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Alessio D'Amato, Roberta Sestini

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Buying or performing abatement: environmental policy and welfare when commitment is (not) credible*

Alessio D'Amato,†

Roberta Sestini ‡

Abstract

We investigate an asymmetric duopoly featuring two polluting firms that are heterogeneous in terms of production efficiency. The less efficient firm performs abatement by buying an environmental good (EG) in exchange of a fixed fee, while the more efficient firm engages directly in abatement effort. The cost asymmetry across the two firms is therefore determined by the nature (fixed or variable) of abatement costs. In this set-up, we compare two environmental policy settings: one where the regulator commits to policy before observing abatement investment, and one where such commitment is not credible (i.e. time-consistency). We conclude that, in the latter setting, emission taxes are lower, whilst environmental innovation, aggregate profits and consumers' surplus are

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†Corresponding author. University of Rome Tor Vergata. Department of Economics and Finance and SEEDS, Via Columbia, 2 - 00133 Rome, Italy. Email: damato@economia.uniroma2.it.

‡Tuscia University, DEIm (Department of Economics, Engineering, Society & Business Organization) Email: roberta.sestini@unitus.it.

enhanced with respect to the case with commitment. The welfare ranking is however not straightforward, as commitment may make society better off than under time-consistency, depending on the degree of technological asymmetry in production. Moreover policy makers might be "trapped" in a time-consistent policy scenario, due to the interest of involved stakeholders, at the expense of environmental policy effectiveness.

Keywords: Eco-industry, Environmental regulation, Time-consistent policies.

1 Introduction

Relevant time inconsistency and credibility problems are intrinsic to environmental policy, as emissions taxes and, more generally, price based instruments are increasingly employed to spur irreversible abatement decisions by firms. As recognized by Helm et al. (2003), among others, whenever environmental targets require substantial capital expenditure and long-term investment decisions, policy credibility is as important as getting the prices right. For instance, establishing a short-term market with appropriate prices is of little use if these price signals are not credible over the long-term horizon.[1] The credibility issue implies that, when designing environmental policy, the (international or national) institutions may obtain less "abatement for bucks" than expected, mostly due to weaker than expected incentives. Our paper contributes to this debate, and is expected to apply both to trans-boundary and to national pollution problems, being our model simple and abstract enough to account for both potential scenarios.

[1] As mentioned in Hepburn (2010), even the EU ETS suffered from acute credibility problems during its first phase, which were partially addressed in the second phase, i.e. 2008-12.

When focusing on trans-boundary pollution, the relevance of commitment is very well exemplified by the negotiations leading to the Paris 2015 Climate Conference (COP 21), where a "pledge-and-review" strategy has been adopted. Under this "bottom up" approach, each country is allowed to develop *voluntary* climate actions and targets by submitting its own nationally determined contribution (NDCs) to cutting global emissions. Thus credibility " defined as the likelihood that policymakers will keep promises to implement their pledges" is crucial for long-term success.[2] Besides, to meet the target to hold average global surface temperature increases below 2 degrees, long-lived greenhouse emissions should be net zero. To this aim, "feasible carbon prices cannot be relied upon to credibly trigger the necessary scale of structural change in the time scale necessary" (Hepburn et al., 2020).

More generally, both developed and developing countries are expected to face important credibility problems. This is testified by the increasing literature assessing the status of credibility enhancing factors, which shows the degree of heterogeneity both within and across countries (e.g. Averchenkova and Bassi, 2016; Victor et al., 2022), including the ability of countries to implement domestically climate-related pledges . We expect this to be relevant in determining climate and environmental policies impacts in relation to emissions abatement. To this aim, we evaluate the effects stemming from the government's ability to commit -or not- to a specific level of emission taxation in terms of both static efficiency and dynamic efficiency properties of environmental policy. Our focus is on a relevant environmental policy tool, namely emissions pricing, in its simplest form, i.e. carbon taxation. This allows us to keep out of the analysis all the potential complexities related to emissions trading (see, among others, Koch et al., 2014).

[2]As claimed in Averchenkova and Bassi, (2016), "as the Paris Agreement does not impose penalties or sanctions for non-compliance, without credible policy implementation, the collective trust needed to support its system of reporting and review will not be built".

The standard approach to determine the optimal emission tax considers the firm(s) as Stackelberg followers choosing the optimal output and abatement levels *given* the optimal tax rate set by the government, behaving as a Stackelberg leader. However, as pointed out in Petrakis and Xepapadeas (1999; 2001; 2003), while decisions about output can be seen as short-term ones, choices on abatement effort or on investment in environmentally-friendly technologies should be considered as longer-term decisions. Thus they are taken sequentially rather than simultaneously. Moreover, the regulator may face the incentive to change the tax level *after* the firms' decisions on abatement. Due to this, time consistency problems intrinsic to environmental policy-making may arise.

The theoretical literature has tackled the issue of commitment *versus* time consistency in environmental taxation with the aim to assess which policy regime - if any- leads to the first best. Among the works closer in spirit to our paper, Petrakis and Xepapadeas (1999) investigate the effects of credibility of environmental policy in a set-up with a single monopolistic polluting firm. Assuming specific functional forms, in particular linear damage, they find that the monopolist always invest more under ex-post (i.e. time-consistent) regulation than in the case of ex-ante commitment, since she can influence the tax rate. Also the emission tax and welfare are always lower under ex-post regulation compared to the case with ex-ante commitment.[3] In a similar vein, Requate and Unold (2003) assess different environmental policy instruments - taxes and permits - in terms of the incentives to adopt more advanced abatement technologies and under two different policy regimes, the first one with commitment and either anticipation or non-anticipation of the new technology, and the second one with anticipation of the technology and the regulator moving after the firms have invested. It comes out that, with taxes and permits, the regulator can induce

[3]Petrakis and Xepapadeas (2001) explore the same issue extending the analysis to the oligopoly case. They conclude that, with a small number of firms, the results found in the monopoly case are confirmed, while they are reversed for less concentrated industries.

first-best outcomes if he moves second, whilst this does not always hold if he moves first.

Even more related to our paper, Requate (2005b) introduces a monopolistic upstream firm engaging in R&D and selling a new abatement technology to some polluting downstream firms, focussing on timing and commitment of regulation under four different games between the regulator and the firms.[4] It is found that ex-ante commitment to a menu of tax rates dominates all other policy regimes. In particular early commitment before R&D activity is socially beneficial since environmental policy has a stronger effect on R&D effort. Several extensions have been developed in the meanwhile. Among them, D'Amato and Dijkstra (2015) consider the incentives for an industry with many firms (symmetric in terms of abatement costs, but asymmetric in terms of fixed adoption costs) to invest in a cleaner technology depending on the timing of the policy regime. In their setting, and under the crucial assumption of asymmetric information, the regulator can implement the first best under time consistency, but not under commitment.

