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Should I stay or should I go? Carbon leakage and ETS in an evolutionary model

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Abstract

Emissions trading is gaining increasing importance around the world as a suitable instrument to address climate change. In the absence of a global carbon market, however, unilateral carbon policies may end up causing carbon leakage effects, the more so if carbon prices are to increase in the future to achieve more ambitious emissions abatement targets. This paper intends to explore the possible delocalization effects of an Emissions Trading System (ETS) by proposing an evolutionary theoretical model in which regulated firms decide whether to stay (keep their production activities in the domestic country) or leave (move production abroad where no ETS is in place) imitating what other firms do. We investigate how this decision is affected by some key ETS design features, such as the emissions cap, the

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number of allowances granted for free to ETS firms, the level of a floor price for allowances. Numerical simulations show that the firms' decision on whether to abate emissions or relocate abroad are more sensitive to policies that reduce the cost of green technologies than to changes in specific features of the ETS design such as the emissions cap, the floor price and the number of permits granted for free.

Keywords: Emission trading system, Carbon leakage, Exponential replicator dynamics, Free allowances, Abatement technologies.

JEL classification: C6; C73; H32; Q48; Q58.

1 Introduction

Climate change and its detrimental consequences call for urgent action by national governments. To fight climate change, a growing number of regions have adopted carbon pricing policies. In particular, many jurisdictions have implemented Emission Trading Systems (ETSs) as their preferred carbon pricing instrument. Among them, the most notable example is certainly the European Emission Trading System (EU ETS), that represents the first transboundary and world largest carbon market, but other ETSs have been rapidly growing elsewhere, including California, Quebec, the Regional Greenhouse Gas Initiative (RGGI), New Zealand, China, Switzerland etc.. As of today, there are 21 ETSs operating in the world, covering 15 per cent of global emissions, and 24 other systems are already planned or under consideration (cf. World Bank, 2019; International Carbon Action Partnership, 2020). In the absence of a global carbon market, the allowance price differentials observed across existing ETSs and the fact that many countries have no price for carbon emissions yet raise concerns over possible carbon leakage effects of ETSs. By this we refer to the risk that domestic firms subject to high allowance prices may shift their production to other geographical areas that have no or laxer environmental regulations.

The empirical literature has shown little to no evidence of carbon leakage in the past (see next section for a discussion of the literature). However, carbon prices have been very low so far, while they are likely to rapidly increase in the future along with the increasing ambition in climate policies required by the so-called ratchet-up mechanism of the Paris Agreement. In this regard, given the urgent challenges posed by climate change, several governments (e.g. the EU, the United Kingdom, New Zealand and California) aim to achieve climate neutrality by 2050 (International Carbon Action Partnership, 2020). But achieving (net) zero emissions will imply a remarkable increase in carbon prices around the world which would need to grow 10 times or even more in the next 30 years (Verde, 2020).[1] Such an increase, therefore, could put ETS-regulated producers at a competitive disadvantage inducing them to offshore their production more and more in the future.

Carbon leakage provisions have been adopted in most ETSs to prevent delocalization of the regulated entities belonging to the most vulnerable sectors, often referred to as emissions-intensive, trade exposed (EITE) sectors. Thus, for instance, during the second phase of the EU ETS (2013-20) the EU decided to exempt from the auctioning of emission allowances those sectors regarded more at risk of carbon leakage, being more carbon intensive and more exposed to international competitiveness.

Carbon leakage provisions can heavily affect the functioning of an ETS. On the one hand, if carbon leakage measures are absent or insufficient, firms may decide to relocate their production activities and related emissions in other countries. If so, this may severely damage the environmental effectiveness of ETSs, that is, their capacity to abate emissions. On the other hand, if the carbon leakage provisions are too generous (i.e. if too many allocation are given for free to firms belonging to sectors at risk of carbon leakage) this may reduce incentives to emissions abatement. The impact that the design of an ETS may have on carbon leakage has spurred a wide debate and a growing literature in recent years (FSR Climate, 2019). Understanding the possible effects of an ETS on delocalization is of crucial importance to properly evaluate its environmental, economic and social consequences. Indeed, the environmental objective of the domestic carbon pricing policy is missed if it ends up causing emissions to increase elsewhere. In the worst case scenario, carbon leakage could even cause global emissions to increase as argued in the literature on this issue (cf. Branger and Quirion, 2014; Fowlie and Reguant, 2018). Moreover, if many firms delocalize their production to escape the ETS, this may adversely affect domestic

[1] Burke et al. (2019) estimate that the highest marginal abatement cost (which should be equal to the carbon price at equilibrium) for full decarbonization by 2050 of regulated sectors in the UK might range between €135 and €225. In simulations on its long-term decarbonization strategy, European Union adopts a carbon price of €350 (European Commission, 2018). Observed carbon prices are much lower and very far from these values. At the moment of writing, the highest carbon prices among the existing ETSs can be found in the EU ETS (around €30 per tonne of carbon dioxide emissions).

production and employment, thus reducing also the inner acceptability of the ETS.

The aim of this paper is to get a deeper understanding on the ETS-related risks of carbon leakage and contribute to this debate by proposing an innovative theoretical framework to address this issue. For this purpose, differently from previous contributions, we set forth an evolutionary model in which ETS firms decide whether to stay (keep their production activities in the domestic country) or leave (move production abroad where no ETS is in place). We investigate how this decision is affected by some key ETS design features, such as the emissions cap, the number of permits granted for free to ETS firms, the existence and level of a floor price for permits. Moreover, we assume that firms' decision on whether to delocalize is also affected by what other firms decide to do and that firms may act myopically imitating what other firms do. For this purpose, we assume that firms' behavior follows the so-called exponential replicator dynamics in which the most profitable strategy spreads within the firms' population. The assumption of bounded rationality underlying replicator dynamics can capture potential myopia of market participants and firms that has been underlined as a key element to be taken into account when designing an ETS (see, e.g., Flachsland et al., 2020).

