Heterogeneous firms in a cap-and-trade program

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Work in progress - Comments welcome

April 2013

Abstract The paper develops a model of heterogeneous firms in monopolistic competition whose activity generates pollution regulated by a cap-and-trade program. The model first shows that in general equilibrium the level of the cap on emissions has no effect on firms' profits and decision to remain on the market. However, the initial allocation of allowances 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. The degree of heterogeneity among firms is decisive with respect to the effect of this policy change on the mass of active firms: when heterogeneity is high the reallocation effect is strong enough to generate a reduction in the mass of active firms. Finally, when firms are informed about the allocation rules, they develop a strategic behavior toward the environmental policy resulting in the increase in the cost of achieving the environmental objective.

Keywords Emissions trading, heterogeneous firms, monopolistic competition

JEL classification D43 - H23 - Q28

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1 Introduction

In 1997 the Kyoto Protocol defined a timetable and quantified greenhouse gas (GHG) emissions limits for 38 industrialized countries and the European Union in order to fight climate change. It also introduced three market based mechanisms amounting to transfers of emissions quotas across countries, a method that should lower the cost of achieving the objective of a 5% reduction in GHG emissions over the period 2008-2012 compared to 1990 levels (Springer, 2003). Emissions trading, an idea that goes back to Dales (1968), is today the cornerstone of climate change policies and proposals in many countries through the implementation of cap-and-trade programs: a cap is defined on the total amount of certain pollutants that can be emitted; emission allowances are issued in accordance to this cap and are allocated to economic agents who can trade them on a dedicated market; finally, at the end of each trading period, regulated agents must surrender as many allowances as emissions they are responsible for[1].

This paper aims at analyzing the economic impacts of a cap-and-trade program when firms are heterogeneous and in monopolistic competition. Firm heterogeneity is key to understand the working of trade in emissions allowances, as well as to determine the impact on firms' profits and to identify the winners and losers of different policy designs. I build on the framework developed by Melitz (2003) featuring heterogeneous firms in terms of labor productivity, in monopolistic competition, with free entry and exit. Their activity generates pollution, an externality regulated by a cap-and-trade program within a closed economy. The initial allocation of allowances is a crucial issue regarding the design of this type of environmental policy. The regulator has to decide first on the relative shares of allowances to be auctioned or given for free, and next on the rules governing free allocation. In the model, free allowances are allocated to firms following an updated benchmarking approach: the average emission intensity of a subset of firms is calculated, and a firm's free allocation is then determined by multiplying this benchmark by its production (Groenenberg and Blok, 2002). The allocation is revised every period to take into account changes in production and benchmark values, as in the New Zealand emissions trading scheme.

The paper shows that the two dimensions of the cap-and-trade program, the cap and the initial allocation, have different implications. On the one hand, the environmental

[1] A mandatory emissions trading scheme covering one or more GHG is currently operating in 32 countries, either at the state level in the United States, at the national level in New Zealand or at the regional level in the European Union. Other schemes are scheduled to be launched in California and 11 Canadian provinces and US states in 2013, and in Australia, China and Korea in 2015.

quality is entirely determined by the cap on emissions, whose level has no effect on firms' profits and decisions to remain on the market once general equilibrium effects are taken into account: the direct negative effect of a more stringent cap is exactly offset by the decrease in the real wage at the equilibrium. The aggregate level of emissions adapts to a new cap through a change in the emission intensity of production and in the firm-level output. On the other hand, given a cap level, the sharing rule of allowances between auctioning and free allocation has no environmental effect, but affects the structure of the market. Allocating more allowances for free reallocates resources toward the most productive firms, so that the productivity cutoff above which a firm decides to stay on the market and produce rises. Only the most productive firms gain from this policy change. The degree of heterogeneity matters when it comes to the determination of the effect on the mass of active firms: larger profit opportunities support an expansion of the mass of firms when heterogeneity is low whereas a more intense selection based on productivity implies a reduction in the mass of active firms when heterogeneity is high. The environmental policy in the form of a cap-and-trade program can therefore be separated into environmental and economic consequences.

Papers considering heterogeneity in a cap-and-trade framework generally look 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). This paper does not compare policy instruments, but investigates the effect of different designs of a cap-and-trade program in relation with firm heterogeneity. In addition the model features free entry and exit of firms on the market, decisions that are clearly overseen by firm heterogeneity, but are absent from the models developed in the previous references.

The paper is also related to the scarce literature addressing environmental issues within the framework of the Melitz (2003) model. Li and Sun (2009) revisit the tax versus standard debate, while 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. Very recently the Melitz (2003) model has also been used to reassess the effect of trade integration on the environment, through induced innovation and selection effects (Holladay, 2010; Batrakova and Davies, 2011; Forslid et al., 2011; Kreickemeier and Richter, 2012).

Finally, this paper is related to the literature debating on the choice between pure grandfathering and updated allocation. Indeed, even if many arguments support the auctioning of allowances - implementing the "polluter pays" principle, providing incentives for technological innovation, raising substantial revenues that can be used to reduce tax distortions (Groenenberg and Blok, 2002; Cramton and Kerr, 2002) - political feasibility can prevent the recourse to this method and promote free allocation of emission allowances, especially when regulated sectors face tough international competition. Experience in the United States and in the European Union shows that free allowances have traditionally been allocated according to the grandfathering approach based on historic emissions, which corresponds to a lump-sum transfer based on individual emissions during a period preceding the announcement and implementation of the emissions trading scheme[2]. As 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 does not account for changes in market conditions (Groenenberg and Blok, 2002; Bohringer and Lange, 2005) - 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. Bohringer and Lange (2005) show in a partial equilibrium setting that this is the case when free allowances are assigned proportionally to firms' production in previous periods as it represents a direct subsidy to production, but not if updating is based on past emissions performance. Rosendahl and Storrosten (2011) extend this result when there is free entry and exit of firms, while Rosendahl (2008) concludes that it no longer holds if marginal abatement costs rise too fast. Furthermore, updated grandfathering would reduce the adjustment costs to the environmental policy compared to grandfathering based on historic data (Jensen and Rasmussen, 2000; Demailly and Quirion, 2008), and can even create welfare gains in a general equilibrium setting once tax distortions and carbon leakage are taken into account (Fischer and Fox, 2007).

The theoretical setting this paper develops allows to reconsider the comparison between updated or not initial allocation when firms are heterogeneous and in monopolistic competition, as all the papers previously mentioned focusing on this issue assume perfect competition (except for Demailly and Quirion, 2008). This market structure implies that the equilibrium price of allowances depends on the way allowances are initially allocated, even if the allowances market is perfectly competitive, because firms exerts a market power over the production of their unique variety of the differentiated good. In addition, updating allowances allocation develops a strategic behavior of firms toward

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

the environmental policy which results in a higher cost of achieving the environmental objective: the emission allowance price is higher, the mass of firms lower and selection is more intense than when this strategic component is absent from the model. Addressing this debate is motivated by the fact that New Zealand implements an emissions trading scheme in which allocation is based on updated data, whereas under the third trading phase of the European Union emissions trading system starting in January 2013 free allowances are still allocated according to historic performance. This paper aims at shedding some light on the economic impacts of these different policy designs.

The rest of the paper proceeds as follows. Section 2 describes the New Zealand and European Union emissions trading schemes and their theoretical counterparts. Section 3 presents the model. Section 4 develops the resolution of the equilibrium when allocation rules are not notified to regulated firms, while section 5 deals with the notified case. Section 6 derives policy implications, and section 7 concludes.

2 The New Zealand and European Union emissions trading schemes

The European Union emissions trading system (EU ETS) is the largest cap-and-trade program ever implemented. Launched in 2005, it operates in 30 countries (the 27 EU member states, plus Iceland, Liechtenstein and Norway) and includes 11,000 installations accounting for almost half of EU's CO_2 emissions. During the first two trading phases (2005-2007 and 2008-2012), up to 96% of emissions allowances have been freely allocated to regulated firms according to the grandfathering method, based on historic emissions. The rest has been auctioned, the scope and frequency differing between countries. In Germany 9% of allowances issued by the government have been allocated through weekly auctions since 2010. In the United Kingdom, 30 auctions have been held between November 2008 and October 2012, 7% of allowances being allocated this way. Auctions have also been taking place in the Netherlands, Austria, Ireland and Hungary. Allocation rules have been heavily revised for the third trading phase of the EU ETS starting in January 2013 for a period of seven years. First, the system is now harmonized at the EU level: a unique cap annually declining to achieve in 2020 a 21% reduction of CO_2 emissions compared to 2005, and allocations of free allowances no longer decided through national allocations plans but resulting from rules enacted by the European Commission that apply to all participants. The system also seeks to be more efficient, with a substantial share of allowances to be auctioned: from 20% in 2013 up to 70% at the end of 2020. In addition free allowances are no longer grandfathered based on historic emissions at the installation level, but are determined by the benchmarking method at the product level. The product benchmark is defined as “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). The amount of allowances an installation receives in then obtained by multiplying the product benchmark by the installation’s historic activity level, defined as the mean annual production for the baseline period, the latter corresponding either to 2005-2008 or 2009-2010[3].