We contribute to the above literature by introducing into an asymmetric duopoly model the hypothesis that one of the two firms - the less efficient one in production - relies on an external abatement device or environmental good (EG).[5] We do not explicitly model the upstream market where an innovator provides the EG to the inefficient (downstream) firm ; we simply assume that it sells its pollution abatement goods through a fixed-fee licensing contract. The more efficient firm in production differs from the less efficient one, as it is

[4]Notice that in both contributions (Requate and Unold, 2003; Requate, 2005b) the product market is assumed to be competitive.

[5]According to OECD/Eurostat (1999) widely-shared definition of EG industry, "the environment industry consists of activities which produce goods and services to measure, prevent, limit, minimize or correct environmental damage to water, air, and soil, as well as problems related to waste, noise and eco-systems" (Organization for Economic Cooperation and Development/Eurostat, 1999). It is well-documented that pollution abatement accounts for most of the industry income.

assumed to have the capability to engage in abatement effort in-house.[6] Our paper also loosely links to a second strand of the literature, namely the one on the provision of environmental goods (EG) and the related market structure.[7]

We investigate the effects of government commitment *versus* time-consistent policies on environmental innovation and welfare, in a second-best set-up with two asymmetric (downstream) firms that differ in terms of production costs efficiency as well as in the adopted abatement technology. Under the former policy scenario, we propose the standard approach for determining the optimal emission tax, where the government precommits to the emission tax and moves first, while firms behave as Stackelberg followers. Instead, under time consistency, government's policy lacks of credibility and the firm(s), rationally anticipating this, can move first and strategically determine the abatement effort in order to affect the emission tax rate.

We find that the second-best optimal tax falls short of the Pigouvian prescription, being higher when the government can precommit with respect to the alternative policy regime. Besides, the time-consistent policy regime spurs abatement efforts, as the more efficient firm, behaving strategically, performs a higher abatement level in order to pull down the emission tax. The effects on aggregate welfare are not clear-cut and point to a trade-off between the effectiveness of environmental policy and overall benefits accruing to the society. In particular, with a low degree of technological (i.e. production cost) asymmetry, welfare is higher when the government can precommit to a specific tax level, but this comes at the expenses of a failure for environmental policy to accomplish one of its primary tasks. Likewise, when firms' heterogeneity is high enough,

[6] The assumptions on the adopted abatement decisions is coherent with a recent contribution (Sestini and Pugliese, 2021) where it is shown that, under *exogenous* (and moderate) emission taxation, the "mixed" configuration with one firm (the more efficient one) engaging in environmental innovation and the rival firm obtaining the license represents an equilibrium for a wide set of hypotheses.

[7] See, among others, Parry (1995), David and Sinclair-Desgagnè (2005), Canton et al. (2008).

the society would be better off under the time-consistent policy regime, whilst overall emissions would be lower under the alternative regulatory rule.

The paper unfolds as follows. Section 2 presents the model and analyses the optimal emission tax and abatement effort under the two alternative policy regimes. Section 3 explores the effectiveness of emissions taxation and carries out welfare analysis. Finally, Section 4 draws some conclusions.

2 The model

We consider a partial equilibrium model with two downstream firms, say firm 1 and firm 2, competing *à la Cournot*. When producing their homogeneous products both firms emit pollutants and face an environmental tax on emissions $t > 0$.

The inverse demand function is linear and given by $P(Q) = A - Q$ where $Q = q_1 + q_2$ is the aggregate output level and q_i is firm i's output level. We also assume that the duopoly is asymmetric, namely the two firms (firm 1 and firm 2) produce with a constant marginal cost c_i with $i = 1, 2$, being firm 1 more efficient than its rival. Normalising the production cost of firm 1 at zero, the production cost of firm 2 is denoted by c_2, with $A/2 > c_2 \geq c_1 = 0$.

Emissions are a by-product of firms' production. The emission function is given by $e_i = e(q_i, a_i) = \frac{(q_i - a_i)^2}{2}$, $i = 1, 2$, where a_i indicates the amount of abatement that reduces emissions, with $0 \leqslant a_i \leqslant q_i$.[8] As well-established in this literature, it holds that $e_{q_i}(q_i, a_i) > 0$, meaning that more production implies more pollution, $e_{a_i}(q_i, a_i) < 0$, so that more abatement decreases total emissions, $e_{q_i q_i}(q_i, a_i) > 0$, i.e. the more the firm produces, the more the last unit pollutes,

[8] This formulation follows Canton et. al (2012) and Kim and Lee (2016). Although many studies on EG provision employ an additively separable emission function, implicitly assuming that firms carry out end-of-pipe pollution abatement (see, e.g., David and Sinclair-Desgagnè, 2005; 2010; Canton, 2007; David et al., 2011), considering a more general emission function allows to include in the analysis additional segments of the eco-industry (see e.g. Greaker and Rosendahl, 2008).

and $e_{a_i a_i}(q_i, a_i) > 0$, i.e. there are decreasing returns in abatement. Lastly, $e_{q_i a_i}(q_i, a_i) < 0$, i.e. the higher the abatement the lower the pollution generated by the last unit of output. The environmental damage function is assumed to be linear in aggregate emissions and is given by $D(E) = dE = \sum_{i=1} = \frac{d}{2}(q_i - a_i)^2$, where d is the marginal damage function, which is constant in total emissions level.

Our focus is on the case where firm 1 (i.e. the efficient firm) exerts abatement effort by developing abatement in house, while firm 2 (the inefficient one) buys the license for a price equal to $\bar{f}$ from an external (upstream) innovator who provides EGs. This is in our view a reasonable assumption. A possible rationale behind it may be linked to the relationship between dimension-efficiency of firms, on one hand, and innovation capabilities, on the other[9]. When the efficient firm (firm 1) engages in abatement effort, this brings about an increase costs by $\frac{a_1^2}{2}$. The cost function for firm 1 is assumed to be additively separable and given by $c(q_1, a_1) = c_1 q_1 + \frac{a_1^2}{2}$, with constant returns to scale in production and decreasing returns in abatement effort (see e.g. Ulph, 1996; Petrakis and Xepapadeas, 2003). As a result of these assumptions, the objective function for firm 1 is as follows:

$$\pi_1 = P(Q)q_1 - [c_1 q_1 + \frac{(a_1)^2}{2}] - te_1 \tag{1}$$

The profit of the inefficient licensed firm, which buys the license at price $\bar{f}$, is instead:

$$\pi_2 = P(Q)q_2 - c_2 q_2 - te_2 - \bar{f} \tag{2}$$

where we normalise $c_1 = 0$, and $e_i = e(q_i, a_i) = \frac{(q_i - a_i)^2}{2}$, with $i = 1, 2$.

[9]In our set-up, it is a prerogative of the efficient firm to produce by itself the abatement technology. This assumption hinges upon some empirical literature, showing that firm investment in abatement technologies is positively related to firm productivity (Forslid et al., 2011; 2018), or exhibits an inverted-U-shape with respect to firm productivity.

