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Long-term versus short-term environmental tax policy under asymmetric information☆

Manel Antelo[a,b,*], Lluís Bru[c], David Peón[d,e]

[a] Departamento de Fundamentos da Análise Económica, Universidade de Santiago de Compostela, 15782, Santiago de Compostela, Spain
[b] ECOBAS, Campus de Vigo, 36310, Vigo, Spain
[c] Departmento D'Economía de L'Empresa, Universitat de Les Illes Balears, Palma de Mallorca, Spain
[d] Universidade da Coruña (UDC), Dpt. of Business, and CISPAC, Spain
[e] Ted Rogers School of Management (Toronto Metropolitan University), Dpt. Finance, Toronto, ON, M5G 2C5, Canada

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ABSTRACT

We examine the interaction between a firm that uses either a dirty or a clean technology to produce a product over two periods, 1 and 2, and an environmentally conscious regulator that chooses the environmental tax/subsidy policy. The regulator ignores with which technology the firm manufactures the product and only has a prior belief about it. In this context, if the regulator can credibly commit to the policy for both periods, social welfare is generally higher than if it cannot commit, because distortions in firm's production at period 1 for signalling purposes strongly reduces the optimality of an environmental policy of short duration. A period-by-period policy in which the regulator does not commit to the policy terms for period 2 (which will be contingent to information provided by the firm in period 1) is only optimal when clean technology is very expensive to produce with it and the regulator's environmental concern is not very high. The results highlight the importance of taking into account the time horizon in policymaking, as well as the limitations of regulatory policies that seek to elicit information about the type of technology used by firms.

1. Introduction

The use of air, water and land to transform raw materials into consumption goods has an impact on the quality of the environment, not only due to high levels of production, but also the technology used. Clean technologies are less damaging to the environment but are often more expensive to produce, with the cost gap well documented in a number of economic sectors. In the power industry, for example, average levelized cost of producing electricity (LCOE)[1] varies according to the different technologies used by plants (U.S. Energy Information Administration, 2022).[2] Another example is the pulp and paper sector, where the different production technologies have different economic performance rates and different potential for reducing global CO_2 emissions (Jönsson, 2011). Likewise, in the concrete industry, the standard production technology uses, as the main ingredient, cement, which accounts for 8% of the world's anthropogenic CO_2 emissions, while the more expensive production technology that uses graphene makes it possible to reduce the amount of cement used by 50%.[3]

Pollution can be limited by command-and-control or market-based instruments (Requate, 2005). Command-and-control approaches typically set specific environmental standards for polluters and caps on their emissions, while market-based instruments (environmentally related

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* Corresponding author. Departamento de Fundamentos da Análise Económica, Universidade de Santiago de Compostela, 15782, Santiago de Compostela, Spain.
E-mail addresses: manel.antelo@usc.es (M. Antelo), lluis.bru@uib.es (L. Bru), david.peon@udc.es (D. Peón).

[1] LCOE measures the per-kilowatt hour cost (in discounted real USD) of building and operating a generating plant over an assumed financial life and duty cycle (EIA, 2017).

[2] See https://www.eia.gov/outlooks/archive/aeo21/pdf/electricity_generation.pdf.

[3] See *The Economist*, "How cement may yet help slow global warming", Nov 4th, 2021 (Updated Mar 22nd, 2022), https://www.economist.com/science-and-technology/how-cement-may-yet-help-slow-global-warming/21806083.

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taxes, subsidies for emissions abatement or tradeable permits) use economic incentives that rely on market forces to reduce emissions, with polluters themselves freely deciding how much they want to emit or to abate (Requate, 2005). In many scenarios, market-based instruments perform better than command-and-control instruments, primarily because of the relative cost savings (Ambec and Coria, 2021).[4] Indeed, the commonly held view is that revenue-raising instruments are preferable over non-revenue-raising instruments (MacKenzie and Ohndorf, 2012). Indirect controls by means of environmental taxes have been demonstrated to represent a good policy tool to reduce pollution (Amacher and Malik, 2002; Krass et al., 2013; Xu et al., 2016), and EU countries are increasingly using taxes to reduce carbon emissions and pesticide use (Ambec and Coria, 2021).

In this context, much environmental economics research addresses the case of a regulator that is imperfectly informed about the specific production technology used by firms (D'Amato and Dijkstra, 2015, 2018; Adetutu and Stathopoulou, 2021). This leads the regulator to ignore emission levels, at least until it can observe some signal that allows it to infer such emissions. Environmental regulation in this setting can thus be viewed as an agency problem, in which the regulator may or may not resort to proxies to infer information about the technology in use (Wainwright, 1999) and selects the optimal environmental policy terms accordingly. Another key aspect of environmental policy design in this context is the choice of its duration over time, in particular, short-term or long-term duration (Sprinz, 2009). For example, in the EU, the European Environment Agency (EEA) formulates environmental and climate policies according to different time scales by setting short-term targets – e.g., achieving reductions in environmental pressures and resource efficiency gains – to address long-term objectives – e.g., restoring ecosystem resilience and improving human well-being (EEA, 2015). Consequently, the integrated environmental strategy of the EU combines long-term sustainability goals (societal transition by 2050 to a low-carbon, climate-neutral and circular economy), medium-term thematic and sectoral policies (a 2030 target for energy transition and achievement of the UN sustainable development goals) and short-term environmental policies implemented as environmental directives with more immediate targets (EEA, 2020).

The distinction between the short and long term has been frequently disregarded in the theoretical literature. Indeed, there is growing concern that the time dimension has broadly been neglected in policy analyses (Daussage-Laguna, 2012), particularly in the field of environmental and resource economics (Dolowitz, 2020). Thus, little data is available on how environmental policy orientations towards the short or long term can have a different impact. Some exceptions are the analyses of the use of emission taxes to solve information asymmetry over time (Costello and Karp, 2004), why environmental policy is biased towards non-renewable resources in the short term (Grimaud and Rouge, 2008), and the conflict between the long-term nature of climate change mitigation and the short-term priorities of decision-makers (Cseh, 2019).

Our goal in this paper is to address the interaction between a profit-maximizing firm and an environmentally concerned regulator in an asymmetric information context. The firm pollutes as a by-product when manufacturing the good by using a clean or dirty technology. The clean technology pollutes less than the dirty technology, but it is more expensive to produce with. The firm knows which technology it uses, but the regulator, which sets a tax-based environmental policy, only knows that it will be one or another type with certain probability. We examine the issue in a setup in which the firm produces over two periods, and the regulator chooses whether to set a long-term or a short-term policy. A long-term policy means that the regulator sets, under incomplete information, the policy terms for period 1 that remain in force for period 2. Conversely, a short-term policy means that period-1 terms will be adjusted in period 2 once the regulator, after monitoring the firm's period-1 output, elicits the firm's information about its technology and recovers full information, possibly at the cost of the firm's strategic behaviour in period 1; this, in turn, may affect expected taxes levied, as well as expected production, total emissions and social welfare.[5] Thus, the short-term policy, aimed at countervailing opportunistic behaviour or rewarding the firm, may distort production in period 1 relative to that prevailing under a long-term policy. In this respect, the cost gap between production with clean or dirty technology plays a crucial role in the magnitude of productive distortions that are induced in period 1 under a short-term policy.

Our paper makes three contributions to the literature. First, long-term environmental policy has, in expected terms, a tax component and a subsidy component, and so leads the firm – regardless of whether its technology is dirty or clean – to produce the good if the regulator's environmental concern is low enough and clean manufacturing technology is not excessively costly, if the regulator's environmental concern is high enough and the clean technology is costly, it prefers to set a high tax that reduces production (and hence pollution) when the technology is dirty, at the social cost of expelling from the industry the clean firm that, in any case, would produce a small quantity and hence contribute little to social welfare.

Second, as the optimal short-term policy, the regulator seeks to set a period-2 subsidy for clean firms and a period-2 tax for dirty firms. Knowing this, the dirty firm will be tempted to mislead the regulator by behaving as a clean firm in period 1 (even though this may imply sacrificing some profits). To counteract this strategic behaviour and encourage the firm to disclose its private information, the regulator may be obliged to set a lower period-1 tax than the one that would be levied in the long-term policy.

Third, when long-term and short-term environmental tax policies are socially compared, the long-term policy is generally preferred. This happens when the clean technology is not very costly or, if costly, when the regulator is highly environmentally concerned. This is because in the short-term environmental policy the regulator is forced to set low taxes in period 1 to prevent the dirty firm from pretending to be clean. The drawback of a low tax is that it leads to increased production when the firm uses dirty technology. When comparing the effect on expected welfare of moving from long-term to short-term policies, this leads to a greater decrease in expected welfare in period 1 than the expected increase in welfare in period 2 (when tax policy is decided with complete information). Our model thus suggests that a short-term policy should not be observed very frequently.

The remainder of the paper is organized in five sections. Section 2 discusses the literature related to our research. Section 3 depicts the model and describes the resolution of the tax game under symmetric information. Section 4 refers to the asymmetric information context and contains the resolution of the game, both when the regulator chooses to implement a long-term environmental policy (Subsection 4.1) and a short-term environmental policy (Subsection 4.2). In Section 5, we compare the outcomes of these two policies, and analyse when one policy is preferable to the other. Finally, Section 6 concludes.

[4] Despite their effectiveness, there is yet some reluctance by policymakers to use market-based instruments, with institutional path dependence and political reasons explaining the paradox (Del Río and Labandeira, 2009). The effect is noticeable for environmental taxes in particular. De Miguel and Manzano (2011) explain that green tax reforms have become an important tool in protecting the environment and in bringing about a more efficient tax system, but often with the risk of political opposition.

[5] We focus on clean and dirty technologies, because they are a prominent example of deliberately different treatment by government policies. Carbon deployment pricing policies incentivize clean and penalize dirty technologies through carbon and energy taxes (Aghion et al., 2012), direct subsidies for clean technologies (Dechezleprêtre et al., 2017) and government expenditure worldwide in support of the development of new clean technologies (renewable energy, hydrogen cars, etc.).

2. Literature review

As a conceptual framework, our research combines two streams of the environmental economics literature: the research dealing with environmental taxation under asymmetric information, and the more recent debate on the time dimension as a key factor in environmental policy design. We review these separately below.

2.1. Environmental tax regulation under asymmetric information

Like much of the research on environmental regulation, our work addresses the case of a regulator who ignores the type of technology used by a polluting firm and only knows that it can be clean or dirty with certain probability. Thus, environmental regulation in this setting can be viewed as an agency problem, in which the regulator may try to elicit information about a firm's technology and emissions (Wainwright, 1999). Literature related to this issue, e.g., Amacher and Malik (2002), Krass et al. (2013) and Yenipazarli (2019), looks at the choice of technology when environmental policy is set to influence the firm's decision.