The New Zealand emissions trading scheme (NZ ETS) has started in 2008, a date which coincides with the beginning of the commitment period of the Kyoto Protocol, according to which the country has to keep its GHG emissions at their 1990 levels. The program covers the six GHG targeted by the Protocol, and provides free emissions allowances to industrial firms whose activities are emissions intensive and exposed to international trade, allocated according to the updated benchmarking approach: the allocative baseline for each product is multiplied by the firm’s current production[4].

The stylized versions of these schemes are built on the following assumptions. First, updated benchmarking is the method to allocate free allowances. The benchmark is defined as the average emission intensity of a subset of firms representing the most efficient ones, and both the benchmark and output data determining initial allocation in a period take values of the preceding period. To differentiate between the EU and the NZ ETS, I assume a different timing regarding the announcement of the environmental policy. In the first case, the regulator announces at the beginning of the period the rule determining the free allocation in the next period, introducing a strategic component in the current firm’s output decision; that scenario stands for the NZ ETS. In the second case, the regulator only announces at the beginning of the period the amount of allowances firms receive in this period, which prevents firms’ manipulation of the environmental policy and therefore approaches the EU ETS spirit. Second, firms in monopolistic competition do not take into account the impact of their decisions on aggregate variables and competitors’ decisions. Consequently I assume that firms take the benchmark as an

[3]This amount is only preliminary as it must be corrected by three factors: a carbon leakage exposure factor, a cross-sectoral correction factor ensuring that the total amount distributed corresponds to the amount defined by the regulator, and a linear annual reduction factor.

[4]Production data of the previous year is used to get a provisional allocation, adjusted in the next period based on actual production.

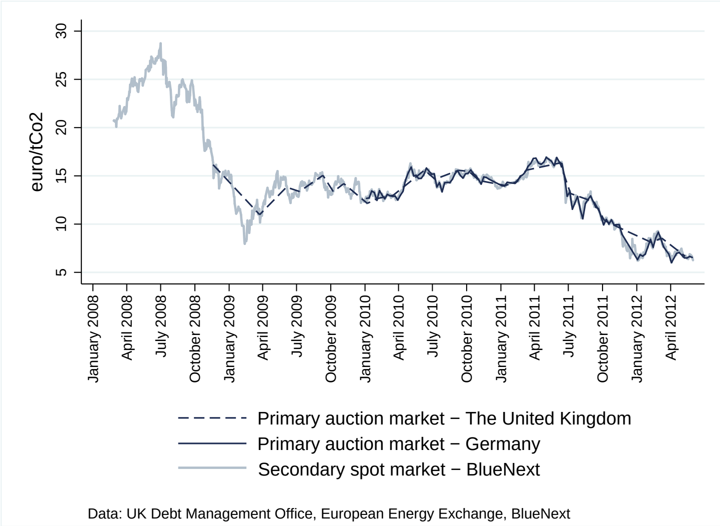

Figure 1: EU emission allowances price on primary and secondary markets (2008-2012)

exogenous variable of the environmental policy, and that competition on the emission allowances market is perfect, an assumption consistent with the EU ETS experience, as documented by Convery and Redmont (2007)[5]. In addition, as the correlation between the price of allowances auctioned and traded on the secondary market during the second phase of the EU ETS is higher than 0.99 (see figure 1), in the model I also assume a unique price of emission allowances, be they obtained through auctions or exchanges on the market.

Two potentially important issues that the paper ignores for the moment are the banking and borrowing of allowances across years, possible under the EU ETS, and the treatment of firms entering and exiting the ETS. On the latter, the literature points up 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 (2012) shows that differences across emissions trading schemes on this particular matter gener-

[5]On the first point, Mackenzie et al. (2008) show that relying on a relative performance mechanism introduces a distortion as firms interact with each other to influence the amount of free allowances they receive, a distortion absent from the present paper. On the second point, the literature has studied various aspects of imperfect competition on the emissions market. Let's cite for instance Hahn (1984) who determines the conditions to get an efficient initial allocation of allowances when one firm has market power; or Von der Fehr (1993) who shows that emission permits can become instruments of monopolization on the product market when firms have market power in the emission allowances market.

ate differences in investment, entry and exit decisions of firms, which have repercussions on aggregate output and prices. In the EU and NZ ETS firms no longer receive free allowances after closure; in addition in the European Union allowances are set aside for new firms, a feature that is, for the moment, absent from the model.

3 Set-up of the model

A dynamic model of a closed economy is developed. Time is discrete, each period is labeled $t = 0, 1, 2....$

3.1 Demand

The economy is populated by a representative infinitely lived consumer who inelastically supplies L units of labor. His preferences are defined in each period over the consumption C of a differentiated product:

$$C_t = \left[\int_{\omega \in \Omega_t} c_t(\omega)^{\frac{\sigma-1}{\sigma}} d\omega \right]^{\frac{\sigma}{\sigma-1}} \qquad \sigma > 1 \tag{1}$$

where $c(\omega)$ is consumption of variety ω, Ω is the mass of varieties available, and σ is the constant elasticity of substitution between any two varieties. As there is no capital and the good can not be stored across periods, the representative consumer faces a static utility maximization problem in each period, where utility $U \equiv C$. That results in the following optimal demand for variety ω in period t:

$$c_t(\omega) = \frac{Y p_t(\omega)^{-\sigma}}{P_t^{1-\sigma}} \tag{2}$$

Y denotes the economy's total expenditure, $p(\omega)$ is the consumer price of variety ω, and P is the price index corresponding to the CES aggregate of varieties:

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

3.2 Production and pollution

In the sole industry of the economy, production by a continuum of firms takes place under increasing returns to scale. To enter the market and start the production of a unique variety of the differentiated good, a firm has to pay a sunk entry cost f_s measured in labor units, the only production factor inelastically supplied at its aggregate level L.

Once this initial investment is paid, each entrant draws a time-invariant marginal productivity of labor φ from a common distribution $g(\varphi)$ over the support $(1, \infty)$. I assume that the distribution is Pareto, with the cumulative distribution $G(\varphi) = 1 - \varphi^{-k}$. The shape parameter k is strictly positive and reflects the degree of productivity dispersion on the market: the lower k, the higher the firm heterogeneity on the market. Upon observing this productivity draw, firms decide whether to stay on the market and immediately produce, or to exit. In each period, all active firms have to pay a fixed cost of production f also expressed in terms of labor, and they face a random shock that occurs with probability γ and forces them to exit.

Pollution arises as a by-product of varieties' production. Following Copeland and Taylor (1994) firms' abatement activity is modeled as the possibility to divert an endogenously determined share θ_t of labor from production to allocate it to pollution abatement. Output q_t and emissions e_t of firm with productivity φ in period t are given by:

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

$$e_t(\varphi) = \left[1 - \theta_t(\varphi)\right]^{\alpha} q_t(\varphi) \qquad \alpha > 0 \tag{5}$$

where l_t is the amount of labor needed to produce q_t units (fixed cost excluded), and $(1 - \theta_t)^{\alpha}$ is the pollution intensity of production. The condition $\alpha > 0$ ensures that an increase in the share of labor assigned to abatement activities induces a decrease in the emission rate[6]. 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 the environmental impact of its producing activities. After some rearrangements, the production function can be formulated as:

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

Polluting emissions appear as an input contributing for the share $1/(1+\alpha)$ to the production of varieties, effective labor contributing for the rest. As an input, emissions have a price p_{e_t} which differs from zero when the environmental policy, which will be detailed in the next subsection, is implemented. Firms operate in monopolistic competition: each variety is identified with a firm, which only produces one variety. As a consequence, firms do not take into account the impact of their decisions on aggregate variables, in the product as well as in the inputs markets, and consider as given the

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

emissions price as well as the wage rate, which serves as the numeraire. A firm's optimal demands for emissions and labor are such that the marginal productivity of a factor equals its price:

$$\begin{aligned} & \frac{1}{1+\alpha} e_t(\varphi)^{\frac{1}{1+\alpha}-1} \left[\varphi\ l_t(\varphi)\right]^{\frac{\alpha}{1+\alpha}} = p_{e_t} \\ \text{and} \quad & \frac{\alpha}{1+\alpha} e_t(\varphi)^{\frac{1}{1+\alpha}} \varphi^{\frac{\alpha}{1+\alpha}}\ l_t(\varphi)^{\frac{\alpha}{1+\alpha}-1} = 1 \end{aligned} \tag{7}$$

Using these equations, the pollution intensity of firm with productivity φ can be written as:

$$[1-\theta_t(\varphi)]^{\alpha} = (\alpha p_{e_t} \varphi)^{-\frac{\alpha}{1+\alpha}} \tag{8}$$

A more productive firm diverts a larger share of labor from producing to emission abatement activities and consequently 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 finding 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; Forslid et al., 2011; Davies and Batrakova, 2011)[7].

3.3 Environmental policy

Polluting emissions are regulated by a cap-and-trade program. Each period t, the regulator defines a cap $\widehat{E}_t$ 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 $1 - B_t$ of the total amount $\widehat{E}_t$) or freely distributed to firms (share B_t). Once allocated, emission allowances can be freely traded among firms on a perfectly competitive market at the clearing price endogenously determined p_{e_t}, this price also being the one at which auctioned emission allowances are sold. At the end of each period, firms must back up each unit of emission they are responsible for with an allowance[8].

