutral.

[19] When firms are (partially) owned by foreigners, Hoel (1997) shows that carbon taxes imply a transfer from the foreign firm owners to the government or local residents. Hence, in the presence of foreign firm ownership, we would expect carbon taxes to be higher than in this model.

[20] The parameter ψ can also be interpreted as political shadow price that the citizens of the home country accept for a marginal increase of emissions.

The welfare contribution of firms depends on their location plan. For the three firm types, the contributions are given by

$$\begin{aligned} W_{AA}(p,P) =& 2-\kappa(k^*_{AA}(p+P))-\gamma(q^*_{AA}(p))-\gamma(Q^*_{AA}(P)) \\ &-\psi\cdot(2\bar{\epsilon}-2k^*_{AA}(p+P)-q^*_{AA}(p)-Q^*_{AA}(P)) \end{aligned} \tag{11}$$

$$W_{AB}(p,\theta) = 2-\kappa(k^*_{AB}(p))-\gamma(q^*_{AB}(p))-\theta-\psi\cdot(2\bar{\epsilon}-k^*_{AB}(p)-q^*_{AA}(p)) \tag{12}$$

$$W_{BB}(\theta) = 2-\theta-2\psi\bar{\epsilon}. \tag{13}$$

where tax payments and transfers have canceled out. Hence, the welfare contribution consists of the firms' revenue, the abatement costs, the relocation costs and the environmental damage. As long as the marginal abatement costs are below the marginal environmental damage, i.e. as long as $p \leq \psi$ and $P \leq \psi$, there is a clear welfare ranking of firms, that is $W_{AA}(p,P) > W_{AB}(p,\theta) > W_{BB}(\theta)$.[21] However, for a sufficiently large p (or P), this welfare ranking may alter because too high carbon prices distort the abatement decision, leading to inefficiently high abatement levels. Relative to both other types, AA-firms are more valuable in welfare terms because they put more effort in internalizing the environmental damage and do not incur relocation costs. While both AB- and BB-firms bear relocation costs, AB-firms internalize some of the environmental damage at least in the first period, implying their welfare contribution to be higher than that of BB-firms as long as they do not abate too much.

For the aggregated welfare, it must be distinguished between three cases. In the first case, there is no relocation, meaning that there are only AA-firms, in the second case, there are only AA- and BB-firms as depicted in Figure 1, and in the third case, there are only AA- and AB-firms as depicted in Figure 2. Aggregating the welfare components over the whole range of values for θ yields the following functions

[21] If AB firms were to transfer their abatement capital to country B, then the welfare contribution of one AB firm would alter to $W_{AB}(p,\theta) = 2-\kappa(k^*_{AB}(p))-\gamma(q^*_{AB}(p))-\theta-\psi\cdot(2\bar{\epsilon}-2k^*_{AB}(p)-q^*_{AA}(p))$, meaning that there would be less environmental damage because the transferred abatement capital also lowers emissions in the second period when the firm is operating in country B. However, this would not change any of the qualitative results since the welfare ranking would be the same.

$$W_{AA}^{AA}(p,P) = \int_{\underline{\theta}}^{\overline{\theta}} W_{AA}(p,P)\, d\theta = (\overline{\theta} - \underline{\theta}) \cdot W_{AA}(p,P) \tag{14}$$

$$W_{AA}^{AB}(p,g,P,G,\theta) = \int_{\underline{\theta}}^{\theta_{AA}^{AB}(p,P,G)} W_{AB}(p,\theta)\, d\theta + \int_{\theta_{AA}^{AB}(p,P,G)}^{\overline{\theta}} W_{AA}(p,P)\, d\theta \tag{15}$$

$$W_{AA}^{BB}(p,g,P,G,\theta) = \int_{\underline{\theta}}^{\theta_{AA}^{BB}(p,g,P,G)} W_{BB}(\theta)\, d\theta + \int_{\theta_{AA}^{BB}(p,g,P,G)}^{\overline{\theta}} W_{AA}(p,P)\, d\theta \tag{16}$$

The overall welfare function that characterizes all relocation scenarios finally reads

$$W(\cdot) = \begin{cases} W_{AA}^{AA}(\cdot) & \text{if} \quad \pi_{AA}(p,P,g,G) \geq \pi_{AB}(p,g,\underline{\theta}) \quad \text{and} \quad \pi_{AA}(p,P,g,G) \geq \pi_{BB}(\underline{\theta}) \\ W_{AA}^{AB}(\cdot) & \text{if} \quad \pi_{AA}(p,P,g,G) < \pi_{AB}(p,g,\underline{\theta}) \quad \text{and} \quad \pi_{AB}(p,g,\underline{\theta}) \geq \pi_{BB}(\underline{\theta}) \\ W_{AA}^{BB}(\cdot) & \text{if} \quad \pi_{AA}(p,P,g,G) < \pi_{BB}(\underline{\theta}) \quad \text{and} \quad \pi_{AB}(p,g,\underline{\theta}) \leq \pi_{BB}(\underline{\theta}) \end{cases} \tag{17}$$

where the arguments of the functions have been partially omitted.

3. Policy analysis

This section analyzes the impact of restricting transfers, i.e. free allowances, in the second period, as was proposed by several NGOs during the stakeholder consultations of the European Commission, and derives optimality conditions for first and second period carbon prices. As a reference case, the analysis starts with the case where transfers are unrestricted in both periods.

3.1. Transfers are unrestricted in both periods

Since the welfare contribution of AA-firms is higher than that of AB-firms, it is a dominant strategy for the social planner to offer transfer payments in the second period only. By doing this, the regulator exclusively enhances the profits of AA-firms, not running the risk to attract firms playing a 'take the money and run'-strategy. Given that transfer payments are welfare-neutral and its availability is unlimited, the social planner uses them in order to raise the profits of AA-firms and to prevent all relocation for any carbon prices. Thus, by setting the second period transfer sufficiently high, the two conditions in the first line of the welfare function (17) are always fulfilled, implying the maximization problem to reduce to

$$\max_{p,P} W_{AA}^{AA}(p,P). \tag{18}$$

The FOCs when maximizing this welfare function with respect to the carbon prices, are given by[22]

$$\begin{aligned}\frac{\partial W_{AA}^{AA}(\cdot)}{\partial p} =&(\overline{\theta}-\underline{\theta})\cdot\big(q_{AA}^{*}{}'(\cdot)\cdot\big(\psi-\gamma'(q_{AA}^{*}(\cdot))\big)+k_{AA}^{*}{}'(\cdot)\cdot\big(2\psi-\kappa'(k_{AA}^{*}(\cdot))\big)\big)\\ =&(\overline{\theta}-\underline{\theta})\cdot\big(q_{AA}^{*}{}'(\cdot)\cdot\big(\psi-p\big)+k_{AA}^{*}{}'(\cdot)\cdot\big(2\psi-p-P\big)\big)\stackrel{!}{=}0 \qquad (19)\\ \frac{\partial W_{AA}^{AA}(\cdot)}{\partial P} =&(\overline{\theta}-\underline{\theta})\cdot\big(Q_{AA}^{*}{}'(\cdot)\cdot\big(\psi-\gamma'(Q_{AA}^{*}(\cdot))\big)+k_{AA}^{*}{}'(\cdot)\cdot\big(2\psi-\kappa'(k_{AA}^{*}(\cdot))\big)\big)\\ =&(\overline{\theta}-\underline{\theta})\cdot\big(Q_{AA}^{*}{}'(\cdot)\cdot\big(\psi-P\big)+k_{AA}^{*}{}'(\cdot)\cdot\big(2\psi-p-P\big)\big)\stackrel{!}{=}0 \qquad (20)\end{aligned}$$

where the profit maximization conditions of AA-firms from equations (4), (6) and (7) have been used. Both FOCs immediately lead to Proposition 1.

Proposition 1

If transfer payments are unrestricted in both periods, then the regulator can implement the first best by setting the carbon prices in both periods equal to the marginal environmental damage and using the second period transfer to prevent all relocation.

