# Abolishing Environmental Regulation: Strategic Effects and Welfare Implications*

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**Abstract**

This paper considers an environmental policy which may be rolled back in future periods by a new administration. We examine how this policy uncertainty reduces firms' incentives to invest in green R&D before the policy is scheduled to come into effect, increasing as a result polluting emissions. We then evaluate the welfare loss generated by policy uncertainty, and compare it against the welfare loss due to abolishing environmental regulation. We identify industries where policy uncertainty can yield larger welfare losses than those from an unregulated externality. We also find under which settings firm profits are larger when environmental policy is likely to remain into effect than rolled back.

KEYWORDS: Environmental policy, Rolled back regulation, Green R&D investment, Welfare losses, Policy uncertainty.

JEL CLASSIFICATION: L13, L51, Q55, Q58.

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# 1 Introduction

Environmental regulation is nowadays facing the threat of potential rollbacks. For instance, in March 2018, the Environmental Protection Agency (EPA) announced it will start a process to repeal the Clean Power Plan policy, easing car fuel efficiency rules put in place under Obama's administration. Other examples include: (1) President Trump rolling back offshore-drilling safety regulations that were put in place in 2016, after the Deepwater Horizon oil rig disaster in 2010; (2) revoking a rule that prohibited mining companies from dumping toxic waste into waterways near their mines; or (3) overturning a ban on lead in ammunition and fishing tackle on public lands and waters.[1] Overall, the Harvard Law School identified more than 45 rollbacks during the Trump administration specifically dealing with environmental policy.[2] Recent examples also exist in Australia, where the new Prime Minister, Scott Morrison, stated he does not plan to implement the National Energy Guarantee of the previous administration, see The Guardian (2018, September 7th); and the increasing opposition that Canadian Prime Minister, Justin Trudeau, faces to rollback his carbon pricing policy, Bloomberg (2018, July 20th). While abolishing environmental regulation can yield an increase in damaging emissions, our paper shows that, in certain industries, the policy uncertainty that firms face in their R&D decisions produces a larger welfare loss than that originating from policy abolishment alone. In other words, the investment inefficiencies that policy uncertainty create can be larger than the welfare loss from socially excessive pollution.

Our model considers a polluting industry with $N$ firms where, in the first stage, the regulator sets an emission fee; in the second stage, every firm responds choosing its R&D investment; and, in the third stage, every firm selects its output level, given the emission fee and profile of R&D investments in previous stages. In our benchmark setting, we assume that in the third stage the emission fee remains into effect with a given probability but is abolished otherwise; where the latter represents the possibility that the incumbent loses control of Congress, or that a new administration takes office. We also evaluate how our results are affected when policy uncertainty arises after the emission fee has been implemented.

We first find equilibrium behavior and evaluate social welfare. While welfare under policy uncertainty is higher than in the absence of policy, we show that a potential regulatory rollback yields a welfare loss. To identify the origin of this welfare loss, we consider two counterfactual scenarios. In Scenario 1, the regulator incorrectly assumes that the policy will remain into effect with certainty, while firms still consider that regulation may be rolled back. In this scenario, we show that all players' behavior coincides with that in the benchmark setting. Consequently, the welfare loss discussed above —i.e., welfare being decreasing in the probability of a regulatory rollback— must be due to the firms' behavior change in the second stage (when they invest in clean R&D) and in the third stage (when they choose their output and emissions). We measure

[1] For each example, see The New York Times (2018, September 27th), Reuters (2017, February 2nd), and Reuters (2018, March 2nd), respectively.

[2] For more details about environmental regulatory rollbacks of the Trump Administration see: http://environment.law.harvard.edu/policy-initiative/regulatory-rollback-tracker/.

this welfare loss in Scenario 2, where now firms incorrectly assume that the policy will remain into effect with certainty, while the regulator does not. By comparing firms' behavior against that in the benchmark, we can isolate the effect of policy uncertainty on firms' R&D decisions.

We then compare the welfare loss from policy uncertainty against that from abolishing environmental regulation, identifying in which cases the former is larger than the latter. This occurs in industries where: (1) policy is unlikely to remain into effect; (2) several firms compete; (3) every unit of pollution causes severe damages; and (4) R&D investment costs are relatively low. In these contexts, the probability of a rolled back regulation triggers large reductions in R&D investments, entailing significant pollution increases. Our results then suggest that, in industries where (1)-(4) concur, regulators should be careful at suggesting that environmental policies can be revisited in the future. For instance, they could require supermajorities for the policy to be adjusted or abolished. In contrast, when (1)-(4) do not hold, our findings suggest that the welfare loss from policy uncertainty is not substantial. In these settings, regulators could openly discuss the possibility of rolling back the policy in future periods without the fear to induce significant changes in firms' strategic R&D decisions.

Furthermore, we demonstrate that, when the policy is implemented with certainty during at least one period, the above welfare losses from regulatory uncertainty are ameliorated. Intuitively, firms have stronger incentives to invest in R&D if they can capture the benefits from their investment during some periods before facing an uncertain policy, reducing the impact that the potential regulatory rollback has on firms' investment decisions today.

While policy stability can be justified in terms of its welfare effects, as discussed above, our paper also shows that firms may support this stability. Our results indicate that, rather than lobbying for an abolishment of environmental regulation, firms in highly contested markets may lobby for policies that are implemented with certainty, or at least with a higher probability.

In summary, our results offer different policy implications. First, we find that environmental policy rollbacks can entail large investment inefficiencies in green R&D, as firms anticipate that regulation may never be implemented, leading to large welfare losses originating from policy uncertainty alone; losses that may actually exceed those stemming from the socially excessive pollution that firms emit if the policy is abolished. This ranking in welfare losses is, essentially, ignored in the current debate on whether to roll back existing regulations, where supporters of abolishing the policy argue firms and consumers will benefit while opponents claim that environmental quality will suffer. Our findings, instead, suggest that the possibility of abolishing the policy (e.g., supermajorities are not required) creates an uncertain regulatory environment where firms' investment decisions are distorted, generating welfare losses that persist even if regulation remains into effect. This policy uncertainty could, nonetheless, be avoided if regulation is difficult to be abolished in future periods, or at least ameliorated if it is implemented during several years before the period when policy may be rolled back.

Finally, our results could be extended to other regulated industries facing potential rollbacks, such as the abolishment of trade agreements between two countries or the elimination of subsidies for green production, since they affect firms' incentives to invest in R&D or expand their plants.

**Related literature.** A large body of empirical literature analyzes the negative effect of uncertainty in future policies on firm-level capital investment; see, for instance, Aizenman and Marion (1993), Stein and Stone (2014), Bontempi (2015), and Lim and Yurukoglu (2018). Some papers specifically study policy uncertainty in the energy industry, such as Meyer and Koefoed (2003), which considers wind promotion policy in Denmark; Agnolucci (2006), which examines the Renewable Energy Act in Germany; Wiser et al. (2007), which studies tax incentives in the US wind energy sector; Barradale (2010), which investigates the federal production tax credit in the US wind industry; and Fabrizio (2012), which examines state-level Renewable Portfolio Standard policies in the US electric utility industry. Overall, these papers empirically find that policy uncertainty — often measured as an index, following Baker et al. (2013)[3]— negatively affects investment decisions in renewable energy projects. In contrast, we examine investment in abatement technology, focusing on the potential abolishment of an existing environmental regulation. Importantly, we isolate the welfare loss originating from policy uncertainty alone and compare it against the loss stemming from policy abolishment, identifying under which industry conditions the former exceeds the latter.