Updated benchmarking is the rule prevailing for the initial allocation of free emission

[7] 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. Forslid et al. (2011) use Swedish data and find that a 1% increase in total factor productivity is associated with a 1% increase in abatement investments. David and Batrakova (2011), using Irish data, find a negative effect of labor productivity on the ratio of energy use over sales.

[8] Perfect compliance with the program is implicitly assumed.

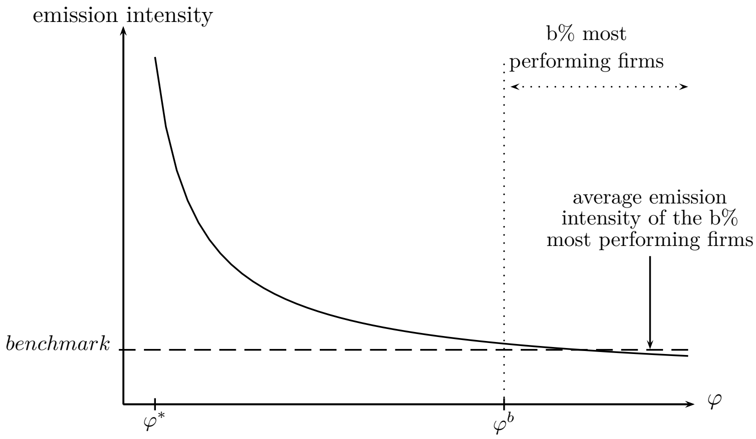

Figure 2: Determination of the benchmark

allowances to firms. The product benchmark is calculated as the arithmetic average emission intensity of the b_t% best performing firms in terms of emission intensity (see figure 2). As emission intensity is monotonically decreasing in firm's labor productivity, the b_t% firms with the lowest emission intensity are the b_t% most productive firms in the industry. In period $t-1$, φ_{t-1}^b, the productivity of the marginal firm belonging to this group, is such that:

$$\int_{\varphi_{t-1}^b}^{\infty} \frac{dG(\varphi)}{1-G(\varphi_{t-1}^*)} d\varphi = b_{t-1} \qquad \Rightarrow \qquad \varphi_{t-1}^b = \varphi_{t-1}^* \times b_{t-1}^{-\frac{1}{k}} \tag{9}$$

where φ_{t-1}^* is the lowest labor productivity level among active firms. The average emission intensity of these b_{t-1}% best performing firms, defining the product benchmark, is:

$$\begin{aligned} benchmark_{t-1} &= \int_{\varphi_{t-1}^b}^{\infty} (\alpha p_{e_{t-1}} \varphi)^{-\frac{\alpha}{1+\alpha}} \frac{dG(\varphi)}{1-G(\varphi_{t-1}^b)} d\varphi \\ &= (\alpha p_{e_{t-1}})^{-\frac{\alpha}{1+\alpha}} b_{t-1}^{\frac{\alpha}{k(1+\alpha)}} \frac{k(1+\alpha)}{k(1+\alpha)+\alpha} (\varphi_{t-1}^*)^{-\frac{\alpha}{1+\alpha}} \end{aligned} \tag{10}$$

This benchmark is associated with the firm's output in period $t-1$ to determine the allocation of free emissions allowances $\widehat{e}_t$ in period t:

$$\widehat{e}_t(\varphi) = benchmark_{t-1} \times q_{t-1}(\varphi) \tag{11}$$

The firm's output decision in any period influences the amount of allowances it receives the next period. Besides, as the reference period governing the allocation rule in t is period $t-1$, only the firms active during the latter receive free allowances. In addition, a firm hit by the death shock in t no longer receives free allowances in $t+1$. As a consequence, the profits function of a new entrant (n) with productivity φ in period t is:

$$\pi_t^n(\varphi) = p_t^n(\varphi)\, q_t^n(\varphi) - \underbrace{\alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\, p_{e_t}^{\frac{1}{1+\alpha}}\varphi^{-\frac{\alpha}{1+\alpha}}}_{\text{marginal cost of production}} q_t^n(\varphi) - f \tag{12}$$

The marginal cost of production is a combination of the price of emissions, common to all firms, and of the cost of effective labor, equal to the inverse of a firm's productivity. The profits function of an already incumbent firm (i) with productivity φ in period t incorporates free emission allowances as a resource:

$$\pi_t^i(\varphi) = p_t^i(\varphi)\, q_t^i(\varphi) - \alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\, p_{e_t}^{\frac{1}{1+\alpha}}\varphi^{-\frac{\alpha}{1+\alpha}} q_t^i(\varphi) - f + p_{e_t}\widehat{e}_t(\varphi) \tag{13}$$

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.

The timing of events in each period t is presented in figure 3. Two alternate cases are considered. In the first one, the environmental policy announcement concerns period t allocation only: firms only learn at the beginning of the period the amount of allowances received in this period, so that they do not know the rules determining initial allocation. As a consequence, they do not take into consideration the influence of current output decision on future allowances allocation. In the second case, the policy announcement in period t consists in the presentation of the allocation rules for the period $t+1$. Firms are therefore aware that their immediate output decision has a direct effect on the amount of free allowances received in the next period, creating incentives for firms to develop a strategic attitude toward the environmental policy.

Finally, it is essential to notice that among the two elements of the cap-and-trade program defining the allocation rules, B and b, only one is exogenously defined by the regulator: the other one is automatically determined at the equilibrium. Indeed, the less ambitious the benchmark, the more allowances firms receive, and mechanically the higher the share of allowances freely distributed (notwithstanding the effect of b on the mass of firms receiving allowances). Conversely, the largest the share of allowances auctioned by the regulator, the lower the amount given for free to firms, and the tighter the benchmark (again, notwithstanding the effect of B on the mass of firms). At the equilibrium, there is a relationship between these two dimensions of the environmental

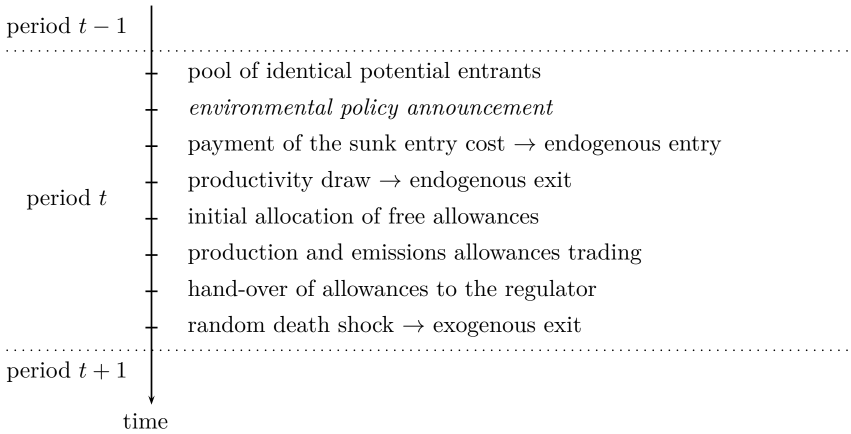

Figure 3: Timing of events

policy, most probably positive, and economic variables can either be expressed in terms of B or b[9].

3.4 Equilibrium

The general equilibrium of the model is determined by the zero cutoff profit condition, the free entry condition, the labor market clearing condition and the emission allowances market clearing condition. The market of varieties clears through firms' optimal output decisions. I focus on the stationary equilibrium of this dynamic model, in which the environmental policy and aggregate variables remain constant over time. Since each firm's productivity also is time-invariant, the optimal per period profits level from the second period of activity of the firm with productivity φ do not change over time, and the profits of a new entrant with productivity φ are the same whatever the period of entry. Assuming that there is no time discounting the value function of a firm with productivity φ entering in any period t is then given by:

$$
\begin{aligned}
v(\varphi) &= \max\left\{0, \pi_t^n(\varphi) + \sum_{s=t+1}^{\infty} (1-\gamma)^{s-t} \pi_s^i(\varphi)\right\} \\
&= \max\left\{0, \pi^n(\varphi) + \frac{1-\gamma}{\gamma}\pi^i(\varphi)\right\}
\end{aligned} \tag{14}
$$

[9]An equivalent approach would be to consider both B and b exogenous instruments of the environmental policy, and to add a correction factor in the definition of free allocation, this factor being determined endogenously such that the amount of allowances allocated free of charge according to the benchmark formula corresponds to the specified level $B\widehat{E}$.

