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To abate, or not to abate? A strategic approach on green production in Cournot and Bertrand duopolies

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Abstract

This research analyses the firms' strategic choice of adopting an abatement technology in an environment with pollution externalities when the government levies an emission tax (to incentivise firms undertaking emission-reducing actions). A set of different Nash equilibria – ranging from dirty to green production – arises in both quantity-setting (Cournot) and price-setting (Bertrand) duopolies depending on the societal awareness towards environmental quality and the relative importance of technological progress in abatement adopted by firms. A synthesis of the main results is the following: if the awareness of the society towards a clean environment is relatively low (resp. high) and the index measuring the relative cost of abatement is relatively high (resp. low), the strategic interaction between two independent, competing and selfish (profit maximising) firms playing *the abatement game* leads to not to abate [NA] (resp. to abate [A]) as the Pareto efficient outcome: no conflict exists between self-interest and mutual benefit to do not undertake (resp. to undertake) emission-reducing actions. Multiple Nash equilibria or a "green" prisoner's dilemma may also emerge in pure strategies. When the choice of adopting a green technology is a deadlock (anti-prisoner's dilemma), the society is better off as social welfare under A is always larger than under NA because pollution and environmental damage are higher in the latter scenario. These findings suggest that living in a sustainable environment challenges and the improvement of public education systems to achieve an eco-responsible attitude and the development of clean technologies through ad hoc R&D.

Keywords: "Green" production; Abatement; Emissions tax; Cournot and Bertrand duopolies

JEL: H23, L1, M5, Q58

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1. Introduction

"The future's uncertain and the end is always near."
Jim Morrison

In recent years, several companies have increasingly adopted measures oriented towards environmental protection, such as, for instance, the reduction of carbon emissions or energy intensity (Wurlod and Noailly, 2018). In this regard, KPMG (2015) informed that the worldwide rate of carbon reporting of the G250 Fortune Index is 82 percent, with rates ranging in the 14 surveyed industries from 67 percent (personal and household goods) to 100 percent (food and beverages). A solid majority of those companies have disclosed targets to cut further carbon emissions: while in 2015 the percentage was 58 percent, in 2017 the figure climbed up to 67 percent. Nonetheless, only a minority (25 percent) of those firms directed their own behaviours to targets related to climate goals set by national governments, regional authorities, or the United Nations, such as The Paris Agreement (KPMG, 2017). This seems to suggest that there is room for intervention to realign firms' targets with environmental targets as planned by public authorities. A question, however, at this point raises: in a strategic context such us an oligopolistic (duopolistic) market, is it beneficial for a firm to invest in a green or clean technology to abate emission when an environmentally concerned government sets an optimal emission tax to incentivise firms undertaking emission-reducing actions? The present work concentrates precisely on this point, which is surprisingly missing in the environmental economics literature framed in strategic competitive markets. Given the growing worries in the public opinion all around the world due to the request of an immediate need to reduce emissions of greenhouse gases launched by climate scientists, because of its potential impact on global and local political and economic systems (see "The climate issue", The Economist, 2019), a timely investigation on this subject is critical and needs to be addressed especially for policy purposes.

There is a vast body of literature that studied environmental issues in economic models, ranging from growth and development to strategic competitive markets. This work concentrates on the latter. Starting from the simple framework in which every firm produces a single homogenous good at a single production plant (see, for example, Simpson 1995; Katsoulacos and Xepapadeas 1995; Carlsson 2000), the economics literature has extended the analysis to different market configurations (e.g. multi-countries, multi-products, unionised, managerial, vertical, differentiated for types of products and competition). A first branch of this literature analysed the strategic environmental policy in an international context, examining the strategic behaviour of countries when they set environmental taxes unilaterally or cooperatively. A pioneering contribution in this direction is Ulph (1996), who analysed a strategic environmental policy in countries engaging in international trade by considering an imperfect competition context. Recently, Hambel et al. (2018) proposed a novel theoretical framework where analysing the problem of optimal carbon abatement in a dynamic non-cooperative game with multiple countries assumed to be open economies. There exist also several works analysing the effects of coordination of environmental taxation on competition in markets and related effects on social welfare. These works are Conrad (1993), Kennedy (1994), Conrad (1996a), Conrad (1996b), Bárcena-Ruiz and Campo (2012) and Bárcena-Ruiz and Garzón (2014). Conrad (1993) considered firms that sell to a third-country market and shows that higher environmental taxes are set when countries do not cooperate than when they do. Alternatively, Kennedy (1994) and Conrad (1996a) assumed home and foreign segmented markets with cross-border pollution. Conrad (1996b) and Bárcena-Ruiz and Campo (2012) extended the latter analysis to Bertrand competition market and cross-ownership of firms, respectively. Finally, Bárcena-Ruiz and Garzón (2014) analysed the coordination of environmental taxes with a supranational organisation considering multiproduct firms.

A second branch of this literature examined the strategic interaction between environmental policy and endogenous location of polluting firms (to name a few, Rauscher 1995; Markusen et al. 1993; Markusen 1997; Bárcena-Ruiz and Garzón 2003). For instance, Markusen et al. (1993) discussed environmental taxation in a two-market, two-firm model where firms locate their plants endogenously, showing that the social cost can be very high if environmental taxation ignores market endogeneity.

A third branch of the literature extended the basic framework of oligopolistic rivalry by assuming – on one hand – separation between ownership and control by also introducing managerial delegation and – on the other hand – the existence of labour market imperfections (unions). Regarding managerial delegation, Bárcena-Ruiz (2002) studied the effects of delegating to managers sales and pollution abatement choices in presence of environmental tax and damage in a context of a competitive labour market and homogeneous product. Pal (2012) extended the framework of Bárcena-Ruiz (2002) to product differentiation and alternative modes of product market competition. Regarding unionised oligopolies, Bárcena-Ruiz (2011), and Bárcena-Ruiz and Garzón (2003, 2009) analysed the role played by different wage-setting structures on the environmental taxes and standards, the preferences of government and the location of polluting firms.

Finally, a fourth branch of literature related environmental policies and market structures. The pioneering works of Lee (1975) and Smith (1976) showed that market structures have an important effect on the efficiency of environmental taxation. Then, other studies have revisited this issue. Oates and Strassmann (1984) examined the efficiency of environmental taxation in a mixed (private and public firms) market; Conrad and Wang (1993) compared pollution taxes and abatement subsidies under three market structures: perfect competition, oligopolistic competition and a dominant firm with a competitive fringe. Focusing on market structures, Lee (1999) revisited environmental taxation under an endogenous oligopolistic market structure; Althammer and Bucholz (1999) investigated the effects of the market structures on the second-best choice of the environmental tax; Katsoulacos and Xepapadeas (1996) found that the optimal emissions tax could exceed marginal environmental damage under an endogenous market structure. Finally, Cato (2010) proposed a three-part environmental tax policy in an endogenous market structure and Lambertini et al. (2017) examined the relationship between competition and innovation in an industry where production is polluting and there exists R&D aims at reducing emissions with both exogenous and endogenous emissions taxes, where Fukuda and Ouchida (2020) considered the environmental concerns in markets with Corporate Socially Responsible firms.

However, despite the different aspects and contexts investigated, none of the contributions mentioned above has embedded into the analysis of oligopoly markets the firms' endogenous strategic choice of adopting an abatement technology in an environment with pollution externalities when the government levies an emission tax to incentivise firms undertaking emission-reducing actions. This article aims at filling this gap by considering Cournot and Bertrand rivalry settings. Definitively, firms are engaged in a two-stage non-cooperative *abatement game* in which they should choose whether to abate pollution through a cleaning technology in a context where the government levies a social-welfare-maximising emission tax (through a linear tax system). At stage one (*the regulator stage*), the government chooses the optimal emission tax to maximise social welfare (defined as the algebraic sum of consumers' surplus, producers' surplus, total tax revenue and environmental damage). At stage two (*the market stage*), firms either simultaneously choose to adopt a clean or green technology to abate emissions and the quantity in the output market in the case of abatement or they simply choose their own optimal amount of production (alternatively, they set the price in a Bertrand setting) in the case of no abatement.

The article begins with the basic Cournot setting with homogenous products. Although for each single player (firm) there exists an optimal level of abated pollutant in a context where pollution abatement is not subject to any strategic choice and both firms abate, it should be critical analysing whether one firm finds more suitable the unilateral choice of non-abatement in the standard context of the simultaneous and independent non-cooperative choice between the strategic profiles "to abate" (A) and "not to abate" (NA). In other words, the decision whether adopting an abatement technology for each firm should emerge as the endogenous Nash equilibrium outcome of the abatement game played by two non-cooperative players. Indeed, after the investment in pollution abatement a reduction in production cost equal to the amount of taxation computed on less emissions than the corresponding case of no abatement is achieved. Under no abatement, in fact, each firm does not incur any costs for pollution abatement but pays more taxes as the amount of pollutant is larger in that case. This implies that existence of a possible trade-off between A and NA so that the outcome of the game is not unambiguous.

Making use of a simple two-stage non-cooperative game structure in which the regulator (government) first levies the emission tax in an environment with pollution externalities and then selfish (profit-maximising) firms choose whether to invest in pollution abatement and finally compete in the output market, the article shows that the abatement game produces a set of different Nash equilibria – ranging from dirty to clean or green production – depending on the societal awareness towards environmental quality and the relative importance of technological progress in abatement that affect the marginal benefits and marginal costs of undertaking emission-reducing actions. The main findings are driven by two indexes: the awareness of the society against the damage generated by industrial production and the relative cost of abatement. When the awareness of the society against the damage generated by industrial production is relatively low and the index measuring the relative cost of abatement is relatively high, the strategic interaction between two non-cooperative profit-maximising firms leads to not to abate (NA) as the Pareto efficient outcome of the game and there is no conflict between self-interest and mutual benefit to do not undertake emission-reducing actions. This is because the amount of abated pollutant is low due to the high abatement costs so that the reduction in production costs – equal to the amount of taxation computed on less emissions – is too low to overcome the costs to invest in pollution abatement. Differently, when the awareness of the society against the damage generated by industrial production is relatively high and the index measuring the relative cost of abatement is relatively low, the strategic interaction between two non-cooperative profit-maximising firms leads to abate (A) as the Pareto efficient outcome of the game and there is no conflict between self-interest and mutual benefit to undertake emission-reducing actions. This is because the amount of abated pollutant is high due to the low abatement costs so that the reduction in production costs – equal to the amount of taxation computed on less emissions – is high enough to overcome the costs to invest in pollution abatement. In addition, pollution and environmental damage in the abatement scenario are always lower than under no abatement so that social welfare under A is larger than under NA. Therefore, if the degree of ecological awareness of the society is large and cost-reducing R&D technological progress is high, adopting a "green" technology becomes a Pareto efficient strategy for both firms and the society, which is therefore willing to accept positive (optimal) taxation to improve environmental conditions. These findings suggest that living in a sustainable environment challenges the development of clean technologies through ad hoc R&D and the improvement of public education to achieve an eco-responsible attitude.