Proof. Given that $q_{AA}^{*}{}'(\cdot)>0$, $Q_{AA}^{*}{}'(\cdot)>0$ and $k_{AA}^{*}{}'(\cdot)>0$, it is easy to verify that the FOCs (19) and (20) are fulfilled for the optimal carbon prices $p=P=\psi$. Suppose that $p<\psi$, then we must have $2\psi-p-P<0$ in order to satisfy FOC (19). This requires that $P>\psi$, which together with $2\psi-p-P<0$ cannot satisfy the FOC (20). The same holds true for $p>\psi$, so that we can conclude that $p=P=\psi$ is the only combination satisfying both FOCs. □

This is the first best result.[23] The Pigouvian carbon prices internalize the negative environmental externality (Pigou 1920), potentially causing some relocation. The relocation problem can be perfectly addressed by the transfers in the second period, which are chosen such that there is no relocation. Since there are two perfect instruments to address the two negative welfare effects, namely the environmental damage and the relocation of firms, the Tinbergen (1952) rule is fulfilled. The same result was obtained by Mæstad (2001) in a static model. However, in contrast to Mæstad, this paper can analyze the effect when transfers are restricted in the second period which will be done in the following.

[22] One can show that the second order conditions for a maximum, i.e. a negative definite Hessian, are satisfied provided that the third derivatives of the abatement cost functions $\gamma(q)$ and $\kappa(k)$ are sufficiently small. This holds true for a wide range of frequently applied cost functions, in particular for quadratic ones where the third derivatives are zero. In the following, I assume that this condition is fulfilled, so that we have a global maximum.

[23] Note that this is only the first best from a national welfare perspective. Since the environmental damage of the foreign country is not taken into account, the global first best may require higher carbon prices.

3.2. Transfers are restricted in the second period

Transfers in the second period may be restricted due to political pressure of lobby groups calling for a reduction of free allowances. In the following, I assume that $\overline{G}$ is the highest possible second period transfer. As before, it is a dominant strategy for the social planner to make use of this transfer as much as possible because AA-firms are more valuable for the regulator than AB-firms. The first period transfer g is unrestricted, implying that the regulator could avert any immediate relocation by offering a sufficiently high g. However, as was shown by Figure 2, increasing g only attracts firms playing a 'take the money and run'-strategy beyond a certain transfer level. Hence, g is an imperfect instrument to address the relocation problem adequately, which may require the social planner to move the carbon prices away from the first best in order to increase the number of AA-firms and thus the welfare. The regulator can implement the first best as long as the profits of AA-firms at first best prices exceed the profit of the AB-firm with the lowest relocation cost, i.e. as long as $\pi_{AA}(p=\psi,g,P=\psi,\bar{G}) \geq \pi_{AB}(p=\psi,g,\underline{\theta})$. This is the case if $\underline{\theta}$ is sufficiently large. If $\underline{\theta}$ is not large enough, some firms will relocate later at first best prices. In this case, the maximization of the welfare from equation (17) reduces to

$$\max \left\{ \begin{array}{llll} \max\limits_{p,P,g} W_{AA}^{AB}(p,P,g,\bar{G},\theta) & \text{s.t.} & \pi_{AB}(p,g,\theta) & \geq \pi_{BB}(\theta) \\ & & \pi_{AB}(p,g,\underline{\theta}) & \geq \pi_{AA}(p,g,P,\bar{G}) \\ \max\limits_{p,P,g} W_{AA}^{BB}(p,P,g,\bar{G},\theta) & \text{s.t.} & \pi_{AB}(p,g,\theta) & \leq \pi_{BB}(\theta) \\ & & \pi_{BB}(\underline{\theta}) & \geq \pi_{AA}(p,g,P,\bar{G}) \end{array} \right\} \tag{21}$$

where the regulator takes the maximum of the result from the optimization problem of either $W_{AA}^{AB}(p,P,g,\bar{G},\theta)$ or $W_{AA}^{BB}(p,P,g,\bar{G},\theta)$. The Lagrangian for the first optimization problem in (21) is given by

$$\mathcal{L} = W_{AA}^{AB} - \lambda\big(\pi_{BB} - \pi_{AB}\big) - \mu\big(\pi_{AA} - \pi_{AB}\big) \tag{22}$$

where the arguments of the functions have been skipped. In the Appendix, I show that the first derivatives of the Lagrangian with respect to p and P when taking into account the first derivative with respect to g can be simplified to

$$\frac{\partial \mathcal{L}}{\partial p} = \underbrace{\big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p}}_{>0} + \underbrace{\big(\theta_{AA}^{AB} - \underline{\theta}\big)}_{>0}\frac{\partial W_{AB}}{\partial p} + \underbrace{\big(\overline{\theta} - \theta_{AA}^{AB}\big)}_{>0}\frac{\partial W_{AA}}{\partial p} \overset{!}{=} 0 \tag{23}$$

$$\frac{\partial \mathcal{L}}{\partial P} = \underbrace{\big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial P}}_{<0} + \underbrace{\big(\overline{\theta} - \theta_{AA}^{AB}\big)}_{>0}\frac{\partial W_{AA}}{\partial P} \overset{!}{=} 0. \tag{24}$$

Assuming $\mu = 0$ for a moment, it follows from equation (23) that increasing p has essentially two effects on the welfare. First, as indicated by the first term, it augments the number of AA-firms and lowers the number of AB-firms by the same amount because θ_{AA}^{AB} decreases in p. An increase in p reduces the profits of AB-firms more than those of AA-firms. Since the abatement capital investments of AA-firms are relatively higher, their actual emissions are lower, which is why their profits do not decrease as much as those of AB-firms. Second, an increase of p alters the abatement decisions and therefore the welfare contribution of both AB- and AA-firms as shown by the second and third term in equation (23). From (24), increasing P impacts welfare through the same channels, namely it decreases the number of AA-firms (first term) and alters their abatement decisions (second term) and welfare contributions. Hence, when choosing the carbon prices, the regulator trades off the number of AA-firms with the abatement decisions of the firms operating in country A.

In the Appendix, I prove that FOCs (23) and (24) can only be satisfied as long as p is above and P is below ψ. Raising p above ψ and lowering P below ψ increases the number of AA-firms and thus the welfare. However, moving the carbon prices away from the first best distorts the abatement decision of firms. Thus, in an interior solution the regulator exactly trades off the welfare gain by increasing the number of AA-firms with the welfare loss that stems from inefficient abatement decisions of AB- and AA-firms.

This qualitative result does not alter for $\mu > 0$ which holds true if the constraint $\pi_{AB}(p, g, \underline{\theta}) \geq \pi_{AA}(p, g, P, \bar{G})$ is binding. In this case, the regulator increases p and decreases P only until there is no relocation anymore, meaning that all firms permanently operate in country A.

Remember that AB-firms are more valuable than BB-firms in welfare terms for $p \leq \psi$. However, for a sufficiently large p, this welfare relation may reverse because $p > \psi$ leads to a distortion of AB-firms' abatement decision to the extent that AB-firms abate inefficiently many emissions. If this distortion is large enough, the welfare contribution of BB-firms is larger than that of AB-firms and the regulator chooses the solution of the second maximization problem of (21). I show in the Appendix that the FOCs of this problem are almost equivalent to the FOCs (23) and (24), implying the regulator to set $p > \psi > P$ as before in order to increase the number of AA-firms.[24] In contrast to the first solution, the regulator chooses the first period transfer such that the profit of BB-firms is marginally higher than that of AB-firms, so that there are only AA- and BB-firms. Proposition 2 summarizes the insights.

Proposition 2

If transfer payments in the second period are restricted and it holds that $\underline{\theta} \geq \psi \cdot (k^*_{AB}(\psi) - k^*_{AA}(2\psi)) - \kappa(k^*_{AB}(\psi)) + \kappa(k^*_{AA}(2\psi)) + \psi \cdot (\bar{\epsilon} - k^*_{AA}(2\psi) - Q^*_{AA}(\psi)) + \gamma(Q^*_{AA}(\psi)) + \bar{G}$, then the regulator implements the first best by setting carbon prices equal to the marginal environmental damage and preventing all relocation through transfers. If transfer payments in the second period are restricted and the above inequality does not hold true, then the regulator sets the first period carbon price above the marginal environmental damage, the second period carbon price below the marginal environmental damage and chooses the first period transfer depending on whether AB- or BB-firms have a higher welfare contribution.