We will describe and compare two alternative policy games, the ex-ante policy game (under commitment) and the ex-post one (under time- consistency). In the former game, given the availability of a number $k = 1$ of licenses for a fixed fee, at the first stage the government commits ex-ante to a specific emission tax level. Then, in the second stage, the two polluting firms, taking this tax rate as given, simultaneously determine their abatement levels and choose their outputs competing *a' la Cournot*. Instead, under the ex-post (or time-consistent) policy game, given that the more efficient firm (firm 1) engages in abatement effort and the less efficient one is a licensee, at the first stage firm 1 optimally chooses the level of abatement, and then the government sets the emission tax level. Finally both firms decide on their outputs and at the same time, given the tax rate, the licensee determines the optimal abatement. In what follows, we will label the commitment and time-consistency scenarios as C and T, respectively.

2.1 Emission taxation under ex-ante policy

The first scenario we consider is when the government can commit to an ex-ante emission tax rate. We assume that the government chooses the emission tax that maximizes domestic welfare, taking into account that the firms will react to environmental taxation. At the second stage firms choose the level of abatement, either developed in-house for firm 1 or bought by firm 2, and the quantities that maximize profits. As usual, the sub-game perfect Nash equilibrium is derived through backward induction. In this set-up, firms can be regarded as Stackelberg followers considering the emission tax level as given, whilst government acts as a Stackelberg leader.

This setting is credible only if the government can commit to the announced policy, for instance for reputational concerns. When the government cannot commit to a specific tax level, firms reasonably expect that it will change the emission tax rate after their abatement decisions. Hence, anticipating this, they decide on their abatement effort in order to influence the emission tax rate choice. Without commitment, thus, the ex-ante policy regime may collapse into the ex-post one (see Section 2.2) where firm 1 acts as a Stackelberg leader in abatement effort choice, while the government plays as a Stackelberg follower and sets, ex-post, its optimal tax rate.

Thus the objective function of the government, i.e. the social welfare function, includes the environmental damage and writes as:

$$W(t) = \int_0^Q P(u)du - c_2 q_2 - \frac{a_1^2}{2} - dE \tag{3}$$

where $q_i = q_i^C(t)$, $i = 1, 2$, $a_1 = a_1^C(t)$.

The optimal tax rate in the ex-ante regime [10] is therefore:

$$t_C^* = \frac{(A + c_2)}{(A + 2\,c_2)}\,d - \frac{A + 4\,c_2}{5(A + 2\,c_2)} \tag{4}$$

Appendix A reports the equilibrium values for the ex-ante policy game. Comparing the expression here above with the Pigouvian prescription, according to which the optimal tax rate t should be equal to the marginal social damage d, we find that:

Proposition 1 *The optimal tax rate in the ex-ante policy scenario is always lower than the marginal social damage d.*

Proof. See Appendix A. ■

As shown in Appendix A, $t_C^* < d$, confirming that, under imperfect compe-

[10] As common in the related literature (see e.g. Requate, 2005a) we assume that the marginal damage coefficient has to be large enough so that environmental policy should be in place, namely $t_C^* > 0$. A sufficient condition for this to hold is given by $d > 2/5$. This is because $t_C^* > 0$ for $d > \frac{(A+4\,c_2)}{5(A+c_2)} \geqslant 0$. This threshold for marginal damage in turn increases in c_2. Thus $\frac{(A+4\,c_2)}{5(A+c_2)} \in (1/5, 2/5)$, being $c_2 \in [0, A/2)$.

tition in the eco-industry, the optimal environmental taxation differs from the marginal social damage. This result is in accordance with Parry's (1995) seminal work, where - in a second-best set-up with competitive production firms getting a license for a patented technology from an upstream monopolist - the optimal tax falls short of marginal damage for two reasons, i.e. to mitigate excessive entry of research firms, and to dampen the monopoly power in the upstream sector thus increasing diffusion. While David and Sinclair-Desgagnè (2005) prove that the optimal pollution tax should be set *above* the marginal social cost of damage, David et al. (2011) find that the impact of environmental policy on the market for abatement goods and services depends on the number of firms and on the elasticity of demand, thus leading to a tax higher than, lower than or equal to the marginal damage of pollution.[11] On the other hand, in our setting the motivation for such a result is different (and simpler): the tax rate is set at a lower level as environmental damages are complemented by abatement costs and consumers' surplus in the social welfare function, in a duopolistic context.

2.2 Emission taxation under ex-post policy

We now tackle the ex-post (or time-consistent) policy regime where the government is not able to pre-commit to an ex-ante tax rate. If the government cannot commit to an ex-ante policy regime, the more efficient firm will rationally anticipate the possibility for the government to change the tax rate and ignore ex-ante taxation while deciding its abatement effort. Thus, if the more efficient firm correctly anticipates the government to optimally set its emission tax in response to its abatement decision, the ex-post policy regime is time-consistent. In the ex-post regime, the game runs as follows. Given that the inefficient firm

[11] In David et al. (2011), provided each environment firm's output decreases with the tax, namely if abatement suppliers' market power increases with the stringency of environmental policy, the best policy would be to set the emission tax below the Pigouvian level.

is the licensee, at the first stage the efficient firm - acting as a Stackelberg leader - optimally determines its abatement effort anticipating the government optimal choice about emission taxes in response to its abatement decision. At the second stage, the government - acting as a Stackelberg follower - chooses the optimal level of emission taxation with the aim to maximize social welfare. Finally, at the third stage, firms choose output competing *à la* Cournot and the inefficient firm buys abatement technology license at price $\bar{f}$. As customary, the sub-game perfect Nash equilibrium is derived through backward induction.

For the sake of space, shows the equilibrium values for output and abatement in the ex-post policy game are relegated to Appendix B.

Given $q_1 = q_1^C(a_1, t)$, $q_2 = q_2^C(a_1, t)$ and $a_2 = a_2^C(a_1, t)$, the social welfare function in this case reads as:

$$W_T = \int_0^Q P(u)du - c_2 q_2 - \frac{(a_1)^2}{2}) - \frac{d}{2}(q_2 - a_2)^2 - \frac{d}{2}(q_1 - a_1)^2$$

By solving the first order condition, we obtain the optimal tax on emissions as function of firm 1's abatement effort, say $t_T(a_1)$. Then, at the first stage, firm 1 optimally chooses its abatement investment. In taking this decision it considers how its choice will affect the government optimal environmental policy in the subsequent stage. It follows that the optimal time-consistent emission tax rate is given by:

$$t_T^* = \frac{2\left[4\,(A+\,c_2)\;d^2 - (5\,A + 26\,c_2)\;d - (A + 4\,c_2)\right]}{(12\,A + 44\,c_2)\;d + 3\,A + 10\,c_2}. \tag{5}$$

Comparing this tax rate with the Pigouvian rule, we can state that:

Proposition 2 *The optimal tax rate under the ex-post policy regime is always lower than the marginal damage d.*

Proof. See Appendix B. ■

Even in the time-consistent policy scenario, we obtain that the optimal tax rate falls short of marginal damage.[12]

3 Policy regimes comparison: equilibrium values

This section presents a comparison between the two policy regimes, the ex-ante and the ex-post one. Besides evaluating the optimal level of emission taxation in the two alternative policy regimes, our main task is to assess the environmental effectiveness of mitigation measures, in terms of the impact the policies have on total production, optimal abatement and thus on the level of emissions.