The zero cutoff profit condition is associated with the endogenous exit decision of a firm, and determines a first expression for φ^*, the lowest productivity level among active firms, such that firms drawing a productivity below this threshold immediately choose to exit as producing would yield a negative present value of profits:

$$\pi^n(\varphi^*) + \frac{1-\gamma}{\gamma}\pi^i(\varphi^*) = 0 \tag{15}$$

The endogenous entry decision of a prospective entrant is determined by the comparison of the sunk entry cost f_s with the present value of expected profits it would generate if it enters in any period t, V:

$$\begin{aligned} V &= \int_0^\infty \left(\pi_t^n(\varphi) + \sum_{s=t+1}^{\infty} (1-\gamma)^{s-t}\pi_s^i(\varphi)\right) dG(\varphi)\, d\varphi \\ &= \int_0^\infty \left(\pi^n(\varphi) + \frac{1-\gamma}{\gamma}\pi^i(\varphi)\right) dG(\varphi)\, d\varphi \end{aligned} \tag{16}$$

The free entry condition ensures that firms enter until this value is driven down to f_s. At the stationary equilibrium the mass of active firms M is constant across time, so that the firms exogenously exiting each period must be replaced by an equal number of new entrants:

$$\gamma M = [1 - G(\varphi^*)]\, M_s \tag{17}$$

where M_s is the mass of firms paying the sunk entry cost and $1-G(\varphi^*)$ is the probability of drawing a productivity above the cutoff and therefore to successfully enter. As a consequence, in each period a share γ of active firms are new entrants earning $\overline{\pi}^n$ on average, while the share $1-\gamma$ are already incumbent firms earning $\overline{\pi}^i$ on average, where:

$$\begin{aligned} \overline{\pi}^n &= \int_{\varphi^*}^\infty \pi^n(\varphi)\frac{dG(\varphi)}{1-G(\varphi^*)}d\varphi \\ \text{and} \qquad \overline{\pi}^i &= \int_{\varphi^*}^\infty \pi^i(\varphi)\frac{dG(\varphi)}{1-G(\varphi^*)}d\varphi \end{aligned} \tag{18}$$

The average per period profits are then defined as:

$$\overline{\pi} = \gamma\overline{\pi}^n + (1-\gamma)\,\overline{\pi}^i \tag{19}$$

The value of entry can therefore be expressed as the present value of the average per period profits, conditional on successful entry, and the free entry condition can be written as:

$$[1 - G(\varphi^*)]\,\frac{\overline{\pi}}{\gamma} = f_s \tag{20}$$

Intuitively, if market entry is more difficult, reflected in a higher φ^*, firms must expect higher per period profits to agree to pay the sunk cost.

Total labor demand is composed of three parts. The first one (L_{M_s}) represents the initial sunk investment cost. From the aggregate stability and free entry conditions, this component of labor demand appears to be equal to the aggregate profit Π:

$$L_{M_s} = f_s M_s = \frac{f_s \gamma M}{1 - G(\varphi^*)} = \overline{\pi} M = \Pi \tag{21}$$

The second component of labor demand (L_M) is labor hired by the mass of active firms to perform producing and abatement activities. The third part represents the payment of the fixed production cost. The labor market clearing condition states that this overall demand must be equal to the inelastic labor supply L:

$$L = L_{M_s} + L_M + Mf \tag{22}$$

Labor market clearing also requires that the aggregate revenue R equals the aggregate expenditure Y. The representative consumer inelastically supplies L units of labor and owns a fund made of all active firms in the economy that distributes dividends. His resources are therefore composed of labor income, of the aggregate profit net of investment in new firms, and also of the revenues from auctions. As the aggregate profit exactly covers the sunk initial investment of prospective entrants, the aggregate expenditure, and therefore the aggregate revenue, are equal to the sum of labor income and environmental policy revenues:

$$Y = R = L + p_e (1 - B) \widehat{E} \tag{23}$$

Finally, to ensure general equilibrium, the emission allowances market also must be cleared:

$$E = \widehat{E} \qquad \text{where} \qquad E = M \times \int_{\varphi^*}^{\infty} e(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi \tag{24}$$

That condition states that the aggregate level of emissions E must be equal to the cap set by the regulator, $\widehat{E}$.

In the next section I develop the resolution of the stationary equilibrium when allocation rules are not notified to firms. Section 5 deals with the notified firms scenario.

4 Allocation rules not notified

4.1 Firms' decisions

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:

$$\max_{q_t(\varphi)} \ \pi_t(\varphi) \tag{25}$$

where π is given by (12) for a new entrant and by (13) for a firm that was already active in $t-1$. To the extent that the amount of allowances received free of charge is given for the firm, new entrants and incumbent firms with the same productivity choose an identical optimal output level. Monopolistic competitive firms take aggregate demand as given and do not take into account the impact of their decisions on the price index. Profits maximization then yields the usual result that firms charge a constant mark-up over the marginal cost of production:

$$p_t(\varphi) = \underbrace{\frac{\sigma}{\sigma-1}}_{\text{mark-up}} \underbrace{\alpha^{-\frac{\alpha}{1+\alpha}} (1+\alpha) p_{e_t}^{\frac{1}{1+\alpha}} \varphi^{-\frac{\alpha}{1+\alpha}}}_{\text{marginal cost of production}} \tag{26}$$

The mark-up is a decreasing function of the elasticity of substitution between varieties. All firms react to a rise in the price of emissions, which increases the marginal cost of production, by charging a higher price. Nonetheless, prices remain different across varieties, since a more productive firm has a lower marginal cost of production and consequently charges a lower price. Given this pricing rule, individual output and emissions are equal to:

$$q_t(\varphi) = \frac{Y}{P_t^{1-\sigma}} \left(\frac{\sigma}{\sigma-1} \alpha^{-\frac{\alpha}{1+\alpha}} (1+\alpha) p_{e_t}^{\frac{1}{1+\alpha}} \varphi^{-\frac{\alpha}{1+\alpha}} \right)^{-\sigma} \tag{27}$$

$$e_t(\varphi) = \frac{Y}{\sigma P_t^{1-\sigma}} \left(\frac{\sigma}{\sigma-1} \alpha^{-\frac{\alpha}{1+\alpha}} (1+\alpha) p_{e_t}^{\frac{1}{1+\alpha}} \varphi^{-\frac{\alpha}{1+\alpha}} \right)^{1-\sigma} \frac{\sigma-1}{(1+\alpha) p_{e_t}} \tag{28}$$

The more productive a firm, the lower its emission intensity but the higher its output. In the end, the output effect dominates and emissions are an increasing function of labor productivity. Profits functions can be rewritten using these optimal values. For a new entrant:

$$\pi_t^n(\varphi) = \frac{r(\varphi)}{\sigma} - f \tag{29}$$

For an already incumbent firm:

$$\pi_t^i(\varphi) = \frac{r(\varphi)}{\sigma} - f + p_{e_t}\widehat{e}_t(\varphi) \tag{30}$$

r is the firm revenue, identical for the two types of firms. For a given productivity level, new entrants make lower profits than firms that were already active in the previous period as they do not receive free allowances, equal to:

$$\begin{aligned}\widehat{e}_t(\varphi) = & \frac{Y}{\sigma P_{t-1}^{1-\sigma}}\left(\frac{\sigma}{\sigma-1}\alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\,p_{e_{t-1}}^{\frac{1}{1+\alpha}}\varphi^{-\frac{\alpha}{1+\alpha}}\right)^{1-\sigma} \\ & \times \frac{\sigma-1}{(1+\alpha)\,p_{e_{t-1}}} b_{t-1}^{\frac{\alpha}{k(1+\alpha)}} \frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\left(\frac{\varphi_{t-1}^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}\end{aligned} \tag{31}$$

This allocation is an increasing function of a firm's productivity as it is based on its previous period output. In the end, within each category of firms, more productive firms charge lower prices, produce and pollute more, receive more free allowances and make higher profits.

4.2 Equilibrium

The zero cutoff profit condition (15) allows to obtain a first expression of φ^*, the productivity of the least productive firm active on the market:

$$\begin{aligned}(\varphi^*)^{\frac{\alpha(\sigma-1)}{1+\alpha}} = & f\left[\frac{Y}{\sigma P^{1-\sigma}}\left(\frac{\sigma}{\sigma-1}\alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\,p_{e_t}^{\frac{1}{1+\alpha}}\right)^{1-\sigma}\right]^{-1} \\ & \times\left(1+(1-\gamma)\frac{\sigma-1}{1+\alpha}b^{\frac{\alpha}{k(1+\alpha)}}\frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\right)^{-1}\end{aligned} \tag{32}$$

The cutoff depends, among other variables, on the environmental policy. A more ambitious environmental policy reflected in the product benchmark dimension (a decrease in b) reduces the amount of allowances the firm receives. Deprived of this resource, the firm's profits decrease, which results in a more intense selection based on labor productivity: the least productive firms are forced to exit, which is reflected in a rise in the productivity cutoff φ^*. Similarly, a rise in the emission price, indirect instrument of the environmental policy as it is endogenously determined, increases the price charged by firms and lowers their output. As the second effect is larger, a rise in p_e lowers the firm's revenue, which again induces exit of the least productive firms. These are of course partial equilibrium results as the environmental will most probably impact the economy's expenditure and price index.

Using this expression of φ^* the average per period profits can be computed as a function of model parameters only:

$$\overline{\pi} = \frac{\alpha(\sigma-1) f}{k(1+\alpha) - \alpha(\sigma-1)} \frac{1 + (1-\gamma) \frac{\sigma}{1+\alpha} b^{\frac{\alpha}{k(1+\alpha)}} \frac{k(1+\alpha)}{k(1+\alpha)+\alpha} \frac{k(1+\alpha)-\alpha(\sigma-1)}{k(1+\alpha)-\alpha\sigma}}{1 + (1-\gamma) \frac{\sigma-1}{1+\alpha} b^{\frac{\alpha}{k(1+\alpha)}} \frac{k(1+\alpha)}{k(1+\alpha)+\alpha}} \tag{33}$$

assuming that $k > \frac{\alpha\sigma}{1+\alpha}$. The free-entry condition can then be used to obtain a second expression of the productivity cutoff.