The work also compares the outcomes of the abatement game in quantity-setting and price-setting duopolies by considering horizontal product differentiation à la Singh and Vives (1984) to allow capturing heterogeneity of consumers' taste (see Nevo, 2000, for an empirical analysis of the market demand under product differentiation). With this kind of product differentiation, goods are different but at the same price some consumers will prefer buying one of them and some will buy other depending on their preferences. The main results of the article are confirmed in both cases of product substitutability and complementarity. However, as product differentiation increases the profitability of firms through the increase in their market power, product substitutability and product complementarity work out in the anti-ecological direction of letting non-abatement be the dominant and Pareto efficient strategy of the game for a large range of values of the key parameters of the model.

The remainder of the article is organised as follows. Section 2 introduces the basic Cournot model with homogenous products. Section 3 discusses the key results by giving an economic intuition of the different scenarios the abatement game can generate (ranging from an anti-ecological deadlock to a "green" deadlock passing from a "green" prisoner's dilemma). Section 4 speculates about a possible ethical-historical-political projection exercise with the aim of distinguishing between the logical or philosophical time of the (timeless or static) one-shot, non-cooperative abatement game and the historical timing of the events (past, present and future) that contributes to generate a chronological structure of sequences, and describing possible policy recipes. Section 5 discusses some extensions of the basic model for robustness check by considering horizontal product differentiation à la Singh and Vives (1984) and progressive taxation. Section 6 concludes the article providing an outline for future research.

2. The abatement game with homogeneous products

Consider a Cournot duopoly industry where firm 1 and firm 2 produce homogeneous products q_1 and q_2, respectively. The existing technology allows firm i $(i=1,2)$ to produce q_i units of output causing e_i units of emissions (pollution), where $e_i = q_i - k_i$ (Ulph, 1996), with $0 \leq k_i < q_i$ representing the abatement level for environmental protection coming from a cleaning technology available to each firm, implying that emissions cannot be entirely eliminated.[1] Available technology is such that firm i $(i=1,2)$ produces with a constant (marginal) returns to labour production function, that is $q_i = L_i$, where L_i represents the labour force employed by the firm, and faces the same (constant) average and marginal cost $w \geq 0$ (representing the wage per unit of labour) for every unit of output produced. Therefore, firm i's cost function is linear and given by $C_i(q_i) = wL_i = wq_i$. In addition, the pollution abatement cost function of firm is $CA_i(k_i) = \frac{z}{2}k_i^2$ $CA = \frac{zk_i^2}{2}$, where $z > 0$ is a parameter that scales up/down the total abatement cost and represents an exogenous index of technological progress measuring, for example, the appearance of a new, cost-effective cleaning technology. Indeed, it measures the degree at which the available technology for pollution abatement impacts on the environment. A reduction in z can be interpreted as an improvement in technological progress in abatement so that abating pollution becomes cheaper. The adoption of a clean technology requires sustaining costs with decreasing returns to investment. That is, when firms choose to abate emissions, they always face some costs. One can think of a cleaning technology not directly linked to output, for example "the number of the filters in a refinery's pipe for CO2 reduction or 'scrubbers' to remove of SO2 from a fuel gas coal fired electric plant" (Asproudis and Gil-Moltó, 2015, p. 169). As k_i represents the pollutant abated per q_i units of output, a larger (resp. smaller) value of k_i corresponds ceteris paribus to a more (resp. less) efficient abatement. Industrial production causes an environmental damage measured by the index $ED = \frac{g}{2}(e_1 + e_2)^2$, where $g > 0$ is the burden the government attaches to the environmental damage, representing the awareness of the overall society towards the environment and thus against the damage (computed as aggregate emission squared) generated by industrial production.[2] An increase

[1] Our assumption is in line with Ulph (1996) and differs from Asproudis and Gil-Moltó (2015), who assumed emissions (pollution) were represented by $e_i = q_i k_i$ so that $k_i \in [0,1)$ is a fraction of total production in that case.

[2] The main results of this article are confirmed by assuming a linear environmental damage function $ED = g(e_1 + e_2)$ where $g > 0$ becomes the marginal damage from emissions (see Kennedy, 1999; Kennedy and Laplante, 1999; Requate, 2005; Asproudis and Gil-Moltó, 2015).

in g implies ceteris paribus an increase in the extent of the relative weight of the environmental damage as measured by the overall society (government). This type of damage function is commonly used in the related literature and assumes that (i) the environmental damage is a convex function of total pollution and (ii) the damage is exogenous for consumers (see, for example, van der Ploeg and de Zeeuw, 1992; Ulph, 1996).[3]

The government levies an emission tax $t \in (0,1]$ per each unit of polluting output to incentivise firms undertaking emission-reducing actions with the aim of maximising social welfare. Consequently, the tax base of firm i without abatement is q_i and the corresponding tax revenue of the government is tq_i. Differently, if firm i chooses to abate emissions the tax base becomes $q_i - k_i$ (i.e., the remaining pollution) and the corresponding tax revenue is $t(q_i - k_i)$.

We assume a linear (inverse) market demand given by $p = \alpha - \beta Q$, where a is a positive parameter representing the market size and $a > w \geq 0$, $\beta > 0$ measure the slope of the market demand being part of its elasticity and $Q = q_1 + q_2$ is total supply.[4] This kind of demand structure comes from the usual specification of quadratic utility for consumers' preferences, that is $U(q_1, q_2) = \alpha(q_1 + q_2) - \frac{1}{2}[\beta(q_1^2 + q_2^2) + 2q_1 q_2]$, as proposed by Dixit (1979) and subsequently used, amongst others, by Singh and Vives (1984), Häckner (2000), and Correa-López and Naylor (2004). For reasons of analytical tractability (and without loss of generality), we assume $\alpha = 1$, $\beta = 1$ and $w = 0$ henceforth.[5]

Definitively, firms are engaged in a two-stage non-cooperative *abatement game* in which they should choose whether to abate pollution through a cleaning technology in a context where the government levies a social-welfare-maximising emission tax. At stage one (the regulator stage), the government chooses the optimal emission tax to maximise social welfare. At stage two (the market stage), firms either simultaneously choose to adopt a clean (or "green") technology to abate pollution and the quantity in the output market in the case of abatement, or simply choose their own optimal amount of production in the case of no abatement.[6] As usual, the game is solved by adopting the backward induction logic.

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[3] Though g is assumed to be exogenous it may be endogenized as it represents a parameter capturing the preferences of the overall society towards environmental quality and therefore it could depend, for example, on preferences of voters by capturing the awareness of the majority to environmental issues. This is however beyond the aim of the present article and it is left for future research.

[4] These inequalities should hold as the (highest) price consumers are willing to pay for the first unit of goods must always be larger than the (lowest) marginal cost firms incur to produce the first unit of goods. Otherwise, the market would not exist.

[5] Indeed, the market size, the slope of the market demand and average and marginal costs do not affect all the relevant feasibility thresholds, profit differentials, environmental damage and social welfare functions in the cases of homogeneous and heterogeneous products in quantity-setting and price-setting duopolies, as will be shown later in this article.

[6] An additional issue concerns the choice of the timing of the game in the setting of the emission tax by the regulator. In this regard, we note that with a linear tax scheme as the one used in this article it is not possible to test the results in case the government would choose the emission tax to incentivise firms undertaking emission-reducing actions at the second stage of the game and firms decide on output and (if they abate) on the level of abatement simultaneously at the first stage. This is because an optimal emission tax rate does not exist in that case. To test for an ex-post versus ex-ante dilemma one should introduce a non-linear environmental tax scheme in the abatement game or avoid considering a government that levies emission taxes by assuming a social planner that chooses the amount of abated pollutant, as e.g. in Asproudis et al. (2019) and references cited therein. However, by assuming that the firm's choices about production and abatement are sequential, it is possible to build on a game where the timing is such that: at stage 1 each firm chooses the emission abatement effort to maximise profit; at stage 2 the regulator (government) chooses the emission tax to maximise social welfare; at stage 3 each firm chooses the output in the product market to maximise profit, then there may exist situations such that (A,A) is the Pareto efficient SPNE (deadlock) or multiple asymmetric Nash equilibria (A,NA) and (NA,A), where only one firm abates pollution.

2.1 Firms do not to abate emissions (NA)

Let us first analyse the symmetric case in which both firms choose not to abate emissions, that is $k_i = 0$ ($i = 1, 2$). The profit function of firm i is therefore the following:

$$\pi_i^{NA} = (1 - q_i - q_j - t)q_i\,,\ i = 1, 2;\ i \neq j\,, \tag{1}$$

where the upper script NA stands for no abatement. In the second stage of the game, each firm chooses its optimal output. Maximisation of (1) with respect to quantities leads to the following system of reaction functions

$$q_i = \frac{1 - q_j - t}{2}\,,\ i = 1, 2;\ i \neq j\,, \tag{2}$$

whose solution gives the following equilibrium output chosen by firm i at the second stage of the game:

$$q_i = \frac{1 - t}{3}\,. \tag{3}$$

Making use of (3), one may directly obtain producer surplus (PS), consumer surplus (CS), the tax revenues (TR) and the environmental damage caused by industrial production (ED) under NA:

$$PS^{NA} = \pi_1^{NA} + \pi_2^{NA} = \frac{2}{9}(1 - t)^2\,, \tag{4}$$

$$CS^{NA} = \frac{(q_1 + q_2)^2}{2} = \frac{2}{9}(1 - t)^2\,, \tag{5}$$

$$TR^{NA} = t(q_1 + q_2) = \frac{2}{3}t(1 - t)\,, \tag{6}$$

$$ED^{NA} = \frac{g}{2}(q_1 + q_2)^2 = \frac{2}{9}g(1 - t)^2\,. \tag{7}$$

The social welfare function is given by the following index:

$$SW^{NA} = PS^{NA} + CS^{NA} + TR^{NA} - ED^{NA} = \frac{2(1 - t)[2 + t - g(1 - t)]}{9}\,. \tag{8}$$

In the first stage of the game, the government chooses the emission tax to maximise social welfare, that is:

$$\frac{\partial SW^{NA}}{\partial t} = 0 \Rightarrow t^{*NA} = \frac{2g - 1}{2(1 + g)}\,. \tag{9}$$

Eq. (9) implies that a positive optimal emission tax under NA exists (i.e., $t^{*NA} > 0$) if and only if the overall social evaluation of the environmental damage (alternatively, the degree of societal awareness against the damage) is sufficiently large, that is $g > \frac{1}{2} := g^{NA}$. Moreover, further substitutions reveal that the non-negativity constraint on output is always fulfilled for $g > g^{NA}$, i.e. $q_i^{NA} > 0$ and $e_i^{NA} = q_i^{NA} > 0$ holds. Substituting back the optimal tax in (9), the first stage equilibrium profits of firm 1 and firm 2 under NA are given by:

$$\pi_1^{*NA} = \pi_2^{*NA} = \frac{1}{4(1 + g)^2}\,. \tag{10}$$

2.2 Firms adopt the abatement technology (A)

Consider now the symmetric case in which both firms adopt the abatement technology, with $k_i \in [0, q_i)$. The profit functions take the following form

$$\pi_i^A = (1-q_i-q_j)q_i - t(q_i-k_i) - \frac{zk_i^2}{2},\ i=1,2, \tag{11}$$

where the upper script A stands for abatement. In the second stage of the game, firms choose both output and the abatement level. After the investment in pollution abatement, a reduction in production cost equal to the amount of taxation computed on less emissions is achieved than the corresponding case of no abatement.