The theoretical literature analyzing how capital investment is affected by policy uncertainty is, however, relatively small, and mostly focuses on utility regulation, such as pricing or rate-of-return policies; see Rodrik (1991) and Dixit and Pindyck (1994). Similarly, another line in this field examines how utility incentives to invest in new plants are reduced by the uncertainty in future capital disallowances; which has been recurrently observed even in regions needing additional electricity capacity, see Leonard et al. (1987), Joskow (1989), Kolbe and Tye (1991), and Lyon and Mayo (2005). In a different context, Chichilnisky (1994) and Costello and Kaffine (2008) examine the effect of insecure property rights (uncertainty on the renewal of a concession) on the overuse of a natural resource.

Finally, Lyon (1991), Gal-Or and Spiro (1992), Gilbert and Newbery (1994) and Lyon and Li (2004) theoretically examine how utility companies may reduce their investments when facing uncertainty about future price regulation, which responds to changes in the realization of the investment cost or demand. However, our setting does not consider changes in demand or costs, instead, we focus on the possibility of an administration change that could renege from previous policies.[4]

The next section presents our model, while section 3 describes equilibrium behavior by firms and regulator. Section 4 then evaluates social welfare in counterfactual scenarios 1 and 2 to isolate the

[3]Baker et al. (2013) propose a policy uncertainty index as a weighted average of: (1) a count of newspaper articles containing key terms related to policy uncertainty (this is the element receiving the highest weight on the index); (2) the dollar impact of tax provisions set to expire in the near future (as a measure of uncertainty about future changes in the tax code); and (3) dispersion in economic forecasts of the CPI and government spending (as a proxy for uncertainty about fiscal and monetary policy).

[4]Svensson et al. (2009) analyze an optimization model considering different types of uncertainty, such as future energy prices or policy instruments, and examine investments decisions in energy efficiency. However, it does not consider the potential abolishment of a policy or evaluate the welfare loss from policy uncertainty.

effect of policy uncertainty on firms' strategic decisions during the second stage. Section 5 extends our model to a setting where the policy remains into effect with certainty during one period, and then faces rollback uncertainty, comparing our result against those in our benchmark. Section 6 concludes and discusses the policy implications of our findings.

# 2 Model

Consider an industry with $N$ firms competing a la Cournot, facing inverse demand function $p(Q) = 1 - Q$, where $Q$ denotes aggregate output; and marginal production cost $0 < c < 1$. Every unit of output from firm $i$, $q_i$, generates emissions $e_i = q_i - z_i$, where $z_i$ denotes the amount of abatement R&D that firm $i$ undertakes. The time structure of the game is the following:

1. In the first stage, the regulator sets an emission fee $t$.

2. In the second stage, every firm $i$ observes the emission fee $t$ and responds simultaneously and independently choosing its investment in R&D, $z_i$.

3. In the third stage, with probability $p \in [0, 1]$ the environmental policy remains into effect, but is abolished with probability $1-p$. Observing the realization of this uncertainty (i.e., whether the policy remains or not), and observing the profile of R&D investments $z \equiv (z_1, ..., z_N)$ from the previous stage, every firm $i$ simultaneously and independently chooses its output level.

Alternatively, the probability that the policy remains into effect, $p$, could decrease in firms' aggregate investment in R&D technologies, $Z \equiv \sum_{i=1}^{N} z_i$. However, policy discussions about rolling back environmental policies generally use other arguments, such as firms' cost of complying with the policy, or the effect on product prices, disregarding previous investment decisions in abatement. Therefore, this probability is independent on aggregate investment carried out in previous periods, $Z$, and can be understood as the likelihood that the incumbent administration is still in office in the third period.

In the next section, we use backward induction to find the subgame perfect equilibrium of the game.

# 3 Equilibrium analysis

**Third stage.** In this period, firms observe whether the environmental policy is still active or not. If emission fee $t > 0$ is still in place (which occurs with probability $p$), every firm $i$ solves

$$\max_{q_i \geq 0} \ (1 - Q)q_i - cq_i - t(q_i - z_i) \tag{1}$$

which yields an individual output of $q_i(t) = \frac{1-(c+t)}{N+1}$, and profits of $\pi_i(t) = \left(\frac{1-(c+t)}{N+1}\right)^2 + tz_i$. If, instead, emission fee $t$ is abolished (which happens with probability $1 - p$), every firm solves problem (1) evaluated at $t = 0$, which yields a higher output of $q(0) = \frac{1-c}{N+1}$, and a larger profit of $\pi_i(0) = \left(\frac{1-c}{N+1}\right)^2$.[5]

Therefore, profits under regulation, $\pi_i(t)$, can be alternatively expressed as $\pi_i(t) = \pi_i(0) + t\left[\frac{t-2(1-c)}{(N+1)^2} + z_i\right]$, where the first term represents profits on the product market while the second term captures tax-saving benefits from investing in abatement. In particular, when $t = 0$, the second term becomes negative, indicating that abatement enters as a cost, but when $t > 0$, the firm's investment can induce lower emission fees (as described below), ultimately reducing its tax bill.

**Second stage.** Every firm $i$ anticipates the equilibrium profits it obtains in the subsequent stage when the emission fee remains into effect, $\pi_i(t)$, and when it does not, $\pi_i(0)$, choosing its R&D investment, $z_i$, to solve

$$\max_{z_i \geq 0} \; p\pi_i(t) + (1-p)\pi_i(0) - \frac{1}{2}\gamma\left(z_i\right)^2 \tag{2}$$

where $\gamma > 0$ represents the cost of additional R&D investment, which is increasing and convex in $z_i$. Intuitively, the first two terms in problem (2) capture future expected profits, while the last term denotes firm $i$'s current cost from investing.[6]

Differentiating with respect to $z_i$ yields $z_i(t) = \frac{pt}{\gamma}$, which is increasing in the probability that the policy remains into effect $p$, in the emission fee $t$, but decreasing in the R&D cost $\gamma$. When firms are certain that the emission fee will be abolished in the third stage ($p = 0$), they invest zero units in green R&D, $z_i(t) = 0$; and a similar argument applies when they face a zero emission fee. Intuitively, investing in green R&D is costly, and firms only incur this cost if they can save future taxes.

**First stage.** The regulator chooses an emission fee $t$ that solves

$$\max_{t \geq 0} \; SW \equiv pSW(t) + (1-p)SW(0) \tag{3}$$

where $SW(t) \equiv CS(t) + PS(t) - Env(t)$ denotes the social welfare when emission $t$ remains into effect, while $SW(0)$ represents that when the fee is abolished. Term $CS(t) + PS(t) = (1-c)Q(t) - \frac{1}{2}Q(t)^2 - \frac{1}{2}\gamma\left(Z\right)^2$ reflects the sum of consumer and producer surplus (including the R&D cost), and $Env(t) \equiv d(Q-Z)^2$ is the environmental damage from pollution, where $Z$ denotes aggregate abatement efforts and $d > 1$.

[5] For presentation purposes, we consider that firm $i$'s investment in abatement, $z_i$, only affects its tax bill (third term in expression 1). Appendix 1 extends our analysis to allow for this investment to also produce a cost-reduction effect in the second term of expression (1), reducing the marginal cost of production from $c$ to $c - \alpha z_i$, where $\alpha \in [0, 1]$ represents to which extent investment in abatement helps firm $i$ reduce its future costs. Appendix 1 shows that our results are qualitatively unaffected.

[6] We consider end-of-pipe investment since marginal production costs are unaffected; see Hart (1995).

**Proposition 1.** *The optimal emission fee is*

$$t^* = \frac{(1-c)\gamma\left[dN\left[p(N+1)+\gamma\right]-\gamma\right]}{dN\left[p(N+1)+\gamma\right]^2+\gamma\left[(N+1)^2p^2+N\gamma\right]}$$

*which is positive if and only if* $d > \overline{d} \equiv \frac{\gamma}{N[p(N+1)+\gamma]}$. *In addition, cutoff* $\overline{d}$ *is decreasing in* $N$ *and* $p$, *but increasing in* $\gamma$.