Proof. See Appendix. □

[24] In fact, the major difference is that the first term of both FOCs read $W_{BB} - W_{AA} + \mu$ instead of $W_{AB} - W_{AA} + \mu$.

Proposition 2 displays the second best solution. Since transfers in the second period are restricted, the regulator must rely on first period transfers to address the relocation problem. However, the first period transfer is an imperfect instrument to induce firms to produce permanently in the regulating country because it only increases the number of AA-firms up to a certain point, but attracts firms playing a 'take the money and run'-strategy beyond that point. Thus, the only option for the regulator to increase the number of AA-firms is to choose a price path according to Proposition 2.

Proposition 2 also displays the lock-in effect. Raising the first period carbon price above the marginal environmental damage triggers higher investments in abatement capital. This reduces the negative impact of the second period carbon price on firms' profits, inducing some firms to produce permanently in country A. The lock-in effect was also illustrated by Schmidt and Heitzig (2014) in a time-continuous model with one firm. In their paper, the regulator offers transfers for a sufficiently long time horizon, thereby increasing the investment in abatement capital of the regulated firm and rendering relocation less attractive after transfer payments have ceased.[25] While in Schmidt and Heitzig (2014) the regulator prolongs the time horizon in which the firm receives transfers to create the lock-in effect, the lock-in effect in the present two period model requires raising p above ψ and, at the same time, adjusting g accordingly. Moreover, Schmidt and Heitzig (2014) analyze only one firm that finally produces permanently in country A, whereas this paper considers a continuum of firms. This allows for deriving the optimal carbon prices from the trade-off between the relocation of some firms and distorting the abatement decision of the remaining firms.

Due to the distortion of the abatement decision, the regulator cannot spread the carbon prices infinitely. Note that the distortion for AA-firms primarily originates from the decision of the short-term abatement that depends on the carbon price in the corresponding period. Since the optimal investment in abatement capital depends on the sum of carbon prices $p + P$ as shown in equation (7), this decision may not be distorted for $p > \psi > P$. Hence, if there was no short-term abatement in the model, Lemma 1 summarizes the model implications.

Lemma 1

If transfer payments in the second period are restricted and if there is no short-term abatement option, then the regulator implements the first best by setting $p = 2\psi$, $P = 0$ and g such that there is no relocation.

Lemma 1 also holds true for other combinations of $p > \psi$ and $P < \psi$ as long as $p + P = 2\psi$ and as long as there is no delayed relocation, meaning that $\pi_{AA}(p, g, P, \bar{G}) \geq \pi_{AB}(p, g, \underline{\theta})$. In the absence of short-term abatement, any deviation of the carbon prices from ψ does not negatively affect the welfare contribution of AA-firms, enabling the regulator to spread carbon

[25] A similar result is found in a setting with asymmetric information by Pollrich and Schmidt (2014), where the regulator offers contracts consisting of emission limits and transfers to a single firm. When the regulator cannot commit to transfers in the second period, she may optimally tighten the emission limit in the first period to trigger investments in abatement capital, inducing the firm to produce permanently in country A.

prices until there is no relocation anymore. As long as $p + P = 2\psi$, AA-firms choose the welfare optimal abatement capital investment so that there is no distortion with respect to the abatement decision. Since the investment decision in abatement capital is not distorted and there is no relocation, the regulator can implement the first best despite the fact that the second period transfer is restricted.

So far, the analysis has assumed first period transfers to be unlimited. However, offering high transfers to all firms may imply substantial transfers from the government to the firms which may lead to a budget deficit of the government. One could argue that alleviating the adverse effects of unilateral climate policy should at least be self-financing. This issue will be addressed in the following Section.

4. Self-financing climate policy

This Section extends the analysis by introducing a budget constraint in the regulator's maximization problem, which reflects the fact that transfers to the firms should be self-financing to the extent that they should be entirely financed by the revenues from carbon taxation. In terms of free allowances, the interpretation of the budget constraint becomes even clearer. In this case, the regulator can at most give 100% free allowances to the firms. If she was to compensate the firms more heavily by offering additional allowances, the regulator would need to take them from another sector, which may not be fully compensated. However, in the present model such sector does not exist, implying 100% to be the highest possible compensation rate.

In the following, it is assumed that the budget constraint must hold at least inter-temporally. Thus, in principle, it is possible that firms receive the free allowances for *both* periods already in the first or only in the second period.[26] The tax revenue from either selling emissions permits or taxing carbon reads

$$T_{AA}(p,P) = p \cdot (\bar{\epsilon} - q^*_{AA}(p) - k^*_{AA}(p+P)) + P \cdot (\bar{\epsilon} - Q^*_{AA}(P) - k^*_{AA}(p+P)) \tag{25}$$

$$T_{AB}(p) = p \cdot (\bar{\epsilon} - q^*_{AB}(p) - k^*_{AB}(p)) \tag{26}$$

for one and each AA- or AB-firm. The analysis starts with the case in which second period transfers are unrestricted except for the budget constraint in order to contrast this case with the restricted scenario.

4.1. Transfers are unrestricted in both periods

When transfers are unrestricted in the second period, it is the dominant strategy for the regulator to use exclusively second period transfers since this only benefits AA-firms while not attracting

[26] Given that banking and borrowing is not allowed, allocating free allowances of the second period already in the first one means that firms can sell their second period permits in the second period regardless of whether or not they are still operating in country A. Receiving free allowances for the first period only in the second one can be thought of as getting a rebate for carbon expenses in the first period conditional on still operating in country A in the second period.

AB-firms. The social planner collects the entire tax revenue from both periods and allocates uniform transfers to all firms that are still operating in the second period in country A subject to the budget constraint. Since there are no AB-firms, the maximization problem reduces to

$$\max \left\{ \begin{array}{llll} \max\limits_{p,P,G} W_{AA}^{AA}(p,g=0,P,G) & \text{s.t.} & \pi_{AA}(p,g=0,P,G) & \geq \pi_{BB}(\underline{\theta}) \\ & & G\cdot(\bar{\theta}-\underline{\theta}) & \leq T_{AA}(p,P)\cdot(\bar{\theta}-\underline{\theta}) \\ \max\limits_{p,P,G} W_{AA}^{BB}(p,g=0,P,G) & \text{s.t.} & \pi_{AA}(p,g=0,P,G) & \leq \pi_{BB}(\underline{\theta}) \\ & & G\cdot(\bar{\theta}-\theta_{AA}^{BB}) & \leq T_{AA}(p,P)\cdot(\bar{\theta}-\theta_{AA}^{BB}) \end{array} \right\} \tag{27}$$

where the second line of each maximization problem represents the budget constraint with $G\cdot(\bar{\theta}-\underline{\theta})$ and $G\cdot(\bar{\theta}-\theta_{AA}^{AB})$ being the total transfer expenditures of the government. Note that since the carbon tax payments and transfers do not differ across AA-firms, each firm gets its entire tax refunded by the transfer if the budget constraint is binding.[27] Even though firms anticipate this refunding, it is still individually rational for each firm to abate emissions until the marginal abatement costs equal the carbon prices.