The existing literature has already established that, to set optimal market-based policies, evaluation of informational conditions for involved players is crucial (Barnet, 1980). The seminal paper is Dasgupta et al. (1980): they assume that, while the regulator can monitor the firm's pollution emissions, it ignores a priori the true value of the cost parameter on which the firm's optimal pollution level depends. Thus, the optimal tax-subsidy scheme in this context depends on a necessary condition involving the relationship between marginal cost and optimal pollution.

Prieger and Sanders (2012) introduce a price-based subsidy that helps the regulator to correct for both external damages and market power with no need to observe the firm's abatement activity, demand, cost or damage functions. Likewise, Miyamoto (2014) compares taxes with quotas under conditions of lobbying by a polluting industry with private information on pollution abatement costs, finding that the disadvantage of taxes relative to quotas is reduced when the government has a low level of concern for social welfare.

In a context of asymmetric information on the abatement costs of firms using a new technology, D'Amato and Djikstra (2015) analyse the incentives of a continuum of small firms to invest in a cleaner technology when the regulator can use two policy instruments (tradable emission permits and emission taxes). Both instruments can lead to under- or over-investment ex post, and if policy is set after firms invest, then the regulator infers cost realization and applies the social optimum with complete information. For a similar context, but this time with a single firm and an environmental policy consisting of emission quotas or emission taxes, D'Amato and Djikstra (2018) argue that under asymmetric information about the firm's cost of employing the new technology and a policy settled either before (commitment) or after (time consistency) the firm invests, quotas provide higher (lower) investment incentives than taxes under commitment (time consistency). This holds because with quotas (taxes), commitment generally leads to higher (lower) welfare than time consistency.

More recently, Adetutu and Stathopoulou (2021) document that less energy efficient firms received higher tax discounts under the UK climate change agreement, while Ambec and Coria (2021), focusing on the informational value of a pollution tax in the design of other environmental regulations when a firm's costs of abating pollution are unknown, investigate whether and how a tax can help regulators to set and update a standard (a cap) on pollutant emissions. Their finding is that the tax rate reveals information about the marginal cost of compliance that can be used to better target the standard to the firm's true cost.

2.2. The neglected time dimension in environmental policymaking

An important aspect of designing environmental policy is its duration over time. A prominent example is the EU integrated environmental strategy that combines the long-term goals of transition to a low-carbon, climate-neutral and circular economy by 2050, a medium-term target for energy transition and the UN sustainable development goals by 2030 and the use of environmental directives with more short-term targets (EEA, 2020).

However, the temporal dimension of environmental policy has frequently been disregarded in environmental and resource economics, with little research available, specifically, on the differential impact of longer versus shorter duration environmental policies. While this shortcoming is being addressed in other areas of economics,[6] there is growing concern that the time dimension has been neglected in policy analysis. A body of literature from the field of politics, but transversal to other disciplines such as economics and sociology, deals with how and why lessons from policies in other nations are knowingly used by regulators in developing similar policies for their own jurisdiction. Daussage-Laguna (2012) discusses how scholarly debates frequently highlight how time factors matter for public administration/policy, yet questions such as 'when', 'for how long' and 'in what sequence' have not been fully addressed. In the same area of political studies, Pollitt (2008), Howlett (2009), Moshe (2010) and Howlett and Goetz (2014) agree that time is a crucial but frequently neglected dimension in contemporary public policymaking. In economics, similar arguments can be found for economic geography (e.g., David (2022) on how timing norms and term limits shape and constrain the mobilization of resources for collective action) and the study of financial markets (e.g., Baker (2013) on how macroprudential regulation following the financial crash of 2008 neglected temporal dynamics and the length of time it takes for regulatory change to unfold). Responding to such calls to pay greater attention to time, a few studies have recently analysed the temporal consequences of policy design choices (Taeihagh, 2017) and how an understanding of administrative and political actors' time horizons can be used to strategically manipulate policy outcomes (Hartlapp, 2017).

The criticism that the time dimension in environmental policies has not been sufficiently analysed is not new in environmental and resource economics. Dolowitz (2020) notes how this literature has discussed everything from cap-and-trade policies to the movement of rain barrels, yet it has neglected the role played by time. Moreover, the fact that the regulator is less well informed than polluters about emissions opens the door to investigating the learning process to overcome this information deficiency, and how the regulator may then revise the terms of environmental policy and better adapt them in the following periods to real conditions. As Chick (2015, p. 77) points out "Making more information available on the sources and effects of pollution may, as with acid rain, improve incentives to address the problem, but equally it could diminish incentives to act".

Four lines of research in environmental economics in which time plays a role are the short-term vs long-term effects of a given policy, sequential game models between firms and the regulator, the impact of environmental policy uncertainty (EPU) in the short and long term, and analysis of the differential impact of different short-term vs. long-term environmental policies. We review these separately below.

Regarding short-term vs. long-term effects of a given policy, and environmental taxation in particular, the classic research by Bosquet (2000) shows that this policy produces a double dividend over the short term, in that it helps the environment without hurting the economy, but not necessarily in the long term. A few recent articles have focused on whether short-term environmental regulations, such as motor vehicle use restrictions, can continue to improve the environment over the long term by stimulating green innovation by companies, e.g., Qi (2014), He

[6] See, for instance, Noland and Kunreuther (1995) on short-run pro-bike policies and long-run anti-auto policies to increase bicycle commuting, and Kiley and Sim (2014) on macroprudential regulation including short-run bank capital policies (capital injections) and long-run policies (higher capital requirements).

et al. (2016) and Lu et al. (2018), while Zeng et al. (2020) find significant short- and long-term effects on air quality improvement arising from the environmental plan implemented for the G20 Hangzhou summit in 2016.

Sequential game models between firms and the regulator are a second way in which time has been included as a variable in environmental regulation analysis. Drawing on the choice of technology under environmental tax regulation, Amacher and Malik (2002) consider the case of a firm that may choose between two technologies to reduce pollution. While an emissions tax may achieve the first-best outcome if the firm moves first, it would be unattainable if the regulator plays first. In modelling a Stackelberg game in which a regulator sets an emissions tax and a polluting monopolist chooses whether to switch to a green technology, Krass et al. (2013) find that an initial increase in taxes may encourage that switch, but further tax increases may lead to a reverse switch. Moreover, when the regulator is moderately concerned about pollution impact, the socially optimal tax-only policy also leads to the choice of the clean technology, but this result is not achieved when the regulator is little or very concerned. Finally, the models by D'Amato and Djikstra (2015, 2018), already described, show that learning and policy adjustment by the regulator take time, particularly when the regulator needs to first infer the cost realization from the firm's behaviour.

As for EPU impact in the short and long term, a large body of literature is concerned with EPU but not with the possibility of the regulator implementing different environmental policies, e.g., empirical evidence on the impact of EPU on CO_2 emissions, including the works by Li et al. (2021) for 30 regions of China, Liu and Zhang (2022) also for China, and Nakhli et al. (2022) for the USA. Some of these articles point to a different relationship between those two variables depending on whether the short or long term is considered. Adedoyin and Zakari (2020) show that EPU reduces the growth of CO_2 emissions more in the short run in the UK than in the long run, and likewise, Anser et al. (2021) provide evidence from the top ten carbon emitter countries that a 1% increase in the world uncertainty index (WUI) mitigates CO_2 emissions in the short run by 0.11%, but increases emissions in the long run by 0.12%. Contrariwise, Syed and Bouri (2022), analysing the impact in the USA, find EPU intensifies CO_2 emissions in the short run and reduces them in the long run. Wang et al. (2020) find WUI to be positively associated with CO_2 emissions in the USA in the long run, while Zakari et al. (2021) find EPU to be positively related with CO_2 emissions by 22 OECD countries in the long run, with no statistical evidence for the short run. Abbasi and Adedoyin (2021) show that energy use and economic growth in China have substantial long-run and short-run positive effects on CO_2 emissions, while EPU has a statistically insignificant effect on emissions due to firms' sustainability policies. Finally, Wen and Zhang (2022) have recently related the impact of EPU on CO_2 emissions with the role of environmental regulation, finding that rising EPU harms the environment by motivating local authorities to reduce environmental supervision, leading to an increase in industrial pollution.

None of those three branches of the literature tackles the line of research that concerns us here: the regulator's decision concerning the choice of a short-term or long-term environmental policy, and how this different orientation can have a differential impact in society. In this regard we could only retrieve a few studies. Costello and Karp (2004) compare dynamic taxes and quotas when both the regulator and polluting firm have asymmetric information. The regulator learns by using either an emissions tax, with which information asymmetry is resolved in one period, or an emissions quota for which optimal learning is less transparent and never occurs gradually. They use this result to assess the informational advantage of taxes compared to quotas under asymmetric information. Grimaud and Rouge (2008) provide a theoretical framework that explains why environmental policy is biased towards non-renewable resources ('grey-biased') in the short term, and towards renewable resources ('green-biased') in the long term. Mu et al. (2018) suggest that the temporal dimension of mitigation costs and of air pollution co-benefits under different sectoral schemes in China's emissions trading systems gives policymakers a degree of flexibility in terms of phasing in additional industries over time. Cseh (2019), who argues that the long-term nature of climate change mitigation often conflicts with the short-term priorities of decisionmakers, proposes a policy based on short-term financial incentives to align the two-time scales offered to governments. Ghosh et al. (2020) describe a model that explains why short-term pollution, unlike long-term pollution, does not affect optimal fiscal policy. Moreover, the impact of environmental policies could be counterproductive since firms might anticipate governments' actions and change their behaviour. Finally, focusing on the impact on social welfare, Peng et al. (2021) find a lack of synchronization between the goals of short-term economic benefits and long-term social benefits and suggest increasing the importance of incentive-based tax rate preferences.

To summarize the discussion above, we conclude that more research is needed that includes "the duration, the tempo, the timing, the sequence, and the periodicity of actions" (Dolowitz, 2020, p. 576). In this article we particularly focus on duration and timing, i.e., the sequence of events leading to a specific environmental tax policy. We complement the extant literature by addressing the issue of the most appropriate environmental tax policy when the regulator needs time to learn and elicit hidden information from polluting firms so that it can adjust its policy to the information available at any moment. We also consider possible distortions in firms' behaviour resulting from policy adjustment and their impact on social welfare.

