FAERE

French Association
of Environmental and Resource Economists

Working papers

Heterogeneous firms and the environment : a cap-and-trade program

Lisa Anouliès

WP 2015.10

ISSN number:

Heterogeneous firms and the environment: a cap-and-trade program

Lisa Anouliès*

April 2015

Abstract Cap-and-trade programs are presently the cornerstone of climate change policies and proposals in many countries. I investigate the economic and environmental effects of different designs for this policy in a general equilibrium setting when firms are heterogeneous and in monopolistic competition. This study first predicts that the cap on emissions perfectly defines the environmental quality but has no effect on firms' profits and decisions to enter or exit the market. On the contrary, increasing the share of free allocation of emissions allowances reallocates resources among firms toward the most productive ones: the initial allocation of allowances therefore impacts firms' entry and exit decisions and aggregate economic variables but not the environment. Firm heterogeneity magnifies this economic effect of a change in the initial allocation of allowances.

Keywords Emissions trading, heterogeneous firms, monopolistic competition

JEL classification Q58 - D43 - H23

*Université Paris-Sud, RITM. lisa.anoulies@u-psud.fr. I am grateful to Philippe Martin and José de Sousa for stimulating discussions. I also thank participants of the EAERE 2013, CESifo Venice Summer Institute 2013, FAERE 2014 conferences, as well as seminars participants at the Paris School of Economics for helpful comments and suggestions on earlier versions of this paper. All remaining errors are mine.

1 Introduction

Emissions trading, an idea that dates to Dales (1968), is presently the cornerstone of climate change policies and proposals in many countries through the implementation of cap-and-trade programs.[1] From an environmental point of view, the main advantage of emissions trading policies is the direct control they exert upon environmental quality. Moreover, cap-and-trade programs are representative of a multidimensional policy because a regulator defines the cap on emissions, and the method for the initial allocation of emission allowances to be traded by firms: auction or free allocation, and the rule governing free allocation. Different possible designs for a cap-and-trade program can therefore be contemplated by a regulator. Actually, mandatory emissions trading schemes currently in place feature different characteristics regarding the initial allocation of allowances, which has been the target of the major revision of the European Union Emissions Trading Scheme (EU ETS) in effect since January 2013. This paper analyzes the economic and environmental impacts of different designs for a cap-and-trade program when firms are heterogeneous and in imperfect competition. Heterogeneity is essential to understand the trading of emissions allowances among firms, to identify the winners and losers as well as the aggregate consequences of different policy designs.

I build on the Melitz (2003) model of heterogeneous firms in monopolistic competition, with free entry and exit. Firms' activities generate pollution regulated by a cap-and-trade program. The program is defined by a cap on emissions and a rule governing the initial allocation of allowances: they can either be auctioned or allocated for free to polluting firms following a dynamic product-based benchmarking approach. The benchmark is the average emission intensity of the best performing firms in terms of pollution intensity, and the allocation is revised every period to take into account changes in production and benchmark values.

The model's first result is that the competence of each of the two policy decisions, the cap on emissions and the initial allocation of allowances, is limited to only one domain. On the one hand, the environmental quality is entirely determined by the cap on emissions, the level of which has no effect on firms' profits and decisions to enter or exit the market; thus there is no effect on the mass of firms once general equilibrium effects are taken into account. The aggregate level of emissions adapts to the new cap only through a scale effect operating at the intensive margin (such that each firm's output decreases) and a technique effect (such that each firm's emission intensity of production declines). On the other hand, the share of free allocation (versus auctioning) affects the structure of the market. Allocating more allowances for free reallocates resources toward the most productive firms due to the benchmark definition: as a result, there is an increase in the productivity cutoff above which a

[1] 17 emissions trading schemes are currently in place at regional, national and subnational levels in 35 countries, 13 provinces or states and 7 cities (ICAP 2015).

firm decides to stay in the market and produce and a contraction in the mass of firms. A change in the initial allocation of allowances has no overall effect on environmental quality, but impacts the different components of aggregate emissions through five effects: scale at the extensive margin, scale at the intensive margin, technique, composition and selection. The policy implication of this first result it that a cap-and-trade program can therefore separately address environmental and economic issues. The second contribution of the present study is to evidence the role of firm heterogeneity in relation to the effects of an environmental policy. As the reallocation of resources among firms intensifies with the degree of firm heterogeneity, the impact of a change in initial allocation also develops with productivity dispersion on the market.

This paper is related to prior studies considering heterogeneity in a cap-and-trade framework, which have generally looked at the effect of heterogeneity in pollution abatement costs on the cost-advantage of emissions trading over command-and-control regulations (Sartzetakis 1997; Ben-David et al. 1999; Newell and Stavins 2003; Goulder and Parry 2008). The present model does not compare policy instruments but investigates the effect of different designs of a cap-and-trade program in relation with firm heterogeneity in terms of productivity. Above all, it features free entry and exit of firms in the market; absent from the models developed in the previous references, these decisions are clearly overseen by firm heterogeneity and have significant impacts at the aggregate level.
This study can also be compared with the literature debating on the choice between pure grandfathering and updated allocation. Many arguments support the auctioning of allowances: implementing the polluter-pays principle, providing incentives for technological innovation, and raising substantial revenues that can be used to reduce tax distortions (Groenenberg and Blok 2002; Cramton and Kerr 2002). Nevertheless, political feasibility can prevent the recourse to this method and promote free allocation of emission allowances. Experiences in the United States (the Acid Rain Program for SO_2 emissions) and Europe (the EU ETS for greenhouse gas emissions) show that free allowances have traditionally been allocated according to the grandfathering approach based on historic emissions. The approach uses a lump-sum transfer based on individual emissions during a period preceding the announcement and implementation of the emissions trading scheme.[2] This method presents serious drawbacks: it puts firms that took early action against emissions at a disadvantage, constitutes a barrier to entry in regulated sectors, and fails to account for changes in market conditions (Groenenberg and Blok 2002; Böhringer and Lange 2005). As a consequence, free allocation based on updated performance has recently aroused interest in the literature. The main argument against this approach is that firms can manipulate their future endowment of allowances, a strategic behavior that could undermine the cost-effectiveness of an emissions trading scheme (see Böhringer and Lange 2005, Rosendahl and Storrosten

[2] Historic data can also alternately refer to production or input use.

2011, Rosendahl 2008), but would reduce the adjustment costs to environmental policies compared to grandfathering based on historic data (Jensen and Rasmussen 2000; Demailly and Quirion 2008). The approach can even create welfare gains in a general equilibrium setting once tax distortions and carbon leakage are taken into account (Fischer and Fox 2007). My theoretical setting allows for a reconsideration of the cost of an updated allocation when firms are heterogeneous and in monopolistic competition, given that the previous studies all assume perfect competition (except Demailly and Quirion 2008). Monopolistic competition implies that the equilibrium price of allowances depends on their initial allocations, even if the allowances market is perfectly competitive. The reason is that free allowances in the presence of updated allocation constitute an output subsidy that partially corrects for insufficient output due to imperfect competition and has repercussions on individual emissions. In addition, the model evidences the cost of updating in terms of selection on the market, of the mass of active firms, and of the price of emissions. One motivation to address this debate is the fact that New Zealand implements an emissions trading scheme in which allocation is based on updated data, whereas since January 2013, free allowances in the EU ETS have been allocated according to historic performance. This paper aims at shedding some light on the economic impacts of these different policy designs, a topical issue as linking emissions trading schemes offers some promise in the context of difficult ongoing international climate negotiations.