Hence, as more firms compete in the industry (higher $N$), the regulator sets a more stringent policy.[7] A similar argument applies when regulation is more likely to remain into effect in future periods (higher $p$). In contrast, when the R&D cost $\gamma$ increases, environmental policy becomes less stringent. For simplicity, our subsequent analysis considers that $d > \overline{d}$ so emission fees are positive.

The following corollary explores some comparative statics of equilibrium emissions, defined as $q_i(t^*) - z_i(t^*)$, and equilibrium social welfare.

**Corollary 1.** *Equilibrium emissions are decreasing in* $p$, *while social welfare is increasing in* $p$, *for all parameters.*

In words, as the policy is more likely to remain into effect (higher $p$), emission fees become more stringent (in expectation) leading firms to reduce their emissions in equilibrium, $q_i(t^*)-z_i(t^*)$; which separates their production decisions away from the profit-maximizing outcome in the absence of regulation. In addition, social welfare increases when the regulation is more likely to stay in place. This result is mainly due to the internalization of the externality (pollution) when the emission fee remains into effect.

## 4 Welfare losses from regulatory uncertainty

In this section, we seek to measure the welfare effects from the potential abolishment of the environmental policy. To isolate these effects, we consider two counterfactual scenarios where: (1) the regulator incorrectly assumes that the policy will remain into effect with certainty, $p = 1$, while firms still consider a probability $1 - p$ that the regulation will be rolled back; and (2) fixing emission fee $t^*$, firms now incorrectly assume that $p = 1$. Scenario (1) helps us isolate to which extent the emission fee design is affected by the regulator's uncertainty about the potential abolishment alone, while scenario (2) helps us measure how firms, after observing the same emission fee as in Proposition 1, strategically alter their R&D and emission decisions when facing an uncertain regulation.[8]

[7] This condition can be rationalized by the usual argument of a regulator facing two market imperfections, market power vs. environmental externalities. An increase in the number of firms yields a larger output (ameliorating the first market failure) but produces more pollution (emphasizing the second market failure). When the former (latter) dominates, $d \leq \overline{d}$ ($d > \overline{d}$), the regulator responds to an increase in the number of firms by setting a less (more, respectively) stringent fee.

[8] We do not consider that the regulator solves problem (3) again by inserting the R&D investment that he anticipates firms choose when assuming $p = 1$. Doing that would generate a different fee, yielding a distinct R&D

### 4.1 Counterfactual scenario 1

In this setting, firm's equilibrium decisions are unaffected since they still consider probability $p \in (0,1)$. Specifically, the equilibrium output in the third stage of the game is not changed, $q_i(t) = \frac{1-(c+t)}{N+1}$, nor is the R&D investment decisions in the second stage, $z_i(t) = \frac{pt}{\gamma}$. Anticipating these equilibrium expressions, the regulator chooses an emission fee $t$ that solves problem (3), but evaluated at $p = 1$, that is

$$\max_{t \geq 0} \; SW(t) \tag{3'}$$

Differentiating with respect to $t$ and solving, yields the following optimal fee.

**Corollary 2.** *When the regulator considers $p = 1$, while firms assume $p \in (0,1)$, the optimal emission fee is still $t = t^*$; where $t^*$ was described in Proposition 1.*

That is, the optimal emission fee is unaffected by the probability that the regulator considers, implying that the solution to (3) and (3') coincides. To understand this point, note that the term measuring social welfare $SW(t)$ in problems (3) and (3') is affected by probability $p$ since this probability affects firms' behavior in subsequent stages. However, probability $p$ does not enter at any other point of the regulator's objective function in (3), other than as a relative weight attached to $SW(t)$ and $SW(0)$. That is, $p$ acts as a vertical "shifter" of the regulator's objective function in (3), implying that it only alters the social welfare that can be achieved, but does not modify the optimal emission fee. When examining industries where firms anticipate that environmental policy may be abolished, our results entail that firms' behavior will be affected –reducing their R&D investments and increasing net emissions– but emission fees are unaffected by the probability that the environmental agency assigns to the policy being rolled back in the future.

This brings us to a natural conclusion: If all players' behavior in Scenario 1 coincides with that in the benchmark setting examined in previous sections, the welfare loss identified in Corollary 1 (where welfare was found to be lower when $p < 1$ than when $p = 1$) must be due to the firms' behavior change in subsequent stages of the game. In the next subsection, we isolate this behavior change when firms face an uncertain policy.

### 4.2 Counterfactual scenario 2

In this context, our analysis in the third stage of the game is unaffected. In particular, output $q_i(t) = \frac{1-(c+t)}{N+1}$ is not a function of probability $p$, and a similar argument applies to profit $\pi_i(t)$. In the second stage, however, every firm $i$'s problem (2) collapses to

$$\max_{z_i \geq 0} \; \pi_i(t) - \frac{1}{2}\gamma\left(z_i\right)^2 \tag{2'}$$

investment and output in equilibrium. In that setting, not only the firm's behavior, but the regulator's, would be different, thus not allowing us to compare our results against those identified in the previous section.

which yields R&D investment of $z_i^C(t) = \frac{t}{\gamma}$, where superscript $C$ denotes this counterfactual setting. In the first stage of the game, the regulator chooses emission fee $t^*$ (from Proposition 1). Intuitively, we fix equilibrium behavior in the first stage of the game, but allow firms to incorrectly consider $p = 1$, helping us isolate how firms' behavior changes due to policy uncertainty.

We can next evaluate the welfare arising in the counterfactual scenario, $SW^C$, and compare it against that in the above section, $SW$, to measure the welfare loss from policy uncertainty, $WL^{PU} \equiv SW^C - SW$. Indeed, $SW^C > SW$ holds under all parameter conditions. To see this point, note that both welfare expressions are evaluated at emission fee $t^*$. However, in $SW^C$ firms have stronger incentives to invest in R&D since they (incorrectly) anticipate that regulation will remain into effect in the future, while in the benchmark case $SW$ they understand that the policy could be rolled back in subsequent periods, leading them to invest less in R&D. Emissions are then larger in the benchmark setting than in the counterfactual scenario, entailing that policy uncertainty produces a welfare loss measured by $WL^{PU} \equiv SW^C - SW > 0$.[9]

Figure 1 illustrates our results, evaluating $WL^{PU}$ at parameter values $c = 1/4$, $N = 2$, $\gamma = 1/4$, and $d = 2$.[10] The figure indicates that policy uncertainty generates the largest welfare loss when probability $p$ is intermediate, but entails minor welfare losses when the policy is very likely kept (or very likely rolled back).

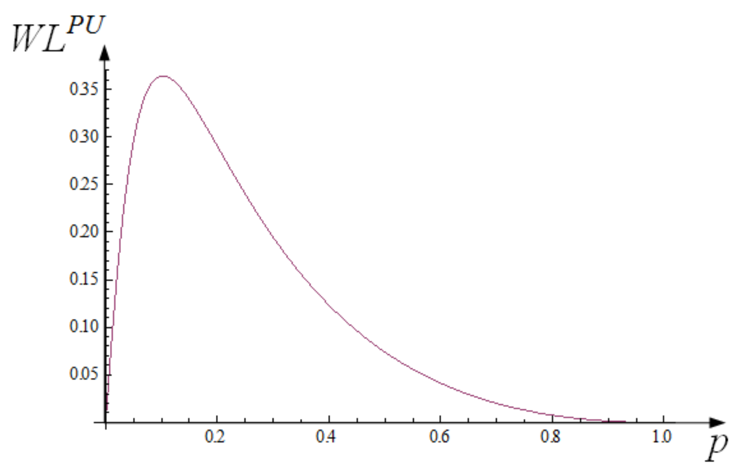


Fig. 1. Welfare loss $WL^{PU}$

The expression of $WL^{PU}$ is highly non-linear, making comparative statics rather intractable.