If the budget constraint is not binding at first best carbon prices, then the regulator can implement the first best by setting $p = P = \psi$. This is the case when $\pi_{AA}(p=\psi, g=0, P=\psi, G=T_{AA}(p,P)) \geq \pi_{BB}(\underline{\theta})$, i.e. when $\underline{\theta} \geq \kappa(k_{AA}^*(2\psi)) + \gamma(q_{AA}^*(\psi)) + \gamma(Q_{AA}^*(\psi))$. However, if the budget constraint at first best prices is binding, then the transfers are not high enough so that some firms will relocate. In this case, the regulator solves the second maximization problem in (27). As shown in the Appendix, the FOCs of the corresponding Lagrangian can be simplified to

$$\frac{\partial \mathcal{L}}{\partial p} = \underbrace{\left(W_{BB} - W_{AA} + \mu\right)\cdot\left(\frac{\partial \theta_{AA}^{BB}}{\partial p} - \frac{\partial T_{AA}}{\partial p}\right)}_{<0} + \underbrace{\left(\bar{\theta} - \theta_{AA}^{BB}\right)}_{>0}\frac{\partial W_{AA}}{\partial p} \stackrel{!}{=} 0 \tag{28}$$

$$\frac{\partial \mathcal{L}}{\partial P} = \underbrace{\left(W_{BB} - W_{AA} + \mu\right)\cdot\left(\frac{\partial \theta_{AA}^{BB}}{\partial P} - \frac{\partial T_{AA}}{\partial P}\right)}_{<0} + \underbrace{\left(\bar{\theta} - \theta_{AA}^{BB}\right)}_{>0}\frac{\partial W_{AA}}{\partial P} \stackrel{!}{=} 0 \tag{29}$$

where μ is the Lagrangian multiplier for the constraint $\pi_{AA}(\cdot) \leq \pi_{BB}(\underline{\theta})$. The first term of each FOC represents the welfare loss caused by more relocation in response to a higher carbon price. Relative to the FOCs (23) and (24) from Section 3, the effect of increasing carbon prices on AA-firms' profits and thus on θ_{AA}^{BB} is attenuated by the effect on the tax revenue $\frac{\partial T_{AA}}{\partial p}$ and $\frac{\partial T_{AA}}{\partial P}$. Since the tax payments of each firm are entirely refunded, but firms increase their abatement effort with rising carbon prices, we have $\frac{\partial \theta_{AA}^{BB}}{\partial i} - \frac{\partial T_{AA}}{\partial i} > 0$ for $i = p$, P, implying the number of AA-firms to decrease.[28] The second term of FOCs (28) and (29) denotes the change of the welfare contribution of all firms permanently operating in country A caused by a marginal increase

[27] If the budget constraint is not binding, then the social planner may choose to refund less than the tax payment.

[28] Formally, we have $\frac{\partial \theta_{AA}^{BB}}{\partial p} - \frac{\partial T_{AA}}{\partial p} = -\frac{\partial \pi_{AA}}{\partial p} - \frac{\partial T_{AA}}{\partial p} = \gamma'(q_{AA}^*(p))\cdot {q_{AA}^*}'(p) + \kappa'(k_{AA}^*(p+P))\cdot {k_{AA}^*}'(p+P) > 0$.

of the carbon price. From both FOCs, Proposition 3 follows immediately.

Proposition 3
If the government budget needs to be balanced and if transfer payments are unrestricted in both periods, then the regulator can implement the first best as long as $\underline{\theta} \geq \kappa(k^*_{AA}(2\psi)) + \gamma(q^*_{AA}(\psi)) + \gamma(Q^*_{AA}(\psi))$*. Otherwise the regulator chooses the optimal carbon prices to be equal in both periods and to be below the marginal environmental damage.*

Proof. See Appendix. □

If the budget balance is binding, the regulator faces a trade-off between the relocation of some firms and distorting the abatement decisions of firms permanently operating in country A. As a solution, the regulator is willing to distort the abatement decision in order to prevent the relocation of some firms and therefore chooses carbon prices to be below the marginal environmental damage. A similar result was also reported by Mæstad (2001) in a static model.[29] However, Mæstad (2001) could not analyze the following case.

4.2. Transfers are restricted in the second period

This Section deals with the case where transfers are not only restricted by the budget constraint of the government, but second period transfers are also restricted due to political reasons. For simplicity, the regulator is assumed to use exclusively first period transfers, meaning that $G = 0$. The use of first period transfers may attract firms playing a 'take the money and run'-strategy. Analogously to the analysis in Section 3, we focus on the more interesting case where the first best is not feasible. In this case, the reduced maximization problem reads

$$\max \left\{ \begin{array}{lll} \max\limits_{p,P,g} W^{AB}_{AA}(p,P,g,G=0) & \text{s.t.} & \pi_{AB}(p,g,\theta) \geq \pi_{BB}(\theta) \\ & & \pi_{AB}(p,g,\underline{\theta}) \geq \pi_{AA}(p,g,P,G=0) \\ & & g\cdot(\bar{\theta}-\underline{\theta}) \leq T(p,P) \\ \max\limits_{p,P,g} W^{BB}_{AA}(p,P,g,G=0) & \text{s.t.} & \pi_{AB}(p,g,\theta) \leq \pi_{BB}(\theta) \\ & & \pi_{BB}(\underline{\theta}) \geq \pi_{AA}(p,g,P,G=0) \\ & & g\cdot(\bar{\theta}-\theta^{BB}_{AA}) \leq T_{AA}(p,P)\cdot(\bar{\theta}-\theta^{BB}_{AA}) \end{array} \right\} \tag{30}$$

where in the first optimization problem $T(p,P) \equiv (\theta^{AB}_{AA}(\cdot)-\underline{\theta})\cdot T_{AB}(p)+(\bar{\theta}-\theta^{AB}_{AA}(\cdot))\cdot T_{AA}(p,P)$ is the aggregate tax revenue when there are both AB- and AA-firms. Note that in this case, the tax and transfer system implicitly redistributes profits from AA- to AB-firms because it allocates the tax revenues generated from AA-firms in the second period uniformly to all firms that operate in

[29] In contrast to this paper, Mæstad (2001) does not assume that the transfers must be self-financing, but analyzes a case where transfers are not available for the regulator.

country A in the first period. As shown in the Appendix, the first derivative of the Lagrangian for the first optimization problem of (30) with respect to p and P can be simplified to

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial p} =& \big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} + \big(\theta_{AA}^{AB} - \underline{\theta}\big)\frac{\partial W_{AB}}{\partial p} + \big(\bar{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial p} + \\ & \nu\left(\frac{\partial T}{\partial p} + \frac{\partial \pi_{AB}}{\partial p}(\bar{\theta} - \underline{\theta})\right) \stackrel{!}{=} 0 \qquad (31)\\ \frac{\partial \mathcal{L}}{\partial P} =& \big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial P} + \big(\bar{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial P} + \nu\frac{\partial T}{\partial P} \stackrel{!}{=} 0 \qquad (32)\end{aligned}$$

where ν is the Lagrangian multiplier for the budget constraint. The FOCs differ from the FOCs in equation (23) and (24) only with respect to the last term that contains ν. Thus, if the budget constraint is not binding, then we have $\nu = 0$ and the regulator optimally chooses the second best prices with $p > \psi > P$ as in Proposition 2. However, if the budget constraint is binding, the regulator needs to adjust the carbon prices. The direction of this adjustment depends on the impact of a price increase on the aggregate tax revenue. Exemplified on the second period carbon price, this impact is given by

$$\frac{\partial T}{\partial P} = \underbrace{(\bar{\theta} - \theta_{AA}^{AB})(\bar{\epsilon} - Q_{AA}^{*} - k_{AA}^{*})}_{>0} \underbrace{-(\bar{\theta} - \theta_{AA}^{AB})((p+P)k_{AA}^{*'} + PQ_{AA}^{*'})}_{<0} \underbrace{+\frac{\partial \theta_{AA}^{AB}}{\partial P}(T_{AA} - T_{AB})}_{<0}. \qquad (33)$$

A marginal increase of P has three effects on the tax revenue which are illustrated by the three terms in equation (33). First, it increases the tax revenue of all AA-firms by their actual emissions. Second, it increases the short-term and long-term abatement which reduces the tax revenues of all AA-firms. Third, it lowers the number of AA-firms and increases the number of AB-firms, implying the aggregate tax revenue to shrink. Due to these opposing effects, the overall effect is indeterminate.

If an increase of P augments the aggregate tax revenue, then it follows from equation (32) that the government will raise P above the second best because this raises the revenue, which enables the government to increase transfers to avert immediate relocation.[30] However, if the opposite holds true, then the regulator chooses a third best P which is below the second best.

Concerning the first period price, the last term of equation (31) indicates that there are two different effects for a change in p. First, as before, a higher p either increases or decreases the aggregate tax revenue.[31] Second, increasing p also reduces the profits of

[30]Note that it is also possible that the social planner raises the second period price above the marginal environmental damage in order to raise more tax revenue.

[31]Note that $\frac{\partial T}{\partial p}$ slightly differs from equation (33) because an increase of p also impacts the tax revenues of AB firms. However, the basic trade-offs are equivalent to those reported above.