Finally, this paper relates to the recent literature addressing environmental issues within the framework of the Melitz (2003) model. Li and Sun (2009) revisit the tax versus standard debate, whereas Yokoo (2009) proposes a novel channel for the Porter hypothesis through the selection of the most productive and most environmentally efficient firms following a rise in the emission tax. In the closest paper to the present one, Konishi and Tarui (2015) study the impacts of different rules for the initial allocation of emissions allowances (auction and several grandfathering approaches) on intra-industry reallocations in the long-run. My contributions with respect to this paper are threefold. First, I investigate a different rule governing free allocation, namely product-based benchmarking. Several emissions trading schemes already implement this rule, for instance the EU ETS since January 2013. It is inherently related to the existence of firm heterogeneity, and involves a reallocation of resources among firms even when they take the environmental policy as given. Then, I consider different designs of a cap-and-trade program pertaining to the scale of auction with respect to free allocation; again this corresponds to the characteristic of most emissions trading schemes currently in place that feature a combination of auction and free allocation. Finally, I use a Pareto firm productivity distribution. The case of this distribution has received particular attention in the literature, for its analytical convenience and empirical relevance (see Arkolakis *et al.* 2012). This assumption allows to obtain closed-form solutions for all, except one, the endogenous variables at the equilibrium. Thus, I am able to stress the separate competences of the cap on emissions and the initial allocation of allowances, and to highlight the economic cost of the strategic behavior of firms toward an environmental policy. Most importantly I evidence the role of firm heterogeneity in relation to the impacts of a change in the scale of free allocation. Recently, the Melitz (2003) model has also been called up to reassess the effect of trade integration on the environment, highlighting induced innovation and selection effects (Batrakova and Davies 2012; Cui *et al.* 2012; Forslid *et al.* 2014; Holladay 2014; Kreickemeier and Richter 2014).

The rest of the paper proceeds as follows. Section 2 presents the model. Section 3 describes the firms' production decision and strategic behavior toward the environmental policy. Section 4 solves the stationary general equilibrium. Section 5 analyzes the effects of the environmental policy. Section 6 concludes.

2 Set-up of the model

A dynamic model of a closed economy is developed. Time is discrete, and each period is labeled t.

2.1 Demand

The economy is populated by a representative infinitely lived consumer that inelastically supplies L units of labor. The consumer's preferences are given by a CES utility function U defined over a continuum of varieties of a differentiated good:

$$U_t = \left[\int_{\omega\in\Omega_t} q_t\left(\omega\right)^{\frac{\sigma-1}{\sigma}} d\omega\right]^{\frac{\sigma}{\sigma-1}}, \tag{1}$$

where $q\left(\omega\right)$ is the consumption of variety ω, Ω is the mass of varieties available, and $\sigma > 1$ is the constant elasticity of substitution between any two varieties. There is no capital, and the good can not be stored across periods. Thus, the representative consumer faces a static utility maximization problem in each period, resulting in the optimal consumption of variety ω in period t:

$$q_t\left(\omega\right) = \frac{R_t p_t\left(\omega\right)^{-\sigma}}{P_t^{1-\sigma}}, \tag{2}$$

where R denotes the economy's total expenditure, $p\left(\omega\right)$ is the consumer price of variety ω, and P is the price index corresponding to the CES aggregate of varieties Q, with $Q \equiv U$:

$$P_t = \left[\int_{\omega\in\Omega_t} p_t\left(\omega\right)^{1-\sigma} d\omega\right]^{\frac{1}{1-\sigma}}. \tag{3}$$

2.2 Production and emissions

There is a continuum of firms. Each one produces precisely one unique variety of the differentiated good under increasing returns to scale, with labor as the only production factor. All firms pay an identical fixed cost of production $f > 0$ in each period. They differ according to their marginal cost of production: firm specific time-invariant productivity φ is Pareto distributed over the support $(1, \infty)$ with the cumulative distribution function $G(\varphi) = 1 - \varphi^{-k}$. The shape parameter $k > 1$ reflects the inverse of the degree of productivity dispersion on the market (the lower the value of k, the higher the firm heterogeneity on the market).

Pollution arises as a by-product of the production of varieties. Following Copeland and Taylor (1994), firms' abatement activity is modeled as the possibility of diverting an endogenously determined share θ of labor from production activity to pollution abatement activity. As a consequence, firms adopt cleaner technologies by abating polluting emissions at the expense of labor input. Output q and emissions e of a firm with productivity φ in period t are then given by:

$$q_t(\varphi) = \varphi\; l_t(\varphi)\left[1 - \theta_t(\varphi)\right], \tag{4}$$

$$e_t(\varphi) = \left[1 - \theta_t(\varphi)\right]^{\alpha} q_t(\varphi). \tag{5}$$

l represents the variable amount of labor needed to produce q units. $(1-\theta)^{\alpha}$ is the pollution intensity of production. α is strictly positive, so that an increase in the share of labor assigned to abatement activities induces a decrease in the emission rate.[3] Furthermore, a higher α is associated with a lower emission intensity. From (5), it is clear that a firm has two non-exclusive options to reduce its emissions: it can either lower its production level, or reduce specific emissions. From (4) and (5) the production function can be formulated as:

$$q_t(\varphi) = \left[\varphi\; l_t(\varphi)\right]^{\frac{\alpha}{1+\alpha}} \left[e_t(\varphi)\right]^{\frac{1}{1+\alpha}}. \tag{6}$$

Polluting emissions now appear as an input contributing the share $1/(1+\alpha)$ to the production of varieties, with effective labor contributing the rest. As an input, emissions have a nonzero price p_e when an environmental policy, as detailed in the next subsection, is implemented. As firms operate in monopolistic competition, they do not consider the impacts of their decisions on aggregate variables, in the product as well as in the inputs markets; they consider as given the wage rate as well as the price of emissions. A firm's optimal demands for labor and emissions are such that the marginal productivity of each factor equals its price:

$$\frac{\alpha}{1+\alpha} e_t(\varphi)^{\frac{1}{1+\alpha}} \varphi^{\frac{\alpha}{1+\alpha}}\; l_t(\varphi)^{\frac{\alpha}{1+\alpha}-1} = w_t, \tag{7}$$

[3] Abatement activities present diminishing (respectively increasing) returns if $\alpha < 1$ (respectively $\alpha > 1$).

$$\frac{1}{1+\alpha} e_t(\varphi)^{\frac{1}{1+\alpha}-1} \left[\varphi \, l_t(\varphi)\right]^{\frac{\alpha}{1+\alpha}} = p_{e_t}. \tag{8}$$

Using these equations, the pollution intensity of a firm can be expressed as a function of its productivity and the relative price of inputs:

$$\left[1-\theta_t(\varphi)\right]^{\alpha} = \left(\frac{w_t}{\alpha p_{e_t} \varphi}\right)^{\frac{\alpha}{1+\alpha}}. \tag{9}$$