[9]If the regulator could re-optimize problem (3) considering the new R&D investment, $z_i^C(t) = \frac{t}{\gamma}$, the optimal emission fee would be $t^C = \frac{(1-c)\gamma[dN(1+N+\gamma)-\gamma]}{\gamma+N\left[d(1+N+\gamma)^2+\gamma(2+N+\gamma)\right]}$, which satisfies $t^C < t^*$ under all parameter conditions. Intuitively, since the regulator anticipates more intensive R&D investment in the counterfactual scenario (where firms consider that the policy will remain into effect) than in the benchmark scenario (where firms consider that the policy may be rolled back), he responds setting a less stringent fee in the former than the latter case. As discussed above, this would lead to a simultaneous change in the equilibrium behavior of different agents, not letting us isolate the strategic effects that policy uncertainty produces on firms' decisions.

[10]Other parameter values yield similar results and can be provided by the authors upon request.

Figures 2a and 2b provide an approximation of these effects, by altering one of the above parameter values at a time. Figure 2a suggests that, as environmental damages become more severe (higher $d$), the welfare loss from policy uncertainty is emphasized, since every unit that society moves away from the first-best outcome generates a larger welfare loss. A similar argument applies when more firms compete; as depicted in Figure 2b. In this setting, pollution moves farther away from the first best, giving rise to larger welfare loss due to the policy uncertainty firms face. In contrast, $WL^{PU}$ is attenuated when firms experience larger R&D costs, since the R&D investment in equilibrium approaches that under the social optimum, limiting the extend of the welfare losses. (Graphically, $WL^{PU}$ shifts downwards when parameter $\gamma$ increases.)

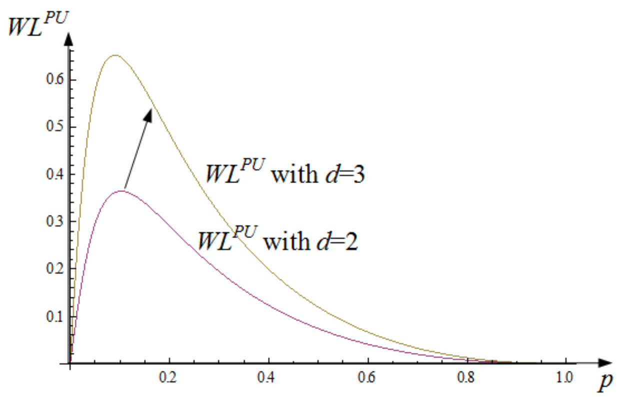


Fig. 2a. $WL^{PU}$ with higher $d$.

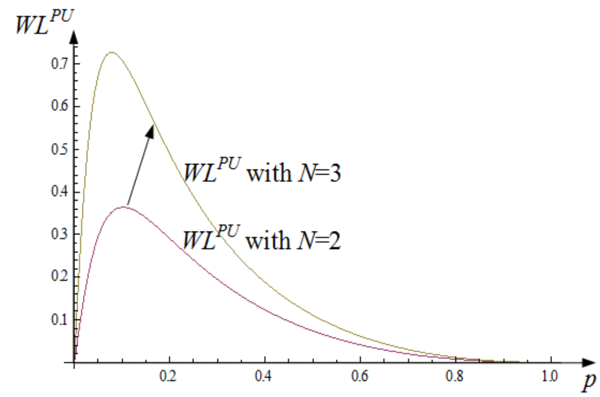


Fig. 2b. $WL^{PU}$ with higher $N$.

Despite the above (rather negative) welfare effects of policy uncertainty, our next corollary shows that environmental regulation, even one which can be rolled back in future periods, is welfare superior than having no regulation at all.

**Corollary 3.** *Social welfare is weakly larger with than without regulation, under all admissible parameter values.*

Therefore, while policy uncertainty generates welfare losses under all parameter conditions, the absence of environmental regulation entails a lower welfare. Importantly, this occurs regardless of the probability that regulation remains into effect, so our finding indicates that even a very unlikely environmental policy (where $p$ is close to zero) generates a larger welfare than no policy at all.

Corollary 3 can be alternatively interpreted as that abolishing the environmental policy generates a welfare loss, $WL^{AP} \equiv SW - SW^{NR}$, measuring the welfare difference between the benchmark scenario (with uncertain regulation), $SW$, and when regulation is absent with certainty,

$SW^{NR} = SW(0)$, that is,

$$WL^{AP} = \frac{Np(1-c)^2\left[\gamma - dN\left[p(N+1)+\gamma\right]\right]^2}{2(N+1)^2\left[dN\left[p(N+1)+\gamma\right]^2 + \gamma\left[(N+1)^2p^2 + N\gamma\right]\right]}$$

Figure 3a depicts $WL^{AP}$ evaluated at the same parameter values as Figure 1. Intuitively, the introduction of environmental regulation yields larger welfare gains, relative to no policy, when regulation is likely to remain into effect (high $p$). Figure 3b indicates that this welfare gain increases when pollution damages become more severe; and a similar argument applies if the number of firms increases. The opposite argument holds when R&D costs increase.

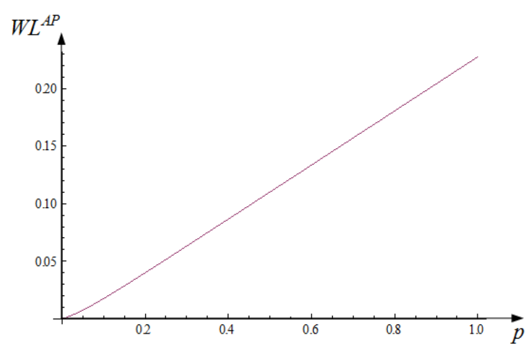


Fig. 3a. Welfare loss $WL^{AP}$.

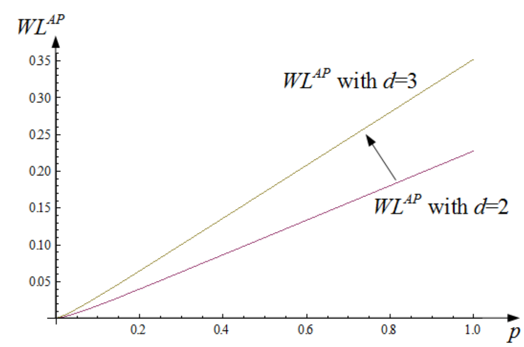


Fig. 3b. $WL^{AP}$ with higher $d$.

### 4.3 Comparing welfare losses

From Corollary 3 and our previous discussion, abolishing environmental regulation creates a welfare loss $WL^{AP} > 0$. Proposition 2, in contrast, identified the welfare loss from policy uncertainty, $WL^{PU}$, which stems from the fact that firms alter their R&D and emission decisions.

To understand the difference, consider a context of regulatory uncertainty where the policy happens to remain into effect. In this setting, society suffers the welfare loss in $WL^{PU}$ but does not suffer $WL^{AP}$ (since $WL^{PU} > 0$ but $WL^{AP} = 0$). However, if the policy is abolished, society would suffer both $WL^{PU}$ and $WL^{AP}$. An interesting question is, then, which of these welfare losses is the largest, and how their relative sizes vary when the policy becomes more likely to remain into effect. Ratio $\frac{WL^{PU}}{WL^{AP}}$ can help us understand the size of $WL^{PU}$, relative to the welfare loss from abolishing the policy, $WL^{AP}$. Comparative statics of this ratio are rather involved, but Figure 4 provides a numerical simulation to illustrate its interpretation using the same parameter values as in previous sections. For illustration purposes, we also include a solid line at the height of 1, so readers can more easily recognize the segment of the ratio $\frac{WL^{PU}}{WL^{AP}}$ where $WL^{PU} > WL^{AP}$, and that where $WL^{PU} < WL^{AP}$.[11]

[11] Alternatively, we can evaluate the welfare loss of policy uncertainty, $WL^{PU}$, relative to the aggregate welfare loss,

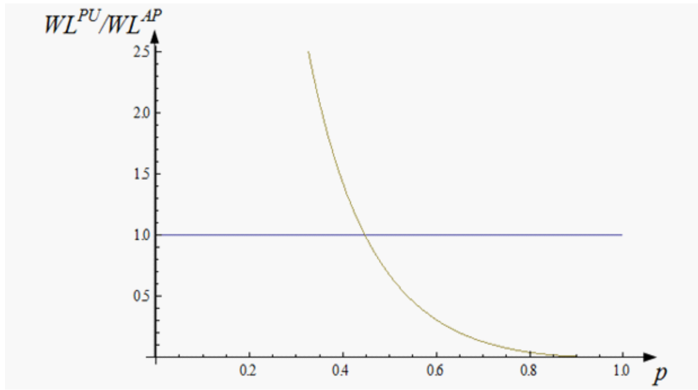


Fig. 4. Welfare ratio $WL^{PU}/WL^{AP}$.