A further - at least as important- criterion for judging environmental policy is the extent to which it provides dynamic incentives to develop new technologies. We will consider then the ranking between environmental innovation carried out by the more efficient firm under the precommitment regime *versus* the time-consistent one. Finally, some attention will be devoted to overall welfare under each policy scenario. For ease of exposition, most of technicalities and all proofs are confined in Appendix C.

To start with, we compare the optimal rate rate in an ex-post policy scenario with the tax rate set under the alternative policy regime. By simple algebra (see Appendix C) we reach the conclusion that:

- the optimal ex-ante taxation is always higher than the optimal ex-post one, i.e. $t_C^* > t_T^*$.

.

[12] See the analogous proposition here above in the precommitment policy scenario for some comments on this point.

Interestingly, if the government opts for a time-consistent emission taxation, it is led to set a lower tax rate with respect to the alternative policy scenario. This result is driven by the more efficient firm behaviour. In fact, knowing that the government will set the tax rate *after* its abatement effort decision, this firm will anticipate the right level of government taxation in its decision on environmental innovation. Therefore, it will exert more effort under the ex-post policy regime with respect to the scenario with precommitment, in order to reduce its emission tax. This strategic behaviour is obviously not in place when the government can precommit to a specific tax rate *before* the firm chooses its abatement effort.

We compare henceforth equilibrium quantities produced by both firms and equilibrium prices under the two policy regimes under analysis. By simple calculations, we obtain that:

- the equilibrium output produced by the more efficient firm is always higher under the ex-post policy regime than under the ex-ante one, namely $q_1^T > q_1^C$.

On the other hand, it comes out that:

- the output produced by the licensee (firm 2) is higher when the government can precommit, i.e. $q_2^C > q_2^T$.

Nevertheless, the combined effect on overall output supplied under the two alternative policy regimes is such that $Q_T > Q_C$ where $Q = q_1 + q_2$.

Besides, regarding equilibrium final prices, we find that:

- the equilibrium price is higher under the ex-ante policy regime as compared with the ex-post one, i.e. $P_C > P_T$.

By combining the above results, we are allowed to conclude that *consumers' surplus* is surely enhanced if the government cannot commit and sets environmental taxes *after* firm 1 has exerted abatement effort. We argue that consumers are better off under the ex-post policy regime due to the lower level of environmental taxation, accompanied by a higher abatement effort, as shown here below.

Focusing then on abatement, we find that:

- under time-consistent taxation, abatement effort by the more efficient firm is higher than under precommitment, i.e. ${a_1}^T > {a_1}^C$.

As shown in Appendix C, this statement holds true for all values of the marginal damage coefficient d such that environmental policy is in place, i.e. for $d > 3.158$ (on this point see also Appendix B). This result might be driven by the firm's strategic behaviour, in that, in the ex-post regime, the firm increases its effort and conveniently induces a lower emission taxation.

Finally, we carry out here a comparison of total emissions under the two different policy scenarios. Our aim is to assess the environmental effectiveness of mitigation measures, focusing on local pollution. We recall that the emission function we employ is defined as: $e_i = e(q_i, a_i) = \frac{(q_i - a_i)^2}{2}$ with $i = 1, 2$. Thus total emissions under any policy regime are given by $E = e_1 + e_2$.
In particular, under the ex-ante policy regime, firms' total emissions read as:

$$
\begin{aligned}
{e_1}^C &= \frac{(A + 2\,c_2)^2}{2\,(5\,d + 2)^2} \\
{e_2}^C &= 0
\end{aligned}
$$

and thus:

$$
E_C = \frac{(A + 2\,c_2)^2}{2\,(5\,d + 2)^2} \tag{6}
$$

Under the ex-post policy regime, firms' emissions are as follows:

$$
\begin{aligned}
{e_1}^T &= \frac{[3\,A\,(1 + 4\,d) + 2\,(5\,c_2 + 11\,d)]^2}{8\,(32\,d^2 + 14\,d + 1)^2} \\
{e_2}^T &= 0
\end{aligned}
$$

and total emissions read as:

$$E_T = \frac{\left[3\,A\,(1+4\,d) + 2\,(5\,c_2 + 11\,d)\right]^2}{8\,(32\,d^2 + 14\,d + 1)^2} \tag{7}$$

Notice that, as it is shown in details in Appendix A and B for the two regimes, emissions by the inefficient firm (firm 2) are 0 in our model specification. Indeed, the inefficient firm only pays fixed costs for the abatement related goods, so that once the EG has been bought it makes sense to reduce emissions to 0 to avoid paying emission taxes. Though this is a peculiar result, this adds interest in our framework, at least looking at settings where firms' asymmetry as modeled here is a sensible assumption.

Let us define the threshold $\tilde{c_2} = \frac{\left(4\,d^2 - 41\,d - 4\right)A}{2(8+11\,d+46\,d^2)}$. Comparing total emissions in the ex-post policy regime versus the ex-ante ones, it is possible to show that:

Proposition 3 *If* $0 \leq c_2 < \tilde{c_2}$ *(*$\tilde{c_2} < c_2 \leq A/2$*) total emissions under the ex-post policy regime are lower (higher) than total emissions under ex-ante taxation.*

Proof. See Appendix C ∎

This proposition highlights that, provided the degree of cost asymmetry is low enough, the effectiveness of emission taxation is enhanced if the government opts for an ex-post policy regime. Besides, the superior performance of this regime is more likely to hold the greater is the market size (i.e. the parameter A) and the higher is the marginal damage coefficient (namely the parameter d). We argue that this might be due to the greater level of abatement carried out by firm 1 when the time-consistent policy regime is in place. However, even production and thus emissions by the more efficient firm are spurred under the ex-post regime. In particular, while output by firm 1 obviously increases with the degree of cost asymmetry (i.e. if c_2 is high), we find that the rate of increase is higher in case of output supplied under the ex-post regime with respect to the ex-ante one, i.e. $\frac{\partial(q_1^T - q_1^C)}{\partial c_2} < 0$. This explains, in our view, why the result on the dominance of total emissions under the ex-ante regime is overturned if the degree of cost asymmetry is high enough.

In other words, even though the abatement effort is always higher in the ex-post policy regime, total emissions might also be higher under this scenario due to the increase in equilibrium output occurring for sufficiently high levels of the c_2 parameter. Thus, in the presence of a high degree of firms' heterogeneity, environmental policy may fail to achieve its primary task in the time-consistent policy scenario.