A more productive firm diverts a larger share of labor from production to emission abatement activities and exhibits a cleaner production process. This comes from the fact that as labor productivity rises, the relative cost of emissions with respect to effective labor increases, leading the firm to substitute labor for emissions in the production process. This result is supported by empirical studies demonstrating that, at the firm level, productivity and environmental performance in terms of pollution intensity of the production process are positively correlated (Shadbegian and Gray 2003, Cui *et al.* 2012, Forslid *et al.* 2014, Batrakova and Davies 2012).[4]

2.3 Environmental policy

Polluting emissions are regulated by a cap-and-trade program. Each period, the regulator defines a cap $\widehat{E}$ on the aggregate level of emissions and issues emission allowances in accordance to this limit: one allowance gives its holder the right to emit one unit of pollution. Allowances are either auctioned (share $1-B$ of the total amount $\widehat{E}$) or freely distributed to firms (share B). Once allocated, emission allowances can be freely traded among firms on a perfectly competitive market at the clearing price endogenously determined, p_e. This price is also the one at which auctioned allowances are sold. These assumptions are supported by evidence from the EU ETS experience.[5] At the end of each period, firms must back up each unit of emission they are responsible for with an allowance. Banking and borrowing of allowances across periods are not allowed in the model.

[4]Shadbegian and Gray (2003) find that, for 68 paper mills in the United States in 1985, a 10% higher total factor productivity is associated with a 2.5% lower air pollution emissions per unit of output. Cui *et al.* (2012) use US data for the years 2002, 2005 and 2008; they find, in particular, that a one percent increase in productivity leads to a 0.96 percent decrease in SO_2 emissions per value of sales. Forslid *et al.* (2014) use Swedish data and find that "the firm-level CO_2 emission intensity is negatively related to firm productivity". Batrakova and Davies (2012), using Irish data, find a negative effect of labor productivity on the ratio of energy use over sales.

[5]Perfect competition on the emission allowances market has been documented by Convery and Redmont (2007). The correlation between the prices of allowances auctioned and traded on the secondary market between February 2008 and April 2012 was higher than 0.99 (calculation of the author, data for auction prices from the UK Debt Management Office and European Energy Exchange, and for allowances traded on the secondary market from BlueNext).

Updated benchmarking is the prevailing rule for the initial allocation of free emission allowances to firms. More precisely, in period t, a firm with productivity φ receives the following quantity of free emissions allowances:

$$\widehat{e}_t(\varphi) = benchmark_{t-1} \times q_{t-1}(\varphi). \tag{10}$$

A firm's output decision in any period influences the quantity of allowances it receives in the next period. Moreover, as the reference period governing the allocation rule in t is period $t-1$, only the firms active during the latter period receive free allowances in t. In addition, there is a random shock occurring with probability $\gamma > 0$ at the end of each period that forces some firms to exit. As firm hit by this shock in t no longer receives free allowances in $t+1$.[6]

The product benchmark for period t is calculated as the arithmetic average emission intensity of the $b\%$ best performing firms in terms of emission intensity in period $t-1$.[7] Figure 1 illustrates this benchmark definition. As emission intensity is monotonically decreasing in productivity, the $b\%$ of firms with the lowest emission intensity in any period are the $b\%$ most productive firms in the industry. φ^b, the productivity of the marginal firm belonging to this group, is such that:

$$\int_{\varphi_{t-1}^b}^{\infty} \frac{dG(\varphi)}{1-G(\varphi_{t-1}^*)} d\varphi = b_{t-1} \qquad \Rightarrow \qquad \varphi_{t-1}^b = b_{t-1}^{-\frac{1}{k}} \varphi_{t-1}^*, \tag{11}$$

where φ^* is the lowest labor productivity level among active firms, and $\frac{dG(\varphi)}{1-G(\varphi^*)}$ is the distribution of productivity among them (the *ex-post* productivity distribution of active firms). Using the previously determined expression of the emission intensity in (9), the benchmark is:

$$\begin{aligned} benchmark_{t-1} &= \int_{\varphi_{t-1}^b}^{\infty} \left(\frac{w_{t-1}}{\alpha p_{e_{t-1}} \varphi}\right)^{\frac{\alpha}{1+\alpha}} \frac{dG(\varphi)}{1-G\left(\varphi_{t-1}^b\right)} d\varphi \\ &= \left(\frac{w_{t-1}}{\alpha p_{e_{t-1}}}\right)^{\frac{\alpha}{1+\alpha}} \frac{k(1+\alpha)}{k(1+\alpha)+\alpha} b_{t-1}^{\frac{\alpha}{k(1+\alpha)}} \left(\varphi_{t-1}^*\right)^{-\frac{\alpha}{1+\alpha}}. \end{aligned} \tag{12}$$

[6] On the treatment of firms entering and exiting the emissions trading scheme, the literature points out a trade-off between efficiency on the one hand, according to which new entrants should not get free allowances and allocation should not be conditioned on the continued economic operation, and common sense on the other hand (Ahman *et al.* 2007). Dardati (*forthcoming*) shows that differences across emissions trading schemes on this particular matter generate differences in investment, entry and exit decisions of firms, which have repercussions on aggregate output and prices.

[7] This definition matches that of the product benchmark implemented in the third phase of the EU ETS which started in January 2013 for a period of seven years: "the arithmetic average of the greenhouse gas performance of the 10% most greenhouse gas efficient installations in 2007 and 2008" (European Commission 2011a), performance "in terms of metric tons of CO_2 emitted per ton of product produced" (European Commission 2011b).

This benchmark corresponds to the emission intensity of a firm with productivity φ^e in period $t-1$:

$$\varphi_{t-1}^{e} = \left(\frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\right)^{-\frac{1+\alpha}{\alpha}} b_{t-1}^{-\frac{1}{k}} \varphi_{t-1}^{*}. \tag{13}$$

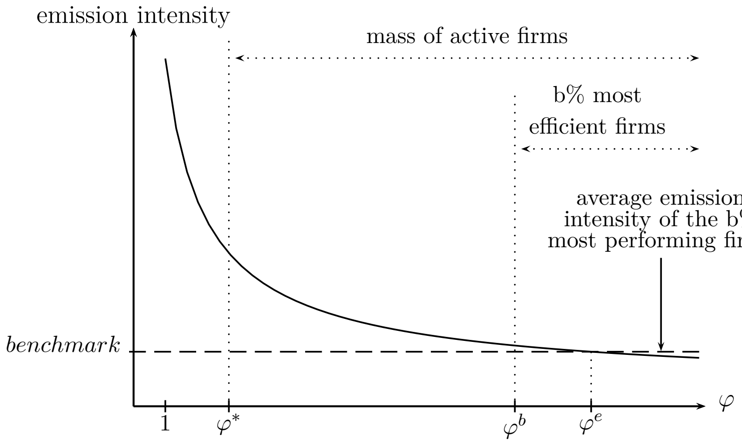

Figure 1: Determination of the benchmark

Finally it is notable that among the two elements of the cap-and-trade program regarding the allocation rule, B and b, only one is exogenously defined by the regulator; at equilibrium, there exists a relationship between these variables.