The different components of labor demand can be written in terms of aggregate economic variables. First, as proved earlier, labor used to pay the sunk investment cost is equal to the aggregate profit, which is equal to:

$$\begin{aligned} \Pi &= \gamma M \int_{\varphi^*}^{\infty} \pi^n(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi + (1-\gamma) M \int_{\varphi^*}^{\infty} \pi^i(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi \\ &= \frac{R}{\sigma} - Mf + p_e B \widehat{E} \end{aligned} \tag{34}$$

R is the aggregate revenue. Second, labor performing producing and pollution abatement activities can also be written as a function of the aggregate revenue:

$$L_M = M \int_{\varphi^*}^{\infty} l(\varphi) \frac{dG(\varphi)}{1 - G(\varphi^*)} d\varphi = \frac{\alpha(\sigma-1)}{\sigma(1+\alpha)} R \tag{35}$$

Consequently, the labor market clearing condition can be expressed as follows:

$$L = \frac{1 + \alpha\sigma}{\sigma(1+\alpha)} R + p_e B \widehat{E} \tag{36}$$

Together with the expression of the aggregate income and the emission allowances market clearing condition, the previous expressions yield the following stationary equilibrium values of the average and aggregate variables, as functions of the environmental policy and model parameters:

$$p_e = \frac{(\sigma-1) L}{[1 + \alpha\sigma + (\sigma-1) B] \widehat{E}} \tag{37}$$

$$\overline{\pi} = \frac{\alpha(\sigma-1)\left(1 + B\frac{\sigma}{1+\alpha}\right) f}{k(1+\alpha) - \alpha(\sigma-1) + B\frac{\sigma-1}{1+\alpha}[k(1+\alpha) - \alpha\sigma]} \tag{38}$$

$$\varphi^* = \left(\frac{f}{\gamma f_s} \frac{\alpha(\sigma-1)\left(1 + B\frac{\sigma}{1+\alpha}\right)}{k(1+\alpha) - \alpha(\sigma-1) + B\frac{\sigma-1}{1+\alpha}[k(1+\alpha) - \alpha\sigma]} \right)^{\frac{1}{k}} \tag{39}$$

$$R = \frac{\sigma (1+\alpha) L}{1 + \alpha\sigma + (\sigma - 1) B} \tag{40}$$

$$\Pi = \frac{\alpha (\sigma - 1) \left(1 + B \frac{\sigma}{1+\alpha}\right) L}{[1 + \alpha\sigma + (\sigma - 1) B] k} \tag{41}$$

$$M = \frac{L}{kf} \frac{k (1+\alpha) - \alpha (\sigma - 1) + B \frac{\sigma - 1}{1+\alpha} [k (1+\alpha) - \alpha\sigma]}{1 + \alpha\sigma + (\sigma - 1) B} \tag{42}$$

The price index can be written in terms of the equilibrium values of the emission price, the marginal productivity cutoff and the mass of active firms:

$$P = \frac{\sigma}{\sigma - 1} \alpha^{-\frac{\alpha}{1+\alpha}} (1+\alpha) p_e^{\frac{1}{1+\alpha}} M^{\frac{1}{1-\sigma}} \left(\frac{k (1+\alpha)}{k (1+\alpha) - \alpha (\sigma - 1)} (\varphi^*)^{\frac{\alpha(\sigma-1)}{1+\alpha}} \right)^{\frac{1}{1-\sigma}} \tag{43}$$

At last, ensuring that the total amount of emission allowances distributed according to the benchmark formula is equal to $B\widehat{E}$ implies the following relation between the two elements of the allocation rule:

$$B = b^{\frac{\alpha}{k(1+\alpha)}} (1 - \gamma) \frac{k (1+\alpha)}{k (1+\alpha) + \alpha} \tag{44}$$

As expected, there is a positive relation between B and b: a decrease in the share of allowances being auctioned (higher B) expands the amount of allowances that can be freely allocated to firms, which translates into a rise in the initial allocation at the firm level through a less strict benchmark (higher b).

4.3 Effects of the environmental policy

4.3.1 The cap on emissions

The cap on emissions is the only element of the cap-and-trade policy that influences the level of pollution. For instance, the regulator willing to improve the environmental quality has to set a lower cap $\widehat{E}$. The counterpart of this policy change is a scarcity of emission allowances on the market, which naturally induces a rise in their price p_e:

$$\frac{\delta p_e}{\delta \widehat{E}} < 0 \tag{45}$$

This price increase generates the adjustment of the aggregate level of emissions to the cap through two channels. At the firm level, a higher price of allowances increases the cost of emissions relative to labor, which generates incentives to undertake additional abatement activities. As a result, firms reduce the emission intensity of the production process, which contributes to the decrease in aggregate emissions. Furthermore, a rise in the emission price increases the marginal cost of production, inducing a higher price of varieties and a lower output. The second effect dominates and the firm's revenue decreases due to this change in marginal cost, which should result in the exit of the firms no longer productive enough.

Nevertheless, this is only a partial equilibrium effect as the variation of the cost of emissions implies a modification of the price index. Indeed, as all firms charge a higher price, the price index rises; as the nominal wage is the numeraire, the real wage diminishes, which lowers the production cost and has a positive effect on firms' output and revenue. This positive general equilibrium effect exactly compensates the negative partial equilibrium effect, so that, in the end, the firm's revenue is independent of the cap on emissions. The final net effect on output is negative, which contributes to the reduction in aggregate emissions to achieve the new environmental objective. Moreover, a reduction of the cap on emissions has no effect on the value of the firm's endowment in allowances since, on the one hand, the allowances price is higher, but on the other hand lower output and emission intensity both induce a lower endowment. In the end, the two effects exactly compensate each other.

The crucial consequence of this general equilibrium effect is that a change in the cap on emissions has no effect on the profits function of both new entrants and incumbents, and therefore does not affect the firm entry and exit decisions. Accordingly the productivity cutoff, the average profits, the mass of active firms, the aggregate revenue and profits are all independent of $\widehat{E}$, whose modification does not generate any change in the market structure.

A change in the cap on emissions affects social welfare defined as the sum of utility derived from consumption, aggregate profit and the environmental damage created by polluting emissions. On the one hand, a reduction in the cap induces a rise in the price index which in turn decreases utility derived from consumption, defined by $C = R/P$ from the consumer's budget constraint. On the other hand, a reduction in the cap on emissions definitely improves the environmental quality. Finally, this dimension of the cap-and-trade program has no effect on the aggregate profit. Eventually, when choosing $\widehat{E}$ as the one maximizing social welfare, the government faces a trade-off between consumption opportunities and the environmental quality.

4.3.2 The initial allocation of allowances

Turning to a modification of the initial allocation of allowances, it is clear that a contraction in the share of auctioning (higher B), for a given cap and a given allowance price, reduces the revenues from the environmental policy rebated to the consumer. As a consequence, the aggregate revenue tends to decline, generating a decrease in the labor demand for initial investment (see (34)), and for producing and abatement activities (see (35)). Meanwhile, allocating for free a larger share of allowances increases firms' resources; this has a positive effect on the aggregate profit, and hence increases the labor demand for initial sunk investment. In the end, the latter resource effect more than compensates the former income effect, and total labor demand expands when B increases. To maintain the equilibrium on the labor market, the only endogenous variable left, which is the price of emission allowances, has to adjust, so that an increase in B generates a decrease in p_e:

$$\frac{\delta p_e}{\delta B} < 0 \tag{46}$$

The decrease in p_e dampens the resource effect and amplifies the reduction in the value of revenues from the environmental policy, so that the aggregate nominal revenue clearly declines when auctioning is scaled-down:

$$\frac{\delta R}{\delta B} < 0 \tag{47}$$

The equilibrium price of allowances then depends on their initial allocation, even if the allowances market is perfectly competitive. That comes from the fact that each firm produces a unique variety of the differentiated good, and accordingly has some market power. As a consequence, the more differentiated the product (the lower σ), the more protected the firms are from changes in market conditions: that implies that the income effect is low, meaning that firms' reduction in labor demand is limited when revenue declines. Thus, the change in p_e has to be high to restore the equilibrium on the labor market. To sum up, the less substitutable the varieties, the larger the effect of a change in the method of initial allocation of allowances on their equilibrium price.