The structure of the paper will be the following. Section 2 provides a short review of the related literature, Section 3 describes the model, Section 4 discusses numerical simulation results, Section 5 provides some concluding remarks.

2 Related literature

The issue of carbon leakage has become widely discussed in the lively debate about climate change, because it represents a recurrent threat that can hinder the effectiveness of environmental regulations. As greenhouse gas emissions are a global source of environmental externality, the possibility that some firms escape environmental regulation by relocating abroad can result in an overall weakening of the effectiveness of climate change mitigation policies.

Carbon leakage can take different forms and can operate through different channels. In this regard, three main channels have been identified in the literature (Antimiani et al., 2013; Fowlie and Reguant, 2018; Görlach and Zelljadt, 2018; Cosbey et al., 2019): (i) the output channel, (ii) the investment channel and (iii) the energy market channel. The first channel suggests that domestic firms may react to higher compliance costs by relocating their production activities abroad in the short run. The second channel looks at possible carbon leakage effects over the long-term arguing that domestic firms may decide to move abroad due to differences in expected returns. Finally, the energy market channel suggests that domestic climate policies (especially when adopted by countries that play a key role at the world level) may lower the global demand and price of fossil fuels. This may cause a rebound effect in other jurisdictions that have less stringent climate policies resulting in an overall increase in their demand of fossil fuels and related emissions that can more than counterbalance the reduction in the domestic jurisdiction.

A vast literature has tried to evaluate whether and to what extent carbon leakage occurs with both ex-ante and ex-post studies which often reach inconclusive or conflicting results. Ex ante analyses find a wide range of carbon leakage rates depending on the methodology being adopted (general versus partial equilibrium models) and on the underlying assumptions of the theoretical models (cf. Paltsev, 2001; Kuik and Gerlagh, 2003; Babiker, 2005; Gerlagh and Kuik, 2007). Computable general equilibrium models generally find much lower carbon leakage rates as compared to partial equilibrium models which tend to focus calibrations on the sectors more exposed to the risk of delocalization.[2]

Using a large-scale computable general equilibrium model to simulate the EU's climate and energy policy and taking international spillovers into account, Gerlagh and Kuik (2014) find that carbon leakage rates might be even negative at moderate levels of technological spillovers. Indeed, if technological innovation can freely spillover across countries, domestic mitigation policies could generate efficiency gains abroad and eventually lead to a reduction (rather than increase) in foreign emissions.[3]

Similarly to ex-ante analyses, also ex-post studies find different results. Most ex post analyses based on empirical estimations tend to conclude against the existence of carbon leakage, but even in this case empirical evidence is still mixed and the debate is far from over (Reinaud, 2005; Taylor, 2005; Carbon Pricing Leadership Coalition, 2019; Ellis et al., 2019; Acworth et al., 2020).

[2]Carbon leakage rates -measured as changes in emissions in the rest of the world as a percentage of domestic emissions reduction- range between 0 and 33 per cent in computable general equilibrium models, between 0 and 100 per cent in partial equilibrium models. See Branger and Quirion (2014), Partnership for Market Readiness (2015), and Carbone and Rivers (2017) for meta-analyses of the estimated effects of unilateral carbon pricing.

[3]See also Dechezleprêtre et al. (2011), Lanjouw and Mody (1996), Popp (2002) for empirical evidence on international spillover effects in environmental and energy-saving technologies.

The studies mentioned above refer to different forms of environmental regulations taking all channels of carbon leakage into account. To further restrict and better specify the perimeter of our analysis in this paper we focus on possible output relocation (the first channel of carbon leakage) induced by a specific kind of environmental regulation, the application of an Emission Trading System.

The competitiveness effects of ETS have been mainly examined by empirical studies, often focusing on the EU ETS as this is the largest cap-and-trade system existing up to now.[4] Most of the studies (e.g. Reinaud, 2008; Sartor, 2012; Petrick and Wagner, 2014; Jaraite and Di Maria, 2016) conclude that ETS provoked little or no competitiveness effects. The same holds for three studies (Dechezleprêtre et al., 2015; aus dem Moore et al., 2019; Naegele and Zaklan, 2019) which directly test for carbon leakage caused by the EU ETS by examining shifts in emission locations rather than competitiveness effects. However, this conclusion might be affected by the low carbon prices that prevailed in the markets (particularly in the EU ETS) in the examined periods, and results might change as carbon prices increase. Moreover, some more recent country-specific studies seem to find some evidence of carbon leakage. In particular, using a large data set of German firms and difference-in-differences estimator, Koch and Basse Mama (2019) find that the EU ETS had a positive causal effect on outward FDI of German multinationals, which turns out to be stronger for regulated sectors that are particularly mobile (e.g. machinery, electrical equipment and automotive sectors). In a similar vein, using a panel data set of manufacturing regulated Italian firms covering the first two phases of the EU ETS, Borghesi et al. (2020) find some evidence of carbon leakage in Italy. In fact, Italian regulated firms operating in sectors particularly exposed to international competition tended to increase their FDI and their production in already existing foreign subsidiaries located in countries not covered by the EU ETS. These country-specific results seem to suggest that the ETS could have relocation effects, the more so in the future as carbon prices are expected to progressively increase to align with more ambitious emission reduction targets.

While the number of empirical studies on the carbon leakage effects of ETS have been rapidly growing as ETS spread at the global level, the theoretical literature on this issue is much smaller.

[4] See Verde (2020), Vivid Economics (2018), Ellis et al. (2019) for recent reviews of the empirical literature on the competitiveness effects of the EU ETS.