3 Firms' production decisions and strategic behavior toward the environmental policy

In each period t, the allocation rules governing the initial allocation of allowances in period $t+1$ are announced before firms decide on their output level. As a consequence, each firm is aware that its immediate output decision has a direct effect on the amount of free allowances it will receive in $t+1$, and hence on its individual profit in $t+1$. Assuming that there is no time discounting, a firms' objective in period t is:

$$\max_{q_t(\varphi)} \sum_{s=t}^{\infty} (1-\gamma)^{s-t} \pi_s(\varphi). \tag{14}$$

A firm's profit π depends on its status because a new entrant (subscript n) does not receive free allowances whereas an incumbent firm (subscript i) does:

$$\pi_t^n(\varphi) = p_t^n(\varphi) q_t^n(\varphi) - m_t(\varphi) q_t^n(\varphi) - w_t f, \tag{15}$$

$$\pi_t^i(\varphi) = p_t^i(\varphi) q_t^i(\varphi) - m_t(\varphi) q_t^i(\varphi) - w_t f + p_{e_t} \widehat{e}_t(\varphi), \tag{16}$$

where $m(\varphi)$ is the marginal cost of production of a firm with productivity φ:

$$m_t(\varphi) = \frac{1+\alpha}{\alpha^{\frac{\alpha}{1+\alpha}}} \left(\frac{w_t}{\varphi}\right)^{\frac{\alpha}{1+\alpha}} p_{e_t}^{\frac{1}{1+\alpha}}. \tag{17}$$

The marginal cost of production is a combination of the price of effective labor, inversely related to a firm's productivity, and the price of emissions, common to all firms. The only difference between these profits is that the latter incorporates free emission allowances as a resource. Notably, the cost of buying an allowance to back up a unit of pollutant is identical to the opportunity cost of holding a free allowance, which could be sold on the allowances market at the same price.

Despite this profit function difference, new entrants and incumbents choose the same level of output in period t because the quantity of free allowances received in t is exogenously given for incumbents in this period and therefore plays no role in their decisions. Subscripts i and n are therefore dropped. Monopolistic competitive firms take aggregate demand as given and neglect the effect of individual decisions on the price index. Given the optimal demand (2), profit maximization yields this optimal pricing rule:

$$p_t(\varphi) = \underbrace{\frac{\sigma}{\sigma-1}}_{\text{mark-up}} \times \underbrace{m_t(\varphi)}_{\text{marginal cost of production}} \times \underbrace{\left[1 - \frac{p_{e_{t+1}}}{p_{e_t}} \frac{k(1-\gamma)}{k(1+\alpha)+\alpha} b_t^{\frac{\alpha}{k(1+\alpha)}} \left(\frac{\varphi_t^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}\right]}_{\text{environmental policy strategic behavior}}. \tag{18}$$

This price is assumed to be strictly positive, and it corresponds to a mark-up charged over what can be called the net marginal cost of production: the marginal cost of production lowered by the value of free allowances to be received in the next period. This latter component of the price disappears when firms do not consider the impact of current output decisions on the next period profit, which is the case, for instance, when they are not informed about the rules for future free allocation; the maximization program and optimal price in this case are presented in appendix A. Taking into account future profits when deciding on current output therefore creates incentives for a firm to set a lower price to increase production in the present and acquire more free emission allowances in the future, reflecting a strategic behavior of firms toward an environmental policy. Free allocation based on updated variables therefore acts as a direct output subsidy by lowering the marginal cost of production. Nevertheless, producing at a large scale in the present to acquire more allowances in the future comes at a price because it implies greater pollution and therefore the necessity of buying more allowances in the present, which increases the total cost of production. The ratio $p_{e_{t+1}}/p_{e_t}$ reflects the relative valuation of free allowances versus emissions cost: the higher the expected future price of allowances relative to their current price, the lower the net marginal cost of production will be, and the more intense the incentives to increase production in the present. Notably, the influence the environmental policy exerts on the

pricing rule intensifies with a firm's productivity. The reason is that as productivity rises, the firm's emission intensity moves closer to the benchmark, which lowers the cost of the strategic behavior (buying emissions allowances in the present).
A more productive firm has a lower marginal cost of production and consequently charges a lower price, thus facing a higher demand. The variety price and optimal output are therefore, respectively, decreasing and increasing functions of a firm's productivity. In this set-up, the increase in output in relation to an increase in productivity dominates the decrease in emission intensity in relation to an increase in the same variable, such that a firm's emissions increase with its productivity. In addition, as output rises with a firm's productivity, so does its allocation of free allowances. At the firm level, free allowances and emissions are then both increasing functions of productivity, the elasticity with respect to this variable being higher for the former because a firm's emission rate is a decreasing function of productivity. Firms have different positions on the allowances market: firms whose productivity φ is strictly inferior to φ^e have a positive net demand for allowances $(e(\varphi) > \widehat{e}(\varphi))$, whereas firms whose productivity φ is superior to φ^e are net sellers of allowances $(e(\varphi) \leq \widehat{e}(\varphi))$. As a consequence, a given environmental policy provides free resources to only the most productive firms.

4 Equilibrium

The complete timing of events in each period is presented in Figure 2. The environmental policy announcement in t consists of the presentation of the allocation rules for the period $t+1$. The equilibrium values are compared to the case in which the environmental policy announcement in t consists of the presentation of the allocation rules for the period t, therefore ruling out any strategic behavior of firms toward the environmental policy. To enter the market and start the production of a unique variety of the differentiated good, firms among an unbounded pool of identical potential entrants must pay a sunk entry cost wf_s. The model encompasses endogenous entry and exit decisions of firms, as well as an exogenous exit possibility due to the random shock at the end of each period.

This paper focuses on the stationary general equilibrium, in which the environmental policy and aggregate variables remain constant over time. Because each firm's productivity is time-invariant, the optimal per-period profit level from the second period of activity of any firm is constant over time, and the profit of a new entrant with productivity φ is identical whatever the period of entry. The value function of a firm with productivity φ entering in

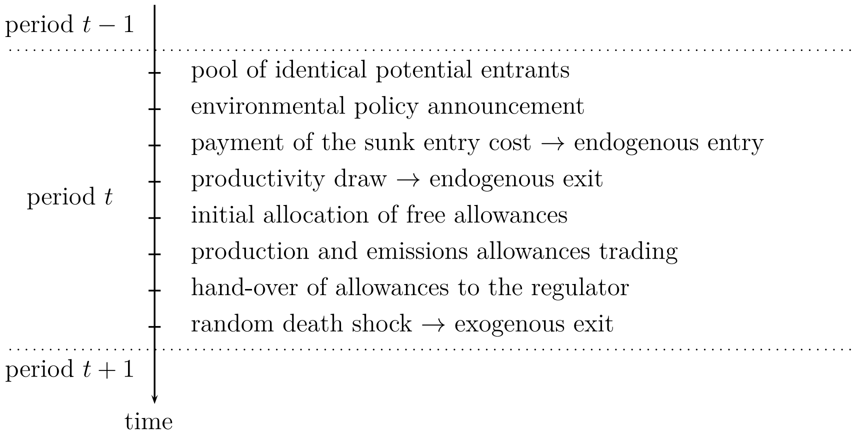

Figure 2: Timing of events

any period t is then:

$$\begin{aligned} v(\varphi) &= \max\left\{0, \pi^n(\varphi) + \sum_{s=t+1}^{\infty} (1-\gamma)^{s-t} \pi^i(\varphi)\right\} \\ &= \max\left\{0, \pi^n(\varphi) + \frac{1-\gamma}{\gamma}\pi^i(\varphi)\right\} \\ &= \max\left\{0, \frac{1}{\gamma}\left(\frac{r(\varphi)}{\sigma} - wf\right)\right\}, \end{aligned} \tag{19}$$

where $r(\varphi)$ is the per-period revenue of a firm with productivity φ, increasing with respect to this variable:

$$r(\varphi) = p(\varphi)\, q(\varphi) = \frac{R}{P^{1-\sigma}}\left[\frac{\sigma}{\sigma-1} m(\varphi)\right]^{1-\sigma}\left[1 - \frac{k(1-\gamma)}{k(1+\alpha)+\alpha} b^{\frac{\alpha}{k(1+\alpha)}} \left(\frac{\varphi^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}\right]^{1-\sigma}. \tag{20}$$