3. The model and equilibrium analysis under symmetric information

Consider a monopolist firm producing a consumption good over two periods, $i = 1, 2$, with a market demand described by the piecewise linear function $p_i(q_i) = \max\{0, 1 - q_i\}$, where p_i denotes the unit price in period i when q_i units of output are produced and sold in that period.[7] This demand remains constant from one period to the other. The final product is identical, regardless of whether it is produced using a more or less polluting technology.[8] However, depending on the technology used, the firm's production can damage the environment more or less. Although there is usually a range of solutions for dealing with pollution, including cleaner production (either process adaptations or new processes) and end-of-pipe solutions (Kemp and Volpi, 2008), we assume, for simplicity sake, that just two technologies are available, one dirty and the other clean, and that the latter reduces emissions at source (no emissions are ever discharged). As in Krass et al. (2013) and Chen et al. (2015), environmental emissions in each period are assumed to be a function of both the quantity produced and the technology used. We normalize the unit of emissions in such a way that one unit of production by a dirty firm causes one unit of emissions, whereas production by a clean technology produces no emissions. Formally, the level of emissions in each period, e_i, when the quantity of production is q_i, is the following[9]

$$e_i(q_i) = \begin{cases} q_i, \text{if the technology used is dirty} \\ 0, \text{if the technology used is clean} \end{cases} \quad (1)$$

The environmental damage per period due to emissions follows the strictly convex function $ED_i(e_i) = de_i^2/2$, where d is an exogenous

[7] This demand can be seen as originating from the maximization problem of a representative consumer with a utility that is linear in money terms (or in a numeraire representing the rest of the economy) and quadratic in the consumption of the good produced by the industry under consideration.

[8] See, e.g., the power industry, where electricity is a homogeneous product measured in kilowatts, irrespective of which production technology is used.

[9] Although a zero-pollution technology is usually prohibitively expensive, to be a zero-pollution technology a clean technology must be interpreted as a normalization to the unavoidable level of pollution that production implies given the technologies available.

parameter measuring the regulator's environmental concern, or alternatively, the social marginal willingness to pay for a one-unit reduction in environmental damage.[10] Environmental quality in each period deteriorates when the used technology is dirty but, for the sake of simplicity, we assume the environment regenerates completely at the end of the period, so there is no pollution stock at the beginning of period 2.[11] We consider that parameter d adopts a value that satisfies $d > 1$,[12] so the environmental concern of the regulator can be low (when the value of parameter d is close to 1) or high (when the value of parameter d is high), as in Gao and Zheng (2017).

Based on the technology used, the firm's marginal (and average) cost, which includes both production and abatement costs, can adopt a high value, c, in the case of clean technology ($c > 0$), or a low value (normalized to 0) in the case of dirty technology, with each one remaining unchanged across periods[13]

$$\widetilde{c} = \begin{cases} 0, \text{if the firm uses dirty technology} \\ c, \text{if the firm uses clean technology} \end{cases} \tag{2}$$

where c is such that $0 < c < 1$.

Fiscal revenue in period i, R_i, amounts to $R_i = t_i q_i$, where t_i denotes the magnitude of the environmental tax/subsidy policy the regulator sets for period i. There is no discount factor between periods and both the polluting firm and the regulator are risk-neutral players.

Finally, we consider a (second-best) scenario in which the regulator does not directly choose the efficient level of firm's production, but can influence the firm's market behaviour through the terms of environmental tax/subsidy policy.

The tax game proceeds as follows. At the beginning of period 1, nature draws the firm's technology, which is revealed to the firm, but not to the regulator, who only knows that the firm uses dirty technology with probability μ, $0 < \mu < 1$. This belief is exogenous and common knowledge. The regulator can set a long-term or a short-term tax/subsidy policy. In the long-term policy, before the firm decides how much to produce in period 1, the regulator, ignoring the technology the firm uses, sets the terms of the environmental policy for period 1 and commits to maintain them for period 2. Next, the firm observes the environmental policy to be complied with throughout period 1 and 2 and chooses the production levels for both periods.

Alternatively, the regulator can apply a short-term tax/subsidy policy, in which it chooses the terms of the environmental policy only for period 1 and does not commit to maintain them for period 2. Rather, the policy terms for period 2 will be contingent on information obtained in period 1. The firm observes the tax policy terms (both the level of tax/subsidy in period 1 and the fact that there is no policy commitment by the regulator for period 2) and chooses a production level for period 1. At the beginning of period 2 the regulator observes period 1 production and infers the firm's technology, so that the tax/subsidy policy for period 2 is decided under complete information about the technology in use. Finally, the firm produces in period 2.

The set of parameters and decision variables that conforms the model can be summarized as indicated in Table 1.

The regulator sets the environmental policy to maximize expected welfare, defined as the unweighted sum in each period of consumer surplus, firm's profits and fiscal revenue (negative, in the case of a subsidy) minus the environmental damage due to emissions (Krass et al., 2013). Hence, per-period welfare is:

$$W_i(c,d) = CS_i + \pi_i + R_i - ED_i = \left(1 - c - \frac{q_i}{2}\right)q_i - d\frac{e_i^2}{2} \tag{3}$$

where $CS_i = \frac{q_i^2}{2}$ and $\pi_i = (1 - c - q_i)q_i - t_i q_i$. On the other hand, parameter c vanishes (and $d > 1$) if the technology in use is dirty, while $c > 0$ (and parameter d vanishes) when it is clean. The regulator seeks to maximize $W_1 + W_2$ in expected terms, due to incomplete information about the technology type the firm uses.

Before looking at the equilibrium for this model under asymmetric information, consider a benchmark scenario in which, from the outset, the regulator has complete information about the firm's technology, whether clean or dirty. In this context, if the firm uses clean technology, production per period is $q_i(t,c) = \frac{1-c-t}{2}$ and, from (3), per-period social welfare amounts to $W_i = \left(1 - c - \frac{1-c-t}{4}\right)\frac{1-c-t}{2}$. Thus, per-period (first-best) welfare, $W_i(c,0) = \frac{(1-c)^2}{2}$, is achieved by setting $t_C = -(1-c)$, i.e., by subsidizing the firm in each period with $s_C = 1 - c$ per unit produced, where subscript C denotes clean technology. Since there is no environmental damage, there is no need to tax the firm. However, the firm is a monopoly and, using its market power to set a high price, produces less than the social optimal quantity unless production is subsidized.

By contrast, if the firm uses dirty technology, production per period is $q_i(t,0) = \frac{1-t}{2}$ and, from (3), per-period social welfare amounts to $W_i = \left(1 - \frac{(d+1)(1-t)}{4}\right)\frac{1-t}{2}$. Thus, the regulator achieves per-period first-best welfare, $W_i(0,d) = \frac{1}{2(d+1)}$, by taxing the firm in each period with $t_D = \frac{d-1}{d+1}$ per unit produced, where subscript D denotes dirty technology. The assumption $d > 1$ implies that the dirty firm, which uses its market power to set high prices, produces too much when environmental damage is considered, and as a consequence, the regulator sets a tax to induce the firm to reduce production.

4. Equilibria under short-term and long-term environmental policies

Consider now a scenario of asymmetric information, in which the regulator does not directly observe the firm's technology and only knows that it has been selected by nature from a {dirty, clean}-set with probability μ for the dirty technology. As stated above, the regulator may either choose a long-term or a short-term policy. In the long-term policy, the terms for period 1 remain in force for period 2 and thus it does not require observing the firm's behaviour in period 1 or, if observed, it requires the regulator to commit not to use this information and maintain the policy terms announced for period 2. In the short-term policy, the terms for period 2 are only settled after the period-1 policy leads the firm to disclose information regarding the type of technology used; thus, a short-term policy is potentially profitable only if the regulator observes period-1 firm's production and uses that information to adjust the period-2 environmental policy to the new conditions of symmetric information.

Table 1
Model parameters and decision variables.

Parameters	Decision variables
d: Regulator's environmental concern	q: Output level
c: Marginal (and average) cost	e: Emissions level
μ: Probability of producing with dirty technology	t: Environmental tax/subsidy policy

[10] Parameter d, measuring the degree of environmental concern, translates environmental impact into monetary units (Krass et al., 2013).

[11] The environmental damage for period 2 can be interpreted, as the limit case of a more general function, i.e., as $ED_2 = d(\lambda e_1 + e_2)^2/2$, where λe_1 $(0 \leq \lambda \leq 1)$ denotes the period 1 emissions that are accumulated in period 2. However, assuming a strictly positive value for the parameter λ does not qualitatively change the results with respect to those obtained when there is no stock pollution. The only nuance is that a lower environmental awareness by the regulator would suffice to prefer a clean technology.

[12] If $d = 1$, the regulator would not tax nor subsidize the dirty firm, whereas $d < 1$ would mean that the regulator is anti-environmentalist, since it negatively distorts the damage by subsidizing the dirty technology.

[13] Amir et al. (2008) state that innovation or technology adoption other than end-of-pipe technology can lead to an upward shift in the marginal abatement cost curve.

4.1. Long-term environmental policy

The environmental tax/subsidy policy that remains unchanged over all periods will be that which maximizes the per-period expected welfare:

$$EW_L(t;\mu,c,d) = \mu\left(1 - \frac{1+d}{2}q(t;0)\right)q(t;0) + (1-\mu)\left(1 - c - \frac{q(t;c)}{2}\right)q(t;c), \quad (4)$$

where subscript L stands for long-term policy, and $q(t;c) = \max\left\{0, \frac{1-c-t}{2}\right\}$[14] and $q(t;0) = \frac{1-t}{2}$ denote the firm's production (depending on the technology in use). If the tax charged is such that $t < 1 - c$, both the clean and dirty firm are active, i.e., $0 < q(t;c) < q(t;0)$, and the marginal effect of tax on welfare evolves according to

$$\frac{\partial EW_L(t;\mu,c,d)}{\partial t} = -\frac{\mu}{2}(1-(1+d)q(t;0)) - \frac{1-\mu}{2}(1-c-q(t;c))$$

In contrast, an environmental tax $t \geq 1 - c$ leads to only the dirty firm being active, i.e., $0 = q(t;c) < q(t;0)$, and the marginal effect of tax on social welfare amounts to

$$\frac{\partial EW_L(t;\mu,c,d)}{\partial t} = -\frac{\mu}{2}(1-(1+d)q(t;0))$$

In these circumstances it follows that when $t \geq 1 - c$ and $d > 1 + \frac{2(1-c)}{\mu c}$, the marginal effect of the tax on social welfare amounts to

$$\frac{\partial EW_L(t;\mu,c,d)}{\partial t} = -\frac{\mu}{2}\left(1 - \frac{(1+d)c}{2}\right) - \frac{1-\mu}{2}(1-c) > 0$$

Thus, it is socially optimal to charge a high tax in the presence of a very dirty technology (or, equivalently, in the presence of a regulator whose parameter d adopts a high value, as indicated, and so is very concerned about environmental damage), or in the presence of an inefficient clean technology (i.e., high values of parameter c) or in both cases. The optimal tax is the one intended for a dirty firm,

$$t_L \equiv t_D = \frac{d-1}{d+1} \quad (5)$$

that leads the firm to produce in each period only by means of dirty technology. On the other hand, it is socially optimal to have the firm active either if the clean technology is quite effective (low values of parameter c) in the sense of $t_D < 1 - c$ or if the dirty technology does not pollute much (i.e., the regulator is little concerned about environmental damage, in the sense of $d < 1 + \frac{2(1-c)}{c}$) or when both circumstances hold; the optimal per-period tax is therefore that which satisfies

$$\frac{\partial EW_L(t;\mu,c,d)}{\partial t} = -\frac{\mu}{2}(1-(1+d)q(t;0)) - \frac{1-\mu}{2}(1-c-q(t;c)) = 0$$

This leads to

$$t_L \equiv t_\alpha(\mu,c,d) = \alpha t_D + (1-\alpha)t_C = \frac{\mu(d-1) - (1-\mu)(1-c)}{\mu d + 1} \quad (6)$$

where $\alpha = \frac{\mu(d+1)}{\mu d+1}$, $t_D = \frac{d-1}{d+1}$ and $t_C = -(1-c)$. In this case, the per-period tax satisfies $t_L(\mu,c,d) < \frac{d-1}{d+1} < 1 - c$ and, as result, it allows a clean as well as a dirty firm to be productively active.