Maximisation of (11) with respect to q_i and k_i leads to the following set of first order conditions:

$$\text{A) } q_i = \frac{1-q_j-t}{2};\ \text{B) } k_i = \frac{t}{z},\ i=1,2;\ i \neq j. \tag{12}$$

The solution of the system of output reaction functions A) in (12) implies that, in equilibrium, output is as in (3). Using (3) and condition B) in (12), one can get the following expressions for the producer surplus, consumer surplus, the tax revenue, and the environmental damage under A:

$$PS^A = \pi_1^{NA} + \pi_2^{NA} = \frac{2}{9}(1-t)^2 + \frac{t^2}{z}, \tag{13}$$

$$CS^A = \frac{(q_1+q_2)^2}{2} = \frac{2}{9}(1-t)^2, \tag{14}$$

$$TR^A = t[(q_1-k_1)+(q_2-k_2)] = \frac{2}{3}t\left[1-\frac{t(3+z)}{z}\right], \tag{15}$$

$$ED^A = \frac{g}{2}\left[(q_1-k_1)+(q_2-k_2)\right]^2 = \frac{2}{9}g\left[1-\frac{t(3+z)}{z}\right]^2. \tag{16}$$

Therefore, the expression of social welfare is the following:

$$SW^A = PA^A + CS^A + TR^A - ED^A = \\ = \frac{2z^2(1-t)[2-g+(1+g)t] + 3zt[4g(1-t)-3t] - 18gt^2}{9z^2}. \tag{17}$$

In the first stage of the game, the government chooses the emission tax such that the expression in (17) is maximised, that is:

$$\frac{\partial SW^A}{\partial t} = 0 \Rightarrow t^{*A} = \frac{z[(2g-1)z+6g]}{2z^2(1+g)+3z(3+4g)+18g}. \tag{18}$$

Eq. (18) implies that a positive optimal emission tax under A exists (i.e., $t^{*A} > 0$) if and only if the overall societal evaluation of the environmental damage is sufficiently large, that is $g > \frac{z}{2(3+z)} := g^A(z) < g^{NA}$. Making use of the optimal tax in (18), one may easily check that if $g > g^A(z)$ then $q_i^A > 0$, $k_i^A > 0$ and the condition $e_i^A = q_i^A - k_i^A > 0$ is always fulfilled. Finally, substituting back the optimal tax in (18), the first stage equilibrium profits of firm 1 and firm 2 under A are the following:

$$\pi_1^{*A} = \pi_2^{*A} = \frac{2z^4 + z^3(4g^2+4g+13) + 2z^2(16g^2+18g+9) + 12zg(7g+6) + 72g^2}{2[2z^2(1+g)+3(4gz+6g+3z)]^2}. \tag{19}$$

2.3 The asymmetric case: one firm abates, the rival does not (A/NA)

To analyse the firms' endogenous incentive to abate emissions, one must evaluate the outcomes of the asymmetric behaviour in which one firm, say firm 1, adopts the abatement technology and the rival (firm 2) does not. The two firms' optimisation problems lead to first order conditions as in (12) for firm 1 and as in (2) for firm 2. Again, the firms' equilibrium output is given by (3) and, together with condition B) in (12), standard substitutions lead to the next expressions for the producer surplus, consumer surplus, the tax revenue and the environmental damage in the asymmetric case:

$$PS^{A/NA} = \pi_1^{A/NA} + \pi_2^{A/NA} = \frac{1}{18}[4z(1+t^2) + t(9t - 8z)], \quad (20)$$

$$CS^{A/NA} = \frac{(q_1+q_2)^2}{2} = \frac{2}{9}(1-t)^2, \quad (21)$$

$$TR^{A/NA} = t[(q_1 - k_1) + q_2] = \frac{t}{3z}[2z(1-t) - 3t)], \quad (22)$$

$$ED^{A/NA} = \frac{g}{2}[(q_1 - k_1) + q_2]^2 = \frac{g}{18z^2}[2z(1-t) - 3t]. \quad (23)$$

The expression of the social welfare under A/NA is the following:

$$SW^{A/NA} = PA^{A/NA} + CS^{A/NA} + TR^{A/NA} - ED^{A/NA} = \\ = \frac{4z^2(1-t)[2-g+(1+g)t] + 3zt[4g-(4g+3)t] - 9gt^2}{18z^2}. \quad (24)$$

Therefore, in the first stage of the game the government chooses the emission tax such that the social welfare is maximised, that is:

$$\frac{\partial SW^{A/NA}}{\partial t} = 0 \Rightarrow t^{*A/NA} = \frac{z[(4g-2)z + 6g]}{4z^2(1+g) + 3z(4g+3) + 9g}. \quad (25)$$

Eq. (25) implies that a positive optimal emission tax in the asymmetric case exists (i.e., $t^{*A/NA} > 0$) if and only if the overall societal evaluation of the environmental damage is sufficiently large, that is $g > \frac{z}{3+2z} := g^{A/NA}(z) < g^{NA}$. Making use of the optimal tax in (25) and accounting for the constraint $g > g^{A/NA}(z)$ it can easily be shown that $q_1^{A/NA} > 0$, $k_1^{A/NA} > 0$, $q_2^{A/NA} > 0$ and $k_2^{A/NA} > 0$. In addition, the inequality $e_1^{A/NA} = q_1^{A/NA} - k_1^{A/NA} > 0$ is satisfied for any $g^{A/NA}(z) < g < \frac{z(2z+5)}{3+2z} := g^T(z)$. The second inequality in the last constraint is a threshold that should be fulfilled as the perceived societal awareness towards the environment should not be too high otherwise the corresponding optimal tax should be set at too high a level not allowing the firm to implement a feasible abatement technology. Finally, inserting back the optimal tax in (25), the first stage equilibrium profits of firm 1 and firm 2 in the case of asymmetric behaviour are the following:

$$\pi_1^{*A/NA} = \frac{4z^4 + 2z^3(4g^2+7) + z^2(28g^2+12g+9) + 6zg(5g+3) + 9g^2}{\{4z[z(1+g)+3g] + 9(g+z)\}^2},$$

$$\pi_2^{*A/NA} = \frac{(2z+3)^2(z+g)^2}{\{4z[z(1+g)+3g] + 9(g+z)\}^2}. \quad (26)$$

It is important to note that the optimal tax rates (9), (18) and (25) in the strategic profiles NA, A and A/NA, respectively, positively depend on g ($\partial t^* / \partial g > 0$). The economic intuition is clear. As g represents the societal awareness towards environment quality (i.e., against the environmental damage generated by industrial production), an increase in g implies that the society is willing to pay more taxes to allocate more resources towards environmental protection by favouring the adoption of clean technologies. This is one important element that will allow to disentangle the effects allowing to incentivise the (endogenous) adoption of environmental-friendly-oriented technologies by firms. The tax rate contributes to increase the marginal cost of industrial production and incentivise abatement. Therefore, the higher the optimal emission tax rate, the lower the quantity produced by each firm in the market and the higher the amount of pollutant that will be abated in equilibrium. Regarding the dependency of t^* on z it is clear that under the strategic profile NA the optimal tax rate is independent of the parameter weighting technological progress in abatement, whereas under A and A/NA there exists a non-monotonic shape (first increasing and then decreasing but the increasing branch of the curve still holds for sufficiently high values of z) depending on the size of g. However, as far as g becomes larger the optimal emission tax rate starts becoming a monotonic increasing function of g (this holds for values of z around 1 in both cases A and A/NA). Therefore, technological progress favouring emission abatement (through reduction in z) generally works in the direction of reducing the tax burden. This is another element that will be useful for the intuition of the results that will be presented later in this article.

3. The abatement game: analysis and results

Making use of the firms' profits in (10), (19) and (26), it is possible to build on the payoff matrix summarised in Table 1 regarding the abatement game.

Table 1. The abatement game (payoff matrix). Cournot competition with homogenous products.

Firm 2 $\rightarrow$ Firm 1 $\downarrow$	A	NA
A	π_1^{*A} , π_2^{*A}	$\pi_1^{*A/NA}$, $\pi_2^{*A/NA}$
NA	$\pi_1^{*NA/A}$, $\pi_2^{*NA/A}$	π_1^{*NA} , π_2^{*NA}

To satisfy all technical restrictions and have well-defined equilibria in pure strategies for every strategic profile, the analysis is restricted to the following feasibility constraints $\frac{1}{2} := g^{NA} < g < g^T(z)$ that hold for any $z > 0.323$ (which is assumed to be always satisfied henceforth). Then, to derive all the possible equilibria of the game, one must study the sign of the following profit differentials for $i = 1, 2$:

$$\Delta\pi_1 := \pi_i^{A/NA} - \pi_i^{NA},\ \Delta\pi_2 := \pi_i^{NA/A} - \pi_i^{A} \text{ and } \Delta\pi_3 := \pi_i^{NA} - \pi_i^{A}, \tag{27}$$

where

$$\Delta\pi_1 = \frac{1}{4(1+g)^2[9(z+g)+4z^2(1+g)+12gz]^2} \times$$

$$(32g^4z^3 + 122g^4z^2 + 64g^3z^3 + 120g^4z + 272g^3z^2 - 8g^2z^3 + 36g^4 + 312g^3z + 28g^2z^2 - 56gz^3 +$$

$$+72g^3 + 48g^2z - 168gz^2 - 16z^3 - 45g^2 - 90gz - 45z^2)$$

$$\Delta\pi_2 = \frac{-z}{2[9(z+g)+4z^2(1+g)+12zg]^2[9(z+2g)+2z^2(1+g)+12gz]^2} \times$$

$$(64g^2z^6 + 864g^4z^5 + 128g^3z^6 + 4800g^4z^4 + 1632g^3z^5 - 16g^2z^6 + 14040g^4z^3 +$$

$$+7920g^3z^4 + 120g^2z^5 - 112gz^6 + 22788g^4z^2 + 1836g^3z^3 - 372g^2z^4 - 1032gz^5 - 32z^6 +$$

$$+19440g^4z + 20412g^3z^2 - 702g^2z^3 - 3024gz^4 - 198z^5 + 6804g^4 +$$

$$+8748g^3z - 567g^2z^2 - 2754gz^3 - 243z^4)$$

and

$$\Delta\pi_3 = \frac{-1}{4(1+g)^2[9(z+2g)+2z^2(1+g)+12gz]^2}\times$$
$$(8g^4z^3+64g^4z^2+24g^3z^3+168g^4z+200g^3z^2+2g^2z^3+144g^4+480g^3z+28g^2z^2-24gz^3+$$
$$+288g^3+24g^2z-144gz^2-10z^3-180g^2-180gz-45z^2)$$