Among theoretical studies on ETS and relocation, Fischer and Fox (2012) compare the capacity of alternative policy approaches to reduce carbon leakage. Hepburn et al. (2013) use a Cournot oligopoly model to investigate what is the amount of free allowances that should be given to firms to preserve industry profits under an ETS compared to an unregulated system. Schmidt and Heitzig (2014) examine how the allocation of free permits under an ETS can be used as an instrument to avert relocation. Using a partial equilibrium model, the authors show that even if grandfathering (i.e. free allocation of permits based on firms' historical emissions) is only temporary it may have long run effects on carbon leakage. In particular, free permits can avert relocation in the long run if the permits' price induces sufficiently high investments in low-carbon technologies that produce a lock-in effect making relocation unprofitable.

The present paper intends to contribute to the theoretical literature on ETS and carbon leakage examining the possible relocation effects of ETS from an evolutionary perspective. This approach differs from previous studies in the literature on carbon leakage as it can account for bounded rationality and imitative behaviors that can often be observed in economic systems. In an evolutionary model, in fact, agents tend to mimic the others adopting the strategy that turns out to be most profitable on average within the whole population at present. In the present context, if moving abroad (to a non-ETS jurisdiction) turns out to be more profitable than staying at home, ETS-regulated firms may decide to follow the example of the firms which already offshored their production. The opposite obviously applies if staying home is on average more profitable. However, even if a strategy is better than the other, in an evolutionary context the economic agents do not change their decision instantaneously. Any decision revision process takes time to operate. This inertia seems particularly realistic in the present case in which firms' decision to move abroad (or come back home if domestic conditions become more favorable) may require some time to be implemented for different reasons (e.g. finding elsewhere the right conditions and/or hiring the workers that are needed to operate, overcoming bureaucratic obstacles in the home country or in the destination country, etc..).

In line with the features and aims described above, in the next section we present a simple evolutionary model in which each firm has to decide between two alternative strategies: keeping production at home or shifting it abroad. Firms decide their production location looking only at current profits, namely, at which of the two strategies is more profitable at present but can revise their strategy based on the relative performance of the two strategies observed within the economy. This simple theoretical framework will be used to examine how modifications in some key elements of the ETS design (e.g. the emissions cap, the number of permits given for free and/or the floor price level) may influence firms' decisions concerning their output production, location of the production and emissions abatement.

3 The Model

Let us consider a large number of firms producing a homogeneous good with a polluting technology. There are two types of firms, h and r. Firms of type h (h-firms) produce the good in the home country in which an ETS is at work. Firms of type r (r-firms) relocate their activity to a foreign country. Let us indicate with x the share of relocating r-firms and with $1-x$ the share of h-firms that stay at home. Denoting with N the total number of firms, it follows that xN represents the total number of firms that move their production towards non-ETS jurisdictions, whereas $(1-x)N$ is the total number of firms that remain at home.

We denote with q_h and q_r the amount produced by each h-firm and r-firm, respectively. For the sake of analytical tractability, we assume that each unit of production generates one unit of polluting emissions, therefore we will indicate with q_i $(i = h, r)$ both production and the resulting emissions.

Each firm maximizes its own profit at each instant of time. We assume that both the output market and the (domestic) carbon market are perfectly competitive. The regulator of the ETS in the home country can decide to give domestic firms an amount of permits F for free to prevent them from moving their production activities abroad. This amount can be sufficient to cover the polluting emissions of firms h (i.e. $F \geqslant q_h$) or not (i.e. $F < q_h$). In the latter case, the firms can decide to buy the missing permits and/or abate emissions to avoid purchasing permits. We indicate with z the amount of emissions abatement performed by the each h-firm.

Firms have both fixed and variable production costs. We assume the latter to be a quadratic function of production. Similarly, abatement costs are assumed to be a quadratic function of the abatement effort.

3.1 Home firms

The profits of each firm that stays at home are:

$$\Pi^h = pq_h - \frac{C_h^v}{2}q_h^2 - C_h^f - \frac{\theta}{2}z^2 - a\max(0, q_h - z - F) \quad (1)$$

where p indicates the price of the produced good, q_h the amount produced by the firm that remains at home, C_h^v and C_h^f denote the variable and fixed costs of the firm, respectively, and a is the price of the emission allowances. Finally, $\theta > 0$ is a parameter which measures the (in)efficacy of the abatement technology: the higher θ, the higher the marginal cost of abating emissions using a given technology (the marginal abatement cost being equal to θz).

Notice that the last term among brackets on the right hand side of the profit function represents the demand of emission allowances of the firm $d_a = \max(0, q_h - z - F)$. The latter is obviously lowered by the permits received for free and by the abatement activities which set the firm free from the need to purchase permits.

Each h-firm chooses the optimal production level and abatement level which maximize its profit, subject to the non-negativity constraints on q_h and z, taking the output price p and the allowance price a as exogenously given (h-firms being price-takers on both the output market and the carbon market). Based on the output price level p, we can distinguish three different sets of solutions maximizing the profit function:[5]

- if $p \leqslant C_h^v F$, then

$$q_h^* = \frac{p}{C_h^v}, \qquad z^* = 0, \qquad d_a^* = 0. \quad (2)$$

- if $C_h^v F < p < \frac{(C_h^v F + a)\theta + aC_h^v}{\theta}$, then

$$q_h^* = \frac{\theta F + p}{C_h^v + \theta}, \qquad z^* = \frac{p - C_h^v}{C_h^v + \theta}, \qquad d_a^* = 0. \quad (3)$$

- if $p \geqslant \frac{(C_h^v y + a)\theta + aC_h^v}{\theta}$, then

$$q_h^* = \frac{p - a}{C_h^v}, \qquad z^* = \frac{a}{\theta}, \qquad d_a^* = \frac{(p - a - C_h^v F)\theta - aC_h^v}{\theta C_h^v}. \quad (4)$$

[5] See the online mathematical appendix for a detailed derivation of the solutions.

where -given the intervals in which the expressions in (2), (3), (4) are defined- it is straightforward to verify that q_h^* in (3) is greater than in (2), that q_h^* in (4) is greater than in (3), and that z^* in (4) is greater than in (3).