Finally, if the regulator is moderately concerned about environmental damage, as $1 + \frac{2(1-c)}{c} < d < 1 + \frac{2(1-c)}{\mu c}$, then the welfare maximization problem has two local maxima. One is located in $t_\alpha(\mu,c,d)$ as given in Eq. (6), the other is located in t_D as given in Eq. (5). These maxima are depicted in both Figs. 1 and 2 for different values of parameter d.

In Fig. 1, the global maximum is at t_D and, at this tax, the firm only produces it has the dirty technology. Hence, the per-period expected welfare defined in Eq. (3) and evaluated at t_D becomes:

$$EW_L(t_D;\mu,d) = \frac{\mu}{2(d+1)} \quad (7)$$

In Fig. 2, instead, the global maximum is located at $t_\alpha(\mu,c,d)$, and the firm is always active, regardless of whether its technology is dirty or clean, when the regulator chooses this tax.

With environmental tax $t_\alpha(\mu,c,d)$ period after period, either the dirty firm or the clean firm produce and the per-period expected welfare defined in Eq. (3) amounts to:

$$EW_L(t_L;\mu,c,d) = \frac{4(1-c)^2 - c[(4-3c)d - (8-5c)]\mu + c[(4-3c)d + c]\mu^2}{4(\mu d + 1)} \quad (8)$$

Finally, whether the welfare function evolves in the tax as in Fig. 1 or 2 can be determined through comparison of Eqs. (7) and (8), which allows us to determine which of the two local maxima is the global maximum for a long-term tax policy. This is recorded as follows.

Proposition 1. *Under asymmetric information, a cut-off value of the regulator's environmental concern exists,* $d_L(\mu,c) \equiv \frac{2(1-c)^2 + [1+(1-c)^2]\mu + 2(1-c)\sqrt{(1-c+\mu c)^2 + (2+\mu)\mu}}{(4-3c)\mu c}$, *such that the optimal long-term environmental policy consists of the following tax period after period:*

(i) *If* $1 < d < d_L(\mu,c)$, *then* $t_L(\mu,c,d) = t_\alpha(\mu,c,d) = \frac{\mu(d-1)-(1-\mu)(1-c)}{\mu d+1} < 1 - c$ *and the firm is active in each period, regardless of whether its technology is dirty or clean.*

(ii) *If* $d \geq d_L(\mu,c)$, *then* $t_L(\mu,c,d) = t_D = \frac{d-1}{d+1} \geq 1 - c$ *and only the dirty firm remains active in each period.*

Proof. See the Appendix.

Thus, what determines the terms of the long-term environmental policy are the regulator's environmental attitude, the efficiency of the clean technology and the probability of dealing with a dirty firm. If the regulator is little concerned about environmental damage (implying great damage when a dirty technology is used), the clean technology is

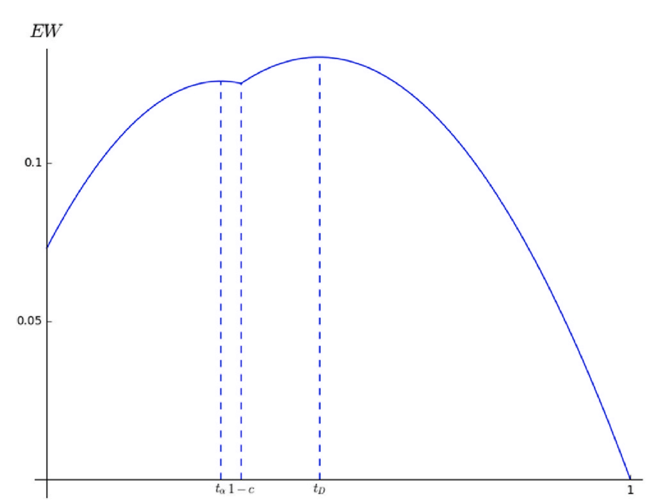

Fig. 1. The long-term environmental policy as given in Eq. (5) defining a global maximum of expected welfare at $t_L = t_D$ (parameter values: $\mu = \frac{1}{2}, c = \frac{2}{3}, d = 3$).

[14] We write $q(t;c) = \max\left\{0, \frac{1-c-t}{2}\right\}$ to contemplate that the clean firm may produce a positive quantity (when the tax charged is such that $t < 1 - c$) or zero-quantity (when $t \geq 1 - c$).

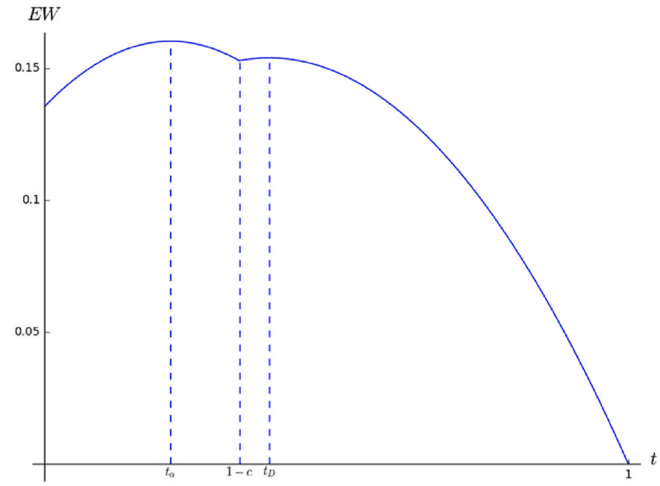

Fig. 2. The long-term environmental policy as given in Eq. (6) defining a global maximum of expected welfare at $t_L = t_\alpha(\mu, c, d)$ (parameter values: $\mu = \frac{1}{2}, c = \frac{2}{3}$, $d = 2$).

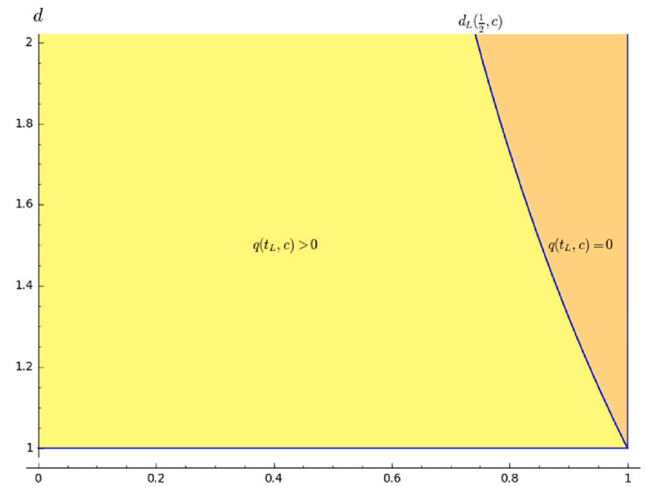

Fig. 3. Region in the (c, d)-parameter space in which the long-term policy leads to production by both the dirty and clean firms (yellow region) or only the dirty firm (orange region) ($\mu = 1/2$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

quite efficient or there is low probability of the firm being dirty, then the long-term policy consists of a tax that allows firms of both kinds to produce. However, if the regulator is little concerned about environmental damage, the clean technology is so costly that the clean firm's output (hence its contribution to aggregate welfare) would be small, and there is high probability μ that the firm uses a dirty technology (the threshold $d_L(\mu, c)$ decreases in μ), the long-term policy consists of tax $t_D = \frac{d-1}{d+1}$, i.e., the tax intended for a dirty firm – the only firm that is active in the market.

In Fig. 3, we depict, in the (c, d)-parameter space and for the case in which the technology can be dirty or clean with equal probability, the region where the long-term environmental policy leads the firm to always produce, irrespective of whether its technology is dirty or clean (the region coloured yellow), and the region where the long-term environmental policy allows the firm to produce only if its technology is dirty (the region coloured orange).[15]

The magnitude of the per-period long-term environmental tax policy stated in Proposition 1 depends on the regulator's environmental concern as follows. When $t_L(\mu, c, d) = \frac{\mu(d-1)-(1-\mu)(1-c)}{\mu d+1}$, it immediately follows that, for a certain value of c, the marginal cost of producing with clean technology, the optimal long-term policy is first a subsidy per unit in each period (when $d = 1$) and then, as d increases, the subsidy eventually becomes a tax. Furthermore, there is a discrete jump upwards in the tax at $d = d_L(\mu,c)$, defined in Proposition 1, since $t_L(\mu, c, d_L(\mu, c)) < t_D$ for $d < d_L(\mu, c)$: the clean technology is so expensive to produce the good that the regulator finds it optimal, at $d = d_L(\mu, c)$, to jump up from $t_L(\mu, c, d_L(\mu, c))$ to t_D, the tax that leads the clean firm not to produce.

Similarly, for a given value of the regulator's environmental concern, d, as the marginal cost of producing with clean technology, c, increases, the tax defining the long-term policy also increases. In particular, when $c = 0$, the optimal tax in each period amounts to $t_L(0, d) = \frac{\mu d-1}{\mu d+1}$, which becomes a subsidy whenever $d < \frac{1}{\mu}$, and then, as c increases, the tax also increases. Furthermore, there is a discrete upward jump in the tax at $c = \frac{2-\mu}{2+\mu(d-1)}$, above which the tax leads the clean firm not to produce, because a clean technology that gives rise to marginal production cost $c > \frac{2-\mu}{2+\mu(d-1)}$ is too expensive to produce the good. Thus, the tax involved in this policy becomes that intended for a dirty firm.