AB-firms, meaning that higher transfers are required to avert immediate relocation. This effect alone would result in a reduction of p relative to the second best price. However, the overall effect is also indeterminate because the second effect could be exceeded by a potential increase of tax revenues from raising p provided that this increase is sufficiently large.

For both prices it holds that departing from the second best prices increases the welfare loss even further because it leads to more relocation and to higher distortions of the abatement decisions. If this welfare loss is very substantial, then the social planner may pursue a different strategy which does not aim at attracting AB-firms. In this case, the first derivatives of the Lagrangian for the second optimization problem in (30) with respect to p and P can be simplified to

$$\frac{\partial \mathcal{L}}{\partial p} = \underbrace{(W_{BB} - W_{AA} + \mu)\left(\frac{\partial \theta_{AA}^{BB}}{\partial p} - \frac{\partial T_{AA}}{\partial p}\right)}_{<0} + \underbrace{(\overline{\theta} - \theta_{AA}^{BB})}_{>0} \frac{\partial W_{AA}}{\partial p} - \lambda\left(\frac{\partial \pi_{AA}^{AB}}{\partial p} + \frac{\partial T_{AA}}{\partial p}\right) \stackrel{!}{=} 0 \tag{34}$$

$$\frac{\partial \mathcal{L}}{\partial P} = \underbrace{(W_{BB} - W_{AA} + \mu)\left(\frac{\partial \theta_{AA}^{BB}}{\partial P} - \frac{\partial T_{AA}}{\partial P}\right)}_{<0} + \underbrace{(\overline{\theta} - \theta_{AA}^{BB})}_{>0} \frac{\partial W_{AA}}{\partial P} - \lambda\frac{\partial T_{AA}}{\partial P} \stackrel{!}{=} 0 \tag{35}$$

where λ is the multiplier for the constraint $\pi_{BB}(\cdot) \geq \pi_{AB}(\cdot)$. If the budget constraint is not binding, then it can be shown that the results correspond to those reported in Proposition 2.[32] However, in the more interesting case when the budget constraint is binding, the social planner may pursue two different strategies, depending on whether or not the constraint $\pi_{BB}(\cdot) \geq \pi_{AB}(\cdot)$ is binding.

First, if this constraint is binding, then $\lambda > 0$ and we have a similar case as was explained before Proposition 2. In short, since the first period carbon price distorts the abatement decisions of AB-firms so much that $W_{BB} > W_{AB}$, the regulator uses transfers only up to the point where the profits of AB-firms are marginally below those of BB-firms. Since the budget constraint is binding, transfers are endogenous and depend on the carbon prices in both periods. Thus, the regulator chooses the third best carbon prices such that there are no AB-firms. It is hard to make any qualitative statement regarding the level of third best prices in this case because of the different impacts on firms' profits and tax revenues. However, equation (35) indicates that the third best P is below ψ as long as an increase in P raises the aggregate tax revenues.

The second strategy refers to the case where the tax revenues and thus the transfers are not large enough to attract AB-firms such that the constraint $\pi_{BB} \geq \pi_{AB}$ is not binding. In this case, we have $\lambda = 0$ and the FOCs (34) and (35) reduce to the FOCs (28) and (29) from Section

[32] To see this, note that $\frac{\partial \mathcal{L}}{\partial g} = W_{AA} - W_{BB} - \lambda - \mu + \nu$. If the budget constraint is not binding, we have $\nu = 0$. Solving equation $\frac{\partial \mathcal{L}}{\partial g} = 0$ for λ and plugging in into equations (34) and (35) leads to equations (A.13) and (A.14), implying that we obtain the same results as in Proposition 2.

4.1. Thus, the social planner trades off the relocation of some firms and the efficiency of the abatement decisions and chooses $p = P < \psi$ as reported in Proposition 3.

Summing up, the social planner has three pricing strategies where one includes AB- and AA-firms while the other two focus on BB- and AA-firms. The properties of these strategies are summarized in Proposition 4.

Proposition 4

If the government's budget needs to be balanced, if transfer payments are restricted to zero in the second period and if the first best and second best are not feasible, then the regulator chooses the welfare maximizing strategy out of the strategies in Table 2 and implements the third best prices accordingly:

Table 2: Third best strategies

Strategy	Firms	Price p	Price P Tax revenue increases in P: no	Price P Tax revenue increases in P: yes
Strategy 1	AA and AB	$p \lesseqgtr \psi$	$P \lesseqgtr \psi$	$P < \psi$
Strategy 2	AA and BB	$p \lesseqgtr \psi$	$P \lesseqgtr \psi$	$P < \psi$
Strategy 3	AA and BB	$p < \psi$	$p = P < \psi$	

Proof. See Appendix. □

Out of the three strategies from Proposition 4, the regulator chooses the one that yields the highest welfare level. Since a qualitative statement regarding the welfare ranking of the strategies is not possible, the following numerical example sheds some light on the choice of the social planner.

Numerical example

The abatement cost functions are assumed to be quadratic and given by $\gamma(q) = (1/2)c_q q^2$ and $\kappa(k) = (1/2)c_k k^2$. For quadratic functions, it can be shown that the welfare contribution of AB-firms always exceeds that of BB-firms in the range of plausible carbon prices.[33] Hence, it is never optimal for the regulator to pursue strategy 2 from Proposition 4, which is why the focus is on the remaining strategies.

Remember that strategy 1 involves a deviation from second best prices because transfers are not sufficiently high to attract AB-firms. If the profit difference between AB-firms and BB-firms for second best prices and the respective transfers is small, the carbon prices need to be adjusted only slightly, implying the associated welfare loss to be rather moderate. However, if the profit

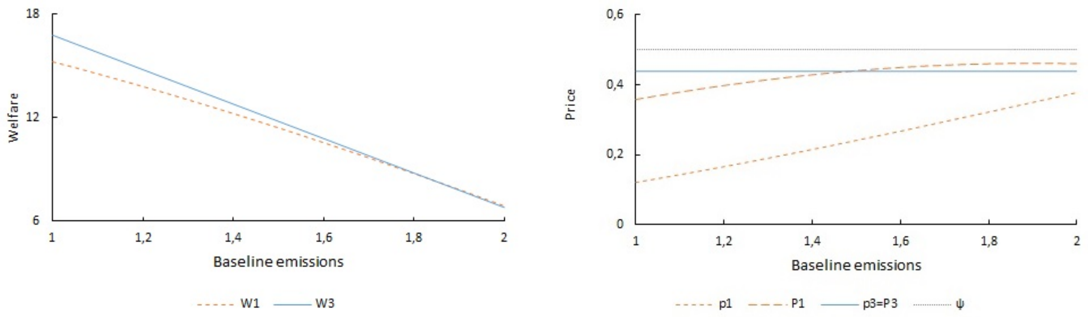
[33]The reason is that the welfare contribution of AB-firms $W_{AB}(p,\theta)$ exceeds $W_{BB}(\theta)$ as long as $0 < p < 2\psi$. Since carbon prices $p + P > 2\psi$ distort the investment decision of AA-firms, it is never optimal to choose $p + P > 2\psi$. Thus, it follows that p is always smaller than 2ψ and therefore $W_{AB}(p,\theta) > W_{BB}(\theta)$.

difference is large, the regulator needs to distort the prices substantially, which leads to a sizable welfare loss, in particular due to the loss of AA-firms. In this case, the welfare under strategy 3, that contains exclusively AA-firms and BB-firms, may be higher.

When choosing between strategy 1 or strategy 3, the regulator faces a trade-off between distorting the carbon prices, but attracting AB-firms and having only BB-firms, but potentially lower carbon price distortions. The choice between both strategies depends, in particular, on the level of the transfer and thus on the tax revenues. As was shown above, strategy 1 entails a redistribution of profits from AA-firms to AB-firms, so that one would expect the regulator to prefer strategy 1 over strategy 3 for high tax revenues, whereas the reverse holds true for low tax revenues. Tax revenues are increasing in baseline emissions $\bar{\epsilon}$. Assuming $c_q = c_k = 1$, $\underline{\theta} = 0$, $\bar{\theta} = 10$ and $\psi = 0.5$, Figure 3 depicts the welfare levels and the carbon prices for strategy 1 and 3 for $\bar{\epsilon}$ ranging from 1 to 2.