4 Equilibrium profits and total welfare comparison.

We now assess whether equilibrium profits in the ex-post scenario are higher than ex-ante ones. By simple calculations (see Appendix D), for firm 1 we get that $\tilde{\pi}_1^T > \hat{\pi}_1^C$, namely equilibrium profits for firm 1 are larger in the ex post scenario. This occurs notwithstanding the higher level of abatement effort carried out under the ex-post policy regime and is driven by the more stringent environmental tax set when the ex-ante regime is in place.

On the other hand, comparing equilibrium profits accruing to firm 2, i.e. to the licensee, we obtain that $\pi_2^T < \pi_2^C$. We argue that this last result is due to the relative disadvantage imposed on firm 2 when its rival enjoys a first mover advantage, playing first and being a Stackelberg leader in the game.

Given these contrasting effects on profits accruing to both firms, the ranking between *aggregate* profits is not clear-cut. In particular, the expression $\pi_1^C + \pi_2^C - (\pi_1^T + \pi_2^T)$ is a quadratic polynomial in x, where $x = c_2$, such as $f(x) = Ax^2 + Bx + C$, with $A < 0$ and two solutions, say $\bar{c_1} < 0$ and $\bar{c_2} > 0$.

According to numerical simulations, aggregate profits accruing to firms under the ex-ante policy regime prevail over profits in the ex-post scenario when the cost asymmetry (i.e. c_2) is sufficiently low, namely in a context characterized by low heterogeneity across firms.

We also recall that consumers are better off if the ex-post policy regime is adopted with respect to the alternative policy scenario.

Overall, the impact on welfare will be the result of the above, possibly countervailing, signs of the comparison between an ex-ante and an ex-post regime. We then carry out a comparison between total welfare under commitment and total welfare with the time-consistent policy, to assess whether $W(d, A, c_2)^*_T \gtrless W(d, A, c_2)^*_C$.

Defining

$$\breve{c}_2 = \frac{A\left(-3232d^4 - 134d - 1285d^2 - 1120d^5 + 12 - 3318d^3\right)}{\Gamma} + \\ + \frac{A\left[5^{1/2}\, d\,(9 + 130d + 344d^2 + 128d^3)(2 + 13d + 20d^2)^{1/2}\right]}{\Gamma}$$

with $\Gamma = 2(1200\,d^5 + 7084\,d^4 + 6496\,d^3 + 2055\,d^2 + 148\,d - 24)$, we can show that:

Proposition 4 *Overall welfare accruing under the ex-ante policy scenario is higher (lower) than welfare under the ex-post policy regime if* $0 < c_2 < \breve{c}_2$ *(*$\breve{c}_2 < c_2 \leq A/2$*).*

Proof. See Appendix D. ■

As shown in Appendix D, welfare under the precommitment regime ($W(d, A, c_2)^*_C$) prevails over welfare under the time-consistent environmental policy ($W(d, A, c_2)^*_T$) only if the degree of technological asymmetry is low enough. Moreover, the threshold value for c_2, i.e. $\breve{c}_2$, depends in turn on A and d, being increasing in both arguments, implying that, as market size and/or the steepness of the marginal damage are greater, it is more likely that the society is better off under the ex-ante policy regime.

By simple algebra we find that the ranking between the two thresholds (the former on total emissions, i.e. $\tilde{c_2} = \tilde{c_2}(A, d)$, and the latter on total welfare, namely $\breve{c_2} = \breve{c_2}(A, d)$), is such that $\tilde{c_2}(A, d) < \breve{c_2}(A, d)$, $\forall A > 0, d > 0$. We are then allowed to conclude that:

- when $0 < c_2 < \tilde{c_2}$, total welfare under the ex-ante policy regime dominates over total welfare under the ex-post one. However, total emissions are higher if the former policy option is in place. On the other hand, abatement effort by the more efficient firm is larger under the ex-post regime, triggering larger abatement costs by the same firm. If the cost differential is very small, the latter effect is expected to dominate;

- if $\tilde{c_2} < c_2 < \breve{c_2}$, the society is better off under the ex-ante policy regime *and also* total emissions are *lower* with respect to the scenario with ex-post emission taxes;

- when $\breve{c_2} < c_2 < A/2$, then total welfare under the ex-post policy regime prevails over total welfare under the ex-ante one. However also total emissions are higher if the time-consistent policy choice is adopted.

We remind that abatement effort by the more efficient firm is *always* enhanced under the ex-post regime with respect to the ex-ante one. However, a trade-off may arise: if the degree of technological asymmetry is quite pronounced, the government should opt for an ex-policy regime. This would imply a failure of environmental policy to fulfill one of its main tasks, i.e. curbing total emissions. Likewise, for very low values of c_2 the society is better off under the ex-ante policy scheme, whilst environmental policy effectiveness is impeded.
As clearly stated in Requate (2005a), "under competitive conditions and per-

fect foresight, different authors established the result that ex-ante commitment and ex- post optimal policies generate equivalent or at least similar allocations. Under imperfect market conditions, the policy conclusions are less clear cut." What could seem surprising, however, is that there are circumstances where time-consistent policies lead to higher welfare than commitment ones, with a ranking crucially depending on the degree of technological asymmetry. Indeed, in most games studied in the theoretical literature, even if commitment cannot implement the first best, it is still preferred to time consistency. Along the lines of Dijkstra (2002), this is due to the emphasis placed on games with many small agents playing with the government.[13] Thus a necessary condition for time consistency to make the society better off is that the regulated agent(s) can affect time-consistent policy. In our set-up, a high degree of technological asymmetry (high c_2) benefits firm 1 thus enhancing its ability to behave strategically *vis a vis* the government. This may represent the driver leading to the welfare superiority of the time-consistent policy regime, under pronounced technological asymmetry.

5 Main Conclusions

We contribute to the debate on time-consistency *versus* precommitment in environmental policy design by comparing two different policy regimes, the ex-ante and the ex-post one. In the ex-ante regime the government is able to commit to a specific tax rate and then firms decide their optimal abatement effort and output. Conversely, in the ex-post regime, the government sets the environmental policy variable (the tax level) after firm's decision on abatement. The latter regime turns out to be time-consistent because firms know that the government

[13] "In these games, each agent considers himself so small that he cannot influence time-consistent policy. In this setting, when the government can commit, it can "commit" to the time-consistent policy and thereby reproduce the outcome of time consistency with commitment. Commitment must then be at least as good as time consistency" (Dijkstra, 2002).

will set its tax level based on their decisions on abatemet.

With this aim in mind, we analyzed both policy games, building an *asymmetric* duopoly model with two polluting firms that differ in terms of production costs and also in terms of abatement technology; more specifically, the less efficient firm in production pays a fixed cost to acquire a license for an exogenous abatement technology, while the most efficient firm performs abatement in-house paying convex abatement costs. The novelty of our approach is also in line with suggestions coming from the existing theoretical literature on environmental goods. In particular, David and Sinclair-Desgagnè (2010) recognize that "studying the consequences of other relevant and more complex industry structures, however, (with asymmetric environment firms or polluters also able to make their own abatement goods, notably) will require additional research".