As emerges from equations (2), (3), (4), one can distinguish three possible cases (and three corresponding optimal values of each variable) depending on the price level of the produced good:

1) if the price p is relatively low, then each $h-$firm produces an amount of output (and of emissions) less than or equal to the number of permits received for free ($q_h^* = \frac{p}{C_h^v}$). No extra permits are, therefore, needed ($d_a^* = 0$) and no abatement activity ($z^* = 0$) is carried out by the firm (see (2));

2) if the price p has intermediate values (see (3)), then h-firms increase their production but prefer to abate the corresponding emissions (z^* being now positive) rather than buying extra permits on addition of those obtained for free ($d_a^* = 0$). In this case, in fact, the permits price is relatively high being $a \geqslant \theta\frac{p-FC_h^v}{\theta+C_h^v} > 0$ which stimulates firms to look for clean technologies in order to avoid the costs of purchasing permits;

3) finally, if the output price p is relatively high (see (4)), this induces firms to further increase their production (being $\frac{p-a}{C_h^v} > \frac{\theta F+p}{C_h^v+\theta}$) but also their abatement levels. However, firms now also buy a positive amount of permits ($d_a^* > 0$) since the pollution price in this case is relatively low ($a < \theta\frac{p-FC_h^v}{\theta+C_h^v} > 0$).

3.2 Relocating firms

Let us now focus on the firms that decide to relocate their activities abroad. In this case, their profit function is:

$$\Pi^r := pq_r - \frac{1}{2}C_r^v q_r^2 - C_r^f \tag{5}$$

Relocating firms decide how much to produce so as to maximize their profit function, q_r being their only choice variable. Indeed, r-firms do not abate emissions and do not buy emission allowances. Therefore, differently from h-firms, their profit function lacks the last two terms on the right-hand side of equation (1).

Solving the maximization problem of r-firms we get the optimal amount produced by r-firms:

$$q_r^* = \frac{p}{C_r^v} \tag{6}$$

According to the equation above, the marginal cost of production of the foreign firm $(q_r C_r^v)$ is equal to the output price p at the equilibrium.

3.3 Equilibrium conditions on the output market and on the allowance market

From the solution of the two optimization problems of h-firms and r-firms described above, we can derive the equilibrium conditions on the output market and on the permits market.

As to the output market, total supply is:

$$S = xNq_r^* + (1-x)Nq_h^* \tag{7}$$

Assuming a standard linear demand function, the equilibrium price on the output market is:

$$p = \overline{p} - \alpha[xNq_r^* + (1-x)Nq_h^*] \tag{8}$$

where $\alpha > 0$ and $\overline{p} > 0$ are parameters.

As to the permits market, the aggregate demand D_a is equal to the individual demand of permits $(d_a^* = q_h^* - z^* - F)$ multiplied by the overall number xN of h-firms, that is:

$$D_a = (q_h^* - z^* - F)(1-x)N \tag{9}$$

Let us indicate with $\overline{Q}$ the number of permits issued by the regulator (the emissions cap of the ETS). A share f of these permits is given for free to each h-firm to prevent it from delocalizing its production. Each h-firm, therefore, receives $F = f\overline{Q}$ free permits, where $f > 0$. We assume that the regulator cannot give away all permits for free. In other words, even in the case in which all firms stay at home ($(1-x)N = N$, i.e., $x = 0$), the number of free permits must be lower than the total number of permits issued by the regulator, therefore, $FN < \overline{Q}$ or, equivalently, $f < 1/N$.

The remaining permits are auctioned by the regulator. The number of permits supplied at the auction, therefore, is equal to the difference between the total amount of permits $\overline{Q}$ and the number of permits that are freely allocated. The latter is given by the number of h-firms (i.e. $(1-x)N$) multiplied by the number of free permits F received by each home firm.

The equilibrium condition on the allowance market is, therefore:

$$(q_h^* - z^* - F)(1-x)N = \overline{Q} - F(1-x)N$$

where the left-hand side represents the aggregate demand of permits from home firms and the right-hand side is the total number of permits actually sold by the regulator (net of those given for free).

Simplifying the common terms which appear on the right-hand side and on the left-hand side of the previous equation, the equilibrium condition can equivalently be re-written as follows:

$$(q_h^* - z^*)(1-x)N = \overline{Q} \tag{10}$$

We assume that the regulatory authority sets a minimum price level $\underline{a}$ (a floor price). Let us indicate with a^* the price that clears the permits market. If $a^* > \underline{a}$, then the aggregate demand of permits equals the aggregate supply. In this case, the equilibrium condition (10) above applies. If, on the contrary, $a^* < \underline{a}$ then an excess supply is observed in the permits market:

$$(q_h^* - z^*)|_{a=\underline{a}}(1-x)N < \overline{Q} \tag{11}$$

In this case, the number of permits sold in the market at the floor price is therefore equal to the actual demand $(q_h^* - z^*)|_{a=\underline{a}}(1-x)N$.

3.4 Evolutionary dynamics

Let us assume that time is discrete (with $t = 0, 1, 2..$ denoting the single time periods). The share of relocating firms x is assumed to follow the so-called exponential replicator dynamics (cf.