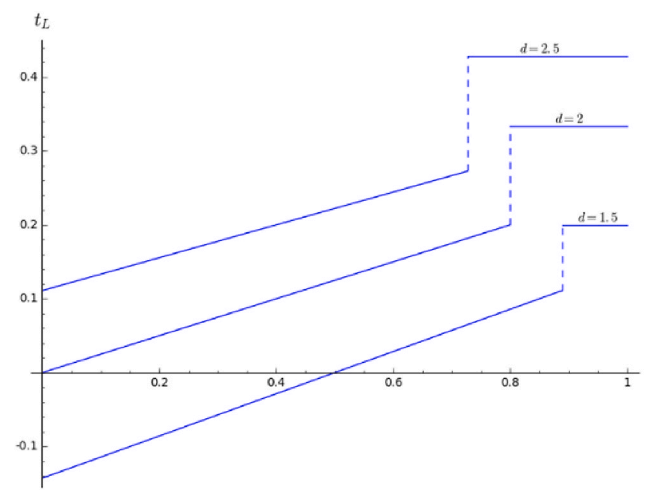

Fig. 4. Long-term environmental policy terms as a function of c (parameter values: $d \in \{1.5, 2, 2.5\}$ and $\mu = 1/2$).

In Fig. 4, we depict, in the particular case in which the regulator believes with equal probability that the firm uses dirty or clean technology, how t_L evolves with c, the marginal cost of producing with the clean technology, for values representing the regulator's environmental concern, $d = 1.5$, $d = 2$ and $d = 2.5$.

If the regulator has little environmental concern, as reflected in $d = 1.5$, the long-term policy may consist of a subsidy (for both clean and dirty firms) or a tax (for both clean and dirty firms) in each period. The policy is a subsidy when c is sufficiently low, $0 < c < .5$, but becomes a tax if $.5 < c < 1$. Moreover, when the clean technology is very expensive, $.9 < c < 1$, and a tax may lead the clean firm to stop producing, the regulator increases the per-period tax and places it at the optimal level intended for a dirty firm. However, a more concerned regulator, in the sense that $d \geq 2$, would never set a subsidy, regardless of whether pro-

[15] In Fig. 3, the $d_L(\mu, c)$-locus that separates the region in which the tax charged leads to $q(t_L, c) > 0$ from that in which the tax charged leads to $q(t_L, c) = 0$ pivots to the right as μ, the regulator's belief of dealing with a dirty firm, decreases and approaches 0 (i.e., the region in which $q(t_L, c) > 0$ increases), but pivots to the left as μ increases and approaches 1 (i.e., the region in which $q(t_L, c) = 0$ increases).

duction with clean technology is cheap or expensive, and furthermore, would jump to t_D when $.8 < c < 1$, i.e., for lower values of c. In general, as can be seen in Fig. 4 and different values of d illustrates,[16] for higher values of d, the jump in the per-period tax to t_D, the optimal level for a dirty firm, occurs for smaller values of c.

Therefore, the greater the environmental concern of the regulator, the more likely that its tax in an incomplete information context will result in non-clean production. This apparent paradox can be explained as follows. The higher d, the more the regulator wants to reduce dirty production and it increases the amount of the tax; since it cannot set a different tax for each technology (as it would do if the information on the technology in use was available), this leads to clean technology no longer being used for lower levels of parameter c.

Finally, the long-term environmental policy stated in Proposition 1 yields the expected welfare per period:

$$EW_L(\mu,c,d) = \begin{cases} EW_L(t_\alpha;\mu,c,d), \text{if } d < d_L(\mu,c) \\ EW_L(t_D;\mu,d), \text{if } d \geq d_L(\mu,c) \end{cases} \tag{9}$$

previously defined in Eqs. (7) and (8).

4.2. Short-term environmental policy

In this scenario, the regulator, to set the optimal ex-post policy terms for period 2, uses the information on production available at the end of period 1. For the policy terms of period 1 to ensure that the regulator is fully informed during period 2, it is necessary to infer from observation of period-1's production the technology in use. Hence, we discuss the convenience of short-term policies that allow a Bayesian separating equilibrium to emerge, so that in period 2 the regulator can set a policy contingent on the observed period-1 production. Such a policy has a clear advantage for welfare purposes when compared with a long-term policy, since it allows policy terms for period 2 to be adapted to the economic and environmental reality; however, it is not immediate that it is better than a long-term policy, because it may also cause strong distortions in period-1 production. When there are no distortions, a short-term environmental policy will unequivocally yield a more efficient outcome than a long-term policy. However, we will see that the absence of commitment by the regulator to the period-2 policy can make it very costly to incentivize the firm to truly disclose its technology through its period-1 production, with the subsequent distortions in that period limiting the parameter values for which an adaptable short-term environmental policy improves welfare over a more rigid long-term environmental policy.

As mentioned, in a Bayesian separating equilibrium the regulator infers, after observing the firm's period-1 production, whether its technology is clean or dirty. Complete information is thus restored in period 2 and the regulator can set the welfare-maximizing environmental policy for this period (see Sect. 3). It is therefore immediate that period-2 expected welfare improves as compared to the welfare for the long-term environmental policy.

Since in period 1 the regulator ignores which technology the firm uses, the environmental policy for this period has to be the same for any firm. Such a policy will induce a Bayesian separating equilibrium if, in period 1, a dirty firm produces $q_D^m(t) = \frac{1-t}{2}$, its optimal quantity as a myopic monopolist, and a clean firm produces a different (lower) separating quantity, $q_s < q_D^m(t)$, which can even be zero. Thus, if the regulator observes a period-1 production above q_s, it will infer that the firm uses dirty technology, $\mu(q_D^m(t)) = 1$, and will tax it with $t_2 \equiv t_D = \frac{d-1}{d+1}$ in period 2, and if the conjecture is correct, aggregate welfare in period 2 will amount to $W_2\left(\frac{1}{d+1};1,0,d\right) = \frac{1}{2(d+1)}$. Alternatively, if the regulator observes that period-1 production is q_s, it will infer that the firm uses clean technology, $\mu(q_s) = 0$, and will subsidize it with $s_2 \equiv s_C = -t_C = 1-c$ in period 2; thus, if the conjecture is correct, period-2 welfare will be $W_2(1-c;0,c,d) = \frac{(1-c)^2}{2}$. In sum, expected welfare in period 2 caused by a short-term policy in the Bayesian separating equilibrium is:

$$EW_2(\mu,c,d) = \mu\frac{1}{2(d+1)} + (1-\mu)\frac{(1-c)^2}{2} \tag{10}$$

When designing the policy terms for period 1, the regulator is constrained to getting the dirty firm not to behave as a clean firm: by producing q_s, it would reduce its period-1 profits, but it would receive a subsidy in period 2 instead of being taxed. The incentive compatibility (IC) constraint to be satisfied by a dirty firm is, therefore:

$$\begin{aligned} \left(\frac{1-t}{2}\right)^2 + \left(\frac{1}{d+1}\right)^2 \geq (1-t-q_s)q_s + \left(\frac{2-c}{2}\right)^2 \rightarrow \left(\frac{1-t}{2}\right)^2 \\ -(1-t-q_s)q_s \geq \left(\frac{2-c}{2}\right)^2 - \left(\frac{1}{d+1}\right)^2 \end{aligned} \tag{11}$$

where $\left(\frac{2-c}{2}\right)^2$ is the period-2 period profit of a dirty firm that misleads the regulator with production q_s in period 1, in which case it has profits $(1-t-q_s)q_s$ in period 1, but then receives subsidy $1-c$ in period 2, while $\left(\frac{1}{d+1}\right)^2$ is its period 2 profit when it produces optimal quantity $\frac{1-t}{2}$ in period 1 and, once understood as a dirty firm, is charged the tax $\frac{d-1}{d+1}$ in period 2. Hence, the IC constraint stated in Eq. (11) establishes that the extra profits for a dirty firm being honest in period 1, $\left(\frac{1-t}{2}\right)^2 - (1-t-q_s)q_s$, must compensate for the extra profits $\left(\frac{2-c}{2}\right)^2 - \left(\frac{1}{d+1}\right)^2$ from being subsidized instead of being taxed in period 2.

The IC condition stated in Eq. (11) can be rewritten as $\left(\frac{1-t}{2} - q_s\right)^2 \geq \left(\frac{h(c,d)}{2}\right)^2$ or, alternatively, as:

$$q_s \leq \frac{1-t-h(c,d)}{2} \tag{12}$$

where $h(c,d) \equiv \sqrt{(2-c)^2 - \left(\frac{2}{d+1}\right)^2}$. Therefore, fulfilment of the IC condition of a dirty firm as given in Eq. (11) constrains the regulator to set a period-1 tax that satisfies $t \leq 1 - h(c,d)$.

The clean firm's optimal production in period 1, $q_C^m(t) = \frac{1-t-c}{2}$, satisfies the IC condition for a dirty firm given in Eq. (11) whenever $\frac{1-t-c}{2} \leq \frac{1-t-h(c,d)}{2}$; this happens only if $c \geq h(c,d)$ or $\frac{3}{4} \leq c \leq 1$ and $1 < d \leq d_c(c) \equiv \frac{1}{\sqrt{1-c}} - 1$, and the clean firm produces a positive quantity only if $t < 1 - c$. When $c < h(c,d)$, instead, the clean firm has to reduce the quantity produced in period 1 from $q_C^m(t) = \frac{1-t-c}{2}$ to $q_s = \frac{1-t-h(c,d)}{2}$ if it wants to be understood as a clean firm, so that it can receive a subsidy in period 2. In this case, the IC condition in Eq. (11) indicates that the regulator cannot set a period-1 tax above $1-h(c,d)$, and q_s is strictly positive only if the period-1 tax satisfies $t < 1-h(c,d)$.

The following lemma summarizes the characterization of the period-1 production for a short-term environmental tax policy that constitutes a Bayesian separating equilibrium.