We find that under both policy regimes, the second-best tax rate falls short of the marginal social cost of damage, thus confirming that, in the presence of market power, the optimal environmental taxation differs from the Pigouvian prescription. Besides, if the government cannot precommit to a specific emission tax level, the more efficient firm enjoys a first mover advantage and may affect the government's choice of the emission tax rate by strategically adjusting its abatement level. As a consequence, when the government opts for a time-consistent policy regime, emission taxes are lower, whilst abatement, efficient firm's profits and consumers' surplus are enhanced with respect to the case with precommitment.

Less clear-cut results are obtained about the effectiveness of environmental policy under the two policy regimes, as only in the case of a very low degree of heterogeneity across firms total emissions under time-consistency turn out to be lower than under the ex-ante scenario. Likewise, when assessing the ranking between aggregate welfare, there are cases where time-consistency makes the society better off than under precommitment. This result heavily depends once again on the degree of technological asymmetry. We argue that, in the presence of a pronounced heterogeneity, the more efficient firm benefits from a greater competitive advantage and thus is more able to behave strategically *vis a vis* the government. This may represent the rationale for welfare gains associated with ex-post environmental policy. Nevertheless, one should be aware of a trade-off: without credibility environmental policy fails to achieve its primary task, i.e. to curb greenhouse gas emissions.

On the other hand, under low heterogeneity the ability to precommit delivers higher welfare along with effectiveness of environmental policy measures. This implies that an ex-ante optimal environmental policy may be fruitfully *accompanied by* credibility-enhancing mechanisms and measures meant to reduce cost asymmetry.

We are aware of the simplifying hypotheses adopted in our study, in particular the fact that the contract for the licensed technology always involves a fixed fee. An explicit modelling of the upstream eco-industry would certainly enrich the analysis. Also introducing a preliminary stage in the game to determine the optimal licensing strategy by the R&D firm would be an interesting breakthrough. Finally, more general functional forms may improve the generality of our analysis. These issues are left for future research.

A Appendix

Appendix A: optimal ex-ante tax rate

We first derive equilibrium values for quantities, abatement and profits. In the last stage of the game the firms, taking the tax rate as given, select output and abatement levels. Solving standard firms' profit maximization problems, we obtain that optimal quantities and abatement effort are as follows:

$$q_1^C(t) = \frac{(A + c_2)(1 + t)}{5t + 3}$$
$$q_2^C(t) = a_2^C(t) = \frac{(2t + 1)A - (3t + 2)c_2}{5t + 3}$$
$$a_1^C(t) = \frac{t(A + c_2)}{5t + 3}$$

Since $q_2^C(t) = a_2^C(t)$ the emissions of firm 2 at the equilibrium are $e_2^C = 0$. Substituting the optimal quantities and optimal abatement levels into the profit functions, equilibrium profits read as follows:

$$\pi_1^C(t) = \frac{(1 + t)(2 + 3t)(A + c_2)^2}{2(5t + 3)^2} \tag{8}$$

$$\pi_2^C(t) = \frac{(A(2t + 1) - (3t + 2)c_2)^2}{(5t + 3)^2} - \bar{f} \tag{9}$$

In the first stage the government determines its optimal environmental policy taking into account how the firms will react to emission taxation in the subsequent stage. Substituting for outputs and abatement efforts - as found above -, the objective function of the government becomes:

$$W_C(t) = \int_0^Q P(u)du - c_2\, q_2^C(t) - \frac{(a_1^C(t))^2}{2} - de_1^C - de_2^C = \frac{(20A^2 - 30Ac_2 + 25c_2^2)t^2 + (26A^2 - 30Ac_2 + 34c_2^2)t}{2(5t+3)^2} + \frac{8A^2 - 2A^2d - 2c_2^2 d - 8Ac_2 + 11c_2^2 - 4Ac_2 d}{2(5t+3)^2} \tag{10}$$

where the subscript refers to the policy regime.

Proof of Proposition 1: We want to show that the optimal tax rate in the ex-ante regime is lower than d. We remind that

$$t_C^* = \frac{(A + c_2)}{(A + 2\, c_2)}\, d - \frac{A + 4\, c_2}{5(A + 2\, c_2)}$$

Since $\frac{A+4\, c_2}{5(A+2\, c_2)} > 0$, we have that $t_C^* < \frac{(A+c_2)}{(A+2\, c_2)}\, d$. Moreover, $\frac{(A+c_2)}{(A+2\, c_2)} < 1$. Therefore:

$$t_C^* < \frac{(A + c_2)}{(A + 2\, c_2)}\, d < d$$

Finally, when the government can commit to a specific tax level, the optimal quantities and the equilibrium abatement level become[14]

$$q_1^C = \frac{5\,(A + c_2)\; d + 4\, A + 6\, c_2}{25\, d + 10}$$
$$q_2^C = a_2^C = \frac{(10\, A - 15\, c_2)\; d + 3\, A - 8\, c_2}{25\, d + 10}$$
$$a_1^C = \frac{5\,(A + c_2)\; d - A - 4\, c_2}{25\, d + 10}$$

[14]Notice that both q_2^C and a_2^C are decreasing in c_2. To ensure that $q_2^C = a_2^C > 0$ a sufficient condition is that $d > 2/5$. Moreover, for $a_1^C > 0$ to hold, it has to be that $d > \frac{A+4c_2}{5(A+c_2)}$. Being this threshold increasing in c_2, a sufficient condition for $a_1^C > 0$ is that $d > 2/5$.

The more efficient firm equilibrium profits are given by:

$$\pi_1^C = \frac{[15\,(A+\,c_2)\,\,d+7\,A+8\,c_2][5\,(A+\,c_2)\,\,d+4\,A+6\,c_2]}{50(2+5\,d)^2} \tag{11}$$

while the less efficient firm equilibrium profits read as:

$$\pi_2^C = \frac{[(10A-15\,c_2)\,\,d+3\,A-8\,c_2]^2}{25\,(5\,d+2)^2} - \bar{f} \tag{12}$$

Appendix B: optimal ex-post tax rate

Given the objective functions in Eqs.(1) and (2), at the third stage of the game both firms choose their outputs while the inefficient firm sets the optimal level of EG to buy. From standard maximization, we obtain that:

$$q_1^T(a_1,t) = \frac{A+c_2+2a_1\,t}{2t+3}$$
$$q_2^T(a_1,t) = a_2^T(a_1,t) = \frac{A(1+t)-c_2(2+t)-a_1\,t}{2t-3}$$

At the second stage the government chooses ex-post its emission tax rate t, by maximizing the social welfare function. It takes into account the firms' reaction in the subsequent choice stage, thus including the optimal quantities and EG level in its objective function.