Kopel et al., 2014; Bischi et al., 2015; Dieci et al., 2018):

$$x_{t+1} = \frac{x_t}{x_t + (1 - x_t)e^{-\beta \Delta_t^{\Pi}}} \tag{12}$$

where $\Delta_t^{\Pi} = \Pi_t^r - \Pi_t^h$ indicates the profit differential between r-firms and h-firms and the parameter $\beta > 0$ measures the speed at which firms change their choice (relocating or staying). Equation (12) suggests that the share of firms that will delocalize in the future (at time $t + 1$) depends on the share of those that relocate their activities in the present (at time t), thus indicating the existence of imitative behaviors in the selection of the preferred strategy (relocating or staying). Notice that if $\Delta_t^{\Pi} = 0$ then $x_{t+1} = x_t$. In this case, therefore, the economy is at a stationary state in which the share x of relocating firms (and the corresponding share $1 - x$ of home firms) remains constant over time. If $\Delta_t^{\Pi} > 0$ then $x_{t+1} > x_t$. In other words, if the payoff of the strategy relocating is higher than that of staying at home then the share of firms which delocalize their production will tend to increase over time. The opposite obviously occurs if $\Delta_t^{\Pi} < 0$.

Fig. 1 illustrates the dynamics associated with equation (12). As the figure shows, numerical simulations find a unique attractive inner stationary state x^* (which is equal to 0.225), while the extreme equilibria $x = 0$ and $x = 1$ are repulsive. It follows that, whatever the initial conditions of the economy, all trajectories will eventually converge to x^*.

4 Numerical simulations

In this section we perform some numerical simulations to analyze the dynamics of the share of relocating firms, of the abatement efforts and of the permits demand that emerge from the model. In particular, we will examine how these variables change both over time and at different values of some key policy parameter values, namely, the price floor, the total number of allowances, the number of free allowances and the level of technological efficiency. The initial parameter values are those underlying the replicator dynamics in Fig. 1.

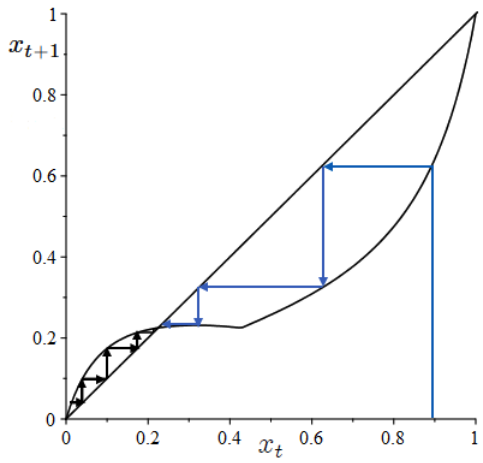
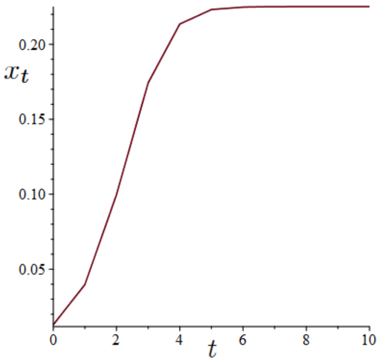


Fig. 1. Replicator dynamics. Parameter values: $N = 50$, $\overline{p} = 150$, $\alpha = 1$, $C_h^v = 0.6$, $C_h^f = 0.5$, $C_r^v = 0.5$, $C_r^f = 1.7$, $\theta = 0.17$, $\overline{Q} = 40$, $f = 0.001$, $\underline{a} = 0.1$, $\beta = 1.5$.

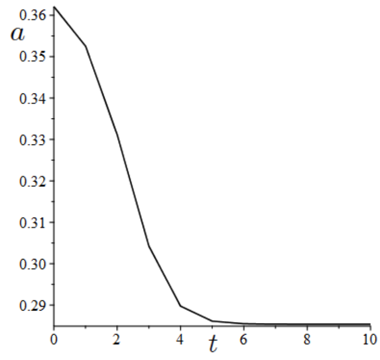
4.1 Time evolution of selected key variables

Let us start from a situation in which almost all firms (98.7% of total firms) initially operate under the home ETS ($x = 0.013$, see Fig. 2(a)). Under this condition and the set of parameter values indicated in Fig. 1, the strategy relocating will be more profitable than that of remaining at home. This leads an increasing number of firms to move their production elsewhere increasing the share x until $x_t \simeq 0.225$ at the stationary state. The migration of firms from the home country to other (non-ETS) jurisdictions obviously reduces the allowance price (see Fig. 2(b)). This tends to lower, in its turn, the firms' incentive to invest in abatement activities and to increase the permits demand until the two variables stabilize at their stationary state levels (around 1.7 and 1.0, respectively, see Fig. 2(c)).

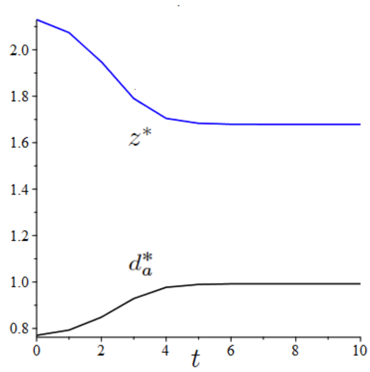
To counterbalance the firms' migration flows illustrated in the figure, the policy-maker can intervene by modifying the value of several policy parameters, such as the floor price level and the number of permits allocated on the market, or by affecting the value of other parameters, such as the marginal abatement cost (e.g. by subsidizing investments in clean technologies). Next section illustrates the possible effects of these policy interventions.



(a) Share of firms that relocate abroad.