The figure indicates that, when the policy is unlikely to remain into effect ($p$ is relatively low), the welfare loss originates mainly from the regulatory uncertainty that firms face. Indeed, $WL^{AP}$ is close to zero (as depicted in Figure 3a and 3b), while $WL^{PU}$ is positive (as indicated in Figures 1-2), yielding a large $\frac{WL^{PU}}{WL^{AP}}$ ratio. In contrast, when the policy becomes more likely to stay in place (relatively high $p$), the welfare loss of regulatory uncertainty represents a smaller share of the welfare loss that occurs if the policy is rolled back. In this context, the welfare loss from abolishing a policy that was likely to remain into effect are large (as discussed in the previous section and Figures 3a-3b), while policy uncertainty is relatively minor. Finally, when the policy is certainly remaining into effect ($p = 1$), policy uncertainty does not generate distortions on players' behavior, thus yielding no welfare losses $WL^{PU} = 0$, while abolishing the policy creates a significant welfare loss (i.e., $WL^{AP}$ is large).

When the environmental damage from pollution becomes more severe (higher $d$), ratio $\frac{WL^{PU}}{WL^{AP}}$ shifts upward, indicating that policy uncertainty generates larger welfare losses than abolishing the regulation in this setting. A similar argument applies when more firms compete in the industry (higher $N$), which also shifts $WL^{PU}$ upwards more significantly than $WL^{AP}$, thus raising ratio $\frac{WL^{PU}}{WL^{AP}}$; and a similar effect occurs when R&D costs become more expensive.

### 4.4 Is policy uncertainty profitable?

A natural question is whether firms can benefit from policy uncertainty. Evaluating profits at the equilibrium emission fee $t^*$ from Proposition 1, the equilibrium R&D $z(t^*) = \frac{pt^*}{\gamma}$, and the equilibrium output $q^*$, we obtain

$$\pi(t^*) = pq^*(1 - c - Nq^*) + (1-p)\left(\frac{1-c}{N+1}\right)^2 - \frac{1}{2}\gamma\left(\frac{pt^*}{\gamma}\right)^2$$

$WL^{PU} + WL^{AP}$, to find ratio $\frac{WL^{PU}}{WL^{PU}+WL^{AP}}$. It is easy to show that this ratio is smaller than one since $WL^{AP} > 0$, or $SW > SW^{NR}$ as shown in Corollary 3.

where we used revenue neutrality, i.e., total tax collection is distributed to firms as a lump-sum transfer. Rearranging and simplifying $\pi(t^*)$, yields

$$\pi(t^*) = \frac{(1-c)^2}{2}\left[\frac{2(1-p)}{(N+1)^2} - \frac{p^2\gamma\left[\gamma - dNB\right]^2 + 2p\left[(N+1)\,p^2\gamma + dN(p+\gamma)BD\right]}{\left[dNB^2 + \gamma\left[(N+1)^2p^2 + N\gamma\right]\right]^2}\right]$$

where $B \equiv p(N+1)+\gamma$ and $D \equiv dNpB + \gamma\left[(N+1)p^2 + \gamma\right]$. Comparative statics with respect to $p$ are highly non-linear, but Figure 5a evaluates $\pi(t^*)$ at the same parameter values as figures 1, 3a and 4. In this setting, equilibrium profits are monotonically decreasing in the probability that the regulation remains into effect, $p$. However, when the number of firms increases enough, equilibrium profits become monotonically increasing in probability $p$.[12]

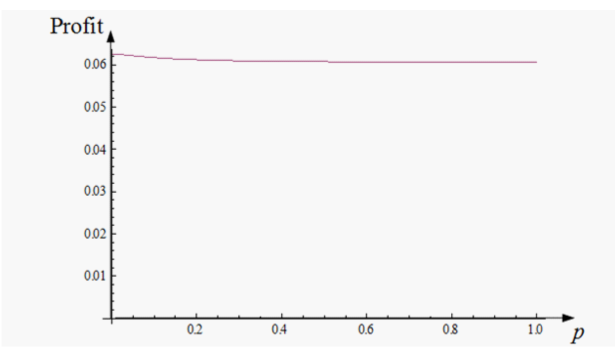


Fig. 5a. Equilibrium profits when $N = 2$.

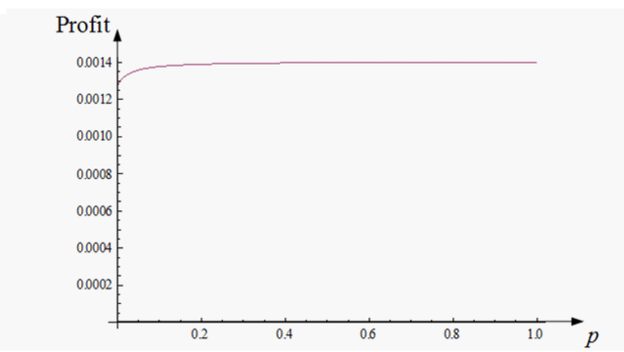


Fig. 5b. Equilibrium profits when $N = 20$.

Intuitively, a marginal increase in probability $p$ produces two opposite effects on firms profits. On one hand, it decreases profits originating from the product market but, on the other hand, a larger $p$ increases the tax-saving benefits from investing in abatement. When few firms operate in the market the first (negative) effect dominates the second (positive) effect, since each firm earns a relatively large profit from the product market thus being highly affected by a more likely policy. However, as more firms compete, profits from the product market approach zero in all regulatory settings, being essentially unaffected by small changes in $p$, which ultimately nullifies the first effect. As a consequence, the second (positive) effect dominates in this case, yielding an overall increase in firms' profits.

[12] Figure 5b considers $N = 20$ firms, for illustration purposes, but as little as $N = 4$ firms produces increasing, or flat, equilibrium profits. In addition, note that equilibrium profit $\pi(t^*)$ shifts downwards when evaluated at more damaging pollution (higher $d$) since the equilibrium emission fee becomes more stringent

## 5 Extension to more periods

In previous sections, we considered that the policy was announced in the first period and, if it happens to remain into effect, becomes implemented in the third period, which was the only moment where firms produce output and emissions. Intuitively, the uncertainty that agents face in that setting could be interpreted as that the regulator designs an environmental policy which should start its application after a year. At that point, the incumbent may have lost its majority in Congress, or a new administration holds office, leading to a regulatory rollback.

In this section, we consider an alternative setting, where the incumbent administration sets a policy that is implemented with certainty during its tenure. However, at the fourth stage the policy becomes uncertain, as it can remain into effect with probability $p$ and be abolished (e.g., by the new administration) with probability $1-p$.[13]

**Fourth stage.** In this period, firms observe whether the new administration kept the environmental policy into effect or not. Therefore, every firm solves problem (1), and we obtain the same equilibrium behavior as in stage 3. That is, when regulation still remains, individual output is $q_i(t) = \frac{1-(c+t)}{N+1}$ while profits are $\pi_i(t) = \left(\frac{1-(c+t)}{N+1}\right)^2 + tz_i$. When regulation is abolished, every firm produces $q(0) = \frac{1-c}{N+1}$, and earns profit $\pi_i(0) = \left(\frac{1-c}{N+1}\right)^2$; see Section 3 for more details.