The higher the productivity, the lower the price charged and the higher the demand addressed to a firm. The quantity effect more than compensates for the price effect, such that the per-period revenue and hence the present value of profits are increasing functions of a firm's productivity.

Equilibrium conditions. The first condition that must be fulfilled at the general equilibrium is the zero cutoff profit condition, which is associated with the endogenous exit decision of a firm. This condition states that firms drawing a productivity below the threshold φ^* immediately choose to exit as maintaining production would yield a negative present value of profits:

$$\frac{r(\varphi^*)}{\sigma} - wf = 0, \tag{21}$$

where φ^* is the lowest productivity level among active firms.
The free entry condition, associated to the endogenous entry decision of a prospective entrant,

ensures that the present value of expected profits if the firm enters the market is driven to the sunk entry cost:

$$[1 - G(\varphi^*)] \frac{\overline{\pi}}{\gamma} = w f_s, \tag{22}$$

where $\overline{\pi}$ is the average per-period profit defined as:

$$\begin{aligned} \overline{\pi} &= \int_{\varphi^*}^{\infty} \left(\gamma \pi^n(\varphi) + (1-\gamma)\, \pi^i(\varphi)\right) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi \\ &= \int_{\varphi^*}^{\infty} \left(\frac{r(\varphi)}{\sigma} - wf\right) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi. \end{aligned} \tag{23}$$

$\overline{\pi}/\gamma$ is the present value of the average per-period profits, and $1 - G(\varphi^*)$ is the ex-ante probability of successful entry. Intuitively, if selection on the market is difficult (i.e., that φ^* is high) firms must expect a high average per-period profit to decide to pay the sunk cost.
At the general equilibrium, labor demand must be equal to the inelastic labor supply L:

$$L = f_s M_s + M \int_{\varphi^*}^{\infty} l(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi + fM. \tag{24}$$

The first component of labor demand corresponds to the sunk entry cost paid by a mass of firms, M_s. At the stationary equilibrium, the mass of active firms, M, is constant, which implies that the mass of active firms hit by the exogenous death shock at the end of any period must be replaced by an equal mass of successful new entrants at the beginning of the next period:

$$\gamma M = [1 - G(\varphi^*)]\, M_s. \tag{25}$$

Labor involved in performing production and abatement activities for active firms is the second component of labor demand, and labor corresponding to the fixed cost of production is the third component.
Two equilibrium conditions relate to emissions allowances. First, the aggregate level of emissions E must be equal to the cap set by the regulator $\widehat{E}$:

$$E = \widehat{E} \qquad \text{where} \qquad E = M \times \int_{\varphi^*}^{\infty} e(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi. \tag{26}$$

Second, the aggregate number of allowances freely allocated to incumbent firms according to the benchmark definition must be equal to the amount of free allowances decided by the regulator:

$$(1-\gamma)\, M \times \int_{\varphi^*}^{\infty} \widehat{e}(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi = B\widehat{E}. \tag{27}$$

Equilibrium values. Equations (21) to (27) comprise the six equilibrium conditions necessary to be solved for the six unknowns: p_e, φ^*, $\overline{\pi}$, M, M_s, and one environmental policy dimension endogenously determined, either b or B. The model is solved using relationships between aggregate and average variables: $\Pi = M\overline{\pi}$ and $R = M\overline{r}$ with Π the aggregate profit and $\overline{r}$ the average revenue. It also makes use of the fact that the aggregate expenditure and revenue of the economy must match the representative consumer's income. The consumer inelastically supplies L units of labor and owns a fund made of all active firms in the economy that distributes dividends. The consumer's resources are the sum of the labor income, the aggregate profit net of the investment in new firms, and the revenues from auctions of allowances. The stability condition and the free entry condition reveal that the sunk entry cost is exactly covered by the aggregate profit Π: $wf_sM_s = \Pi$. As the aggregate profit exactly covers the sunk entry cost for new entrants, the aggregate expenditure and revenue is:

$$R = wL + p_e\,(1 - B)\,\widehat{E}. \tag{28}$$

Unfortunately, the definition of the average profit includes the following integral I, which is not analytically solvable:

$$I = \int_{\varphi^*}^{\infty} \varphi^{\frac{\alpha(\sigma-1)}{1+\alpha}} \left[1 - \frac{k\,(1-\gamma)}{k\,(1+\alpha)+\alpha} b^{\frac{\alpha}{k(1+\alpha)}} \left(\frac{\varphi^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}\right]^{1-\sigma} \frac{dG\,(\varphi)}{1 - G\,(\varphi^*)} d\varphi. \tag{29}$$

As a consequence, I can consider only the case in which B is exogenously determined without being in a position to retrieve the relation between the two dimensions of the environmental policy regarding the free allowances, b and B. The five endogenous variables that can be expressed in terms of model parameters and the environmental policy instruments B and $\widehat{E}$, with the wage rate w serving as the numeraire, are:

$$p_e = \frac{(\sigma-1)\,L}{(1+\alpha\sigma-B)\,\widehat{E}}, \tag{30}$$

$$\varphi^* = \left(\frac{f}{\gamma f_s} \frac{\alpha\,(\sigma-1)}{k\,(1+\alpha) - \alpha\,(\sigma-1) - kB}\right)^{\frac{1}{k}}, \tag{31}$$

$$\overline{\pi} = \frac{\alpha\,(\sigma-1)\,f}{k\,(1+\alpha) - \alpha\,(\sigma-1) - kB}, \tag{32}$$

$$M = \frac{L}{kf} \frac{k\,(1+\alpha) - \alpha\,(\sigma-1) - kB}{1+\alpha\sigma-B}, \tag{33}$$

$$M_s = \frac{L}{kf_s} \frac{\alpha\,(\sigma-1)}{1+\alpha\sigma-B}, \tag{34}$$

assuming that $k\,(1+\alpha) - \alpha\,(\sigma-1) - kB > 0$. The aggregate variables at the equilibrium, also in terms of model parameters and the environmental policy instruments B and $\widehat{E}$, are:

$$R = \frac{\sigma\,(1+\alpha-B)\,L}{1+\alpha\sigma-B}, \tag{35}$$

$$\Pi = \frac{\alpha\left(\sigma-1\right)L}{k\left(1+\alpha\sigma-B\right)}. \tag{36}$$

5 Effects of the environmental policy

Comparative statics on the previous stationary equilibrium variables brings out the effects of the environmental policy. I first present the consequences of a modification of the cap on emissions and then present the impacts of a change in the initial allocation of allowances.