(b) Permits price

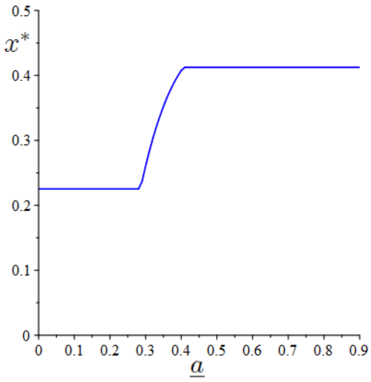


(c) Abatement activities and permits demand

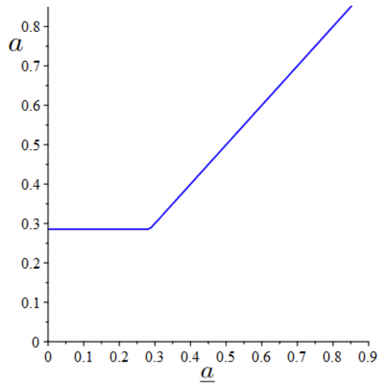
Fig. 2. Intertemporal evolution of relocating firms (x^*), permits price (a), abatement activities (z^*) and permits demand (d_a^*)

4.2 Effects of changes in policy variables

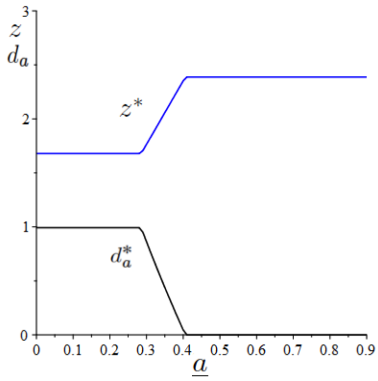
Let us first consider an increase in the floor price $\underline{a}$ (see Fig. 3). As one can reasonably expect, this will tend to increase the number of delocalizing firms since it raises the minimum cost of purchasing allowances. As the figure shows, however, the firms' decision to delocalize their activities does not change at very low or very high levels of the floor price. Indeed, the floor price is inactive if it is below the market-clearing price ($\underline{a} \simeq 0.3$ in Fig. 3). In this case, it does not affect any of the variables taken into account which remain constant as illustrated in the various panels of Fig. 3. As the floor price rises above the market-clearing price, the permits' price equals the floor price and the two variables (measured on the axes of figure Fig. 3(c)) keep growing hand-in-hand with further increases in the minimum price. The increase in permits'



(a) Share of firms that relocate abroad.



(b) Permits price



(c) Abatement activities and permits demand

Fig. 3. Evolution of relocating firms (x^*), permits price (a), abatement activities z^*, and permits demand (d_p^*) at different values of the floor price ($\underline{a}$).

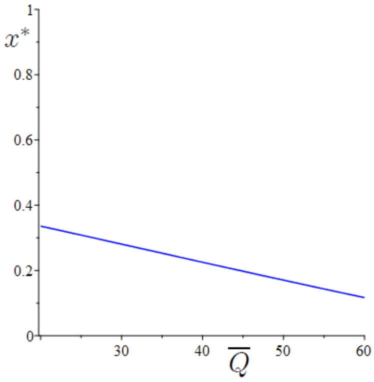
price induces a progressive migration flow towards other non-ETS jurisdictions (x^* increases in Fig. 3(a)), a fall in the permits' demand and more abatement activities to avoid paying higher compliance costs (cf. Fig. 3(c)).

When the floor price gets sufficiently high ($\underline{a} \simeq 0.4$), the demand of permits gets to zero. As a consequence, firms' abatement and relocation decisions become independent of the permits' price (as firms do not buy permits any longer). Therefore, both z^* and x^* become constant again and further increases in the floor price will have no effect on the variables taken into account. This can explain why all variables shown in Fig. 3 (excluding the permits' price) change only for intermediate values of the floor price, while they remain constant if the floor price is very low or very high.

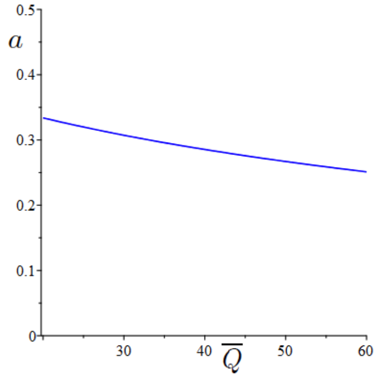
Let us now analyse the effects of changes in the total number of permits $\overline{Q}$ (the emissions cap). In most ETS the emissions cap tends to become more stringent over time, therefore in what follows we will describe the simulation results as $\overline{Q}$ decreases (i.e. moving from the right to the left along the horizontal axis). As one could reasonably expect, the permits price increases as the emissions cap falls (Fig. 4(b)). This provokes a reduction in the individual permits' demand and an increase in the abatement activities to avoid the higher costs of purchasing allowances (Fig. 4(c)). Moreover, the more stringent cap and the consequent higher permits price induce a larger share of firms to delocalize their activities to escape the higher ETS-related costs (Fig. 4(a)). A reduction in the emissions cap will thus provoke more abatement under the ETS but also less firms subject to the ETS as long as they can flee away towards other jurisdictions with laxer or no regulations.

We then examined how the variables of interest react to changes in the share f and thus also in the number $F = f\overline{Q}$ of permits allocated for free. A higher share of free permits induces less firms to delocalize their production and, therefore, more firms to stay at home (see Fig. 5(a)). This tends to increase -ceteris paribus- the aggregate demand of permits and thus also the permits price (see Fig. 5(b)), which raises in its turn the abatement activities and lowers the individual demand of permits (Fig. 5(c)). Simulation results seem to suggest that a larger number of free allocations can be effective in reducing carbon leakage and inducing higher emissions abatement. However, the variables taken into account show more limited variations as compared to the simulations shown above, suggesting that an increase in f may have a lower impact on the system than a change in the emissions cap or in the floor price.