**Third stage.** In this stage, firms are certain that regulation remains into effect, solving problem (1) too, which yields an individual output of $q_i(t) = \frac{1-(c+t)}{N+1}$ and profits of $\pi_i(t) = \left(\frac{1-(c+t)}{N+1}\right)^2 + tz_i$.

**Second stage.** Every firm $i$ anticipates that, at stage 3, it will obtain profit $\pi_i(t)$ with certainty. However, in the fourth stage, the new administration may take office, implying that the emission fee remains into effect (which entails profits $\pi_i(t)$ with probability $p$) or roll back the policy (yielding profit $\pi_i(0)$ with probability $1-p$). Therefore, firm $i$ chooses its R&D investment, $z_i$, to solve

$$\max_{z_i \geq 0} \ \pi_i(t) + p\pi_i(t) + (1-p)\pi_i(0) - \frac{1}{2}\gamma\,(z_i)^2 \tag{2''}$$

where the first term represents the profits that the firm obtains, with certainty, while the current administration holds office; and the remaining terms coincide with those in problem (2), i.e., expected profits and R&D costs. Differentiating with respect to $z_i$ yields $z_i^{**}(t) = \frac{(1+p)t}{\gamma}$, which exhibits similar comparative statics as $z_i(t)$. Relative to $z_i(t)$, however, introducing the profits that the firm obtains when facing a certain regulation during one period induce this company to invest more in R&D, since it can benefit from lower emission fees during more periods.

**First stage.** The regulator solves the emission fee that maximizes the sum of social welfare across periods

$$\max_{t \geq 0} \ SW_1(t) + SW_2(t) \tag{3''}$$

[13] For simplicity, we assume that the regulator does not have the ability to redesign the environmental policy across these two periods.

where, in the last period, $SW_2(t) \equiv pSW(t) + (1-p)SW(0)$ coincides with social welfare in previous sections since firms face regulatory uncertainty; while in the period of regulatory certainty, $SW_1(t) \equiv SW(t, p=1) - \frac{1}{2}\gamma\left(z_i\right)^2$, indicating that the planner evaluates social welfare at $p = 1$, and ignores the R&D investment cost. This investment is only undertaken in the second stage of the game, so the planner can only consider it in either $SW_1(t)$ and $SW_2(t)$, but not in both.

Solving for fee $t$ in problem $(3'')$, yields

$$t^{**} = \frac{(1-c)(1+p)\gamma\left[dN\left[p(N+1)+\gamma\right]-\gamma\right]}{dN(1+p)\left[p(N+1)+\gamma\right]^2 + \gamma\left[(N+1)^2p^3 + N\gamma(1+p)\right]}$$

which is positive if and only if $d > d^{**} \equiv \frac{\gamma}{N[1+N+p(N+1)+\gamma]}$, where cutoff $d^{**}$ satisfies $d^{**} > \overline{d}$. Therefore, relative to the emission fee of Proposition 1, $t^*$, fee $t^{**}$ is positive under more restrictive conditions. Intuitively, the regulator anticipates that firms respond to a marginal increase in fees investing more significantly in R&D. The regulator then sets a less stringent emission fee when regulation remains into effect for one period than when it does not.

**Welfare losses.** Policy uncertainty still produces a welfare loss in this setting since firms face less incentives to invest in R&D when they anticipate that regulation can be rolled back in future periods (benchmark scenario) than when they incorrectly assume that regulation will remain into effect (counterfactual scenario). However, this reduction in R&D incentives is now ameliorated by the presence of a period when regulation remains into effect with certainty. Therefore, the welfare loss from policy uncertainty $WL^{PU} \equiv SW^C - SW$ is in this context smaller than in previous sections, as firms' behavior is not so sensitive to the probability that the policy is abolished.

However, the welfare loss from abolishing the policy, $WL^{AP} \equiv SW - SW^{NR}$, is in this setting more significant, since under no policy equilibrium emissions are suboptimal during two periods, as opposed to one period in the context considered in previous sections (where regulation can only be in effect during one period). Therefore, the ratio $\frac{WL^{PU}}{WL^{AP}}$ becomes in this setting smaller, suggesting that regulators should pay close attention to policy uncertainty when the regulation can be rolled back in the next period, or just a few periods into the future. In contrast, when regulation may only be abolished in a distant future, the welfare loss from policy uncertainty $WL^{PU}$ (as well as the size of $WL^{PU}$ relative to the welfare loss from abolishing the policy, $WL^{AP}$) becomes minor, indicating that regulatory agencies could ignore the strategic effects of policy uncertainty on firms' decisions.

## 6 Discussion

*Welfare loss from policy uncertainty.* Our model helped isolate the elements giving rise to welfare losses from policy uncertainty. Specifically, firms reduce their R&D investment (thus increasing emissions) when they anticipate that regulation may not stay into effect in future periods. This welfare loss occurs under all parameter conditions, implying that it should not be overlooked by regulatory agencies. This is particularly the case of environmental regulations announced during previous administrations which should come into effect with the new President (or new majorities in the House or Senate), the latter considering to abolish these regulations so they do not become during their term.

*Larger welfare losses.* We also identified that the welfare loss from policy uncertainty can be particularly large in industries where: (1) several firms compete; (2) every unit of pollution causes severe damages; and (3) R&D investment costs are relatively low. In these contexts, the probability of a rolled back regulation triggers large strategic shifts in firms' behavior, leading to significant reductions in R&D investments and pollution increases. Therefore, in industries where (1)-(3) concur, regulators should be extremely careful at suggesting that environmental policies could be revisited in future periods, e.g., requiring supermajorities (or a large share of votes) for this policy to be abolished or even adjusted. In contrast, when (1)-(3) do not hold, our findings suggest that the welfare loss from policy uncertainty is not substantial. In these settings, regulators could openly discuss the possibility of rolling back the policy in future periods without the fear to induce significant R&D changes in firms' behavior.

*Profit gains.* Our results suggest that firms in highly contested markets could lobby in favor of policy stability ($p = 1$, or at least a high $p$) since they can see their equilibrium profits increase as a result of the decrease in output that environmental regulation entails. In contrast, firms in highly concentrated markets would lobby for policy uncertainty ($p = 0$, or low $p$) since regulation yields an unambiguous profit decrease in this setting.

*Benefits from early implementation.* Our findings indicate that, if regulators set an environmental policy that faces a potential rollback in future periods, they should try to implement it as soon as possible so the policy remains into effect with certainty for several periods before the moment when it faces the possibility of being abolished. Consider, for instance, an administration setting a new environmental regulation on coal-fired power plants. Anticipating the possibility of losing office to a new administration opposed to such a policy, the incumbent implements the policy several years before the next election, limiting the welfare loss from policy uncertainty $WL^{PU}$. If the new administration rolls back the regulation, it generates a welfare loss $WL^{AP}$, but at least the welfare loss from policy uncertainty had been minimized by an early implementation of the regulation by the previous administration.

# 7 Appendix

## 7.1 Appendix 1 - Allowing for cost-reducing investment

In this appendix, we extend our results to a setting where firm $i$'s investment, $z_i$, not only reduces its future taxes but also its marginal cost of production, from $c$ to $c - \alpha z_i$, where $\alpha \in [0, 1]$ represents the cost-reducing effect of every unit of investment, $z_i$. Intuitively, when $\alpha = 0$ investment does not generate cost-reducing effects, yielding the same results as in Section 3. However, when $\alpha > 0$, investing in abatement produces two positive effects on profits: reduces future production cost and decreases the firm's tax bill, from $tq_i$ to $t(q_i - z_i)$.