Lemma 1. *Let* $h(c,d) = \sqrt{(2-c)^2 - \left(\frac{2}{d+1}\right)^2}$ *and* $d_c(c) \equiv \frac{1}{\sqrt{1-c}} - 1$. *The period-1 tax that forms part of the short-term environmental policy leads the firm to produce in this period as follows. When using dirty technology, its production amounts to* $q_D = \frac{1-t}{2}$ *and when using clean technology, its production is the following:*

(i) *In the* (c,d)*-parameters region defined by* $0 \leq c < \frac{3}{4}$ *or* $\frac{3}{4} \leq c \leq 1$ *and* $d > d_c(c)$, $q_s = \begin{cases} \frac{1-h(c,d)-t}{2} > 0, \text{ if } t < 1-h(c,d) \\ 0, \text{ if } t = 1-h(c,d) \end{cases}$.

[16] The magnitude of t_L always depends on the parameters μ, c and d.

(ii) *In the region defined by* $\frac{3}{4} \le c \le 1$ *and* $1 < d \le d_c(c)$, $q_s = \begin{cases} \dfrac{1-c-t}{2} > 0, \text{ if } t < 1-c \\ 0, \text{ if } 1-c \le t \le 1-h(c,d) \end{cases}$.

Lemma 1 states when the firm needs or needs not to distort its period-1 production to be understood as a clean firm by the regulator. When the clean technology is cheap or, if expensive, the regulator is highly concerned about the environmental damage caused by a dirty technology, the regulator is forced to set a period-1 tax that distorts production of the firm in this period. In this case, the policy set for period 1 is that which solves the problem:

$$\max_t EW_1 = \mu\left(1 - \frac{(d+1)(1-t)}{4}\right)\frac{1-t}{2} + (1-\mu)\left(1-c-\frac{q_s}{2}\right)q_s, \text{ s.t : } t \le 1-h(c,d) \tag{13}$$

which yields the result stated in the following lemma.

Lemma 2. *In the parameters region defined by* $0 \le c < \frac{3}{4}$ *or* $\frac{3}{4} \le c \le 1$ *and* $d > d_c(c)$, *the optimal tax in the first period of the short-term policy is*

$$t_S(\mu,c,d) = \begin{cases} \dfrac{\mu(d-1) - (1-\mu)(1-c) - (1-\mu)(h(c,d)-c)}{\mu d + 1} < 1-h(c,d), & \text{if} \quad \min\{1, d_c(c)\} < d \le d_h(\mu,c) \\ 1-h(c,d), & \text{if} \quad d \ge \max\{d_h(\mu,c), d_c(c)\} \end{cases}$$

where $d_h(\mu,c) = \max\left\{1, \frac{2\sqrt{[1-(1-\mu)c]^2+\mu^2}}{\mu(2-c)} - 1\right\}$ and subscript S denotes short-term policy.

Proof. See the Appendix.

Finally, if we compare $t_S(\mu,c,d)$ as given in Lemma 2, the period-1 tax of a short-term policy, with $t_L(\mu,c,d)$ as given in Eq. (6), the per-period tax of a long-term policy, it follows that whenever $c < h(c,d)$

$$t_S(\mu,c,d) = t_L(\mu,c,d) - (1-\mu)\frac{h(c,d)-c}{\mu d + 1} \tag{14}$$

that is, the distorted period-1 tax of the short-term policy is lower than that of the long-term policy, $t_S(\mu,c,d) < t_L(\mu,c,d)$. Hence, the regulator, to elicit information about the firm's technology, is forced to set the period-1 terms of a short-term policy that are softer than the period-1 terms of a long-term policy. This is because an increase in period-1 profits (induced by a lower tax) reduces the temptation of the dirty firm to misrepresent itself as a clean firm, and limits the distortion of the production of the clean firm as much as possible. Indeed, the regulator reduces more the period-1 tax when $1-\mu$ is greater, i.e., when the firm is more likely to be clean, since it does not want the clean firm to produce too little, and, since the probability of the firm being dirty is low, it is not so harmful if the dirty firm increases its production.

The period-1 tax $t_S(\mu,c,d)$ given in Lemma 2 leads the clean firm to produce in this period the separating quantity $q_s = \max\left\{0, \frac{1-t_S(\mu,c,d)-h(c,d)}{2}\right\}$; thus $q_s > 0$, whenever $t_S(\mu,c,d) < 1-h(c,d)$, in which case both the dirty and clean firm produce in period 1. However, when $t_S(\mu,c,d) \ge 1-h(c,d)$, it follows that $q_s = 0$, i.e., the clean firm does not produce in period 1; in spite of this, the regulator cannot charge in this period the firm with tax $t_D = \frac{d-1}{d+1}$, the optimal tax under complete information for a dirty firm, but instead is forced to set a lower tax $t_S(\mu,c,d) = 1-h(c,d)$.[17]

On the other hand, Part (ii) of Lemma 1 indicates the region of parameter values where the clean firm, given a tax t, does not need to distort its production because, provided that the regulator can still elicit the firm's technology, the dirty firm prefers to produce its optimal quantity $\frac{1-t}{2}$. If in addition the regulator can set for period 1 the same tax $t_L(\mu,c,d)$ than in a long-term environmental policy, it means that it can set the optimal tax policy under complete information in period 2 at no social cost in period 1, compared with a long-term policy. It is thus obvious that in this case the short-term policy is socially better than the long-term one for these parameter values.

When the optimal long-term tax is $t_L(\mu,c,d) = t_\alpha(\mu,c,d) < 1-c$, the regulator can just set this tax in period 1. When the optimal long-term tax is $t_L(\mu,c,d) = t_D = \frac{d-1}{d+1}$ (which implies that the clean firm does not produce in period 1), the IC condition (11) is satisfied only if $d < d_h(1,c) \equiv \frac{2\sqrt{2}}{2-c} - 1$.

Therefore, when the regulator's environmental concern is low as $1 < d < d_L(\mu,c)$, the optimal period 1 short-term tax equals the long-term tax, $t_S(\mu,c,d) = t_L(\mu,c,d) = \frac{\mu(d-1)-(1-\mu)(1-c)}{\mu d+1}$, production of the clean firm amounts to $q = \frac{1-t_S(\mu,c,d)-c}{2}$, and expected welfare in period 1 is as stated in Eq. (8). On the other hand, when $d_L(\mu,c) < d < d_h(1,c)$, the optimal long term tax $t_L(\mu,c,d) = t_D = \frac{d-1}{d+1}$ is also feasible and it is optimal to set the period 1 short-term tax equal to the long-term tax, $t_S(\mu,c,d) = t_D = \frac{d-1}{d+1}$.

Finally, when $d_h(1,c) < d < d_c(c)$, the regulator can no longer achieve in period 1 the expected welfare obtained by long-term taxation, because it can no longer set the optimal tax for this dirty firm, $\frac{d-1}{d+1}$, but must set a lower tax $t_S(\mu,c,d) = 1-h(c,d)$ (a tax at which a clean firm is still non-active).

The regulator must then compare the expected welfare with a clean firm active, as stated in Eq. (8), with expected welfare with only a dirty firm active under period-1 tax $t_S(\mu,c,d) = 1-h(c,d)$,

$$\mu\left(1 - \frac{(1+d)(1-t_S(\mu,c,d))}{4}\right)\frac{1-t_S(\mu,c,d)}{2} \tag{15}$$

From here, the regulator chooses a period-1 tax leading the clean firm to be active if the expected welfare in Eq. (8) is larger than the one obtained in Eq. (15), i.e.,

$$\frac{4(1-c)^2 - c[(4-3c)d-(8-5c)]\mu + c[(4-3c)d+c]\mu^2}{2(\mu d+1)} \ge \mu\left(1 - \frac{(1+d)h(c,d)}{4}\right)\frac{h(c,d)}{2} \tag{16}$$

and otherwise chooses a period-1 tax leading the clean firm not to be active. This leads to an active clean firm if $d \le d_{ds}$, where d_{ds} is the value of d for which the inequality in Eq. (16) holds as an equality.

[17] The optimal tax for a dirty firm, $t_D = \frac{d-1}{d+1}$, does not satisfy the dirty firm's IC constraint. The best period-1 tax is therefore the highest tax that satisfies that constraint.

Proposition 2 below summarizes the characterization of the optimal period-1 tax involved in the short-term tax policy.

Proposition 2. *The optimal period-1 tax that forms part of a short-term environmental policy is as follows:*

(i) *In the parameter region defined by $0 \le c < \frac{3}{4}$ or $\frac{3}{4} \le c \le 1$ and $d > d_c(c)$,*

$$t_S(\mu, c, d) = \begin{cases} \dfrac{\mu(d-1) - (1-\mu)(1-c) - (1-\mu)(h(c,d) - c)}{\mu d + 1} < 1 - h(c,d), & \text{if} \quad \min\{1, d_c(c)\} < d \le d_h(\mu, c) \\ 1 - h(c,d), & \text{if} \quad d \ge \max\{d_h(\mu, c), d_c(c)\} \end{cases}$$

where $d_h(\mu, c) = \max\left\{1, \frac{2\sqrt{[1-(1-\mu)c]^2 + \mu^2}}{\mu(2-c)} - 1\right\}$.

(ii) *In the parameter region defined by $\frac{3}{4} \le c \le 1$ and $d < d_c(c)$,*

$$t_S(\mu, c, d) = \begin{cases} \dfrac{\mu(d-1) - (1-\mu)(1-c)}{\mu d + 1}, & \text{if} \quad d < d_L(\mu, c) \text{ or } d_h(1, c) < d < d_{ds} \\ \dfrac{d-1}{d+1}, & \text{if} \quad d_L(\mu, c) < d < d_h(1, c) \\ 1 - h(c,d), & \text{if} \quad d_{ds} < d \end{cases}$$

where d_{ds} solves as an equality Eq. (16).

Figs. 5a, 5b and 5c below illustrate, in the (c, d)-parameter space, for various values of parameter μ, the period-1 tax that forms part of the short-term environmental policy, where the yellow area is the region in which both firm types are active and the orange area is the region where the only active firm is the dirty firm, but not the clean firm.

In general, if (a) $d > d_h(1, c)$, i.e., the regulator has an environmental concern above $d_h(1, c)$, (b) the Bayesian separating equilibrium requires distorted (reduced) period-1 production by the clean firm, and (c) parameter μ, the regulator's prior estimation of having a firm producing the good with dirty technology, increases, then the range of parameters values for which the clean firm is active is reduced. It is not surprising that, given μ, a clean firm is more forced to exit the market for larger values of parameter *d*: the regulator must set higher taxes (to reduce the activity of the more probably present dirty firm), and this leads the clean firm to stop producing.

For low values of μ, the regulator sets low taxes and only very inefficient clean firms are inactive. Strikingly, however, for high values of μ, even a highly efficient clean firm can be inactive. An efficient clean firm receives a large subsidy in period 2, and the only way to signal itself as clean in period 1 is to be inactive in period 1. The dirty firm's temptation to behave as a clean firm is much reduced, however, if a clean firm is inefficient, since the subsidy for period 2 would be small.