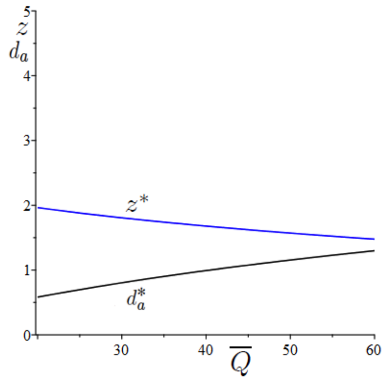
Finally, let us consider the possible dynamics deriving from changes in the parameter θ. Recall that this parameter measures the (in)efficiency of the abatement technologies, the marginal abatement cost being θz. Differently from the other policy variables considered above, the value of θ cannot be directly controlled by the regulatory authority. The latter, however, can influence it through proper interventions such as subsidies or tax credits to green investments. Similarly to what already done when commenting changes in the emissions cap $\overline{Q}$, even in this case it is convenient to interpret the figures looking at a reduction in the parameter (namely, moving leftward along the horizontal axis), as technological abatement efficiency tends to improve (i.e. θ tends to fall) over time. As Fig. 6(c) shows, lower abatement costs induce firms to abate more



(a) Share of firms that relocate abroad.



(b) Permits price.

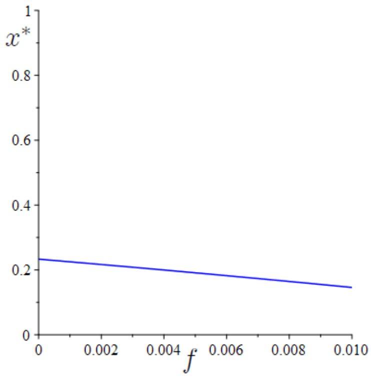


(c) Abatement activities and permits demand

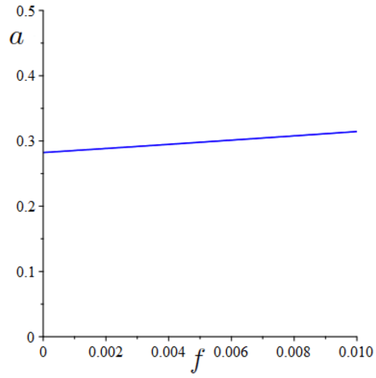
Fig. 4. Evolution of relocating firms (x^*), permits price (a), abatement activities z^*, and permits' demand (d_p^*) at different values of the emissions cap ($\overline{Q}$).

emissions (z^* increases) rather than buying permits. This reduces -ceteris paribus- the demand of permits (d_a^* decreases) as well as the permits' price (see Fig. 6(b)). The increased capacity to abate emissions at a lower cost and the reduction in the permits' price induce more firms to stay in the country, progressively reducing also x^* until this variable eventually gets to zero when the marginal abatement cost is extremely low. This is clearly illustrated in Fig. 6(a) in which the curve reaches the horizontal axis along which $x^* = 0$ (that is, all firms stay at home) when $\theta < 0.1$.

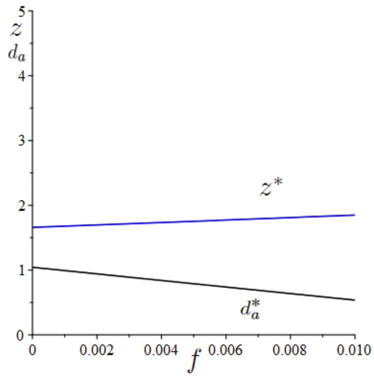
Summing up, simulation results suggest that if the regulatory authority aims at reducing delocalization and increasing abatement it should enhance the number of free permits and/or adopt measures that contribute to lower the cost of green technologies. The latter measure,



(a) Share of firms that relocate abroad.



(b) Permits price



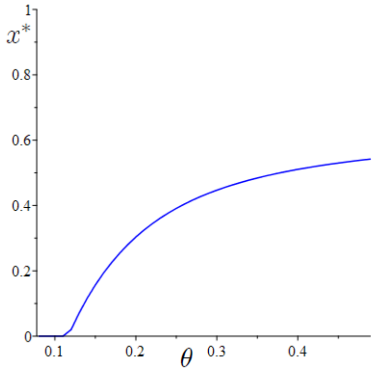
(c) Abatement activities and permits demand

Fig. 5. Evolution of relocating firms (x^*), permits price (a), abatement activities z^*, and permits' demand (d_p^*) at different values of the share of free allowances (f).

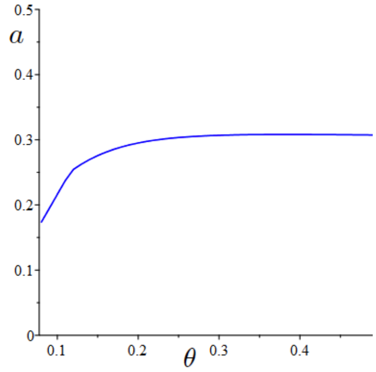
however, appears to be more effective having a larger impact both on x^* and on z^*. Opposite effects emerge, instead, from the other policy measures taken into account, namely, a reduction in the emissions cap and an increase in the floor price. Both measures promote higher abatement efforts but induce a larger migration flow towards non-ETS jurisdictions leading to more carbon leakage.

5 Conclusions

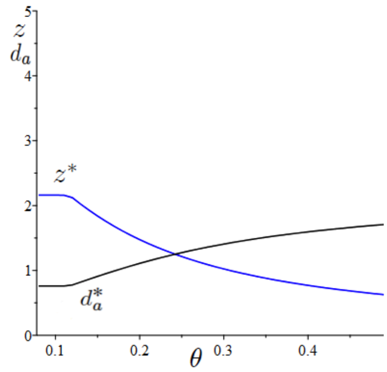
Emissions trading is gaining increasing importance around the world as a suitable instrument to address climate change. In the absence of a global carbon market, however, unilateral carbon



(a) Share of firms that relocate abroad.