The average profits and the productivity cutoff are jointly determined as the result of the endogenous entry and exit decisions of firms. Two relationships between these variables can be computed[10]:

$$\overline{\pi} = \frac{f}{1 + B\frac{\sigma-1}{1+\alpha}\frac{1}{1-\gamma}\frac{k(1+\alpha)-\alpha\sigma}{k(1+\alpha)-\alpha(\sigma-1)}} \times \frac{\int_{\varphi^*}^{\infty} \varphi^{\frac{\alpha(\sigma-1)}{1+\alpha}} \frac{dG(\varphi)}{1-G(\varphi^*)} d\varphi}{\varphi^{*\frac{\alpha(\sigma-1)}{1+\alpha}}} + \frac{f\frac{1}{1-\gamma}B\frac{\sigma-1}{1+\alpha}\frac{k(1+\alpha)-\alpha\sigma}{k(1+\alpha)-\alpha(\sigma-1)}}{1 + B\frac{\sigma-1}{1+\alpha}\frac{1}{1-\gamma}\frac{k(1+\alpha)-\alpha\sigma}{k(1+\alpha)-\alpha(\sigma-1)}} \times \frac{\int_{\varphi^*}^{\infty} \varphi^{\frac{\alpha\sigma}{1+\alpha}} \frac{dG(\varphi)}{1-G(\varphi^*)} d\varphi}{\varphi^{*\sigma\alpha}} - f \tag{48}$$

and:

$$\overline{\pi} = \gamma f_s \varphi^{*k} \tag{49}$$

The first relation comes from the zero cutoff profit condition, and is represented in figure 4 by the ZCP curve, monotonically decreasing in the (φ, π) space. The second one is the free entry condition, illustrated by the FE curve, monotonically increasing in the (φ, π) space. The intersection of these two curves defines the unique equilibrium. When the share of auctioning is reduced, more free allowances are given to firms, which implies a reduction in the revenue to maintain the zero cutoff profit condition. In the end, the positive resource effect is larger than the negative revenue effect and the ZCP curve is shifted upward. A modification in B has no effect on the FE curve, meaning that the environmental policy does not directly affect the endogenous entry decision of firms. As a consequence, a new equilibrium is reached, with higher labor productivity cutoff and average profits:

$$\frac{\delta\varphi^*}{\delta B} > 0 \qquad \text{and} \qquad \frac{\delta\overline{\pi}}{\delta B} > 0 \tag{50}$$

Increasing the share of free allocation makes market entry more difficult: the self-selection of firms based on labor productivity intensifies, which corresponds to a re-allocation of resources towards the most productive firms. This reallocation effect comes with higher average per period profits.

At the firm level, the decrease in the emission allowances price reduces the incentives to divert labor from producing to abatement activities. As a result, the emission intensity rises, and output tends to increase. In addition, a decrease in the price of allowances reduces the marginal cost of production, which also supports production through the demand channel. Nevertheless these positive partial equilibrium effects on output are challenged by positive general equilibrium effects. First, lower aggregate income reduces the demand for each variety. Second, lower marginal cost and reallocation of resources

[10]See the derivations in the appendix.

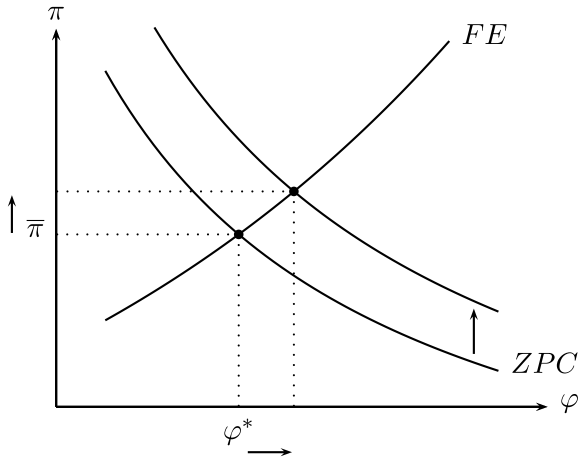

Figure 4: Effects of a reduction in the share of auctioning on the productivity cutoff and the average profits

toward the most productive firms imply a reduction in the price index which increases the real wage and discourages production. In the end, the negative general equilibrium effects on output exceed the positive partial equilibrium effects, and firm-level output declines following a rise in the share of free allocation.

This scaling down of production results in the decrease of firm-level emissions, even if firms have a higher emission rate. However, the reallocation of resources induced by the policy change corresponds to a more intense selection on the market: active firms are not only more productive but also pollute more than the firms that are no longer productive enough to operate on the market. That tends to increase the average per firm emission level in the economy. In the end, the evolution of the average emission level depends on the relative strength of the reallocation of resources effect and of the decrease in firm-level emissions. Let's define $\widetilde{k}$ as:

$$\widetilde{k} = \frac{\alpha\sigma\left(\sigma-1\right)+1+\alpha}{\left(1+\alpha\right)\left(\sigma-1\right)} \tag{51}$$

When heterogeneity is high ($k < \widetilde{k}$) large and polluting firms represent a high fraction of firms: as a consequence the reallocation effect is strong enough to produce a rise in the average emission level. Consequently the mass of active firms must decrease so that the cap on emissions is respected. Conversely, when heterogeneity is low ($k > \widetilde{k}$) a high fraction of firms is concentrated toward the minimum productivity cutoff, so that the reallocation of resources generates a too limited effect, and the average emission level decreases. As a result the mass of firms expands to maintain the cap on emissions:

$$\begin{cases} \frac{\delta M}{\delta B} < 0 & \text{if} \quad k < \widetilde{k} \\ \frac{\delta M}{\delta B} \geq 0 & \text{if} \quad k \geq \widetilde{k} \end{cases} \tag{52}$$

The possible expansion in the mass of active firms originates from the effect of a decrease in auctioning on the aggregate profit. Indeed, allocating for free a larger share of allowances, even if their price is lower, has a positive impact on the aggregate profit:

$$\frac{\delta \Pi}{\delta B} > 0 \tag{53}$$

As a consequence, the mass of potential entrants widens, attracted by larger profits opportunities. However at the same time entry on the market is more difficult. In the end, when heterogeneity is low, the positive aggregate profit effect is larger than the negative selection effect, and the mass of active firms expands. The result is reversed when heterogeneity is high.

The ambiguous effect of an increase in the share of free allocation on the mass of active firms generates in turn an ambiguous effect on the price index, which can be decomposed into three components:

$$\begin{aligned} \frac{\delta P}{\delta B} = & \frac{\sigma}{\sigma - 1} \alpha^{-\frac{\alpha}{1+\alpha}} (1+\alpha) p_e^{\frac{1}{1+\alpha}} M^{\frac{1}{1-\sigma}} \left(\frac{k(1+\alpha)}{k(1+\alpha) - \alpha(\sigma - 1)} (\varphi^*)^{\frac{\alpha(\sigma-1)}{1+\alpha}} \right)^{\frac{1}{1-\sigma}} \\ & \times \left[\frac{1}{1+\alpha} \frac{1}{p_e} \frac{\delta p_e}{\delta B} - \frac{1}{\sigma - 1} \frac{1}{M} \frac{\delta M}{\delta B} - \frac{\alpha}{1+\alpha} \frac{1}{\varphi^*} \frac{\delta \varphi^*}{\delta B} \right] \end{aligned} \tag{54}$$

The first and third terms under brackets are related to the effects of a change in the share of auctioning on the marginal cost of production and on the average price: both are negative. The second term under brackets represents the effect on the mass of active firms, whose sign depends on the degree of firm heterogeneity: when heterogeneity is low ($k > \widetilde{k}$) this term is negative, and the price index unambiguously decreases when the share of auctioning is reduced. However, when heterogeneity is high ($k < \widetilde{k}$) the second term under brackets is positive and the net effect on the price index is not determined.

Despite its ambiguous impact on the price index, a change in B has a clear effect on utility derived from consumption: increasing the share of free allocation reduces utility derived from consumption through its negative impact on aggregate income. As a consequence, as expanding free allocation deteriorates consumer's utility, improves aggregate profits and has no impact on the environmental quality, the government faces a trade-off between the consumer's and firms' respective interests when choosing the level of B maximizing social welfare.

The scale of free allocation also influences the structure of the emission allowances market. A firm with productivity φ is a net buyer on this market if:

$$\begin{aligned} & e(\varphi) - \widehat{e}(\varphi) \geq 0 \quad \Rightarrow \quad \varphi \leq \varphi^e \\ & \qquad \text{with} \quad \varphi^e = \varphi^* \left(\frac{1-\gamma}{B} \frac{k(1+\alpha) - \alpha(\sigma-1)}{k(1+\alpha) - \alpha\sigma} \right)^{\frac{1+\alpha}{\alpha}} \end{aligned} \tag{55}$$

Both emissions and free allocations are increasing functions of a firm's productivity, but the latter increase more rapidly with φ than emissions. Firms with productivity below the threshold φ^e pollute more than the allowances they receive, and have to buy the difference on the market; their net demand is represented on figure 5 by the area between the two curves when the firm's productivity lies between φ^* and φ^e[11]. At the opposite, firms with productivity above the threshold pollute less than the allowances they receive, and sell the spare allowances on the market; their net supply is represented on figure 5 by the area between the two curves when the firm's productivity is above φ^e. Moreover $\varphi^e > \varphi^b$: the firms selling allowances are a subset of the firms constituting the reference group for the benchmark definition. A change in the initial allocation modifies the structure of the allowance market. Indeed, a rise in B increases a firm's resources, and its probability to be a net seller:

$$\frac{1-G(\varphi^e)}{1-G(\varphi^*)} = \left(\frac{B}{1-\gamma} \frac{k(1+\alpha) - \alpha\sigma}{k(1+\alpha) - \alpha(\sigma-1)} \right)^{\frac{k(1+\alpha)}{\alpha}} \tag{56}$$

Finally, the winners and losers from a policy change can be identified. Increasing the share of free allocation generates an increase in the aggregate and average profits, but that masks contrasted situations among firms. First, it is clear that the firms that are no longer productive enough to continue to be active loose from the policy change. Second, all new entrants have lower profits since their revenue decreases. As far as incumbent firms are concerned, they experience a decrease in their revenue but an increase in the value of the allowances they receive. The relative strength of these effects depends on the firm productivity. Let's define the following productivity level:

$$\varphi^B = \varphi^* \left((1-\gamma) \frac{k(1+\alpha) - \alpha(\sigma-1)}{k(1+\alpha) - \alpha\sigma} \right)^{\frac{1+\alpha}{\alpha}} \tag{57}$$

[11] e and $\widehat{e}$ are represented here as convex functions of productivity, while this property actually depends on model parameters: e is convex if $\sigma > \frac{1+2\alpha}{\alpha}$ and $\widehat{e}$ is convex if $\sigma > \frac{1+\alpha}{\alpha}$.