5. Long-term vs short-term environmental tax policy

Once the optimal long-term and short-term taxes in Propositions 1 and 2 have been characterized, we can evaluate the effects of these tax policies both in the level of total emissions and on expected welfare. Regarding the level of emissions, we obtain the following result.

Proposition 3. *As compared to the long-term environmental policy, the short-term environmental policy leads to:*

(i) *Lower expected emissions period by period, if the regulator's environmental concern is low as $1 < d \le d_h(\mu, c)$.*

(ii) *Higher expected emissions in period 1, but lower expected emissions in period 2, if the regulator's environmental concern is sufficiently high as $d > d_h(\mu, c)$.*

That the short-term environmental policy results in lower expected period-2 emissions than the long-term policy is due to the fact that it allows the regulator to restore complete information about technology type and, accordingly, to set the optimal tax. Whether the short-term policy causes an expected level of period-1 emissions that is also lower than for the long-term policy depends on the tax that each policy implies for said period. If the regulator's environmental concern is such that $1 < d \le d_h(\mu, c)$, the tax associated with the short-term policy is higher and emissions are lower than for a long-term policy, Otherwise, the period-1 tax in the short-term policy is lower than for the long-term policy and emissions are higher.

We investigate the regulator's decision when, seeking to maximize social welfare, it chooses between implementing a long-term or short-term environmental policy. To this end, we define, in the case of the long-term tax policy, $EW_L^1(\mu, c, d)$ as the sum of the expected welfare over the two periods when the regulator sets a tax equal to $t_L(\mu, c, d) = t_\alpha(\mu, c, d)$ in each period, so that the firm produces a positive quantity, regardless of whether its technology is dirty or clean; namely

$$EW_L^1(\mu, c, d) = 2 \cdot EW_L(t_\alpha; \mu, c, d) \tag{17}$$

where $EW_L(t_\alpha; \mu, c, d)$ is the per-period expected welfare defined in Eq. (8). We also define $EW_L^0(\mu, c, d)$ as the sum of the expected welfare over the two periods when the regulator sets $t_L(\mu, c, d) = t_D$ in each period, so that only the dirty firm produces a positive quantity; namely

$$EW_L^0(\mu, c, d) = 2 \cdot EW_L(t_D; \mu, d) \tag{18}$$

where $EW_L(t_D; \mu, d)$, is the per-period expected welfare defined in Eq. (7). In Proposition 3 below, we evaluate the expected welfare under a long-term policy using either $EW_L^0(\mu, c, d)$ or $EW_L^1(\mu, c, d)$ according to the characterization obtained in Proposition 1.

Similarly, we define, for the short-term tax policy, $EW_S^1(\mu, c, d)$ as the sum of the expected welfare over the two periods when the regulator sets a tax such that the clean firm produces a positive quantity in the first period; and $EW_S^0(\mu, c, d)$ as the sum of the expected welfare over the two periods when only the dirty firm produces a positive quantity in period 1. With short-term taxes, the regulator has complete information at the beginning of the second period, and expected welfare in this period amounts to

$$\mu\frac{1}{2(d+1)}+(1-\mu)\frac{(1-c)^2}{2} \tag{19}$$

since the regulator can set the optimal tax when the firm's technology is dirty (what happens with probability μ) and clean (with probability $1-\mu$). First period expected welfare is either $EW_S^1(\mu,c,d)$ or $EW_S^0(\mu,c,d)$ according to the characterization of short-term taxes obtained in Proposition 2.[18]

Proposition 4. *There exist:*

(a) *Three cut-off values for the production cost resulting from the clean technology,* $c_1=\sqrt{2}+2-\frac{2}{7}\sqrt{14(9\sqrt{2}+13)}\approx 0.7$, $c_2(\mu)$ *being the solution to the equation* $EW_L^1(\mu,c,d_h(\mu,c))=EW_S^1(\mu,c,d_h(\mu,c))$, *and* $c_3(\mu)$ *being the solution to the equation* $EW_L^0(\mu,c,d_L(\mu,c))=EW_S^0(\mu,c,d_L(\mu,c))$, *with* $c_1<c_2(\mu)<c_3(\mu)$,
and.

(b) *Three cut-off values for the regulator's environmental concern,* $d_a(\mu,c)$ *being the solution to the equation* $EW_L^1(\mu,c,d_a(\mu,c))=EW_S^1(\mu,c,d_a(\mu,c))$, $d_b(\mu,c)$ *being the solution to the equation* $EW_L^1(\mu,c,d_b(\mu,c))=EW_S^0(\mu,c,d_b(\mu,c))$, *and* $d_c(\mu,c)$ *being the solution to the equation* $EW_L^0(\mu,c,d_c(\mu,c))=EW_S^0(\mu,c,d_c(\mu,c))$, *with* $d_a(\mu,c)<d_b(\mu,c)<d_c(\mu,c)$,
such that the regulator chooses.

(i) *A long-term environmental policy in the* (c,d)*-space of parameters in which* $c\in[0,c_1]$, *for every* $d>1$, *or* $c\in(c_1,c_2(\mu)]$ *and* $d>d_a(\mu,c)$, *or* $c\in(c_2(\mu),c_3(\mu)]$ *and* $d>d_b(\mu,c)$, *or* $c\in(c_3(\mu),1]$ *and* $d>d_c(\mu,c)$.

(ii) *A short-term environmental policy in the* (c,d)*-region as otherwise defined.*

Proof. See the Appendix.

The content of Proposition 4 is graphically illustrated in Fig. 6a, b and 6c, for certain values of parameter μ, the regulators's belief of dealing with a firm that uses dirty technology. The (c,d)-regions coloured orange and coloured yellow denote the regions in which the regulator prefers to use a long-term environmental policy and a short-term policy, respectively.

Proposition 4 suggests that a long-term environmental policy is generally preferable to a short-term policy, either when the clean technology is not very expensive, or when the clean technology is expensive and the regulator's environmental awareness is high. In both cases, the regulator renounces to force the firm to disclose its technology and prefers a long-term environmental policy with the same terms applying to all periods. In contrast, when producing with clean technology becomes very expensive and the regulator's environmental awareness is low, the regulator finds it optimal to set a short-term policy in which the period-2 terms differ from the period-1 terms. While the policy valid for period 1 is the same for any firm, the policy for period 2 is contingent on the firm's production in period 1. The superiority of a short-term policy in this case would follow from the fact that the welfare gaining in period 2 due to restoring complete information outweighs the welfare loss in period 1 due to productive distortions caused if the firm uses the clean technology. Furthermore, from Figs. 6a, 6b and 6c, it follows that as the firm's technology is more likely to be dirty, the regulator will more often use a long-term policy over a short-term

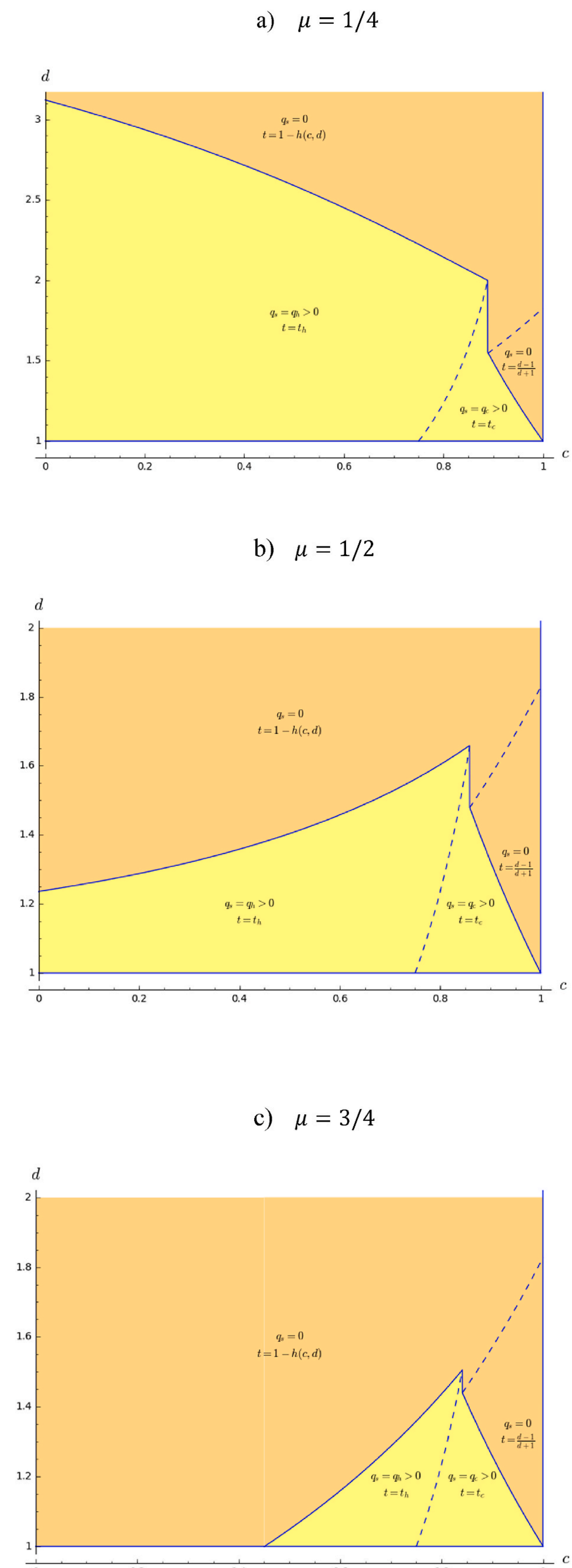

Fig. 5. The period-1 tax that forms part of the optimal short-term environmental policy in the (c,d)-space.

[18] In the Appendix, we offer the expression of expected welfare $EW_S^1(\mu,c,d)$ and $EW_S^0(\mu,c,d)$ in each case.