(b) Permits price



(c) Abatement activities and permits demand

Fig. 6. Evolution of relocating firms (x^*), permits price (a), abatement activities (z^*) and permits' demand (d_a^*) at different values of the abatement cost parameter (θ).

policies may end up causing carbon leakage effects, the more so if carbon prices are to increase in the future to achieve more ambitious emissions abatement targets.

Carbon leakage may threaten not only the environmental effectiveness of domestic climate policies, but also their very existence. Indeed, if polluting activities simply shift elsewhere as a result of unilateral climate policies, this may adversely affect domestic production and employment without having significant impacts on global emissions, which eventually reduces also the inner acceptability of the domestic climate policy.

Given the existence of significant differences in climate policy ambition across jurisdictions, increasing attention has been devoted in the literature to the possible leakage effects of a unilateral carbon pricing instrument such as the ETS.

Differently from previous theoretical studies on this issue, this paper adopts an evolutionary approach to address the problem. In our view, this approach -which has been largely used in other contexts- can provide interesting and possibly innovative insights to this research strand. In fact, evolutionary models allow to describe myopic and imitative behaviors that are frequently observed in the economic systems and can characterize also the firms' choice on where to locate their production activities.

For this purpose, we propose a simple evolutionary model in which ETS-regulated firms have to decide whether to stay at home or shift their production abroad to some other non-ETS country. Firms tend to imitate the others and adopt the best-performing strategy, namely, the alternative that results more profitable on average among all firms. We assume that both the output market and the carbon market are perfectly competitive. The latter market has a floor price to prevent price from getting too low and admits free allocation of a share of the allowances to prevent/reduce carbon leakage.

To show the dynamics resulting from the model, we performed numerical simulations on a few key parameters which reveal some interesting insights.

First, a more stringent emissions cap promotes emissions abatement under the ETS through an increase in the price of allowances but it also induces a higher share of firms to delocalize their production activities following the (more profitable) experience of other relocating firms. The same applies to an increase in the floor price. The latter, however, turns out to be effective only at intermediate values of the parameter: indeed, firms' behavior is unchanged if the floor price is too low (below the market-clearing price and, therefore, inactive) or too high (so that no firm is willing to stay at home).

Second, the regulator can increase the share of permits allocated for free to induce more firms to stay (or come back home) and thus avoid carbon leakage. However, numerical simulations suggest that this intervention seems to have a relatively low impact on firms' behavior. A more effective policy measure turns out to be promoting technological improvements that reduce the marginal cost of emissions abatement. Under the parameters set adopted in the simulations, when the marginal abatement cost gets very low the latter policy may eventually lead all firms to stay home. In this case, therefore, one strategy (stay) spreads across all agents who operate the same choice due to the imitation process characterizing the evolutionary model.

The analytical model proposed in this paper gives a deliberately simplified representation of the real economy, therefore its results should be taken with much caution. However, in our opinion the "toy" model described above provides a general framework that can be easily extended in several directions. For instance, since carbon markets are rapidly spreading around the world, it would be interesting to investigate the results emerging in the case of multiple ETSs which differ in terms of floor price level, number of free allocations and/or exemptions criteria. The extension of the analysis to multiple countries would also allow to consider the role of potential spillover effects across countries. Indeed, the decision to relocate abroad may be influenced by the relevance of the destination country as trading partner and the existence of a similar policy instrument/mix in that country. Firms may decide to move to foreign countries not only for the existence of lower production costs as assumed here, but also because the host countries share similar environmental policies, which may ease doing business abroad. If so, the adoption of a policy instrument like the ETS in one country might have spillover effects in terms of policy across countries, leading other jurisdictions to adopt similar policies if they want to remain among the trading partners of the country. This aspect may play a key role in the relationships across countries, as shown by the recent debate around the EU proposal of introducing a Carbon Border Adjustment Mechanism.

Moreover, the model could be easily extended to account for competitiveness effects of the ETS within the country. In other words, another fruitful research line could be to examine not only multiple countries with different ETSs, but also multiple sectors within each country. For this purpose, rather than assuming a unique type of home firms, we could distinguish two firms (say, h_1 and h_2) corresponding to two sectors (regulated vs. unregulated by the ETS) and/or with different abatement parameters (θ_1 and θ_2) and thus different marginal abatement costs. Indeed, existing ETSs do not cover all sectors within a jurisdiction but just a share of them (corresponding, for instance, to approximately 40 per cent of total GHG emissions in the case of the EU ETS). More stringent climate policies may cause structural changes within a country, leading to a shift from more to less carbon-intensive sectors with a related shift in the sectors' employment levels. The dynamic nature of the model allows to capture the size and speed of the transition dynamics towards cleaner sectors and jobs within a country and to assess how this process is affected by carbon leakage risks.

Another potentially interesting extension of the model would be to enrich the analysis by introducing a third strategy at disposal of home firms, that is, investing in clean technologies. While in the present model home firms are assumed to be polluting and have, therefore, to buy emission permits, we might allow home firms to choose between two alternative strategies, a dirty and a clean one. Firms adopting a clean (green) strategy can operate in the country without buying emission permits. In such a context, one could analyze the impact of the ETS on the interaction dynamics of green, dirty, and relocating firms in a three-dimensional system.

Finally, future research should be devoted to examining how the pollution dynamics emerging from the model might affect the stringency of the ETS, inducing the regulator to adjust the cap reduction rate and/or possibly phase out free allowances according to the dynamics of the polluting emissions. While these and other questions could be addressed within the analytical framework presented here, this article just wanted to move a first step in a new research direction that can enrich the debate on the carbon leakage effects of ETSs.

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