Let $g_{\Delta_1}(z)$, $g_{\Delta_2}(z)$ and $g_{\Delta_3}(z)$ be three threshold values of g as a function of z such that the profit differentials $\Delta\pi_1 = 0$, $\Delta\pi_2 = 0$ and $\Delta\pi_3 = 0$, respectively. The shape of $g_{\Delta_1}(z)$ (solid line), $g_{\Delta_2}(z)$ (dashed line) and $g_{\Delta_3}(z)$ (dotted line) is depicted in Figure 1 in the parameter space (g,z). The solid red increasing curve $g^T(z)$ is the boundary of the (red) area representing the unfeasible parameter space (otherwise the optimal tax rate should be set at too high a level not allowing the firm to implement a feasible abatement technology). An analytical inspection of each profit differential in (27) reveals that for $g < g_{\Delta_1}(z)$ (resp. $g > g_{\Delta_1}(z)$) we have that $\Delta\pi_1 < 0$ (resp. $\Delta\pi_1 > 0$), for $g < g_{\Delta_2}(z)$ (resp. $g > g_{\Delta_2}(z)$) we have that $\Delta\pi_2 > 0$ (resp. $\Delta\pi_2 < 0$) and for $g < g_{\Delta_3}(z)$ (resp. $g > g_{\Delta_3}(z)$) we have that $\Delta\pi_3 > 0$ (resp. $\Delta\pi_3 < 0$). As is clear by looking at the figure and the shapes of the thresholds, the larger the parameter measuring the relative cost of technological progress in abatement (z) and the smaller the societal awareness against the environmental damage (g), the higher the firms' incentive to do not adopt an abatement technology as the benefits of abatement (the amount of the emission tax levied by the regulator on the differences between production and abatement) are smaller than the costs (as measured by the effectiveness of the abatement technology). Differently, the firms' incentive to abate emissions increases if the abatement technology becomes more efficient (z reduces) and the society's degree of environmental awareness becomes higher (g increases). The relative shapes of the three thresholds contribute to determine the outcomes of the abatement game. To this purpose, Result 1 shows the spectrum of Nash equilibria of this two-stage non-cooperative game for different parameter values.

Result 1. If the regulator levies an emission tax to incentivise firms undertaking emission-reducing actions, the abatement game produces the following set of Nash equilibrium outcomes in pure strategies.

[1] Let $z > 3.702$ hold. (1) If $g^{NA} < g < g_{\Delta_2}(z)$ then (NA,NA) is the unique Pareto efficient SPNE of the game (deadlock) and NA is the dominant strategy (there is no conflict between self-interest and mutual benefit to do not undertake emission-reducing actions). (2) If $g_{\Delta_2}(z) < g < g_{\Delta_1}(z)$ then there exist two pure-strategy Nash equilibria given by (NA,NA) and (A,A), and NA payoff dominates A (coordination game). (3) If $g_{\Delta_1}(z) < g < g_{\Delta_3}(z)$ then (A,A) is the unique Pareto inefficient SPNE of the game (prisoner's dilemma) and A is the dominant strategy (there is a conflict between self-interest and mutual benefit of undertaking emission-reducing actions). (4) If $g_{\Delta_3}(z) < g < g^T(z)$ then (A,A) is the unique Pareto efficient SPNE of the game (deadlock) and A is the dominant strategy (there is no conflict between self-interest and mutual benefit of undertaking emission-reducing actions).

[2] Let $2.107 < z < 3.702$ hold. (1) If $g^{NA} < g < g_{\Delta_2}(z)$ then (NA,NA) is the unique Pareto efficient SPNE of the game (deadlock) and NA is the dominant strategy (there is no conflict between self-interest and mutual benefit to do not undertake emission-reducing actions). (2) If $g_{\Delta_2}(z) < g < g_{\Delta_3}(z)$ then there exist two pure-strategy Nash equilibria given by (NA,NA) and (A,A), and NA payoff dominates A (coordination game). (3) If $g_{\Delta_3}(z) < g < g_{\Delta_1}(z)$ then there exist two pure-strategy Nash equilibria given by (NA,NA) and (A,A), and A payoff dominates NA (coordination game). (4) If

$g_{\Delta_1}(z) < g < g^T(z)$ then (A,A) is the unique Pareto efficient SPNE of the game (deadlock) and A is the dominant strategy (there is no conflict between self-interest and mutual benefit of undertaking emission-reducing actions).

[3] Let $0.593 < z < 2.107$ hold. (1) If $g^{NA} < g < g_{\Delta_3}(z)$ then there exist two pure-strategy Nash equilibria given by (NA,NA) and (A,A), and NA payoff dominates A (coordination game). (2) If $g_{\Delta_3}(z) < g < g_{\Delta_1}(z)$ then there exist two pure-strategy Nash equilibria given by (NA,NA) and (A,A), and A payoff dominates NA (coordination game). (3) If $g_{\Delta_1}(z) < g < g^T(z)$ then (A,A) is the unique Pareto efficient SPNE of the game (deadlock) and A is the dominant strategy (there is no conflict between self-interest and mutual benefit of undertaking emission-reducing actions).

[4] Let $0.323 < z < 0.593$ hold. (1) If $g^{NA} < g < g_{\Delta_1}(z)$ then there exist two pure-strategy Nash equilibria given by (NA,NA) and (A,A), and NA payoff dominates A (coordination game). (2) If $g_{\Delta_1}(z) < g < g_{\Delta_3}(z)$ then (A,A) is the unique Pareto inefficient SPNE of the game (prisoner's dilemma) and A is the dominant strategy (there is a conflict between self-interest and mutual benefit of undertaking emission-reducing actions). (3) If $g_{\Delta_3}(z) < g < g^T(z)$ then (A,A) is the unique Pareto efficient SPNE of the game (deadlock) and A is the dominant strategy (there is no conflict between self-interest and mutual benefit of undertaking emission-reducing actions).

The analysis of the abatement game in the case of quantity competition with homogenous products shows that the comparison between the behaviours of selfish economic agents in a strategic context may have different outcomes resembling several paradigms of the game theory. To this purpose, Result 1 (whose geometric pattern is represented in Figure 1) clearly implies that the emergence of these outcomes depends on a combination of two parameters representing, respectively, the relative impact on profits of the costs should be sustained by the firms to adopt a technology to reduce pollution (z) and the relative weight of the (optimal) emission tax in the different strategic profiles (g) to incentivise firms undertaking emission-reducing actions. The higher (resp. lower) z, the higher (resp. lower) the cost each firm should incur to abate pollution by choosing the optimal amount of pollutant to be abated. This may happen, for example, because technological progress for abatement has not yet allowed to develop adequately (resp. has already allowed) an efficient cleaning technology to reduce abatement costs and improve environmental quality. The lower (resp. higher) g, the lower (resp. higher) the societal awareness towards environmental quality and the lower (resp. higher) the amount of emission tax firms are paying to favour abatement. An obvious scenario emerging by the study of the game is that adopting a cleaning technology is a matter of comparing marginal benefits and marginal costs of abatement when the regulator levies an emission tax whose burden changes depending on the amount of abated pollutant. In fact, on one hand, the emission tax increases the marginal cost of production. On the other hand, the abatement technology allows firm to reduce marginal costs, to reduce pollution and eventually the tax base. However, it requires an investment with diminishing returns (Asproudis and Gil-Moltó, 2015) that reduces profits.

The larger the quantity of pollutant abated (which, at the optimum, positively depends on the emission tax rate and thus on g, and negatively depends on z), the higher the costs for abatement, but the lower the tax base (i.e., the difference between industrial production and abated pollutant) and the amount of emission tax should be paid in equilibrium. The smaller the quantity of pollutant abated, the lower the costs for abatement but the higher the tax base and the amount of emission tax should be paid in equilibrium. In the ultimate case of no abatement, each firm does not incur in abatement costs, but the tax base and the amount of emission tax are the highest. Therefore, there are conflicting effects, and the outcome of the abatement game depends on whether the benefits arising from adopting an abatement technology overcome or not the corresponding costs.

The economic intuition of the different results of the abatement game can be carried out following the narrative of and the cases detailed in Result 1 (whose ethical-historical-political reading is presented in Section 3) starting from a combination of parameters in (g, z) plane belonging to the north-west area of Figure 1 (i.e., high abatement costs and low awareness towards environmental quality) and moving to the right by increasing the degree of awareness of the society towards the environment. In this case, the comparison between profits of two profit-maximising firms that must choose to abate or not to abate pollutants from industrial production supports the strategic profile NA. Indeed, on one hand a firm that chooses to do not abate pollution pays a relatively low amount of emission tax though computed on the whole quantity produced. This is because the awareness towards environmental quality is low and it does not incur any abatement cost so that the tax rate at the optimum is low enough in that case. On the other hand, choosing to abate pollution implies incurring high abatement costs (as z is high) that will in turn imply a small amount of pollutant abated at the optimum but the rate of environmental taxation applied by the government in that case will be relatively high because of the high value of z (though g is low). In addition, a lower amount of goods will be produced in the product market (which will be sold at a higher price) than in the case of non-abatement. The combination of high costs and low benefits of abatement implies that adopting an abatement technology is expensive and profits under A will be lower than profits under NA, which is therefore a dominant strategy. This outcome is Pareto efficient for firms and there is no conflict between self-interest and mutual benefit to do not undertake emission-reducing actions.