5.1 The cap on emissions

The regulator sets a lower cap to improve environmental quality. That action creates a scarcity of emission allowances that naturally translates into a rise in their price p_e:

$$\frac{\delta p_e}{\delta \widehat{E}} < 0. \tag{37}$$

The aggregate level of emissions adapts to the new cap through two channels. First, as the cost of emissions relative to labor increases, firms undertake additional abatement activities: their emission intensity decreases. Second, firms react to the increase in their marginal cost of production by charging a higher price and reducing their output. Nevertheless, all firms are uniformly impacted by the emission price increase, so they uniformly react by raising the product price. As a result, the relative demand for any two varieties is unmodified. This general equilibrium effect mitigates the initial individual output decrease, such that the firm's revenue is eventually independent of the price of allowances and the cap on emissions. As a consequence, the cap does not influence firms' entry and exit decisions, nor the aggregate economic variables. Therefore, the aggregate level of emissions adapts to a lower cap only through a technique effect (a decrease in the emission intensity of all firms) and a scale effect operating at only the intensive margin (a decrease in the individual output of all firms forming a constant mass of polluters). Proposition 1 summarizes the effects of a change in the cap on emissions.

Proposition 1. *On the one hand, the cap on emissions impacts the environmental quality through a technique effect and a scale effect at the intensive margin. On the other hand, the cap on emissions has no economic impact.*

5.2 The initial allocation of allowances

Market structure. Aggregate emissions increase with the share of allowances allocated for free because firms act to receive these resources in the future by scaling up their outputs in the present. When the cap on emissions is constant, the price of allowances increases to neutralize this initial rise in emissions:

$$\frac{\delta p_e}{\delta B} > 0. \tag{38}$$

The initial allocation of allowances affects their price, even if the market in which they are traded is perfectly competitive, because firms are in monopolistic competition in the market for the varieties of the differentiated good.[8]. Free allocation acts as a subsidy that corrects for the insufficient output due to imperfect competition, which has repercussions on the firms' emissions. When more allowances are given for free, revenues from auctions of allowances that are rebated to the consumer decrease (even if their price increases), and so does the aggregate revenue:

$$\frac{\delta R}{\delta B} < 0. \tag{39}$$

Resources that are removed from the consumer accrue to the firms, but firms do not equally benefit from them. Because of the benchmark definition, the strategic behavior toward the environmental policy intensifies with a firm's productivity. When more allowances are given for free, they are reallocated among firms toward the most productive ones. As a consequence, some firms are no longer productive enough to remain on the market: they choose to exit, and selection on the market is more intense. A higher average per-period profit matches this lower probability of successful entry into the market, such that the present value of expected profit is unchanged:

$$\frac{\delta \varphi^*}{\delta B} > 0 \qquad \text{and} \qquad \frac{\delta \overline{\pi}}{\delta B} > 0. \tag{40}$$

A lower aggregate revenue translates into lower labor demands from potential entrants and from active firms. Preserving the equilibrium in the labor market requires that the mass of active firms contracts to increase the aggregate profit and compensate for the initial decrease in labor demand:

$$\frac{\delta M}{\delta B} < 0 \qquad \text{and} \qquad \frac{\delta \Pi}{\delta B} > 0. \tag{41}$$

The mass of firms endogenously choosing to enter the market increases as a result of larger profit opportunities:

$$\frac{\delta M_s}{\delta B} > 0. \tag{42}$$

As market entry is more selective, the mass of firms endogenously choosing to exit the market after the productivity draw and before starting to produce also expands. Eventually, there are fewer firms in the market, which are on average more productive.

[8] When varieties are perfectly substitutable, the price of allowances does no longer vary with the share of allowances allocated for free:

$$\lim_{\sigma \to \infty} p_e = \frac{L}{\alpha \widehat{E}}$$

The scale of free allocation impacts the market structure through the reallocation of resources it induces among firms, in favor of the most productive ones. This impact therefore accentuates with the degree of firm heterogeneity. When heterogeneity is high, larger, more polluting firms represent a high fraction of firms and the reallocation effect is strong. Conversely, when heterogeneity is low, a high fraction of firms is concentrated toward the minimum productivity cutoff, such that the reallocation of resources is limited. Taking into account the degree of heterogeneity is crucial when determining the scale of free allocation of allowances. Proposition 2 summarizes the effects of a change in the initial allocation of allowances on the economy in relation to firm heterogeneity.

Proposition 2. *In a cap-and-trade program, the initial allocation of allowances affects the market structure through a reallocation of resources effect. The degree of firm heterogeneity determines the scale of the reallocation of resources among firms, and the magnitude of the impact of the initial allocation on the economy.*

Strategic behavior of firms. The strategic behavior of firms toward the environmental policy imposes an economic cost to achieve an environmental objective. This effect can be evidenced by comparing the previous equilibrium values with the ones resulting when firms do not take into account future profits in the current output decision presented in Appendix B. First, as it induces firms to increase their output and emissions, the strategic behavior translates into a higher price of allowances for a given cap on emissions. Second, the reallocation of resources among firms that occurs because of the benchmark definition accentuates with the strategic behavior of the firms: the productivity cutoff and the average per-period profit are higher, and the mass of firms is lower in the strategic case than in the non-strategic one. The difference between the equilibrium values of these variables in the two scenarios, which is equal to zero when all allowances are auctioned, deepens with the scale of free allocation because it intensifies the strategic behavior of firms.
The comparison of aggregate profits does not bring a similar clear-cut result: the difference between the strategic and non-strategic values has the sign of $B\left[B-\alpha\left(\sigma-1\right)\right]$. Again, there is no difference between equilibrium values of the aggregate profit when all allowances are auctioned and the strategic behavior of firms cannot be expressed. For any other scale of auction of allowances, the values differ: as long as $\alpha\left(\sigma-1\right)>1$, the aggregate profit is higher in the non-strategic case than in the strategic one.

Winners and losers. Clearly, firms that are no longer productive enough to remain in the market lose from an expansion of free allocation. Using the zero cutoff profit condition, the average profit can be written as:

$$\overline{\pi}=f\left(\varphi^{*}\right)^{-\frac{\alpha(\sigma-1)}{1+\alpha}}\left(1-\frac{k\left(1-\gamma\right)}{k\left(1+\alpha\right)+\alpha}b^{\frac{\alpha}{k(1+\alpha)}}\right)^{\sigma-1}I-f. \tag{43}$$

At the equilibrium, this expression must match the one given in (32). Equating and differentiating these two expressions with respect to b and B allows for the recovery of the following derivative of b with respect to B:

$$\frac{db}{dB} = \frac{kb}{k(1+\alpha) - \alpha(\sigma-1) - kB}\left(1 - \frac{k(1-\gamma)}{k(1+\alpha)+\alpha} b^{\frac{\alpha}{k(1+\alpha)}}\right) \times \left(\frac{B}{1+\alpha} - \frac{k(1-\gamma)}{k(1+\alpha)+\alpha} b^{\frac{\alpha}{k(1+\alpha)}}\right)^{-1}. \tag{44}$$

The first two terms are positive, so the derivative has the sign of the last term in parentheses. Interestingly, this last term equals zero in the non-strategic case (see (A8)). On the one hand, $db/dB \geq 0$ if the subset of firms defining the benchmark is smaller in the strategic case for a given level of B: as individual firms pollute more due to their strategic behavior, the benchmark must be higher. In that case, an increase in free allocation translates into a less strict benchmark and only the most productive firms win from this policy change. On the other hand, $db/dB < 0$ if the subset of firms defining the benchmark is larger in the non-strategic case for a given level of B: as firms are on average more productive and the price of emissions is higher due to their strategic behavior, their emission intensity is lower; thus, the severity of the benchmark can also be reduced. In this case, an increase in free allocation translates into a stricter benchmark, and all firms lose from this policy change.