Figure 3: Comparison of tax and quantity regulation

(a) Welfare (b) Prices



In the left panel of Figure 3, it can be seen that the welfare levels of both strategies are decreasing in the baseline emissions $\bar{\epsilon}$ because higher emissions cause more damage from global warming. As was expected, for low values of $\bar{\epsilon}$, the welfare from strategy 3 outweighs that of strategy 1 whereas this relationship reverses for sufficiently large $\bar{\epsilon}$. The reason for this can be inferred from the right panel of Figure 3, which shows the carbon prices of both strategies. While the carbon prices of strategy 3 remain constant[34], those of strategy 1 start from a rather low level for small values of $\bar{\epsilon}$ and increase with higher values of $\bar{\epsilon}$. If $\bar{\epsilon}$ is low, so are the tax revenues and the transfers to the firms. Thus, in order to attract AB-firms, it is necessary to reduce p substantially relative to the second best prices. A small p implies low investments in abatement capital which is why the regulator also wants to set P rather low in order to prevent the relocation of too many AA-firms. Higher values of $\bar{\epsilon}$ increase the tax revenues and transfers to the firms, allowing the regulator to raise both carbon prices towards the second best. For sufficiently large $\bar{\epsilon}$, the regulator finally prefers strategy 1 over strategy 3.

[34]Constant carbon prices imply the abatement effort of firms to remain constant as well, causing the welfare level of strategy 3 to decline linearly in $\bar{\epsilon}$.

5. Conclusion

This paper studied the consequences of a restriction of free allowances in the near term as was demanded by many members of the civil society during the stakeholder consultations of the European Commission regarding the future of the carbon leakage list within the EU ETS. Allocating free allowances has not only distributive consequences, but also allocative implications to the extent that it alters the profits of firms and thus their location decision.

Using a stylized two-period two-country framework with mobile firms, this paper shows that when transfers or free allowances are unrestricted in both periods, the social planner can perfectly address the relocation problem and implements the first best by setting carbon prices equal to the marginal environmental damage and preventing any relocation by sufficiently high transfer payments. However, if transfers in the second period are restricted, the first best may not be achieved because first period transfers are an imperfect instrument for inducing firms to produce permanently in the regulating country. For a sufficiently high first period transfer, some firms will play a 'take the money and run'-strategy and relocate in the second period. The social planner addresses this problem by raising the first period carbon price above the marginal environmental damage, which creates a lock-in effect. It triggers higher investments in abatement capital, which benefits firms permanently producing in the regulated country disproportionately more than those that planned to relocate later. In the second best, the planner faces a trade-off between locking some firms in and distorting the abatement decisions of firms, resulting in strictly lower welfare levels relative to the first best.

Section 4 requires the government's budget to be balanced. If the budget constraint is binding and transfers in the second period are not restricted, then the regulator optimally sets both carbon prices to be equal and below the marginal environmental damage, trading-off the distortion of firms' abatement decision and the relocation pressure. If transfers in the second period are restricted, the regulator may choose essentially between two strategies. Either she chooses the carbon prices to be equal and below the marginal environmental damage as in the unrestricted scenario or she attempts to attract AB-firms and sets the carbon prices accordingly.

In the case where transfers are not restricted in the second period, this paper derives the same results as Mæstad (2001). However, since Mæstad (2001) uses a static model, he cannot analyze the implications of phasing out free allowances in the middle term for the current and future carbon prices and thus cannot obtain the lock-in effect. The lock-in effect was shown by Schmidt and Heitzig (2014) in a time-continuous model with one firm. While in Schmidt and Heitzig (2014), the regulator locks the firm in by offering transfers for a sufficiently long time horizon which increases the investments in abatement capital and induces the firm to produce permanently in the regulating country, the lock-in effect in this paper results from raising the carbon price in the first period. Since in Schmidt and Heitzig (2014) there is only one firm, they cannot derive the trade-off between the relocation of some firms and the distortion of the abatement decision of the remaining firms, which characterizes the second and third best results of this paper.

The policy implications of this paper are twofold. First, it argues for maintaining a high share of free emission allowances for energy-intensive firms that are subject to relocation and therefore opposes the position of the stakeholders calling for a phasing out in the near term. By restricting the share of free allowances in the future, the regulator loses one powerful instrument that perfectly addresses the relocation problem caused by carbon pricing. Hence, free allowances should be maintained as long as there are substantial carbon price differences between the countries despite a potential overcompensation of firms. In order to reduce the overallocation, this paper suggests to narrow the allocation of free allowances to the most mobile firms, i.e. the firms with the lowest relocation costs. The European Union partially follows this strategy in recent years to the extent that in the third trading period of the EU ETS, local electricity producers do not get any free allowances and that there are special provisions for firms with high relocation risk in form of the carbon leakage list. Currently, the European Commission seems to pursue a refinement of that list and has proposed a differentiated allocation scheme that takes the sector-specific relocation risk into account. The second implication refers to the choice of carbon prices (or the emissions cap) provided that free allowances are to be phased out in the near future. In this case, the EU ETS should strive for a high carbon price in the near term in order to trigger investments in abatement capital and to create the lock-in effect. Thus, recently implemented measures aiming at raising the carbon price such as backloading or proposed measures such as the introduction of a floor price go in the right direction.

For future research, this paper could be extended towards several directions. First, it may take into account the loss of jobs that is associated with the relocation of firms and which is the major argument in the political debate. Accounting for this would only strengthen the result of this paper, implying unrestricted transfers to become even more important. Second, the model could account for foreign firm ownership of domestic firms. While taxes imply a redistribution from foreign owners to the government or local residents, transfers or free allowances work in the other direction, meaning that there are further trade-offs that need to be considered for the optimal tax and transfer scheme. Third, this model restricted the regulator to use uniform taxes and transfers because firm-specific relocation costs were private information. However, the regulator could also make use of more sophisticated tax and transfer schemes as suggested by the mechanism design literature. The paper of Pollrich and Schmidt (2014) goes in this direction. Using a different setting, they also conclude that the regulator should require a high first period carbon price or a tough emission reduction target in order to prevent the relocation of the firm permanently.

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A. Appendix

Proof of Proposition 2

The Kuhn-Tucker conditions for the Lagrangian from equation (22) read

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial p} =& \big(W_{AB} - W_{AA}\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} + \big(\theta_{AA}^{AB} - \underline{\theta}\big)\frac{\partial W_{AB}}{\partial p} + \big(\overline{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial p} \\
&+ \lambda \frac{\partial \pi_{AB}}{\partial p} - \mu\left(\frac{\partial \pi_{AA}}{\partial p} - \frac{\partial \pi_{AB}}{\partial p}\right) && \overset{!}{=} 0 && \text{(A.1)} \\
\frac{\partial \mathcal{L}}{\partial P} =& \big(W_{AB} - W_{AA}\big)\frac{\partial \theta_{AA}^{AB}}{\partial P} + \big(\overline{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial P} - \mu \frac{\partial \pi_{AA}}{\partial P} && \overset{!}{=} 0 && \text{(A.2)} \\
\frac{\partial \mathcal{L}}{\partial g} =& \lambda \frac{\partial \pi_{AB}}{\partial g} - \mu \underbrace{\left(\frac{\partial \pi_{AA}}{\partial g} - \frac{\partial \pi_{AB}}{\partial g}\right)}_{=0} && \overset{!}{=} 0 && \text{(A.3)} \\
& \lambda(\pi_{BB} - \pi_{AB}) + \mu(\pi_{AA} - \pi_{AB}) && = 0 && \text{(A.4)} \\
& \lambda, \mu && \geq 0 && \text{(A.5)}
\end{aligned}$$

Since $\frac{\partial \pi_{AB}}{\partial g} = 1 > 0$, FOC (A.3) can only be satisfied for $\lambda = 0$. Using $\frac{\partial \theta_{AA}^{AB}}{\partial p} = \frac{\partial \pi_{AB}}{\partial p} - \frac{\partial \pi_{AA}}{\partial p}$ and $\frac{\partial \theta_{AA}^{AB}}{\partial P} = -\frac{\partial \pi_{AA}}{\partial P}$ immediately leads to equations (23) and (24) which are the starting points for the proof of Proposition 2.