**Third stage.** In this period, firms observe whether the environmental policy is still active or not. If emission fee $t > 0$ is still in place (which occurs with probability $p$), every firm $i$ solves

$$\max_{q_i \geq 0} \ (1 - Q)q_i - (c - \alpha z_i)\, q_i - t(q_i - z_i) \tag{A1}$$

Differentiating with respect to $q_i$ and simultaneously solving yields an individual output of $q_i(t) = \frac{1-(c-\alpha z_i+t)}{N+1}$, and similarly for all other firms. This output is increasing in the cost-reducing effect of investment, $\alpha$, and collapses to $q_i(t) = \frac{1-(c+t)}{N+1}$ when cost-reducing effects are absent, $\alpha = 0$, coinciding with the expression we found in Section 3 of the paper. Therefore,

$$Q_{-i} = \sum_{j \neq i} q_j(t) = (N-1)\left(\frac{1-(c+t)}{N+1}\right) + \frac{\alpha Z_{-i}}{N+1},$$

where $Z_{-i} \equiv \sum_{j \neq i} z_j$ denotes aggregate investment from firm $i$'s rivals. Inserting these output expressions into (A1), we obtain that firm $i$'s profits are

$$\pi_i(t) = \frac{(1 - c + \alpha z_i)\,[1 - c + \alpha(N z_i + Z_{-i})]}{(N+1)^2} - \frac{t\,[2(1-c) - t - z_i(N+1)(N+1-\alpha) - \alpha Z_{-i}]}{(N+1)^2}$$

which is a function of firm $i$'s investment, $z_i$, and in its rivals' investment, $Z_{-i}$, to allow for the possibility that firms investment in the second stage of the game is asymmetric (in the next section, however, we show that investment profiles are symmetric). If, instead, emission fee $t$ is abolished (which happens with probability $1 - p$), every firm solves problem (A1) evaluated at $t = 0$, which yields a higher output of $q(0) = \frac{1-c}{N+1}$, and a larger profit of

$$\pi_i(0) = \frac{(1 - c + \alpha z_i)\,[1 - c + \alpha(N z_i + Z_{-i})]}{(N+1)^2}.$$

Finally, note that when cost-reducing effects are absent, $\alpha = 0$, profits with regulation $\pi_i(t)$ collapses to $\pi_i(t) = \left(\frac{1-(c+t)}{N+1}\right)^2 + tz_i$, as in Section 3 of the paper, and similarly, when firms face no regulation, profits $\pi_i(0)$ simplify to $\pi_i(0) = \left(\frac{1-c}{N+1}\right)^2$, as in Section 3.

**Second stage.** Every firm $i$ anticipates the equilibrium profits it obtains in the subsequent stage when the emission fee remains into effect, $\pi_i(t)$, and when it does not, $\pi_i(0)$, choosing its R&D investment, $z_i$, to solve

$$\max_{z_i \geq 0} \ p\pi_i(t) + (1-p)\pi_i(0) - \frac{1}{2}\gamma\,(z_i)^2 \tag{A2}$$

where we assume $\gamma > \frac{\alpha^2}{N+1}$, to guarantee weakly positive investment levels under all regulatory contexts. Differentiating with respect to $z_i$ yields

$$z_i(t) = \frac{pt(N+1-\alpha)+\alpha(1-c)}{\gamma(N+1)-\alpha^2},$$

which is increasing in the cost-reducing effect of investing in abatement, $\alpha$, since

$$\frac{\partial z_i(t)}{\partial \alpha} = \frac{(1-c)\left[\gamma(N+1)+\alpha^2\right] - pt\left[2(N+1)\alpha - \alpha^2 - \gamma(N+1)\right]}{\left[\gamma(N+1)-\alpha^2\right]^2} = 0$$

holds when $\gamma > \gamma_A \equiv -\frac{2pt\alpha(N+1)+\alpha^2(1-c-pt)}{(N+1)(1-c-pt)}$ given that cutoff $\gamma_A < 0$. In addition, equilibrium investment $z_i(t)$ collapses to $z_i(t) = \frac{pt}{\gamma}$ when cost reducing effects are absent, $\alpha = 0$, coinciding with our results in Section 3. This equilibrium investment is increasing in the probability that the regulation remains into effect, $p$, and in the emission fee, $t$, since

$$\frac{\partial z_i(t)}{\partial p} = \frac{t(N+1-\alpha)}{\gamma(N+1)-\alpha^2} > 0 \quad \text{and} \quad \frac{\partial z_i(t)}{\partial t} = \frac{p(N+1-\alpha)}{\gamma(N+1)-\alpha^2} > 0$$

but decreasing in the investment cost, $\gamma$, since

$$\frac{\partial z_i(t)}{\partial \gamma} = -\frac{(N+1)\left[(1-c)\alpha + pt(N+1-\alpha)\right]}{\left[\gamma(N+1)-\alpha^2\right]^2} > 0.$$

yielding similar comparative statics as those in Section 3. Finally, equilibrium investment $z_i(t)$ is decreasing in the number of firms, $N$, if

$$\frac{\partial z_i(t)}{\partial N} = -\frac{\alpha\left[(1-c)\gamma + pt(\gamma-\alpha)\right]}{\left[\gamma(N+1)-\alpha^2\right]^2} < 0$$

which, solving for $\gamma$, holds if $\gamma > \gamma_B \equiv \frac{pt\alpha}{1-c+pt}$. Recall that $\gamma > \frac{\alpha^2}{N+1}$ holds by assumption, and that cutoff $\gamma_B$ satisfies $\gamma_B > \frac{\alpha^2}{N+1}$ if $\alpha < \overline{\alpha} \equiv \frac{pt(N+1)}{1-c+pt}$. Therefore, when $\alpha < \overline{\alpha}$, we have that the range of admissible values of $\gamma$ is divided into two regions: (1) $\frac{\alpha^2}{N+1} < \gamma < \gamma_B$, where equilibrium investment $z_i(t)$ decreases in the number of firms, $N$; and (2) $\gamma \geq \gamma_B$, where equilibrium investment $z_i(t)$ increases in $N$. Intuitively, in region (1), the free-riding effect that every firm $i$ obtains from its rivals' investment in abatement (yielding a lower tax) dominates the incentive to invest in cost-reducing technologies, whereas in region (2) the opposite ranking applies. In contrast, when $\alpha$ satisfies $\alpha \geq \overline{\alpha}$, cutoff $\gamma_B$ lies below $\frac{\alpha^2}{N+1}$. In this case, for all admissible values of $\gamma$, i.e., $\gamma > \frac{\alpha^2}{N+1}$, equilibrium investment $z_i(t)$ increases in the number of firms, $N$.

In this context, equilibrium investment becomes $z_i(t) = \frac{(1-c)\alpha}{\gamma(N+1)-\alpha^2}$ in the absence of regulation (i.e., when $t = 0$ and/or $p = 0$), thus being positive, as opposed to equilibrium investment decisions when firms only benefit from a tax-saving effect (Section 3). In our present setting, firms can still capture a cost-reducing benefit and thus have incentives to invest positive amounts even without regulation.