Environmental quality. As the environmental quality is entirely defined by the cap on emissions, a change in the initial allocation of allowances has no environmental impact. Nonetheless, this impact can be decomposed into five distinct effects, all nonzero: a scale effect at the extensive and intensive margins, a technique effect, a composition effect, and a selection effect. The aggregate level of emissions is calculated as:

$$E = M \times \int_{\varphi^*}^{\infty} \underbrace{q(\varphi)}_{\text{output}} \times \underbrace{[1-\theta(\varphi)]^{\alpha}}_{\text{emission intensity}} \times \underbrace{\frac{dG(\varphi)}{1-G(\varphi^*)}}_{\text{distribution}} d\varphi. \tag{45}$$

Noting $i(\varphi)$, the firm's emission intensity, and $D(\varphi)$, the distribution, the derivative of aggregate emissions with respect to B brings the five previously mentioned effects out:

$$\begin{aligned}
\frac{\delta E}{\delta B} = & \frac{\delta M}{\delta B} \times \int_{\varphi^*}^{\infty} q(\varphi) \times i(\varphi) \times D(\varphi)\, d\varphi && \textit{(scale effect at the extensive margin)} \\
& + M \times \int_{\varphi^*}^{\infty} \frac{\delta q(\varphi)}{\delta B} \times i(\varphi) \times D(\varphi)\, d\varphi && \textit{(scale effect at the intensive margin)} \\
& + M \times \int_{\varphi^*}^{\infty} q(\varphi) \times \frac{\delta i(\varphi)}{\delta B} \times D(\varphi)\, d\varphi && \textit{(technique effect)} \\
& + M \times \int_{\varphi^*}^{\infty} q(\varphi) \times i(\varphi) \times \frac{\delta D(\varphi)}{\delta B} d\varphi && \textit{(composition effect)} \\
& - M \times \frac{\delta \varphi^*}{\delta B} \times q(\varphi^*) \times i(\varphi^*) \times D(\varphi^*). && \textit{(selection effect)}
\end{aligned} \tag{46}$$

The scale effect can be decomposed into an extensive (first term) and an intensive margin (second term). The first one is negative (the mass of firms decreases following an expansion of free allocation), whereas the sign of the second one is undetermined as it depends on the ambiguous effect of B on b. The technique effect (third term) is negative, as the increase in the emission price following a reduction in auctioning prompts an increase in abatement activities. The fourth term is positive and corresponds to the composition effect. The last term reflects a selection effect: selection on the market is more intense when more allowances are allocated for free, which tends to decrease emissions.

6 Conclusion

The study described herein develops a model of heterogeneous firms in monopolistic competition whose activity generates pollution regulated by a cap-and-trade program. The first policy implication of the model is that the environmental and economic issues can be separately addressed by a cap-and-trade program. On the one hand, the level of the cap on emissions has no effect on the market structure: in particular, the marginal productivity cutoff and the mass of active firms are independent of the environmental objective of the emissions trading scheme. Achieving an environmental objective through the implementation of a cap-and-trade program can be done without consequences to firms' profits and decisions to enter or remain in the market. On the other hand, the initial allocation of allowances has no impact on the environmental quality but impacts firms' entry and exit decisions and aggregate economic variables. Auctioning a lower share of allowances induces a reallocation of resources toward the most productive firms, reflected in an increase in the productivity level above which a firm is productive enough to stay on the market, and a reduction in the mass of active firms. The least productive firms must exit the market and clearly lose from this policy change.

The level of heterogeneity among firms in the market impacts the effect of a change in free allocation on the economy because the reallocation of resources intensifies with heterogeneity. The second policy implication of the model is therefore that paying attention to this characteristic of the market matters when choosing the method for the initial allocation of allowances.

Finally, the timing for announcing the rule for free allocation, when it is based on updated variables, can generate a strategic behavior of firms toward an environmental policy that raises the economic cost of achieving an environmental objective. Such a cost is reflected in a higher price of emission allowances, a lower mass of firms, and a more intense selection on the market.

Appendix A Firm's production decision in the absence of a strategic behavior of firms toward the environmental policy

When firms do not know that their current decisions have an impact on future emission allowances allocation, and accordingly on future profits, each period they face a static problem which is to choose the output level maximizing their profits:

$$\max_{q_t(\varphi)} \ \pi_t(\varphi), \tag{A1}$$

where π is given by (15) for a new entrant and by (16) for a firm that was already active in $t-1$. Profits maximization yields the usual optimal pricing rule:

$$p_t(\varphi) = \underbrace{\frac{\sigma}{\sigma-1}}_{\text{mark-up}} \underbrace{\frac{1+\alpha}{\alpha^{\frac{\alpha}{1+\alpha}}} \left(\frac{w_t}{\varphi}\right)^{\frac{\alpha}{1+\alpha}} p_{e_t}^{\frac{1}{1+\alpha}}}_{\text{marginal cost of production}}. \tag{A2}$$

Appendix B Equilibrium in the absence of a strategic behavior of firms toward the environmental policy

The equilibrium values of endogenous and aggregate variables in terms of B and $\widehat{E}$, using w as the numeraire, are:

$$p_e = \frac{(\sigma-1)L}{[1+\alpha\sigma+(\sigma-1)B]\widehat{E}} \quad \Rightarrow \quad \frac{\delta p_e}{\delta \widehat{E}} < 0 \text{ and } \frac{\delta p_e}{\delta B} < 0, \tag{A3}$$

$$\varphi^* = \left(\frac{f}{\gamma f_s} \frac{\alpha(\sigma-1)\left(1+B^{\frac{\sigma}{1+\alpha}}\right)}{k(1+\alpha)-\alpha(\sigma-1)+B^{\frac{\sigma-1}{1+\alpha}}[k(1+\alpha)-\alpha\sigma]}\right)^{\frac{1}{k}} \quad \Rightarrow \quad \frac{\delta\varphi^*}{\delta B} > 0, \tag{A4}$$

$$\overline{\pi} = \frac{\alpha(\sigma-1)\left(1+B^{\frac{\sigma}{1+\alpha}}\right)f}{k(1+\alpha)-\alpha(\sigma-1)+B^{\frac{\sigma-1}{1+\alpha}}[k(1+\alpha)-\alpha\sigma]} \quad \Rightarrow \quad \frac{\delta\overline{\pi}}{\delta B} > 0, \tag{A5}$$