By increasing slightly environmental awareness when abatement costs are high implies entering a parametric area in which there are multiple pure-strategy Nash equilibria, where NA payoff dominates A. The increase in g causes an increase in the emission tax rate should be paid at the optimum in the different strategic profiles of the game. This in turn implies a reduction in the amount of industrial production and an increase in the price consumers are willing to pay in the market. In addition, the amount of pollutant abated raises as g is increased. The combination of these effects implies a drop in profits in all (symmetric and asymmetric) strategic profiles as the negative effects on profits of the reduction in the amount of industrial production overcomes the positive effects due the increase in the market price. However, the fall in profits is larger under NA than under A as pollution abatement (implying a higher amount of abated pollutant than when g was lower) also works in the direction of reducing the overall burden of the emission tax and provides an incentive for firms to deviate towards abatement if the rival also choose to abate. No dominant strategies do exist in this case. Definitively, the outcome of the game is a priori uncertain. In fact, on one hand each player is interested in NA if the rival chooses to do not abate pollution, because everyone would like to play NA. On the other hand, no one is willing to adopt an abatement technology if the rival does not abate as no one wants to be the sole player to incur abatement costs. Again, no one would like to make decisions that he might regret, but no one can foresee the rival's decisions (this is because firms are playing a simultaneous non-cooperative game). It could happen, however, that the two players make non-consistent choices: if someone chooses not to abate to avoid losing the opportunity to get higher profits and the rival chooses to abate to reduce the tax burden, players may end up in a situation where only one of them adopts the abatement technology representing for both an unsatisfied outcome as everyone could be better off with a different choice. Differently, if decisions were compatible both players will choose not to abate pollution if they are not willing to be the unique player to adopt the abatement technology (which is relatively expensive) achieving a Pareto efficient outcome. Players may also make compatible decisions ensuring a sub-optimal result and thus they may both choose to adopt the abatement technology if they are willing to reduce the tax burden in a context where social awareness against pollution is not sufficiently high. In this context, however, players are interested in agreeing to do not abate (NA). Furthermore, by choosing NA everyone would be interested in complying with the agreement as no one would have the incentive to deviate towards A with a

Pareto dominated outcome. Though the game is non-cooperative, both players have an incentive to coordinate towards NA by producing with a dirty technology.[7]

A further increase in the societal awareness towards environmental quality (g) allows entering a small portion of the plane (area c) in which the game becomes a prisoner's dilemma, where there is a conflict between self-interest and mutual benefit of undertaking emission-reducing actions. The increase in g causes a significant increase in the emission tax rate under NA and a slight increase in the tax rate under A. The quantity of goods produced in all strategic profiles reduces and the market price increases. The increase in the amount of abated pollutant also reduces the tax burden of emissions in comparison with the case of no abatement. The combination of these effects implies that the reduction in profits under NA is larger than the reduction in profits under A. Payoffs in this case imply that each player would be fully satisfied to adopt the cleaning technology with the lowest tax burden, but each player would prefer to cooperate with the rival to do not abate (thus producing the highest possible amount of goods) achieving higher profits than when both firms chose to adopt the abatement technology. Each player, however, would prefer to abate and reduce the tax burden rather than being the only one choosing not to abate, paying the highest possible amount of emission taxes thus getting the lowest possible amount of profits. In this context, each player has a dominant strategy (A) allowing to get the best result regardless of the rivals' choice. In fact, no one is interested in playing NA if the rival plays A as everyone prefers to be the only one to abate with the lowest tax burden (and highest profit) rather than being the only one not to abate with the highest tax burden (and lowest profit). Also, no one is interested in not abating pollution even when the rival choose to do not abate as everyone prefers to adopt the cleaning technology to reduce the tax burden rather than producing with a dirty technology by paying more taxes. Regardless of the rival's decision, no one will decide to play NA and both players will agree to reduce their profits by adopting an abatement technology. If both players had decided to cooperate by playing NA, however, they would have jointly achieved a better outcome. This result is interesting as it highlights the existence of a conflict between self interest and mutual benefits. By making decisions that guarantee each selfish player the best result unilaterally, both achieve a Pareto dominated outcome than that they would have obtained if both had chosen not to abate.[8]

Though the strategic profile A was a dominant strategy in area c of Figure 1, there was a conflict between self-interest and mutual benefit of undertaking emission-reducing actions. However, the model reveals that raising further the public awareness towards environmental quality solves the dilemma and the game becomes a deadlock. Indeed, an increase in g increases taxation in all the strategic profiles (causing a reduction in the industrial production of goods and an increase in the market price) but also contributes to increase the amount of abated pollutant in equilibrium. The combined effect of these changes works in the direction of reducing profits for both NA and A. The

[7] A result with multiple equilibria in pure strategies similar to the one outlined here can be obtained in area b of the parametric space (g,z) in Figure 1, where A payoff dominates NA. By increasing environmental awareness when abatement costs are lower than before causes an increase in the amount of pollutant abated (as g is increased) that may make it convenient the adoption of a cleaning technology through the reduction in the marginal costs of production. No dominant strategies do exist, and the outcome of the game is a priori uncertain also in this case. If decisions were compatible both players will choose to abate pollution if they are not willing to be the unique player to do not adopt the abatement technology (which is cheaper) achieving a Pareto efficient outcome. Players may also make compatible decisions ensuring a sub-optimal result and thus they may both choose not to abate if each player is not willing the be the unique to reduce the tax burden though in a context where social awareness against pollution is larger than before and abatement costs are lower than before. In this context, however, players are interested in agreeing to coordinate towards A by producing with a clean technology though the game is non-cooperative. By choosing A everyone would be interested in complying with the agreement as no one would have the incentive to deviate towards NA with a Pareto dominated outcome.

[8] The same kind of prisoner's dilemma can be obtained with low values of z and g (area a in Figure 1). In this case, in fact, technological progress for abatement has worked out by sharply reducing costs firms should incur to adopt a green technology so that the environment is already clean and a small value of g is enough to go through the adoption of a cleaning technology as a dominant strategy.

reduction in profits under NA, however, is much larger than those observed under A. This is because the increase in the amount of emissions abated reduces the tax burden for the firm adopting the cleaning technology to the extent profits under A becomes larger than profits under NA. Therefore, there is no longer any conflict between self-interest and mutual benefit of undertaking emission-reducing actions as the adoption of a clean technology is Pareto efficient for firms.[9]

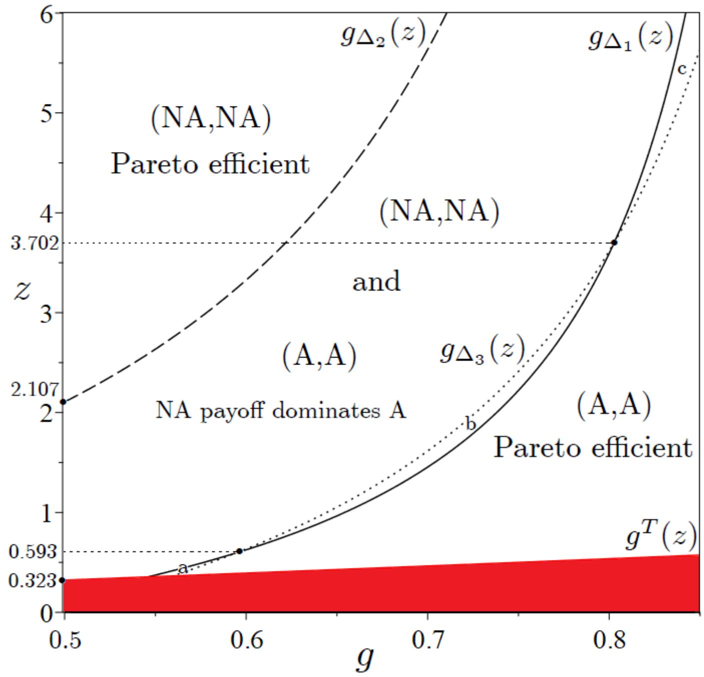


Figure 1. The abatement game. Nash equilibrium outcomes in (g, z) plane. The solid (resp. dashed) [resp. dotted] black line represents the threshold value $g_{\Delta_1}(z)$ (resp. $g_{\Delta_2}(z)$) [resp. $g_{\Delta_3}(z)$] such that $\Delta\pi_1 = 0$ (resp. $\Delta\pi_2 = 0$) [resp. $\Delta\pi_3 = 0$]. The solid red increasing curve $g^T(z)$ is the upper boundary of the red area representing the unfeasible parameter space (alternatively, the technical non-feasibility of pollution abatement). The SPNE in the areas denoted by a and c is (A,A). This outcome is Pareto inefficient (prisoner's dilemma). In the area denoted by b there are multiple Nash equilibria in pure strategy: (NA,NA) and (A,A), where A payoff dominates NA.

Now, having identified the endogenous choice of the firms regarding abatement decisions, let us investigate the effects (at the equilibrium) on total pollution (P^*), environmental damage (ED^*) and social welfare (SW^*) by comparing the cases (NA,NA) and (A,A) as mixed Nash equilibria do not exist in this game. Making use of the expressions of the optimal tax rates in (9) and (18), one gets the equilibrium values of the amount of pollution generated by industrial production, the corresponding environmental damage and social welfare under the strategic profiles NA and A, that is:

$$P^{*NA} = e_1^{*NA} + e_2^{*NA} = q_1^{*NA} + q_2^{*NA} = \frac{1}{1+g}, \tag{28}$$

$$P^{*A} = e_1^{*A} + e_2^{*A} = (q_1^{*A} - k_1^{*A}) + (q_2^{*A} - k_2^{*A}) = \frac{2z(4+z)}{2z^2(1+g) + 3[3z + 2g(3+z)]}, \tag{29}$$

[9] The same kind of Pareto efficient outcome can be achieved with low values of g by reducing z adequately. In fact, a sufficient reduction of z through R&D for cleaning purposes sharply reduces the costs a firm should incur for adopting a cleaning technology and makes it convenient to increase the amount of emissions abated so that the tax burden also decreases.

$$ED^{*NA} = \frac{g}{2}(e_1^{*NA} + e_2^{*NA})^2 = \frac{g}{2(1+g)^2}, \quad (30)$$

$$ED^{*A} = \frac{g}{2}(e_1^{*A} + e_2^{*A})^2 = \frac{2z^2 g(4+z)^2}{\{2z^2(1+g)+3[3z+2g(3+z)]\}^2}, \quad (31)$$

$$SW^{*NA} = \frac{1}{2(1+g)}, \quad (32)$$

$$SW^{*A} = \frac{(4+z)(z+2g)}{2z^2(1+g)+3[3z+2g(3+z)]}. \quad (33)$$

Straightforward comparison of the expressions in (28)-(33) yields:

$$P^{*A} - P^{*NA} = \frac{-[z(1+4g)+18g]}{(1+g)\{2z^2(1+g)+3[3z+2g(3+z)]\}} < 0, \quad (34)$$

$$ED^{*A} - ED^{*NA} = \frac{-g(z+18g+4zg)(4z^2 g+20zg+4z^2+18g+17z)}{2(1+g)^2\{2z^2(1+g)+3[3z+2g(3+z)]\}^2} < 0, \quad (35)$$

$$SW^{*A} - SW^{*NA} = \frac{z(4g^2-1)+2g(8g-1)}{2(1+g)\{2z^2(1+g)+3[3z+2g(3+z)]\}} > 0, \quad (36)$$

for any $\frac{1}{2} := g^{NA} < g < g^T(z)$ and $z > 0.323$. Therefore, the following proposition holds.

Proposition 1. The aggregate amount of pollution and the environmental damage generated by industrial production when firms abate are smaller than when firms do not abate. Social welfare when firms abate is higher than when firms do not abate for any $\frac{1}{2} := g^{NA} < g < g^T(z)$ and $z > 0.323$.

Proof. The proof easily follows from the sign of the expressions in (34)-(36).

The result of Proposition 1 has an interesting and simple intuition: the reduction in environmental damage coming from adopting a cleaning technology always compensates the reduction in consumers' and producers' surpluses due the reduction in the quantity of goods from industrial production that abatement implies. Combining Result 1 and Proposition 1, the next result immediately follows.