Maximizing the social welfare function, we obtain the optimal tax on emissions as function of firm 1's abatement effort, namely:

$$t_T(a_1) = \frac{2\,(A-3\,a_1+\,c_2)}{A-a_1+3\,c_2}\,d - \frac{A+4\,c_2}{A-a_1+3\,c_2} \tag{13}$$

Finally, at the first stage of the game, firm 1 makes its abatement choice. In taking this decision it considers how its choice will affect the government optimal environmental policy in the subsequent stage. Solving a standard profit maximization problem, we get the optimal abatement effort[15], i.e.:

$$a_1^T = \frac{16\,(A + c_2)\,d^2 + 4\,A\,d - (A + 4\,c_2)}{2\,(32\,d^2 + 14\,d + 1)}$$

By substituting for $a_1 = a_1^T$ into $t_T(a_1)$, we find the optimal tax rate.

Proof of Proposition 2: We have here to assume that the coefficient d is large enough that environmental policy has to be in place, i.e. $t_T^* > 0$. Being t_T^* a second degree polynomial in d, this is solved for, say, d_1 and d_2, with d_1 and d_2 increasing in c_2. Since $\lim_{c_2 \to A/2} d_1 = \dfrac{3 - \sqrt{11}}{2} \approx -0.158$, $d_1 < 0$. Further, $\lim_{c_2 \to 0} d_2 \approx 1,425$, and $\lim_{c_2 \to A/2} d_2 = \dfrac{3 + \sqrt{11}}{2} \approx 3,158$. Therefore we obtain that $d > 3,158$ is a sufficient condition for $t_T^* > 0$ to hold.

Now we show that $t_T^* < d$. We define:

$$\gamma = t_T^* - d = \frac{(8\,A + 8\,c_2)\,d^2 - (10\,A + 52\,c_2)\,d - 2\,A - 8\,c_2}{(12\,A + 44\,c_2)\,d + 3\,A + 10\,c_2} - d \tag{14}$$

which is equal to

$$-\frac{(4\,A + 36\,c_2)\,d^2 + (13\,A + 62\,c_2)\,d + 2\,A + 8\,c_2}{(12\,A + 44\,c_2)\,d + 3\,A + 10\,c_2}. \tag{15}$$

Thus $\gamma < 0$, $\forall c_2 \geq 0$, $A > 0$, $d \geq 0$.

Finally, the optimal quantities and the consumption of abatement goods by the less efficient firm are as follows:

$$q_1^T = \frac{(8\,A + 8\,c_2)\,d^2 + (8\,A + 22\,c_2)\,d + A + 3\,c_2}{32\,d^2 + 14\,d + 1}$$

[15]Notice that a_1^T is a quadratic polynomial in d. This is solved for, say, $\tilde{d_1} < 0$ and $\tilde{d_2} > 0$. Being $\tilde{d_2}$ decreasing in A, and given that $\lim_{A \to 0} \tilde{d_2} = \dfrac{1}{2}$, thus $a_1^T > 0$ for $d > \frac{1}{2}$ (a sufficient condition).

$$q_2^T = a_2^T = \frac{(12\,A - 20\,c_2)\;d^2 + (3\,A - 18\,c_2)\;d - 2\,c_2}{32\,d^2 + 14\,d + 1}$$

Notice that $q_1^T > a_1^T$. In fact

$$q_1^T - a_1^T = \frac{12Ad + 88c_2d + 3A + 10c_2}{2(128d^2 + 28d + 1)} > 0$$

which means that the efficient firm will always invest in abatement at a level that is not sufficient to cover its output (and related emissions).

Plugging the optimal tax rate t_T^* into the equilibrium profits we obtain the following expression for the more efficient firm profit:

$$\pi_1^T = \frac{16\,(A + c_2)^2\,d^2 + \left(16\,A^2 + 56\,A\,c_2 + 40\,{c_2}^2\right)\;d}{256\,d^2 + 112\,d + 8} + \\ + \frac{5\,A^2 + 28\,A\,c_2 + 40\,{c_2}^2}{256\,d^2 + 112\,d + 8} \tag{16}$$

while the equilibrium profit for firm 2 is given by:

$$\pi_2^T = \frac{[(3A - 18c_2)\;d + (12A - 20c_2)\;d^2 - 2\,c_2]^2}{(14\,d + 32\,d^2\; + 1)^2} - \bar{f}. \tag{17}$$

Appendix C: comparisons, ex ante *versus* ex post

Tax rate comparison

Let us define $\lambda = t_C - t_T$. It comes out that

$$\lambda = \frac{(140\,d^2 + 394\,d + 40)\,{c_2}^2 + (160\,A\,d^2 + 333\,d\,A + 38\,A)c_2}{5\;(A + 2\,c_2)\;(3\,A + 12\,d\,A + (44\,d + 10)c_2)} + \\ + \frac{20\,A^2\,d^2 + 53\,A^2\,d + 7\,A^2}{5\;(A + 2\,c_2)\;(3\,A + 12\,d\,A + (44\,d + 10)c_2)}$$

Thus $\lambda > 0,\ \forall c_2 \geq 0,\ A > 0,\ d \geq 0$.

Equilibrium outputs and price comparison

Considering first the equilibrium quantity produced by firm 1, we define $\phi = {q_1}^T - {q_1}^C$, where ϕ is as follows:

$$\phi = \frac{2\,\left(3\,A + 12\,c_2 + 22\,A\,d + 103\,c_2\,d + 41\,A\,d^2 + 20\,A\,d^3 + 184\,c_2\,d^2 + 20\,c_2\,d^3\right)}{5\,\left(32\,d^2 + 14\,d + 1\right)\left(2\, + 5\,d\right)}$$

Thus $\phi > 0$, $\forall d \geq 0$. Regarding the equilibrium quantity produced by firm 2, we define $\sigma = {q_2}^C - {q_2}^T$, where σ reads as follows:

$$\sigma = \frac{\left(10\,d^2\,A + 22\,d\,A + 3\,A + 184\,d^2\,c_2 + 103\,d\,c_2 + 12\,c_2 + 20\,d^3\,A + 20\,A\,d^2 + 20\,d^3\,c_2\right)}{5\,\left(32\,d^2 + 14\,d + 1\right)\left(2\, + 5\,d\right)}$$

Thus $\sigma > 0$, $\forall d \geq 0$.

Likewise, for aggregate quantities supplied under the two alternative policy regimes, we consider: $Q_T = q_1^T + q_2^T$ and $Q_C = q_1^C + q_2^C$.