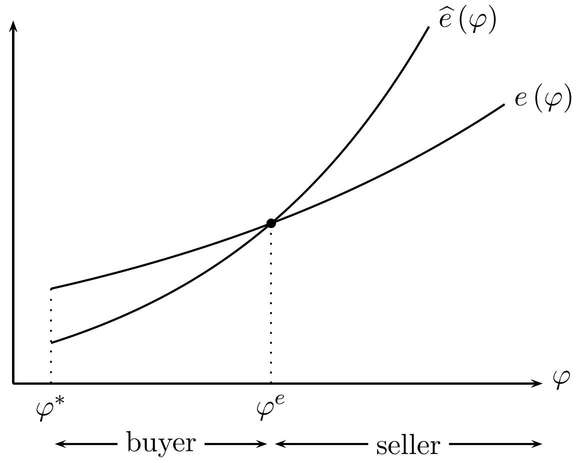

Figure 5: Firm status on the emission allowance market

This threshold is lower than φ^e and allows to define three types of firms. First, the least productive ones ($\varphi < \varphi^B$) lose from the environmental policy change as the increased value of free allowances does not counterbalance the decrease in revenue. Second, for the firms with intermediate productivity ($\varphi^B \leq \varphi < \varphi^e$), the positive resource effect is stronger than the negative income effect, and their profits increase, even if these firms remain buyers on the allowances market. The most productive firms ($\varphi^e \leq \varphi$) clearly gain from the reduction in the share of auctioning as the value of allowances they sell on the market is higher, offsetting the fall in revenue.

5 Allocation rules notified

5.1 Firms' decisions

As they explicitly take into account the impact of current output decision on upcoming emission allowances allocation and profits, the firms' objective in period t is[12]:

$$\max_{q_t(\varphi)} \left(\sum_{s=t}^{\infty} (1-\gamma)^{s-t} \pi^s(\varphi) \right) \tag{58}$$

with π given by (12) for a new entrant and by (13) for a firm that was already active in $t-1$. Period t allocation has no impact on this maximization problem since it is exogenously given; new entrants and already incumbent firms therefore choose the same level of optimal output in period t. Taking the aggregate demand as given and

[12] I assume that all firms have equal expectations about future allowances price.

neglecting the effect of individual decisions on the price index, profits maximization yields the following optimal pricing rule:

$$p_t(\varphi) = \frac{\sigma}{\sigma-1}\alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\,p_{e_t}^{\frac{1}{1+\alpha}}\varphi^{-\frac{\alpha}{1+\alpha}} \times\left(1-\frac{p_{e_{t+1}}}{p_{e_t}}\frac{1-\gamma}{1+\alpha}b_t^{\frac{\alpha}{k(1+\alpha)}}\frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\left(\frac{\varphi_t^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}\right) \tag{59}$$

The price still corresponds to a mark-up charged over the marginal cost of production, but the latter is now lowered by the value of the free emission allowances the firm will receive in the next period. This price is assumed to be strictly positive:

$$1-\frac{p_{e_{t+1}}}{p_{e_t}}\frac{1-\gamma}{1+\alpha}b_t^{\frac{\alpha}{k(1+\alpha)}}\frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\left(\frac{\varphi_t^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}>0 \tag{60}$$

Given the pricing rule, optimal individual output and emissions are equal to:

$$q_t(\varphi) = \frac{Y}{P_t^{1-\sigma}}\left(\frac{\sigma}{\sigma-1}\alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\,p_{e_t}^{\frac{1}{1+\alpha}}\varphi^{-\frac{\alpha}{1+\alpha}}\right)^{-\sigma} \times\left(1-\frac{p_{e_{t+1}}}{p_{e_t}}\frac{1-\gamma}{1+\alpha}b_t^{\frac{\alpha}{k(1+\alpha)}}\frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\left(\frac{\varphi_t^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}\right)^{-\sigma} \tag{61}$$

$$e_t(\varphi) = \frac{\sigma-1}{(1+\alpha)\,p_e}\frac{Y}{\sigma P_t^{1-\sigma}}\left(\frac{\sigma}{\sigma-1}\alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\,p_{e_t}^{\frac{1}{1+\alpha}}\varphi^{-\frac{\alpha}{1+\alpha}}\right)^{1-\sigma} \times\left(1-\frac{p_{e_{t+1}}}{p_{e_t}}\frac{1-\gamma}{1+\alpha}b_t^{\frac{\alpha}{k(1+\alpha)}}\frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\left(\frac{\varphi_t^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}\right)^{-\sigma} \tag{62}$$

Constantly updating the free allocation acts as a direct output subsidy by lowering the marginal cost of production. Indeed, compared to the previous scenario, taking into account future profits when deciding on current output creates incentives for the firm to set a lower price and produce more today, in order to get more free emission allowances tomorrow. This strategic attitude toward the environmental policy aggravates firm's pollution, as emission intensity is unaffected by this change in behavior. The strength of these incentives clearly depends on the strictness of the environmental policy: a more generous allocation through a looser benchmark further reduces the marginal cost of production. Furthermore, producing at a large scale today in order to get more allowances tomorrow comes at the price since it implies to pollute more and therefore to buy more allowances today, 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 future price of allowances relative to their current price, the more intense the incentives to produce today.

5.2 Equilibrium

The zero cutoff profit condition generates the following expression of the marginal labor productivity:

$$\begin{aligned}(\varphi^*)^{\frac{\alpha(\sigma-1)}{1+\alpha}} = f & \left[\frac{Y}{\sigma P^{1-\sigma}}\left(\frac{\sigma}{\sigma-1}\alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\, p_e^{\frac{1}{1+\alpha}}\right)^{1-\sigma}\right]^{-1} \\ & \times\left(1-\frac{1-\gamma}{1+\alpha}b^{\frac{\alpha}{k(1+\alpha)}}\frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\right)^{\sigma-1}\end{aligned} \tag{63}$$

The b element of the initial allocation rule has a partial equilibrium effect on this cutoff similar to the one in the un-notified case, driven by a different mechanism. Indeed, following a more ambitious environmental policy, reflected in a decrease in b, the firm anticipates a lower number of free allowances in the next period. That reduces the importance of current output decision on future profits, and tends to increase the marginal cost of production net of future environmental resources. The firm then charges a higher price and scales down its production, the net effect on revenue being negative. That in turn implies more selection on the market, reflected in a rise in φ^*.
The rest of the resolution of the stationary equilibrium follows the same procedure presented in the un-notified case, albeit with a technical difficulty. Indeed, the average per period profits needed to write the free entry condition can not be expressed in an explicit analytical form on the basis of its definition as it involves an unsolvable integral:

$$\begin{aligned}\overline{\pi} = & \frac{Y}{\sigma P^{1-\sigma}}\left(\frac{\sigma}{\sigma-1}\alpha^{-\frac{\alpha}{1+\alpha}}(1+\alpha)\, p_{e_t}^{\frac{1}{1+\alpha}}\right)^{1-\sigma} \\ & \times\int_{\varphi^*}^{\infty}\varphi^{\frac{\alpha(\sigma-1)}{1+\alpha}}\left(1-\frac{1-\gamma}{1+\alpha}b_t^{\frac{\alpha}{k(1+\alpha)}}\frac{k(1+\alpha)}{k(1+\alpha)+\alpha}\left(\frac{\varphi^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}\right)^{1-\sigma}\frac{dG(\varphi)}{1-G(\varphi^*)}d\varphi \\ & - f\end{aligned} \tag{64}$$

This value can nevertheless be recovered, making use of the fact that $\overline{\pi} = \overline{r}/\sigma - f$, where $\overline{r}$ is the average revenue, whose equilibrium value can be computed without difficulty. The consequence, however, is that I am not able to edit the equilibrium relation between the two elements of the allocation rule, B and b, and that all equilibrium values can only be expressed in terms of B:

$$p_e = \frac{(\sigma-1)L}{(1+\alpha\sigma-B)\widehat{E}} \tag{65}$$

$$\overline{\pi} = \frac{\alpha(\sigma-1)f}{k(1+\alpha)-\alpha(\sigma-1)-kB} \tag{66}$$

$$\varphi^* = \left(\frac{f}{\gamma f_s}\frac{\alpha(\sigma-1)f}{k(1+\alpha)-\alpha(\sigma-1)-kB}\right)^{\frac{1}{k}} \tag{67}$$

$$R = \frac{(1 + \alpha - B)\,\sigma L}{1 + \alpha\sigma - B} \tag{68}$$

$$\Pi = \frac{\alpha\,(\sigma - 1)\,L}{k\,(1 + \alpha\sigma - B)} \tag{69}$$

$$M = \frac{L}{kf}\frac{k\,(1 + \alpha) - \alpha\,(\sigma - 1) - kB}{1 + \alpha\sigma - B} \tag{70}$$

with $k > \frac{\alpha(\sigma-1)}{1+\alpha-B}$.