Result 2. The abatement game produces the following Pareto efficient outcomes for the society depending on the relative size of z and g.

[1] Let $z > 3.702$ hold. If $g_{\Delta_3}(z) < g < g^T(z)$ then (A,A) is the unique Pareto efficient SPNE of the game (deadlock) and $SW^{*A} > SW^{*NA}$.

[2] Let $2.107 < z < 3.702$ hold. If $g_{\Delta_1}(z) < g < g^T(z)$ then (A,A) is the unique Pareto efficient SPNE of the game (deadlock) and $SW^{*A} > SW^{*NA}$.

[3] Let $0.593 < z < 2.107$ hold. If $g_{\Delta_1}(z) < g < g^T(z)$ then (A,A) is the unique Pareto efficient SPNE of the game (deadlock) and $SW^{*A} > SW^{*NA}$.

[4] Let $0.323 < z < 0.593$ hold. If $g_{\Delta_3}(z) < g < g^T(z)$ then (A,A) is the unique Pareto efficient SPNE of the game (deadlock) and $SW^{*A} > SW^{*NA}$.

The analyses of Results 1 and 2 and Proposition 1 show a clear policy statement that we believe it is important to stress here. In fact, moving from north-west to south-east in Figure 1 marks the start from a polluted environment – in which firm produce with a dirty technology and the society is not too much aware about environmental issues (this outcome is Pareto efficient for firms but it is Pareto dominated for the society as $SW^{*A} > SW^{*NA}$ always holds) – to a sustainable or clean environment, where the awareness towards environmental quality is high, and firms and the society are better off than under no abatement. This result confirms the rationale for working for a cleaner world by properly modifying individual incentives. Indeed, the improvement in R&D fostering cleaner technology (Jaffe et al., 2003) allows firms to reduce the costs should be incurred to install and adopt environmentally beneficial technologies allowing to decrease sharply the amount of emissions from industrial production. Indeed, by stimulating innovations profit-maximising firms may reduce marginal costs and gain from the adoption of new technologies spreading the beneficial effects of reducing emissions on the society. In addition, the government should pursue the aim of increasing the public awareness towards environmental quality through the improvement of the public education system (school, universities, etc.) as well as by ad hoc programmes to be shared by the media for a thoughtful understanding of environmental issues. Indeed, education is associated with growth trajectories with higher technological progress, human capital, working income (Galor, 2011) and eventually increased environmental awareness (Gori et al., 2020) than trajectories where education is lower or even absent. This may help individuals escaping from poverty and starving to experience health gains and improving also their own education decisions by creating a virtuous circle that may generate – amongst other things – demand for goods and services produced with cleaner technologies and less emissions protecting the environment form degradation.

We should pinpoint that though improvements in R&D is a stylised fact in history – so that z can unambiguously represent the degree of technological progress, which can also reasonably be the subject to ongoing improvements (through reductions in z), less obvious is the timeline of parameter g. Indeed, g can represent both the degree of ecological awareness of the society/government (in this case one should conjecture that g increases over time) or – alternatively – it can be the actual degree of pollutant damage coming from industrial production. In this case, it is hard to have a timeline with increasing values of g as a low g can be related to the production of goods coming from a non-polluting, low value-added technology and a high g instead to a polluting, high valued-added technology (the petrochemical sector or the steel sector). This would lead to a different, counterintuitive interpretation: social welfare could be larger with the production of polluting goods than with the production of non-polluting goods.

The next section focuses on the analysis of a possible ethical-historical-political scenario based on the conjecture that the timeline of z is decreasing and the timeline of g is increasing for the reasons discussed above.

4. An ethical-historical-political projection exercise

The aim of this section is to speculate about a possible ethical-historical-political trajectory that the analysis detailed in the previous section may generate. For doing this, a methodological premise is useful as we need to distinguish between the logical or philosophical time of the (timeless or static) one-shot, non-cooperative abatement game (out of historical time) played by two selfish (profit-maximising) firms and the historical timing of the events (past, present and future) that contributes to generate a chronological structure of sequences. The logical structure of sequences of the model presented in Section 2 represents the usual linkage of variables (having a causal relationship amongst them) that move towards the same logical (not necessarily chronological) direction.

However, given the structure of the model, nothing can be said about the chronological linkage amongst the variables get involved into the analysis. Therefore, to write down a narrative of the story behind out results outlining it in space and historical time, it is important to abstract going beyond the implicit logical narrative of the model (which was just detailed in Section 2 to give an economic intuition of Result 1) following the methodological premise made at the end of the previous section, which was based on the conjecture that the timeline of z is decreasing and the timeline of g is increasing (Figure 2). This implies that a reduction in z can be associated with technological improvements observed in history (assuming also that we will continue to observe them in the future) and an increase in g can be conjectured to be associated with improvements in the degree of ecological awareness of the society. Our projection exercise aims to speculate about possible trajectories an economy can follow depending on the relative size of g and z. To this purpose, Figure 2 depicts a timeline of the events where the future with different environmental conditions can be reached following trajectories with improvements in either cost-reducing R&D for cleaning purposes (for a given g) or public awareness towards the environment (for a given z) or both (see the direction of the arrows in the figure).

The story started from the north-west of Figure 2, resembling a moment in history in which industrial production took place with dirty technologies and the societal awareness towards the environmental damage was relatively low. This occurred since the beginning of the Industrial Revolution until almost the middle of the 20th century. Firms had an incentive to adopt a dirty technology as the costs of abatement were relatively high – alternatively, the benefits of the "green" technology were still low (indeed cleaning R&D was almost absent or not adequately developed). This is because industrial production had not yet caused relevant (perceived) damages to the environment to generate individual incentives for sustaining abatement costs. Since this point in time, development trajectories can be different, generating a timeline going along dystopian, utopian, or sustainable paths with dirty, clean, or sustainable environments depending on whether the economy will follow, respectively, a trajectory with improvements in the public awareness towards environmental quality (increases in g) for a given (high) abatement cost, a trajectory with improvements in cleaning R&D that contribute to reduce the costs to abate pollution (reductions in z) for a given (low) value of the degree of ecological awareness, a trajectory with gradual improvements in cleaning R&D and ecological awareness. The first case represents a dystopian path (according to the view of the epic science fiction film by Christopher Nolan, we define this as the "Interstellar scenario") as the environment would be highly polluted due to the lack of developments in adequate cleaning R&D. The adoption of an abatement technology will be delayed and will happen only when g will be high enough to increase the emission tax rate to incentivise firms to increase abatement and reduce the tax burden to compensate the high degree of pollution. Environmental quality following this trajectory, however, is in danger of being compromised and the future of human being may not be on earth due to a severe environmental degradation. In the second scenario economies would follow a utopian development path as the environment would be clean thanks to the dramatic improvements in cleaning R&D that make it convenient abatement even with a very low degree of ecological awareness (individual-selfish behaviour matters). The combination of low z and g would allow to keep the emission tax rate to incentivise emission-reducing actions at low a level. The third case represents a scenario resembling actual development paths of economies observed in history that gradually become aware of the need to increase environmental awareness and at the same time to develop and adopt cost-reducing clean technologies, leading to lie on sustainable environmental trajectories. Indeed, since almost the middle of the 20th century environmental sustainability stared become part of political agendas in several governments of Western countries due to the increasing perceived environmental damages coming from industrial production (see Brock and Scott Taylor, 2010 for an empirical finding of the so-called Environmental Kuznets Curve, EKC, shown by augmenting the Solow growth model to incorporate technological progress in abatement). As far as the societal awareness towards environmental quality increased and cost-reducing R&D to favour abatement reduced, firms started having an incentive to adopt "green" technologies through pollution abatement though they may got entrapped in a situation in which choosing to abate, or not to abate was a priori uncertain. This resembles an intermediate phase in history occurred from the 1960s to the 1980s. As the EKC represents a condition to converge towards a sustainable path, further improvements in cost-reducing R&D and ecological awareness (from the 1980s onwards) are a necessary condition to live in a sustainable environment.

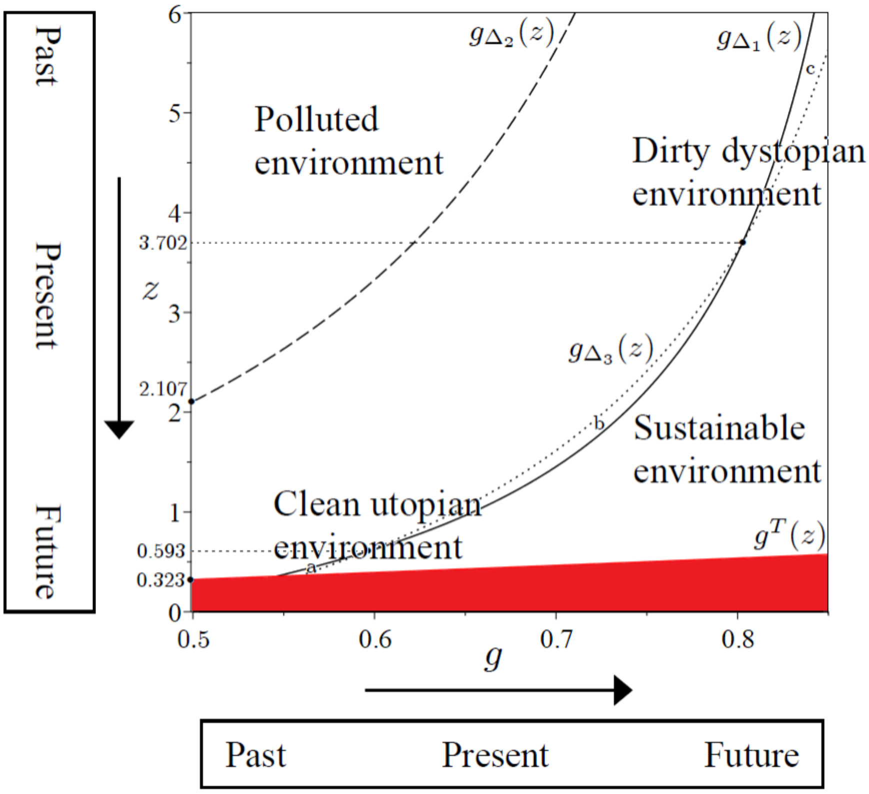


Figure 2. Timeline

5. Extensions: horizontal product differentiation and progressive taxation

The robustness of the key feature of the basic model detailed in Section 2 is now tested in the case of Cournot and Bertrand competition with differentiated products (Singh and Vives, 1984). If products are perceived as heterogeneous, the linear inverse market demand modifies to become:

$$p_i = 1 - q_i - dq_j, \quad i, j = 1, 2, \quad i \neq j, \tag{37}$$

where p_i denotes price of firm i, q_i and q_j are the firms' output levels and $-1 < d < 1$ is the parameter that weights the degree of product differentiation. When $d < 0$ (resp. $d > 0$) products are complements (resp. substitutes); when $d = 0$, goods are completely differentiated and each firm is a monopolist for its own product.