**First stage.** The regulator chooses an emission fee $t$ that solves

$$\max_{t\geq 0} \; SW \equiv pSW(t) + (1-p)SW(0) \tag{A3}$$

where $SW(t) \equiv CS(t) + PS(t) - Env(t)$ denotes the social welfare when emission $t$ remains into effect, while $SW(0)$ represents that when the fee is abolished. Differentiating with respect to $t$ and solving, yields an optimal emission fee

$$t^* = \frac{(1-c)(N+1)\left[dN\left(\alpha-\gamma\right)p(N+1-\alpha)^2+\theta)+\gamma(\alpha(p-1)\alpha-(N+1)p)+\gamma(N+1))\right]}{2p\alpha(N+1-\alpha)\theta+N\theta^2+dN(p(N+1-\alpha)^2+\theta)^2+p^2(N+1-\alpha)^2(\gamma+(2+N)(N\gamma-\alpha^2))}$$

where $\theta \equiv \gamma(N+1)-\alpha^2$, which collapses to

$$t^* = \frac{(1-c)\gamma\left[dN\left[p(N+1)+\gamma\right]-\gamma\right]}{dN\left[p(N+1)+\gamma\right]^2+\gamma\left[(N+1)^2p^2+N\gamma\right]}$$

when cost-reducing effects are absent, $\alpha = 0$, thus coinciding with the equilibrium emission fee in Proposition 1. When cost-reducing effects are positive, $\alpha > 0$, emission fee $t^*$ is positive if and only if $d > \overline{d}_A$, where

$$\overline{d}_A \equiv \frac{\gamma\left[\alpha\left[(1-p)\alpha-(N+1)p\right]+\gamma(N+1)\right]}{N(\gamma-\alpha)\left[p(N+1-\alpha)^2-\alpha^2+\gamma(N+1)\right]}$$

This cutoff simplifies to $\overline{d} \equiv \frac{\gamma}{N[p(N+1)+\gamma]}$, as stated in Proposition 1.

## 7.2 *Proof of Proposition 1*

Using symmetry, the expression of $SW(t)$ can be written as

$$SW(t) = (1-c)(Nq_i(t)) - \frac{1}{2}(Nq_i(t))^2 - N\frac{1}{2}\gamma(z_i(t))^2 - \frac{1}{2}d\left[N(q_i(t)-z_i(t))\right]^2$$

where $q_i(t) = \frac{1-(c+t)}{N+1}$ from our analysis of the third stage, and $z_i(t) = \frac{pt}{\gamma}$ from our analysis of the second stage. Differentiating with respect to emission fee $t$ in problem (3), and solving for $t$, yields

$$t^* = \frac{(1-c)\gamma\left[dN\left[p(N+1)+\gamma\right]-\gamma\right]}{dN\left[p(N+1)+\gamma\right]^2+\gamma\left[(N+1)^2p^2+N\gamma\right]}$$

Setting it equal to zero and solving for $d$, we obtain that $t^* > 0$ if and only if $d > \overline{d} \equiv \frac{\gamma}{N[p(N+1)+\gamma]}$. Cutoff $\overline{d}$ is positive and lower than one for all $p > \frac{(1-N)\gamma}{N(N+1)}$, which holds by assumption since $N \geq 1$. In addition, differentiating cutoff $\overline{d}$ with respect to $\gamma$ yields

$$\frac{\partial\overline{d}}{\partial\gamma} = \frac{p(N+1)}{N\left[p(N+1)+\gamma\right]^2} > 0,$$

differentiating it with respect to $N$ we obtain

$$\frac{\partial \overline{d}}{\partial N} = -\frac{\gamma\left[p(1+2N)+\gamma\right]}{N^2\left[p(N+1)+\gamma\right]^2} < 0,$$

and differentiating it with respect to $p$, we find

$$\frac{\partial \overline{d}}{\partial p} = -\frac{\gamma(N+1)}{N\left[p(N+1)+\gamma\right]^2} < 0.$$

### 7.3 *Proof of Corollary 1*

*Emissions.* Evaluating equilibrium output $q_i(t) = \frac{1-(c+t)}{N+1}$ at the equilibrium fee $t^*$, yields

$$q_i(t^*) = \frac{(1-c)\left[dNp\left[p(N+1)+\gamma\right]+\gamma\left[(N+1)p^2+\gamma\right]\right]}{dN\left[p(N+1)+\gamma\right]^2+\gamma\left[(N+1)^2p^2+N\gamma\right]}$$

and evaluating equilibrium R&D investment, $z_i(t) = \frac{pt}{\gamma}$ at $t = t^*$, we obtain

$$z_i(t^*) = \frac{(1-c)p\left[dN\left[p(N+1)+\gamma\right]-\gamma\right]}{dN\left[p(N+1)+\gamma\right]^2+\gamma\left[(N+1)^2p^2+N\gamma\right]}$$

implying that the equilibrium emissions become

$$q_i(t^*) - z_i(t^*) = \frac{(1-c)\gamma\left[p^2(N+1)+\gamma+p\right]}{dN\left[p(N+1)+\gamma\right]^2+\gamma\left[(N+1)^2p^2+N\gamma\right]}.$$

Differentiating with respect to $p$, setting the result equal to zero, and solving for $d$, yields that $q_i(t^*) - z_i(t^*)$ increases in $p$ as long as $d > d_1$, where $d_1 \equiv \frac{\gamma\left[p^2(N+1)^2-N\gamma+2p\gamma(N+1)\right]}{N[p(N+1)+\gamma][(N+1)p(2\gamma-1)-\gamma(1+2N)]}$. In addition, the difference between cutoff $\overline{d}$ and $d_1$, $\overline{d} - d_1$, simplifies to

$$\overline{d} - d_1 = \frac{\gamma(N+1)\left[p^2(N+1)+\gamma+p\right]}{N\left[p(N+1)+\gamma\right]\left[\gamma(1+2N)+p(N+1)(1-2\gamma)\right]}$$

Setting $\overline{d} - d_1 > 0$ and solving for $N$ yields two roots, both of them negative. Therefore, for all admissible parameters ($N \geq 2$) the difference $\overline{d} - d_1$ is positive, entailing that $\overline{d} > d_1$. Since condition $d > \overline{d}$ by assumption, the above condition $d > d_1$ holds as well.

*Social welfare.* The expression of $SW(t)$ is

$$SW(t) = (1-c)(Nq_i(t)) - \frac{1}{2}(Nq_i(t))^2 - N\frac{1}{2}\gamma(z_i(t))^2 - \frac{1}{2}d(N(q_i(t)-z_i(t)))^2$$

where $q_i(t) = \frac{1-(c+t)}{N+1}$ from our analysis of the third stage, and $z_i(t) = \frac{pt}{\gamma}$ from our analysis of the second stage. Therefore, the expected social welfare is $SW = pSW(t) + (1-p)SW(0)$. Differentiating with respect to $p$, we obtain that $\frac{\partial SW}{\partial p} > 0$ for all admissible values of $d$, i.e., $d > \overline{d}$.

### 7.4 *Proof of Corollary 2*

Differentiating with respect to emission fee $t$ in problem (3') yields

$$-\frac{N\left[\gamma\left[(N+1)^2p^2t+(1-c+Nt)\gamma\right]+dN\left[p(N+1)+\gamma\right]\left[(N+1)pt-(1-c-t)\gamma\right]\right]}{\gamma^2(N+1)^2}=0$$

which coincides with that found for problem (3), except for probability $p$ that was multiplying all the terms in the numerator. Solving for emission fee $t$, we obtain

$$t^* = \frac{(1-c)\gamma\left[dN\left[p(N+1)+\gamma\right]-\gamma\right]}{dN\left[p(N+1)+\gamma\right]^2+\gamma\left[(N+1)^2p^2+N\gamma\right]}$$

which coincides with that in problem (3).

### 7.5 *Proof of Corollary 3*

Social welfare under no regulation was defined in Proposition 1 as $SW(0) = \frac{N(1-c)^2[2+N(1-d)]}{2(N+1)^2}$, while that under uncertain regulation, $SW$, was found in Corollary 1. Finding the difference $SW - SW(0)$, we obtain that

$$SW - SW(0) = \frac{Np(1-c)^2\left[\gamma - dN\left[p(N+1)+\gamma\right]\right]^2}{2(N+1)^2\left[dN\left[p(N+1)+\gamma\right]^2+\gamma\left[(N+1)^2p^2+N\gamma\right]\right]}$$

which is positive by definition, entailing that $SW > SW(0)$ under all admissible parameter values.

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