5.3 Effects of the environmental policy

The cap on emissions still only directly influences the emission allowance price, which is a decreasing function of $\widehat{E}$, for reasons perfectly identical to the non strategic scenario. Again, the cap on emissions has no effect on market conditions and aggregate variables.

Turning to the effect of a change in the initial allocation, a reduction in auctioning (higher B) induces, for a given price of allowances and a given cap, lower revenues from the environmental policy rebated to the consumer. That in turn leads, for a given mass of active firms, to lower aggregate profit: as a consequence, the labor demands used to pay the sunk initial investment, and to produce and to abate pollution, both decline. To maintain the equilibrium on the labor market, as the wage rate is fixed, the mass of active firms decreases: that indeed reduces the labor demand corresponding to the fixed cost of production, whereas the aggregate profit, and by extension the other two components of labor demand, increase. At this stage of the analysis the increase in B has generated a rise in the aggregate profit: as the total level of emissions is an increasing function of the aggregate profit, pollution expands. The adjustment on the emission allowances market goes through the allowances price, which rises in order to offset the initial deterioration of the environmental quality and maintain pollution to the cap on emissions:

$$\frac{\delta p_e}{\delta B} > 0 \tag{71}$$

The increases in B and in p_e finally translate into a rise in the aggregate income and revenue, followed by a reduction in the mass of active firms at the equilibrium:

$$\frac{\delta R}{\delta B} > 0 \qquad \text{and} \qquad \frac{\delta M}{\delta B} < 0 \tag{72}$$

The combination of the rise in R and the decrease in M generates an increase in the aggregate profit:

$$\frac{\delta \Pi}{\delta B} > 0 \tag{73}$$

That definitely contributes to increase the average per period profits, which goes along with an increase in the marginal productivity level to maintain valid the free entry condition:

$$\frac{\delta\overline{\pi}}{\delta B} > 0 \qquad \text{and} \qquad \frac{\delta\varphi^*}{\delta B} > 0 \tag{74}$$

Again a reduction in the share of auctioning induces a reallocation of resources toward the most productive firms and selection of firms on the market is more intense.

6 Policy implications

The first implication of the model is that the determination of the level of the cap on emissions has no effect on the market structure: the marginal productivity cutoff and the mass of active firms are independent of the environmental objective of the emissions trading scheme. Indeed, the negative partial equilibrium effect a more stringent cap exerts on these variables is exactly offset by a positive general equilibrium effect which goes through a decrease in the real wage. This result, which holds whatever the timing regarding the policy announcement, means that achieving an environmental objective through the implementation of a cap-and-trade program can be done without consequences on firms' profits and decisions to remain on the market.

In contrast with this result, the initial allocation of allowances 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 the increase in the productivity level above which a firm is productive enough to stay on the market. Consequently, the most productive firms clearly gain from this policy change whereas the least productive loose from it. The degree of heterogeneity among firms is decisive to determine the outcome of this policy change on the mass of active firms, which can actually expand due to larger profits opportunities. When heterogeneity among firms is high the reallocation effect is strong enough to produce a contraction in the mass of active firms.

The third policy implication of the model regards the timing of the policy announcement. When firms are informed about the allocation rules, they develop a strategic behavior toward the environmental policy resulting in a higher cost of achieving the environmental objective. Indeed, with respect to the non strategic case, the emission allowance price is higher, the mass of firms lower and selection is more intense. Moreover, this strategic effect complements the effect of the reallocation of resources among firms so that the mass of active firms always decrease when the share of free allocation increases, whatever the degree of heterogeneity among firms. In addition, the strategic behavior of firms induces a rise in the price of emission allowances when the share of auctioning decreases whereas the effect is opposite when this component is absent from the model.

7 Conclusion

This paper has developed a model of heterogeneous firms in monopolistic competition whose activity generates pollution regulated by a cap-and-trade program. The model first finds that an emissions trading scheme designed in the spirit of the EU ETS is likely to reach the environmental objective at a lower cost than a scheme designed more in accordance to the NZ ETS, due to the appearance of a strategic behavior of firms toward the environmental policy in the latest. Second, the model shows that environmental and economic issues can be separately addressed by a cap-and-trade program: the cap on emissions determines the environmental quality and has no effect on the market structure, whereas the method of initial allocation of allowances does not impact the pollution level but affects the firms' entry and exit decisions, the mass of active firms and other aggregate economic variables.

In future revisions of the paper I intend to further analyze the welfare implications of the model. At this stage, welfare values can not be computed in the second scenario considered. It would be essential to get at least some insights on this issue, for instance by using simulations, in order to propose a comprehensive evaluation of an emissions trading scheme in the presence of heterogeneous firms operating in monopolistic competition. The fact that the method of initial allocation of free allowances constitutes a direct subsidy to production can eventually reverse the relative evaluation of the two types of emissions trading schemes analyzed in the paper: the un-notified system generates the lowest price of emissions, but the notified case may induce a higher welfare through the correction of insufficient output due to imperfect competition (Fischer, 2003).
An extension to an open economy model is currently in progress, to study the carbon leakage issue, the coordination of different cap-and-trade programs, and the effect of trade integration when economic and environmental considerations can be separately addressed by the two elements of the emissions trading scheme.

8 Appendix

8.1 Determination of the ZCP and FE curves.

Let's first write emission allowances allocation as a function of the firm revenue:

$$\widehat{e}\left(\varphi\right)=r\left(\varphi\right)\times\frac{1}{p_e}\frac{B}{1-\gamma}\frac{\sigma-1}{\sigma\left(1+\alpha\right)}\frac{k\left(1+\alpha\right)-\alpha\sigma}{k\left(1+\alpha\right)-\alpha\left(\sigma-1\right)}\left(\frac{\varphi^*}{\varphi}\right)^{-\frac{\alpha}{1+\alpha}}$$

Then compute the following ratios:

$$\frac{\overline{r}}{r\left(\varphi^*\right)}=\frac{\int_{\varphi^*}^{\infty}\varphi^{\frac{\alpha(\sigma-1)}{1+\alpha}}\frac{dG(\varphi)}{1-G(\varphi^*)}d\varphi}{\left(\varphi^*\right)^{\frac{\alpha(\sigma-1)}{1+\alpha}}}\qquad\text{and}\qquad\frac{\overline{\widehat{e}}}{\widehat{e}\left(\varphi^*\right)}=\frac{\int_{\varphi^*}^{\infty}\varphi^{\frac{\alpha\sigma}{1+\alpha}}\frac{dG(\varphi)}{1-G(\varphi^*)}d\varphi}{\left(\varphi^*\right)^{\frac{\alpha\sigma}{1+\alpha}}}$$

where $\overline{r}$ is the average revenue and $\overline{\widehat{e}}$ is the average free emission allowances allocation. Given that $\overline{\pi}=\frac{\overline{r}}{\sigma}-f+p_e\overline{\widehat{e}}$, the zero cutoff profit condition then implies a first relationship between $\overline{\pi}$ and φ^*. Indeed:

$$\pi\left(\varphi^*\right)=0\qquad\Rightarrow\qquad r\left(\varphi^*\right)=\frac{\sigma f}{1+\frac{B}{1-\gamma}\frac{\sigma-1}{1+\alpha}\frac{k(1+\alpha)-\alpha\sigma}{k(1+\alpha)-\alpha(\sigma-1)}}$$

Finally:

$$\begin{aligned}\overline{\pi}=&\frac{f}{1+B\frac{\sigma-1}{1+\alpha}\frac{1}{1-\gamma}\frac{k(1+\alpha)-\alpha\sigma}{k(1+\alpha)-\alpha(\sigma-1)}}\times\frac{\int_{\varphi^*}^{\infty}\varphi^{\frac{\alpha(\sigma-1)}{1+\alpha}}\frac{dG(\varphi)}{1-G(\varphi^*)}d\varphi}{\varphi^{*\frac{\alpha(\sigma-1)}{1+\alpha}}}\\&+\frac{f\frac{1}{1-\gamma}B\frac{\sigma-1}{1+\alpha}\frac{k(1+\alpha)-\alpha\sigma}{k(1+\alpha)-\alpha(\sigma-1)}}{1+B\frac{\sigma-1}{1+\alpha}\frac{1}{1-\gamma}\frac{k(1+\alpha)-\alpha\sigma}{k(1+\alpha)-\alpha(\sigma-1)}}\times\frac{\int_{\varphi^*}^{\infty}\varphi^{\frac{\alpha\sigma}{1+\alpha}}\frac{dG(\varphi)}{1-G(\varphi^*)}d\varphi}{\varphi^{*\sigma\alpha}}-f\end{aligned}$$

That defines the ZCP curve, monotonically decreasing in the (φ,π) space. Next, the free entry condition directly defines a second relationship between $\overline{\pi}$ and φ^*, the FE curve, increasing in the (φ,π) space:

$$\overline{\pi}=\gamma f_S\varphi^{*k}$$

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