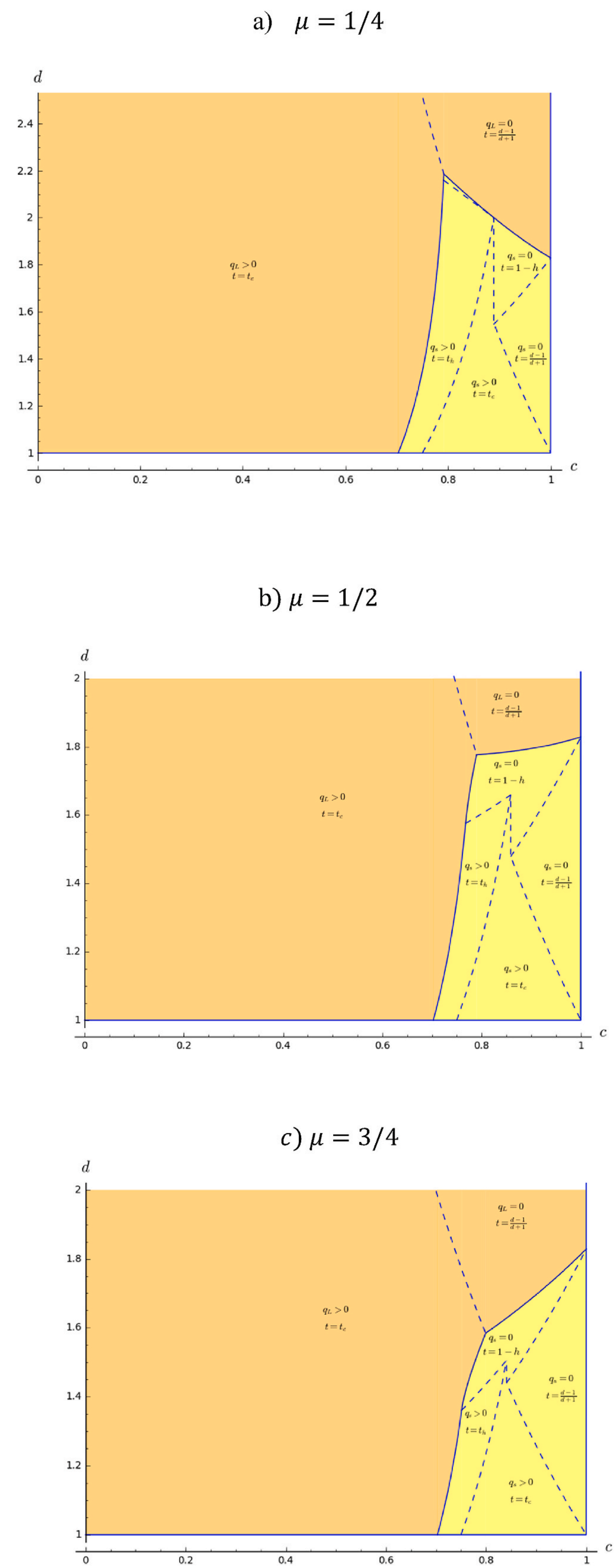

Fig. 6. The choice of the regulator in the (c, d)-space of parameters.

policy.

6. Conclusions

In this paper, we have analysed the interaction between a firm that pollutes and a regulator concerned about environmental damage, but unaware of whether the technology in use is more or less polluting. The firm knows which technology it uses, whereas the regulator only has a prior belief. In this context, the regulator can design a tax/subsidy policy over two periods that can be long-term or short-term, i.e., the regulator commits to not vary the policy terms in the two periods, or the regulator does not commit to any period 2 policy, respectively. The results we obtained highlight the importance of time horizon in policy setting, as well as the limitations for tax policies under asymmetric information to control pollution.

Indeed, in designing an environmental policy, not only is the tool used important, but also the period of time it will be in force. Whether the period is longer or shorter may influence the behaviour of polluting firms and, consequently, the very terms of the policy. Following this, our model suggests that a long-term policy is generally preferred to a short-term one; namely, when clean technology is not very expensive to produce with or, being expensive, when the regulator is highly environmentally concerned. On the contrary, a short-term policy in which the regulator forces the firm to disclose whether its technology is dirty or clean is only optimal when the regulator has little environmental concern and the clean technology is very expensive.

The results obtained have very relevant implications for the implementation of environmental policies. Thus, it is observed that when the regulator's environmental concern is low, firms of any kind – using dirty or clean technologies – will produce, whatever the duration of the policy implemented. However, if the regulator is environmentally very concerned, a counterintuitive result emerges: higher taxes associated with higher environmental awareness will distort firm's market behaviour, to the extent of driving clean firms out of the market. In more detail, if clean technology is expensive, the optimal environmental policy is a long-term policy that sets a tax so high that is prohibitive for clean firms. Only if clean technology is competitive enough in terms of production costs, the tax imposed will not be prohibitive and firms of any kind would produce.

This has two alternative interpretations for policy setting. On one hand, it states that the best environmental tax policy available is long-term and patient: despite our article does not explore the impact of technological innovation, it shows that the regulator will find it socially desirable to establish a less distorting environmental tax policy only when clean technologies are efficient (cheap) enough. On the other hand, it also shows the limits of environmental tax policies to be used by environmentally conscious regulators: under asymmetric information, a one-size-fits-all policy will prove counterproductive, discouraging green innovation.

Two extensions of the research reported in this paper would be worth exploring. First, our model is based on a single firm, so it would be useful to extend the framework to a setup with several polluting firms in the industry. In this case, the terms of any long- or short-term environmental policy could notably differ from those obtained in the model, due to market interactions between firms and interactions between each firm and the regulator. In addition, when several firms exist in the industry, the optimal environmental policy may depend on market competition holding through quantities or prices or on market competition being simultaneous or sequential. Second, our conclusion that short-term environmental policy is infrequently observed (unlike long-term environmental policy) is due to the fact that the regulator, in choosing the short-term policy, does not commit to the terms of that policy for period 2. This leads the period-1 revealing equilibrium to be very costly. However, if the regulator could commit to the terms of period-2 policy, it would be easier to elicit hidden information and the short-term policy would become superior to the long-term policy in a greater region of parameters. The analysis of these extensions is left for future research.

CRediT authorship contribution statement

Manel Antelo: The three authors have equally contributed to the, Conceptualization, Formal analysis, discussion and writing of the article, They have approved this revised version. **Lluís Bru:** The three authors have equally contributed to the, Conceptualization, Formal analysis, discussion and writing of the article. They have approved this revised version. **David Peón:** The three authors have equally contributed to the, Conceptualization, Formal analysis, discussion and writing of the article. They have approved this revised version.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix

Proof of Proposition 1. There is a value of parameter d for which the values of expected welfare in Eqs. (7) and (8) are equal, i.e.,

$$EW_L(t_\alpha;\mu,c,d)=\frac{4(1-c)^2-c[(4-3c)d-(8-5c)]\mu+c[(4-3c)d+c]\mu^2}{4(\mu d+1)} =\frac{\mu}{2(d+1)}=EW_L(t_D;\mu,d) \tag{A1}$$

The solution of Eq. (A1) is the value $d_L(\mu,c)$ stated in the proposition. For values of d in $1<d<d_L(\mu,c)$ we have $EW_L(t_\alpha;\mu,c,d)>EW_L(t_D;\mu,d)$; for $d>d_L(\mu,c)$, the other way around. This leads to the optimal values of the tax stated in Parts (i) and (ii) of the proposition.■

Proof of Lemma 2. To solve the maximization problem stated in Eq. (13), first note that EW_1 is strictly concave in t. Then, the first-order condition

$$\frac{\partial EW_1}{\partial t}=-\frac{\mu}{2}\left(1-\frac{(d+1)(1-t)}{2}\right)-\frac{1-\mu}{2}(1-c-q_s)=0 \tag{A2}$$

is verified for $t^*=\frac{\mu(d-1)-(1-\mu)(1-c)-(1-\mu)(h(c,d)-c)}{\mu d+1}$. If parameter d takes values in the interval $(\min\{1,d_c(c)\},d_h(\mu,c))$ as stated in the lemma, then $t^*<1-h(c,d)$ and therefore this is the solution of the maximization problem. For the remaining values of d, we have that t^* does not satisfy the restriction in the maximization problem, $t^*>1-h(c,d)$. Since for $t=1-h(c,d)$ it follows that $\frac{\partial EW_1}{\partial t}>0$, we have a corner solution, $t^*=1-h(c,d)$. ■

Proof of Proposition 4. To prove the result indicated we need to compare the values of expected welfare under the optimal short-term and long-term tax policy. The different values of expected welfare under long-term taxes are those defined in Eqs. (17) and (18), respectively.

On the other hand, with short-term taxes, the regulator has complete information at the beginning of period 2 and expected welfare in this period is

$$\mu\frac{1}{2(d+1)}+(1-\mu)\frac{(1-c)^2}{2} \tag{A3}$$

since the regulator can set in that period the optimal tax when the firm's technology is dirty (what happens with probability μ) and clean (what happens with probability $1-\mu$).

In addition, $EW_S^1(\mu,c,d)$ is the sum of expected welfare over the two periods when the regulator sets a tax in the first period such that the clean firm produces a positive quantity. If the regulator can set in the first period the tax $t=t_\alpha(\mu,c,d)$, then

$$EW_S^1(\mu,c,d)=\frac{4(1-c)^2-c[(4-3c)d-(8-5c)]\mu+c[(4-3c)d+c]\mu^2}{2(\mu d+1)}+\left[\mu\frac{1}{2(d+1)}+(1-\mu)\frac{(1-c)^2}{2}\right], \tag{A4}$$

where the first term in (A4) is the expected welfare in the first period (from Eq. (8)), while the second term (in brackets) is expected welfare in the second period as stated in (A3).

Contrariwise, if the regulator cannot set $t=t_\alpha(\mu,c,d)$ in the first period, then

$$EW_S^1(\mu,c,d)=\left[\mu\left(1-\frac{(d+1)(1-t)}{4}\right)\frac{1-t}{2}+(1-\mu)\left(1-c-\frac{q_s}{2}\right)q_s\right]+\left[\mu\frac{1}{2(d+1)}+(1-\mu)\frac{(1-c)^2}{2}\right] \tag{A5}$$

with the tax in the first period as stated in Proposition 2 leading to the first period welfare stated in the first bracket of (A5).

Finally, $EW_S^0(\mu,c,d)$ is the sum of the expected welfare over the two periods under short-term taxes when only the dirty firm produces a positive quantity in period 1. Expected welfare is equal to

$$EW_S^0(\mu,c,d)=\mu\left(1-\frac{(d+1)(1-t)}{4}\right)\frac{1-t}{2}+\left[\mu\frac{1}{2(d+1)}+(1-\mu)\frac{(1-c)^2}{2}\right] \tag{A6}$$

where the first term in (A6) is the expected first-period welfare when only a dirty firm produces, and the first-period tax is the one stated in Proposition 2.

Then, the evaluation of the overall optimality of long-term taxes versus short-term taxes amounts to the comparison of EW_L^i and EW_S^i with $i = 1, 2$ for different values of parameters μ, c and d, which lead to the cut-off values c_1, $c_2(\mu)$, $c_3(\mu)$, $d_a(\mu, c)$, $d_b(\mu, c)$ and $d_c(\mu, c)$ stated in Proposition 4. ■

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