$$\begin{aligned} M &= \frac{L}{kf}\frac{k(1+\alpha)-\alpha(\sigma-1)+B^{\frac{\sigma-1}{1+\alpha}}[k(1+\alpha)-\alpha\sigma]}{1+\alpha\sigma+(\sigma-1)B} \\ &\Rightarrow \begin{cases} \frac{\delta M}{\delta B} < 0 & \text{if } k < \frac{\alpha\sigma(\sigma-1)+1+\alpha}{(1+\alpha)(\sigma-1)} \\ \frac{\delta M}{\delta B} \geq 0 & \text{if } k \geq \frac{\alpha\sigma(\sigma-1)+1+\alpha}{(1+\alpha)(\sigma-1)} \end{cases}, \end{aligned} \tag{A6}$$

$$M_s = \frac{\alpha(\sigma-1)\left(1+B^{\frac{\sigma}{1+\alpha}}\right)L}{(1+\alpha\sigma+(\sigma-1)B)kf_s} \quad \Rightarrow \quad \frac{\delta M_s}{\delta B} > 0, \tag{A7}$$

$$b = \left(\frac{B}{1+\alpha}\frac{k(1+\alpha)+\alpha}{k(1-\gamma)}\right)^{\frac{k(1+\alpha)}{\alpha}} \quad \Rightarrow \quad \frac{\delta b}{\delta B} > 0, \tag{A8}$$

$$R = \frac{\sigma(1+\alpha)L}{1+\alpha\sigma+(\sigma-1)B} \quad \Rightarrow \quad \frac{\delta R}{\delta B} < 0, \tag{A9}$$

$$\Pi = \frac{\alpha(\sigma-1)\left(1+B\frac{\sigma}{1+\alpha}\right)L}{[1+\alpha\sigma+(\sigma-1)B]k} \quad \Rightarrow \quad \frac{\delta\Pi}{\delta B} > 0, \tag{A10}$$

with $k(1+\alpha)-\alpha\sigma > 0$.

References

Ahman, M., Burtraw, D., Kruger, J., and Zetterberg, L. (2007). A Ten-Year Rule to guide the allocation of EU emission allowances. *Energy Policy*, 35(3):1718–1730.

Arkolakis, C., Costinot, A., and Rodriguez-Clare, A. (2012). New Trade Models, Same Old Gains? *American Economic Review*, 102(1):94–130.

Batrakova, S. and Davies, R. (2012). Is there an environmental benefit to being an exporter? Evidence from firm level data. *Review of World Economics*, 148(3):449–474.

Ben-David, S., Brookshire, D. S., Burness, S., McKee, M., and Schmidt, C. (1999). Heterogeneity, Irreversible Production Choices, and Efficiency in Emission Permit Markets. *Journal of Environmental Economics and Management*, 38(2):176–194.

Böhringer, C. and Lange, A. (2005). On the design of optimal grandfathering schemes for emission allowances. *European Economic Review*, 49(8):2041–2055.

Convery, F. J. and Redmond, L. (2007). Market and Price Developments in the European Union Emissions Trading Scheme. *Review of Environmental Economics and Policy*, 1(1):88–111.

Copeland, B. R. and Taylor, M. S. (1994). North-south trade and the environment. *The Quarterly Journal of Economics*, 109(3):755–87.

Cramton, P. and Kerr, S. (2002). Tradeable carbon permit auctions: How and why to auction not grandfather. *Energy Policy*, 30(4):333–345.

Cui, J., Lapan, H., and Moschini, G. (2012). Are Exporters More Environmentally Friendly than Non-Exporters? Theory and Evidence. Staff General Research Papers 35549, Iowa State University, Department of Economics.

Dales, J. H. (1968). *Pollution Property and Prices - An essay in policy-making and economics.* University of Toronto Press.

Dardati, E. Pollution Permit Systems and Firm Dynamics: How Does the Allocation Scheme Matter? *International Economic Review.* Forthcoming.

Demailly, D. and Quirion, P. (2008). European Emission Trading Scheme and competitiveness: A case study on the iron and steel industry. *Energy Economics*, 30(4):2009–2027.

European Commission (2011a). Commission Decision determining transitional union-wide rules for harmonised free allocation of emission allowances.

European Commission (2011b). Guidance Document n°1 on the harmonized free allocation methodology for the EU-ETS post 2012.

Fischer, C. and Fox, A. K. (2007). Output-Based Allocation of Emissions Permits for Mitigating Tax and Trade Interactions. *Land Economics*, 83(4):575–599.

Forslid, R., Okubo, T., and Ulltveit-Moe, K.-H. (2014). Why are Firms that Export Cleaner? International Trade and CO_2 Emissions. CESifo Working Paper Series 4817, CESifo Group Munich.

Goulder, L. H. and Parry, I. W. H. (2008). Instrument Choice in Environmental Policy. *Review of Environmental Economics and Policy*, 2(2):152–174.

Groenenberg, H. and Blok, K. (2002). Benchmark-based emission allocation in a cap-and-trade system. *Climate Policy*, 2(1):105 – 109.

Holladay, J. S. (2014). Exporters and the Environment. Mimeo.

International Carbon Action Partnership (ICAP) (2015). Emissions trading worldwide.

Jensen, J. and Rasmussen, T. N. (2000). Allocation of CO2 Emissions Permits: A General Equilibrium Analysis of Policy Instruments. *Journal of Environmental Economics and Management*, 40(2):111–136.

Konishi, Y. and Tarui, N. (2015). Emissions Trading, Firm Heterogeneity, and Intra-industry Reallocations in the Long Run. *Journal of the Association of Environmental and Resource Economists*, 2(1):1 – 42.

Kreickemeier, U. and Richter, P. M. (2014). Trade and the Environment: The Role of Firm Heterogeneity. *Review of International Economics*, 22(2):209–225.

Li, Z. and Sun, J. (2011). Environmental Policy with Heterogeneous Plants. Mimeo.

Melitz, M. J. (2003). The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity. *Econometrica*, 71(6):1695–1725.

Newell, R. G. and Stavins, R. N. (2003). Cost Heterogeneity and the Potential Savings from Market-Based Policies. *Journal of Regulatory Economics*, 23(1):43–59.

Rosendahl, K. E. (2008). Incentives and prices in an emissions trading scheme with updating. *Journal of Environmental Economics and Management*, 56(1):69–82.

Rosendahl, K. E. and Storrøsten, H. B. (2011). Emissions Trading with Updated Allocation: Effects on Entry/Exit and Distribution. *Environmental & Resource Economics*, 49(2):243–261.

Sartzetakis, E. (1997). Tradeable emission permits regulations in the presence of imperfectly competitive product markets: Welfare implications. *Environmental & Resource Economics*, 9(1):65–81.

Shadbegian, R. J. and Gray, W. B. (2003). What Determines Environmental Performance at Paper Mills? The Roles of Abatement Spending, Regulation, and Efficiency. *The B.E. Journal of Economic Analysis & Policy*, topics.3(1):15.

Yokoo, H.-F. (2009). Heterogeneous Firms, the Porter Hypothesis and Trade. Kyoto Sustainability Initiative - Communications 2009-001, Kyoto University.