Therefore, under Cournot competition profits of firm i in the cases of abatement (A) and no abatement (NA) become the following (the first superscript, *C*, stands for Cournot):

$$\pi_i^{C,A} = (1 - q_i - dq_j)q_i - t(q_i - k_i) - \frac{zk_i^2}{2}, \tag{38}$$

and

$$\pi_i^{C,NA} = (1 - q_i - dq_j - t)q_i \,. \tag{39}$$

Differently, the Bertrand rivalry setting implies the use of the direct version of the expression of the inverse market demand in (37), that is:

$$q_i = \frac{1 - p_i - d(1 - p_j)}{1 - d^2}, \quad i, j = 1, 2, \quad i \neq j \,, \tag{40}$$

and the corresponding firm i 's profits in the cases of abatement (A) and no abatement (NA) are (the first superscript, *B*, stands for Bertrand):

$$\pi_i^{B,A} = p_i \left[\frac{1 - p_i - d(1 - p_j)}{1 - d^2} \right] - t \left[\frac{1 - p_i - d(1 - p_j)}{1 - d^2} - k_i \right] - \frac{zk_i^2}{2} \,, \tag{41}$$

and

$$\pi_i^{B,NA} = (p_i - t) \left[\frac{1 - p_i - d(1 - p_j)}{1 - d^2} \right], \tag{42}$$

By using the standard optimisation techniques detailed in Section 2, it is possible to build on the payoff matrices of the abatement game in both Cournot and Bertrand rivalry settings with differentiated products. The corresponding outcomes (profits) of the differentiated Cournot and Bertrand duopoly games are summarised in Table 2 and Table 3, respectively.

Table 2. The abatement game (payoff matrix). Cournot competition with differentiated products.

Firm 2 → Firm 1 ↓	A	NA
A	$\pi_1^{*C,A}, \pi_2^{*C,A}$	$\pi_1^{*C,A/NA}, \pi_2^{*C,A/NA}$
NA	$\pi_1^{*C,NA/A}, \pi_2^{*C,NA/A}$	$\pi_1^{*C,NA}, \pi_2^{*C,NA}$

where

$$\begin{aligned}\pi_i^{*C,A} = {} & \frac{1}{8\left\{ \left[\frac{1}{2}(1+d) + g \right] z^2 + \frac{z(2+d)(2+d+4g)}{2} + g(2+d)^2 \right\}^2} \times \{12z^4 + \\ & + z^3(4g^2 + 4d + 4g + 9) + z^2[8g^2(3+d) + 12g(1+d) + 2(2+d)^2] + \\ & + 4(2+d)[g(6+d) + 2d + 4]gz + 8g^2(2+d)^2\}\end{aligned} \,, \tag{43}$$

$$\pi_i^{*C,NA} = \frac{1}{(1 + d + 2g)^2} \,, \tag{44}$$

$$\begin{aligned}\pi_1^{*C,A/NA} = {} & \frac{1}{[2z^2(d + 2g + 1) + z(2+d)(d + 4g + 2) + g(2+d)^2]^2} \times \{4z^4 + \\ & + z^3(8g^2 + 4d + 10) + z^2[4g^2(5 + 2d) + 4g(2+d) + (2+d)^2] + \\ & + 2gz(2+d)[(4+d)g + 2 + d] + g^2(2+d)^2\}\end{aligned} \,, \tag{45}$$

and

$$\pi_2^{*C,A/NA} = \frac{(g+z)^2(d + 2z + 2)^2}{[2z^2(d + 2g + 1) + z(2+d)(d + 4g + 2) + g(2+d)^2]^2} \,. \tag{46}$$

Table 3. The abatement game (payoff matrix). Bertrand competition with differentiated products.

Firm 2 → Firm 1 ↓	A	NA

A	$\pi_1^{*B,A}, \pi_2^{*B,A}$	$\pi_1^{*B,A/NA}, \pi_2^{*B,A/NA}$
NA	$\pi_1^{*B,NA/A}, \pi_2^{*B,NA/A}$	$\pi_1^{*B,NA}, \pi_2^{*B,NA}$

where

$$\pi_1^{*B,A} = \frac{1}{8\left\{\left[\frac{1}{2}(1+d)+g\right]z^2 + \frac{z(1+d)(2-d)(2+d+4g-d^2)}{2} + g(1+d)^2(2-d)^2\right\}^2} \times \{2z^4(1-d^2) + \\ +z^3[5d^4-4d^3-2d^2(7+2g)+4(d+g^2+g)+9]+ \\ -2z^2(1+d)[d^5-3d^4-d^3(1+6g)+d^2(7+12g)+2dg(3+g)-12g(1+g)-4] \\ +8zg(2-d)(1+d)^2\left[d^3-2d^2-d\left(1+\frac{5g}{2}\right)+3g+2\right]+8g(1-d)(1+d)^3(2-d)^2\}, \quad (47)$$

$$\pi_i^{*B,NA} = \frac{1-d^2}{(1+d+2g)^2}, \quad (48)$$

$$\pi_1^{*B,A/NA} = \frac{1}{\{d^3(g+z)(d-2)-d^2[3g+z(3+4g)]+d[2z^2+4z(1+g)+4g]+2z(2+z)(1+2g)+4g\}^2} \times \\ \times\{4z^4(1-d^2)+2z^3(3d^4-2d^3-8d^2+4g^2+d+5)+ \\ -z^2(1+d)[d^5-3d^4-d^3(1+4g)+d^2(8g+7)+4dg(1+3g)-4(5g^2+2g+1)] \\ +2gz(2-d)(1+d)^2[d^3-2d^2-d(1+3g)+4g+2]+g^2(1-d)(2-d)^2(1+d)^3\} \quad (49)$$

$$\pi_2^{*B,A/NA} = \frac{(1-d^2)(g+z)^2[2(1+z)+d(1-d)]^2}{\{d^3(g+z)(d-2)-d^2[3g+z(3+4g)]+d[2z^2+4z(1+g)+4g]+2z(2+z)(1+2g)+4g\}^2} \quad (50)$$

From the payoffs in Table 2 and Table 3 it is possible to compute the profit differentials as in (27). The relevant parametric constraints and Nash equilibria are shown in Panels A-D of Figure 3 (Cournot) and Panels A-D of Figure 4 (Bertrand), plotted in (g, z) plane for four different values of the degree of product differentiation (Panel A: $d = 0.8$, Panel B: $d = 0.4$, Panel C: $d = -0.4$, Panel D: $d = -0.8$). The results shown in the figures qualitatively hold for the whole range of values of d for the cases of both product substitutability and product complementarity (we do not report them in other figures to save space) and basically confirm the findings of the Cournot model with homogeneous products. Product differentiation, however, works in the direction of widening the area in which (NA,NA) is the Pareto efficient Nash equilibrium. Indeed, increasing the degree of product differentiation of consumers implies an increase in the market power of firms and this in turn causes an increase in profits. The incentives to abate therefore require extra efforts either in term of increasing the degree of ecological awareness of the society or in cost-reducing cleaning R&D (or both), thus raising the optimal emission tax rate levied by the government that should be used to incentivise firms undertaking emission-reducing actions. The same result holds for product complementarity. Definitively, product differentiation – which is a measure of the degree of market (monopoly) power – in Cournot and Bertrand duopolies is anti-ecological. Therefore, our result implies that not only the degree of market power is harmful for social welfare, as is known in the traditional market theory, but – by including the problem of the negative externality in production into the model – it also degrades environment quality.

Moreover, we have tested the robustness of the main results of the Cournot model with homogeneous products by considering a linear progressive tax scheme (superscript *pro*) according to which abating pollution up to a given threshold implies a lump-sum tax deduction (subsidy) and above it firms pay emission taxes according to the standard linear tax scheme, that is $t^{pro} = -T + t(q_i - k_i)$. The results (available upon request from the authors) substantially remain unaltered compared to those of the model specification of Section 2.