First, note that at $p = P = \psi$, we have $\frac{\partial W_{AB}}{\partial p}\big|_{p=P=\psi} = \frac{\partial W_{AA}}{\partial p}\big|_{p=P=\psi} = \frac{\partial W_{AA}}{\partial P}\big|_{p=P=\psi} = 0$. Since $\frac{\partial \theta_{AA}^{AB}}{\partial P} > 0$, $\frac{\partial \theta_{AA}^{AB}}{\partial p} < 0$ and $(W_{AB} - W_{AA} - \mu) < 0$, it follows that $\frac{\partial \mathcal{L}}{\partial p}\big|_{p=P=\psi} = \big(W_{AB} - W_{AA} - \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} > 0$ and $\frac{\partial \mathcal{L}}{\partial P}\big|_{p=P=\psi} = \big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial P} < 0$. Hence, a marginal increase (decrease) of p (P) raises the welfare at $p = P = \psi$.

Second, given that $\frac{\partial \theta_{AA}^{AB}}{\partial p} < 0$ and assuming for a moment that $\big(W_{AB} - W_{AA} + \mu\big) < 0$, we must have $\frac{\partial W_{AA}}{\partial P} = {Q_{AA}^*}'(\psi - P) + {k_{AA}^*}'(2\psi - p - P) > 0$ to satisfy equation (24). For $p \geq \psi$, this requires P to be smaller than ψ. As $\big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} > 0$, we must have $p > \psi$ for $P \leq \psi$ to satisfy FOC (23). This leads to $p > \psi > P$. Moreover, we can exclude the case $P > \psi > p$ because $P > \psi$ requires $2\psi - p - P > 0$ to satisfy equation (24), whereas $p < \psi$ requires $2\psi - p - P < 0$ to satisfy FOC (23), leading to a contradiction. Thus, we must have $p > \psi > P$ to satisfy both FOCs.

Third, to show that $\big(W_{AB} - W_{AA} + \mu\big) < 0$, note that for $\mu > 0$ we must have $\pi_{AA}(p, g, P, \bar{G}) = \pi_{AB}(p, g, \underline{\theta})$. If $\big(W_{AB} - W_{AA} + \mu\big) > 0$, then we would have $p < \psi < P$ for the same reasons as above. But then $\pi_{AA}(p < \psi, g, P > \psi, \bar{G}) = \pi_{AB}(p < \psi, g, \underline{\theta})$ implies that $\pi_{AA}(\psi, g, \psi, \bar{G}) > \pi_{AB}(\psi, g, \underline{\theta})$, meaning that the first best was feasible. Hence, we must have $\big(W_{AB} - W_{AA} + \mu\big) < 0$.

The Lagrangian for the second maximization problem of (21) is given by

$$\mathcal{L} = W_{AA}^{BB} - \lambda\big(\pi_{AB} - \pi_{BB}\big) - \mu\big(\pi_{AA} - \pi_{BB}\big) \tag{A.6}$$

and the Kuhn-Tucker conditions read

$$\frac{\partial \mathcal{L}}{\partial p} = \big(W_{BB} - W_{AA}\big)\frac{\partial \theta_{AA}^{BB}}{\partial p} + \big(\overline{\theta} - \theta_{AA}^{BB}\big)\frac{\partial W_{AA}}{\partial p} - \lambda \frac{\partial \pi_{AB}}{\partial p} - \mu \frac{\partial \pi_{AA}}{\partial p} \overset{!}{=} 0 \tag{A.7}$$

$$\frac{\partial \mathcal{L}}{\partial P} = \big(W_{BB} - W_{AA}\big)\frac{\partial \theta_{AA}^{BB}}{\partial P} + \big(\overline{\theta} - \theta_{AA}^{BB}\big)\frac{\partial W_{AA}}{\partial P} - \mu \frac{\partial \pi_{AA}}{\partial P} \overset{!}{=} 0 \tag{A.8}$$

$$\frac{\partial \mathcal{L}}{\partial g} = \big(W_{BB} - W_{AA}\big)\frac{\partial \theta_{AA}^{BB}}{\partial g} - \lambda \frac{\partial \pi_{AB}}{\partial g} - \mu \frac{\partial \pi_{AA}}{\partial g} \overset{!}{=} 0 \tag{A.9}$$

$$\lambda(\pi_{AB} - \pi_{BB}) + \mu(\pi_{AA} - \pi_{BB}) \overset{!}{=} 0 \tag{A.10}$$

$$\lambda, \mu \geq 0 \tag{A.11}$$

Since $\frac{\partial \pi_{AA}}{\partial g} = \frac{\partial \pi_{AB}}{\partial g} = 1$ and $\frac{\partial \theta_{AA}^{BB}}{\partial g} = -\frac{\partial \pi_{AA}}{\partial g} = -1$, it follows from equation (A.9) that

$$\lambda = W_{AA} - W_{BB} - \mu > 0. \tag{A.12}$$

In order to satisfy equation (A.10), we must have $\pi_{AB} = \pi_{BB}$, meaning that the regulator chooses g such that firms are indifferent between relocating later or immediately. Note that $\pi_{AB} = \pi_{BB}$ implies $\theta_{AA}^{BB} = \theta_{AA}^{AB}$. Plugging in equation (A.12) into equation (A.7) and using the facts that $\frac{\partial \theta_{AA}^{BB}}{\partial p} = -\frac{\partial \pi_{AA}}{\partial p}$ and $\frac{\partial \theta_{AA}^{AB}}{\partial p} = \frac{\partial \pi_{AB}}{\partial p} - \frac{\partial \pi_{AA}}{\partial p}$ immediately leads to

$$\frac{\partial \mathcal{L}}{\partial p} = \big(W_{BB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} + \big(\overline{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial p} \overset{!}{=} 0. \tag{A.13}$$

Using $\frac{\partial \theta_{AA}^{BB}}{\partial P} = -\frac{\partial \pi_{AA}}{\partial P} = \frac{\partial \theta_{AA}^{AB}}{\partial P}$ for equation (A.8) yields

$$\frac{\partial \mathcal{L}}{\partial P} = \big(W_{BB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial P} + \big(\overline{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial P} \overset{!}{=} 0. \tag{A.14}$$

Equations (A.13) and (A.14) are almost equivalent to the FOCs (23) and (24). Hence, for the same reasons as above, we must have $p > \psi > P$.

Proof of Proposition 3

The Lagrangian of the second maximization problem of (27) is given by

$$\mathcal{L} = W_{AA}^{BB} - \mu(\pi_{AA} - \pi_{BB}) - \nu(G - T_{AA}) \tag{A.15}$$

where the term $(\overline{\theta} - \theta_{AA}^{BB})$ in the budget constraint has canceled out. The Kuhn-Tucker conditions read

$$\frac{\partial \mathcal{L}}{\partial p} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial p} + (\bar{\theta} - \theta_{AA}^{BB})\frac{\partial W_{AA}}{\partial p} - \mu \frac{\partial \pi_{AA}}{\partial p} + \nu \frac{\partial T_{AA}}{\partial p} \overset{!}{=} 0 \tag{A.16}$$

$$\frac{\partial \mathcal{L}}{\partial P} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial P} + (\bar{\theta} - \theta_{AA}^{BB})\frac{\partial W_{AA}}{\partial P} - \mu \frac{\partial \pi_{AA}}{\partial P} + \nu \frac{\partial T_{AA}}{\partial P} \overset{!}{=} 0 \tag{A.17}$$

$$\frac{\partial \mathcal{L}}{\partial G} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial G} - \mu \frac{\partial \pi_{AA}}{\partial G} - \nu \overset{!}{=} 0 \tag{A.18}$$

$$\mu(\pi_{AA} - \pi_{BB}) + \nu(G - T_{AA}) \overset{!}{=} 0 \tag{A.19}$$

$$\mu, \nu \geq 0 \tag{A.20}$$

Taking into account that $\frac{\partial \theta_{AA}^{BB}}{\partial G} = -1$ and $\frac{\partial \pi_{AA}}{\partial G} = 1$, it follows from equation (A.18) that $\nu = W_{AA} - W_{BB} - \mu$. Substituting ν in equations (A.16) as well as (A.17) and bearing in mind that $\frac{\partial \theta_{AA}^{BB}}{\partial i} = -\frac{\partial \pi_{AA}}{\partial i}$ for $i = p,\ P,\ G$ leads to equations (28) and (29) from the text. Moreover, note that

$$\frac{\partial \theta_{AA}^{BB}}{\partial p} - \frac{\partial T_{AA}}{\partial p} = p(q_{AA}^{*'} + k_{AA}^{*'}) + P(Q_{AA}^{*'} + k_{AA}^{*'}) > 0. \tag{A.21}$$

For the first part of Proposition 3, note that if the regulator sets the highest possible transfer $G = T_{AA}(p, P)$, then the profit of an AA firm reads $\pi_{AA}^*(p, P, g = 0, G = T_{AA}(p, P)) = 2 - \kappa(k_{AA}^*(p+P)) - \gamma(q_{AA}^*(p)) - \gamma(Q_{AA}^*(P))$. Thus, there is no relocation for first-best prices as long as $\underline{\theta} \geq \kappa(k_{AA}^*(2\psi)) + \gamma(q_{AA}^*(\psi)) + \gamma(Q_{AA}^*(\psi))$ and the regulator can implement the first-best.