Defining $\tau = Q_T - Q_C$, we have that:

$$\tau = \frac{3\,A + 12\,c_2 + 22\,A\,d + 103\,c_2\,d + 41\,A\,d^2 + 20\,A\,d^3 + 184\,c_2\,d^2 + 20\,c_2\,d^3}{5\,\left(32\,d^2 + 14\,d + 1\right)\left(2\, + 5\,d\right)}$$

It is then straightforward that $\tau > 0$, $\forall d$. Finally, let us consider the ranking between equilibrium prices, say P_T and P_C. It is easily found that $P_C - P_T$ is equal to $Q_T - Q_C$. As shown here above, then $P_C > P_T$, $\forall d$.

Abatement effort comparison

Let us define $\nu = {\tilde{a_1}}^T - {\hat{a_1}}^C$, with

$$\nu = \frac{A + 4\,c_2 - d\,\left(5\,A + 5\,c_2\right)}{25\,d + 10} - \frac{\left(-16\,A - 16\,c_2\right)\,d^2 - 4\,A\,d + A + 4\,c_2}{64\,d^2 + 28\,d + 2}$$

First notice that ν is a continuous monotonous function in A and in c_2, increasing in both arguments. Given the assumption that $\frac{A}{2} > c_2 \geq 0$, we can substitute in the above equation for $c_2 = 0 = c_2^{min}$, obtaining the expression:

$$\frac{A\,\left(80\,d^3+184\,d^2+33\,d-8\right)}{10\,\left(32\,d^2+14\,d+1\right)\left(2+5\,d\right)}$$

This expression is strictly positive $\forall d > 0.14$ and $A > 0$. Therefore we can infer that $\nu = {a_1}^T - {a_1}^C > 0$, $\forall d > 3.158$ and $c_2 \in [0, A/2)$.

Total emissions comparison

Proof of Proposition 3: Let us define $\zeta = E_T - E_C$:

$$\zeta = \frac{\left(3\,A+10\,c_2+12\,A\,d+44\,c_2\,d\right)^2}{8\left(32\,d^2+14\,d+1\right)^2} - \frac{\left(A+2\,c_2\right)^2}{2\left(5\,d+2\right)^2}$$

By simple algebra it comes out that ζ is a is a quadratic polynomial in x with $x = c_2$, such as $f(x) = Ax^2 + Bx + C$, with $A > 0$. This is solved for, say, $\tilde{c_1} < 0$ and $\tilde{c_2}$, with $\tilde{c_2} = \frac{\left(4\,d^2-11\,d-4\right)A}{2(8+11\,d+46\,d^2)} > 0$ for $d > 3.158$. Therefore, $\zeta = E_T - E_C < 0$ for $0 \leq c_2 < \tilde{c_2}$ and $\zeta = E_T - E_C > 0$ for $c_2 > \tilde{c_2}$. Notice finally that the threshold $\tilde{c_2}$ increases in A and in d.

Appendix D: equilibrium profits and welfare comparison

First, let us define $\chi = \pi_1^T - \pi_1^C$. By simple algebra we obtain that:

$$\chi = \frac{16\,A^2\,d^2+16\,A^2\,d+5\,A^2+32\,A\,c_2\,d^2+56\,A\,c_2\,d+28\,A\,c_2+16\,{c_2}^2\,d^2+40\,{c_2}^2\,d+40\,{c_2}^2}{256\,d^2+112\,d+8} + \\ - \frac{74\,A\,c_2+d\,\left(95\,A^2+225\,A\,c_2+130\,{c_2}^2\right)+28\,A^2+d^2\,\left(75\,A^2+150\,A\,c_2+75\,{c_2}^2\right)+48\,{c_2}^2}{1250\,d^2+1000\,d+200}$$

Since χ is a continuous monotonous function of A and knowing that $\frac{A}{2} \geq c_2$, we can minorate the above expression substituting for $A = 2c_2 = A_{min}$ getting that:

$$\chi(A_{min}) = \frac{{c_2}^2\,\left(450\,d^4+5790\,d^3+12377\,d^2+7314\,d+1296\right)}{25\left(5\,d+2\right)^2\,\left(32\,d^2+14\,d+1\right)} > 0$$

Therefore we can conclude that $\chi = \pi_1^T - \pi_1^C > 0$, $\forall A > 2\,c_2$.

We then compare firm 2's equilibrium profits, considering $\beta = \pi_2^C - \pi_2^C$. It comes out that $\beta(c_2)$ is a is a quadratic polynomial in x with $x = c_2$, such as $f(x) = ax^2 + bx + c$, with $a < 0$, and two solutions, say $\hat{c_1} < 0$ and $\hat{c_2} > 0$. Moreover $\hat{c_2}$ is an increasing function of both A and d. Substituting for $d = 3.158 = d_{min}$ we obtain unfeasible values for c_2, such that $c_2 > A/2$, $\forall A$. Thus $\pi_2^C > \pi_2^T$.

Regarding aggregate profits, the expression $\pi_1^C + \pi_2^T - (\pi_1^T + \pi_2^T)$ is a quadratic polynomial in x with $x = c_2$, such as $f(x) = Ax^2 + Bx + C$, with $A < 0$, with two solutions, say $\bar{c_1} < 0$ and $\bar{c_2} > 0$. We found that $\pi_1^C + \pi_2^C - (\pi_1^T + \pi_2^T) > 0$, for $c_2 = 0$, and $\pi_1^C + \pi_2^C - (\pi_1^T + \pi_2^T) > 0$ for $c_2 = A/2$. Being the expression rather cumbersome, we resorted also to numerical simulations, getting that aggregate profits under the ex-ante regime prevail over profits in the ex- post scenario when the cost asymmetry (i.e.c_2) is not very pronounced.

Proof of Proposition 4:

We want to assess whether $W(d, A, c_2)^*_T \gtreqless W(d, A, c_2)^*_C$. Let us define $\theta = W(d, A, c_2)^*_C - W(d, A, c_2)^*_T$. We consider θ as a quadratic polynomial in c_2, such as $f(x) = ax^2 + bx + c$, with $a < 0$, $x = c_2$. This is solved for $\breve{c_1} < 0$ and $\breve{c_2}$, with:

$$\breve{c_2} = \frac{A\,(-3232d^4 - 134d - 1285d^2 - 1120d^5 + 12 - 3318d^3)}{\Gamma} + \\ + \frac{\sqrt{5}A\,d\sqrt{(2+5d)(1+4d)(4d+9)^2(14d+32d^2+1)^2}}{\Gamma}$$

with $\Gamma = 2(1200\,d^5 + 7084\,d^4 + 6496\,d^3 + 2055\,d^2 + 148\,d - 24)$. It is possible to verify that $\breve{c_2} > 0$, implying also feasible values for c_2, i.e. satisfying $c_2 < A/2$, provided $d \geq 3.158$. Moreover $\breve{c_2}(A, d)$ is monotonically increasing in both arguments. Therefore, $W(d, A, c_2)^*_C > W(d, A, c_2)^*_C$ for $0 \leq c_2 < \breve{c_2}$, and viceversa $\theta = W(d, A, c_2)^*_C < W(d, A, c_2)^*_C$ for $c_2 > \breve{c}_2$.

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