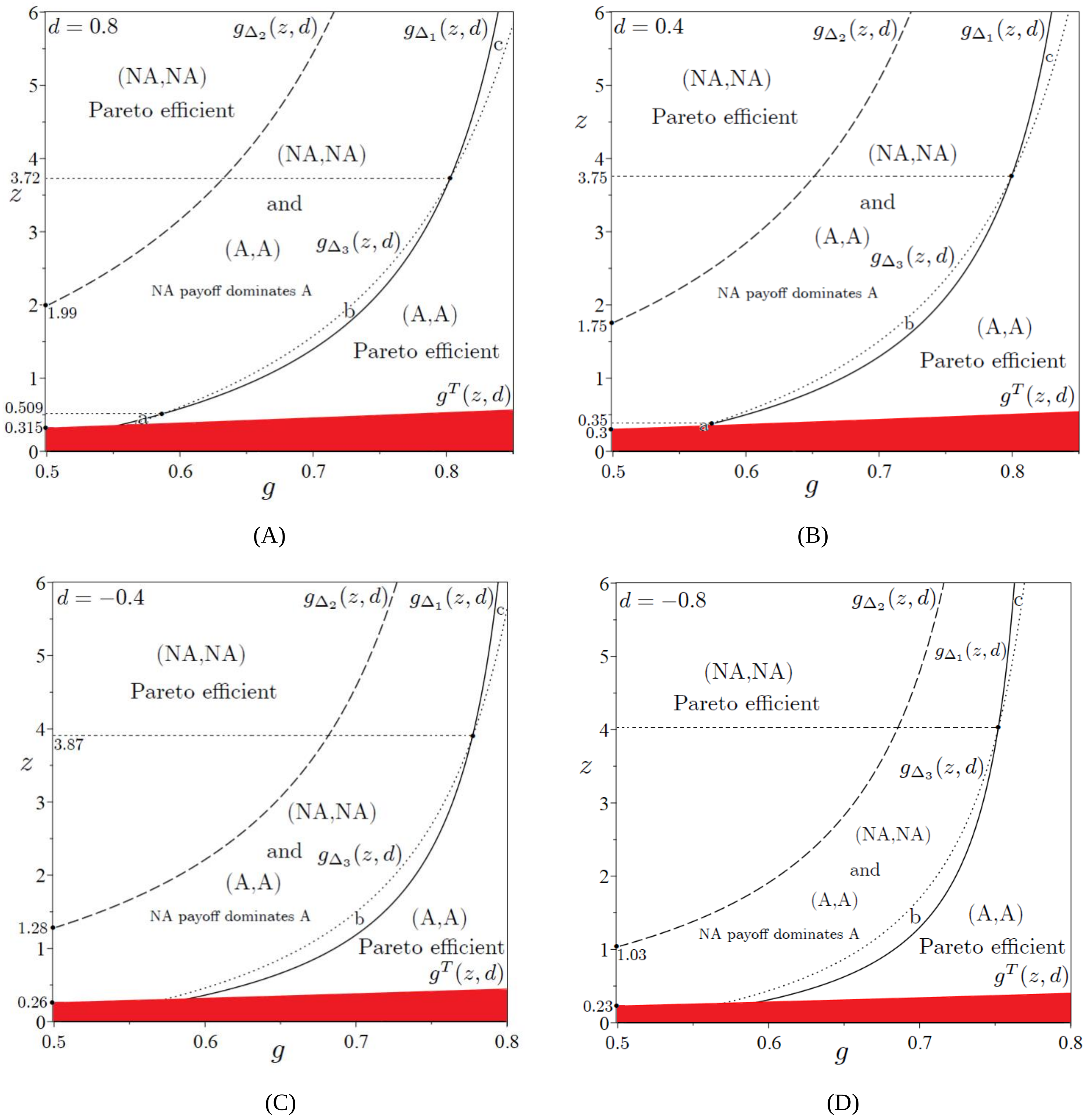
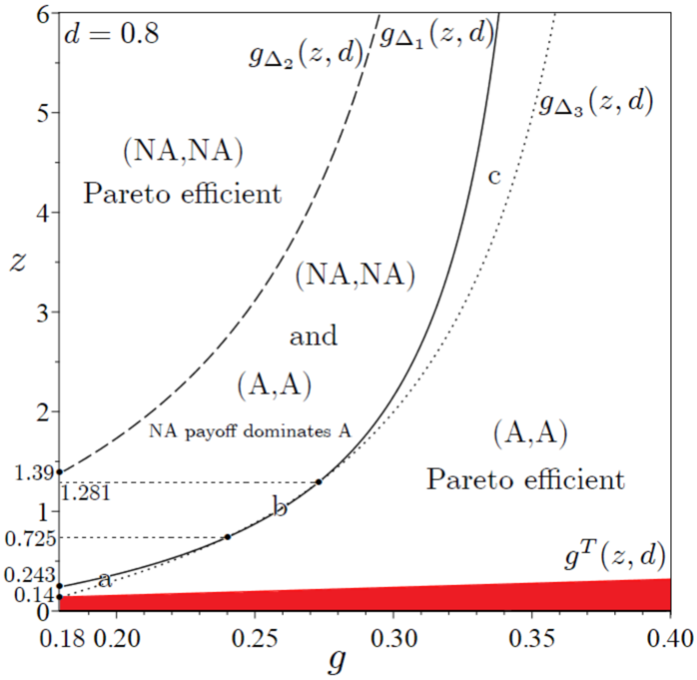
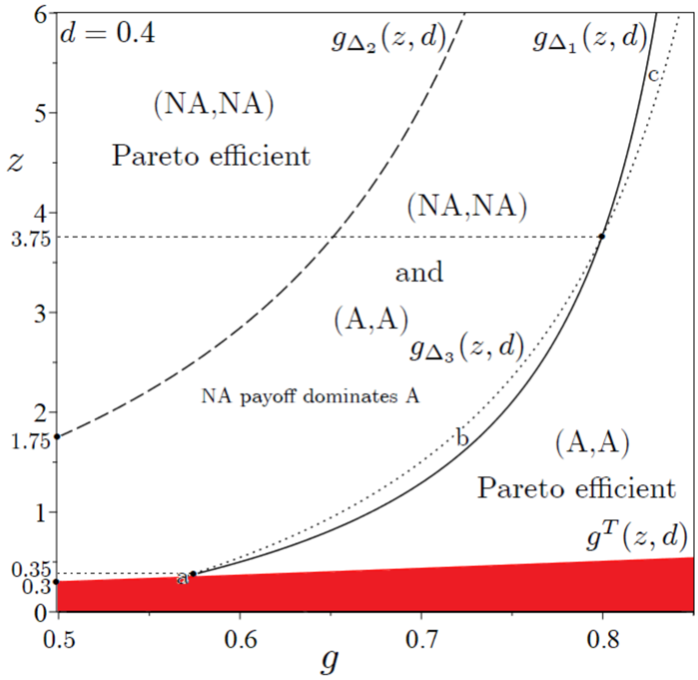


Figure 3. The abatement game with differentiated products (Cournot competition). Nash equilibrium outcomes in (g, z) plane. The solid (resp. dashed) [resp. dotted] black line represents

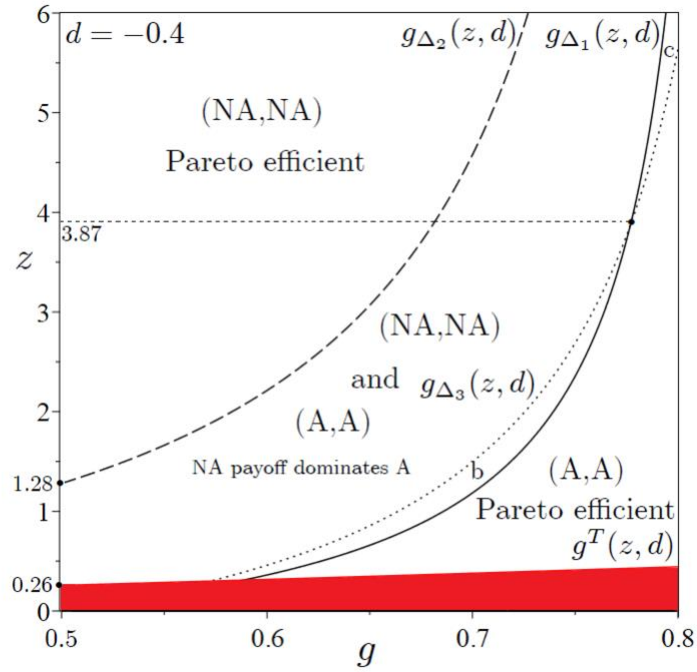
the threshold value $g_{\Delta_1}(z,d)$ (resp. $g_{\Delta_2}(z,d)$) [resp. $g_{\Delta_3}(z,d)$] such that $\Delta\pi_1 = 0$ (resp. $\Delta\pi_2 = 0$) [resp. $\Delta\pi_3 = 0$]. The solid red increasing curve $g^T(z,d)$ is the upper boundary of the red area representing the unfeasible parameter space (alternatively, the technical non-feasibility of pollution abatement). The SPNE in the areas denoted by a and c is (A,A). This outcome is Pareto inefficient (prisoner's dilemma). In the area denoted by b there are multiple Nash equilibria in pure strategy: (NA,NA) and (A,A), where A payoff dominates NA. Panel (A): $d = 0.8$. Panel (B): $d = 0.4$. Panel (C): $d = -0.4$. Panel (D): $d = -0.8$.



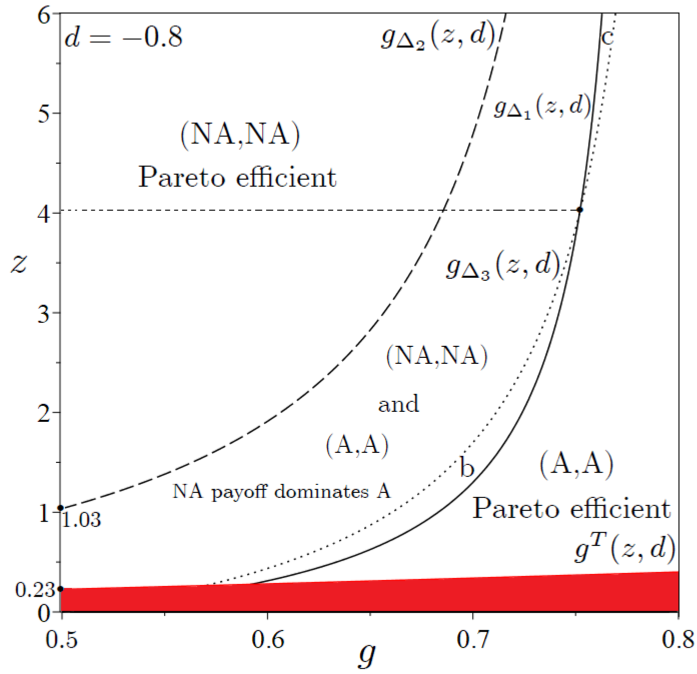
(A)



(B)



(C)



(D)

Figure 4. The abatement game with differentiated products (Bertrand competition). Nash equilibrium outcomes in (g,z) plane. The solid (resp. dashed) [resp. dotted] black line represents the threshold value $g_{\Delta_1}(z,d)$ (resp. $g_{\Delta_2}(z,d)$) [resp. $g_{\Delta_3}(z,d)$] such that $\Delta\pi_1 = 0$ (resp. $\Delta\pi_2 = 0$) [resp. $\Delta\pi_3 = 0$]. The solid red increasing curve $g^T(z,d)$ is the upper boundary of the red area representing the unfeasible parameter space (alternatively, the technical non-feasibility of pollution abatement). The SPNE in the areas denoted by a and c is (A,A). This outcome is Pareto inefficient (prisoner's dilemma). In the area denoted by b there are multiple Nash equilibria in pure strategy: (NA,NA) and (A,A), where A payoff dominates NA. Panel (A): $d = 0.8$. Panel (B): $d = 0.4$. Panel (C): $d = -0.4$. Panel (D): $d = -0.8$.

6. Conclusions

This article developed a novel two-stage non-cooperative game framed in a theoretical strategic competitive context allowing to study the firms' strategic adoption of an abatement technology for cleaning purposes – surprisingly overcome in the existing literature framed in strategic competitive markets – by considering a textbook Cournot duopoly with homogeneous products. For doing this, it was assumed, as usual in the related environmental economics literature, that 1) industrial production generates pollution externalities causing environmental damages, and 2) a government choosing an optimal (welfare-maximising) emission tax to incentivise firms undertaking emission-reducing actions. After the investment in the pollution abatement technology a reduction in production cost equal to the amount of taxation computed on less emissions than the corresponding case of no abatement is achieved. Therefore, there exists a trade-off between abating or not abating. Choosing to abate (or not to abate) depends on the relative size of the ecological awareness of the society and the degree of improvement in technological progress in abatement. The firms' strategic interactions in this context generates a set of rich Nash equilibrium outcomes ranging from the (Pareto efficient) choice of dirty technology to clean production. Our results confirm the rationale that working for a cleaner world should pass through individual incentives: 1) improvements in R&D fostering cleaner production to reduce the costs should be incurred to install and adopt environmentally beneficial technologies, and 2) increasing the public awareness towards environmental quality through the improvement of the public education system for a thoughtful understanding of environmental issues.

The model analysed in this article made simplicity its major point by considering a set of precise assumptions that immediately call for substantial extensions. Indeed, as a first extension one may relax the assumptions of linear market demand and linear marginal costs. It would be also interesting to account for the separation between ownership and control to analyse how and who would take abatement decisions in managerial firms as well as the interplay between managers and unions in the adoption of clean technologies would also be of interest. These subjects are left to future research.

Compliance with Ethical Standards

Disclosure of potential conflict of interest The authors declare that they have no conflict of interest.

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Informed consent Informed consent was obtained from all individual participants included in the study.

Declarations of interest None.

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