For the second part, if $\underline{\theta} < \kappa(k_{AA}^*(2\psi)) + \gamma(q_{AA}^*(\psi)) + \gamma(Q_{AA}^*(\psi))$, the regulator optimally reduces the carbon prices. At $p = P = \psi$, we have $\frac{\partial W_{AA}}{\partial p}\big|_{p=P=\psi} = \frac{\partial W_{AA}}{\partial P}\big|_{p=P=\psi} = 0$, meaning that $\frac{\partial \mathcal{L}}{\partial p}\big|_{p=P=\psi} = \frac{\partial \mathcal{L}}{\partial P}\big|_{p=P=\psi} = \big(W_{BB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{BB}}{\partial i} < 0$ for $i = p,\ P$. Since $\frac{\partial \theta_{AA}^{BB}}{\partial p} > 0$ as well as $\frac{\partial \theta_{AA}^{BB}}{\partial P} > 0$ and $W_{BB} - W_{AA} + \mu < 0$, we must have $\frac{\partial W_{AA}}{\partial p} > 0$ and $\frac{\partial W_{AA}}{\partial P} > 0$ to satisfy the FOCs (28) and (29). This requires $p + P < 2\psi$. Since the FOCs (28) and (29) are symmetric, there is a unique welfare maximum with $p = P < \psi$.

Proof of Proposition 4

The Lagrangian for the first optimization problem in (30) reads

$$\mathcal{L} = W_{AA}^{AB} - \lambda(\pi_{BB} - \pi_{AB}) - \mu(\pi_{AA} - \pi_{AB}) - \nu(g(\bar{\theta} - \underline{\theta}) - T) \tag{A.22}$$

and the Kuhn-Tucker conditions are given by

$$\frac{\partial \mathcal{L}}{\partial p} =(W_{AB} - W_{AA})\frac{\partial \theta_{AA}^{AB}}{\partial p} + (\theta_{AA}^{AB} - \underline{\theta})\frac{\partial W_{AB}}{\partial p} + (\bar{\theta} - \theta_{AA}^{AB})\frac{\partial W_{AA}}{\partial p} +$$

$$\lambda\frac{\partial \pi_{AB}}{\partial p} - \mu\left(\frac{\partial \pi_{AA}}{\partial p} - \frac{\partial \pi_{AB}}{\partial p}\right) + \nu\frac{\partial T}{\partial p} \overset{!}{=} 0 \tag{A.23}$$

$$\frac{\partial \mathcal{L}}{\partial P} =(W_{AB} - W_{AA})\frac{\partial \theta_{AA}^{AB}}{\partial P} + (\bar{\theta} - \theta_{AA}^{AB})\frac{\partial W_{AA}}{\partial P} - \mu\frac{\partial \pi_{AA}}{\partial P} + \nu\frac{\partial T}{\partial P} \overset{!}{=} 0 \tag{A.24}$$

$$\frac{\partial \mathcal{L}}{\partial g} =\lambda\frac{\partial \pi_{AB}}{\partial g} - \mu\left(\frac{\partial \pi_{AA}}{\partial g} - \frac{\partial \pi_{AB}}{\partial g}\right) - \nu(\bar{\theta} - \underline{\theta}) \overset{!}{=} 0 \tag{A.25}$$

$$\lambda(\pi_{BB} - \pi_{AB}) + \mu(\pi_{AA} - \pi_{AB}) + \nu(g(\bar{\theta} - \underline{\theta}) - T) \overset{!}{=} 0 \tag{A.26}$$

$$\lambda, \mu, \nu \geq 0 \tag{A.27}$$

Taking into account that $\frac{\partial \pi_{AB}}{\partial g} = 1$ and that $\frac{\partial \pi_{AA}}{\partial g} - \frac{\partial \pi_{AB}}{\partial g} = 0$, equation (A.25) can be reduced to $\lambda = \nu(\bar{\theta} - \underline{\theta})$. Plugging this in into equation (A.23) and performing the same transformations as in the proof of Proposition 2 leads to equation (31) from the text. For the first line in Table 2 from Proposition 4 note that the sign of the last term of equation (31) is indeterminate. Hence, the third best p can be either above or below ψ. For the last entry in the first line, the last term of equation (32) is certainly negative, implying the term $\frac{\partial W_{AA}}{\partial P}$ to be positive which holds only true for $P < \psi$ for the same reasons as pointed out in the proof of Proposition 2. However, if $\frac{\partial T(p,P)}{\partial P} > 0$, then P can be below or above ψ.

The Lagrangian for the second optimization problem in (30) reads

$$\mathcal{L} = W_{AA}^{BB} - \lambda(\pi_{AB} - \pi_{BB}) - \mu(\pi_{AA} - \pi_{BB}) - \nu(g - T_{AA}) \tag{A.28}$$

and the Kuhn-Tucker conditions are given by

$$\frac{\partial \mathcal{L}}{\partial p} =(W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial p} + (\bar{\theta} - \theta_{AA}^{BB})\frac{\partial W_{AA}}{\partial p} - \lambda\frac{\partial \pi_{AB}}{\partial p} - \mu\frac{\partial \pi_{AA}}{\partial p} + \nu\frac{\partial T_{AA}}{\partial p} \overset{!}{=} 0 \tag{A.29}$$

$$\frac{\partial \mathcal{L}}{\partial P} =(W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial P} + (\bar{\theta} - \theta_{AA}^{BB})\frac{\partial W_{AA}}{\partial P} - \mu\frac{\partial \pi_{AA}}{\partial P} + \nu\frac{\partial T_{AA}}{\partial P} \overset{!}{=} 0 \tag{A.30}$$

$$\frac{\partial \mathcal{L}}{\partial g} =(W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial g} - \lambda\frac{\partial \pi_{AB}}{\partial g} - \mu\frac{\partial \pi_{AB}}{\partial g} + \nu \overset{!}{=} 0 \tag{A.31}$$

$$\lambda(\pi_{BB} - \pi_{AB}) + \mu(\pi_{AA} - \pi_{BB}) + \nu(g - T_{AA}) \overset{!}{=} 0 \tag{A.32}$$

$$\lambda, \mu, \nu \geq 0 \tag{A.33}$$

Taking into account that $\frac{\partial \theta_{AA}^{BB}}{\partial g} = -1$ and $\frac{\partial \pi_{AB}}{\partial g} = 1$, equation (A.31) reduces to $\nu = W_{AA} - W_{BB} - \lambda - \mu$. Plugging this into equations (A.29) and (A.30) leads to equations (34) and (35) from the text. If $\lambda > 0$, then p can be above or below ψ because the sign of the last term in equation (34) is indeterminate which proofs the first entry in the second line of Table 2. If $\frac{\partial T_{AA}}{\partial P} > 0$, then the last term of equation (35) is negative and P must be below ψ. If the opposite holds true, then P can be above or below ψ which proofs the other entries of the second line.

For the last line, if $\lambda = 0$, then the FOCs (34) and (35) are equivalent to (28) and (29) and we have $p = P < \psi$ for the same reasons as outlined in the proof of Proposition 3.

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