The Effect of Environmental Regulation on Strategic Decision in Product Markets

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1 Introduction

In this paper, we study environmental regulation and market equilibrium. The global warming is an urgent issue to be addressed throughout the entire world. Industrialized nations have emitted far more greenhouse gas emissions, consequently, the significance of environmental regulation are discussed broadly in recent years. The argument of environmental regulation is developed at not only the political level, but also the academic level. In fact, there are many existing literature studying environmental regulation.

Existing literature consider pollution taxes, tradable emission permits and imperfect competition, however, they do not consider any uncertainty. von der Fehr (1993) studies tradable emission rights and strategic interaction. He shows strategic manipulation may have negative welfare effects in the market. Simpson (1995) studies optimal pollution tax in Cournot duopoly. He shows the optimal tax rate may exceed the marginal damage. Sartzetakis (1997) studies tradable emission permits regulations under imperfect competition. He shows social welfare is higher under the TEP relative to the CC regulation. Tanaka and Chen (2012) study tradable emission permits in electricity markets. They show diverting emission permits reduces the power and the permit prices. Mansur (2013) studies tradable permits are preferable to taxes under imperfect competition. He shows strategic behavior reduced local emissions by approximately 9%.

Goto et al. (2016) consider uncertainty of pollution, firm's entry-exit decision and pollution tax in Cournot duopoly by combining Wirl (2006) and Simpson (1995). Outputs of their model are dynamics of pollution and equilibrium market supply. It is shown that environmental regulation decreases duration and amount of pollution, pollution uncertainty increases duration and amount of pollution, and market size increases increment of pollution. However, there is the difficulty of definition of pollution uncertainty. In this paper, we consider demand uncertainty instead of pollution uncertainty so as to clarify the definition of uncertainty.

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2 Monopoly

First, we consider firm i produces q_i units using technology i at cost per unit c_i in monopoly market. Market demand is given by

$$P(X_t, q_i) = X_t - \eta q_i, \tag{1}$$

where X_t follows a geometric Brownian motion

$$\mathrm{d}X_t = \alpha X_t \mathrm{d}t + \sigma X_t \mathrm{d}W_t, \qquad X_0 = x. \tag{2}$$

We assume the firm is imposed damage function, such as environmental tax, which has the quadratic form of

$$D(q_i) = \lambda \theta_i^2 q_i^2, \tag{3}$$

where λ is the constant damage parameter and θ_i is the constant emission rate of firm i's technology. Then, firm i's profit is given by

$$\pi(X_t, q_i) = (P(X_t, q_i) - c_i) q_i - \lambda \theta_i^2 q_i^2. \tag{4}$$

The first-order condition

$$\frac{\partial \pi(X_t, q_i)}{\partial q_i} = 0 \tag{5}$$

gives the optimal output level of firm i

$$q_i^* = \left\{ \frac{X_t - c_i}{\gamma_i} \right\}^+, \tag{6}$$

where

$$\gamma_i = 2(\eta + \lambda \theta_i^2), \tag{7}$$

and the equilibrium market price is

$$P(X_t, q_i^*) = \frac{(\gamma_i - \eta) X_t + \eta c_i}{\gamma_i}, \qquad X_t > c_i. \tag{8}$$

The firm i's optimal profit is given by

$$\pi(X_t, q_i^*) = \frac{(X_t - c_i)^2}{2\gamma_i}, \qquad X_t > c_i. \tag{9}$$

Then, firm's decision is as follows:

1. Operate
   The firm earns the profit $\pi(X_t, q_i^*)$ and emits $\theta_i q_i^*$.

2. Suspend operation
   The firm maintains the technology at the cost m_i and $q_i = 0$.

3. Restart operation
   The firm incurs scrapping cost E_i.

Next, we derive value functions of firm i in monopoly. Suppose firm i produces q_i^* and emits forever, we have

$$V_0(x) = \mathbb{E}\left[\int_0^\infty \mathrm{e}^{-\rho t}\pi(X_t, q_i^*)\mathrm{d}t\right] = \frac{1}{2\gamma_i}\left(\frac{x^2}{\rho - 2\alpha - \sigma^2} - \frac{2c_i x}{\rho - \alpha} + \frac{c_i^2}{\rho}\right), \qquad x > c_i, \tag{10}$$

where ρ ($> 2\alpha + \sigma^2$) is a discount rate. Value of operation with the option to suspend is given by

$$V_1(x) = V_0(x) + A_1 x^{\beta_1}, \tag{11}$$

where A_1 is an unknown coefficient and

$$\beta_1 = \frac{-(\alpha - \sigma^2/2) - \sqrt{(\alpha - \sigma^2/2)^2 + 2\sigma^2\rho}}{\sigma^2} < 0. \tag{12}$$

Suppose the firm suspends operation ($q_i = 0$) and maintain ($-m_i$) the technology forever, we have

$$\mathbb{E}\left[\int_0^\infty \mathrm{e}^{-\rho t}(-m_i)\mathrm{d}t\right] = -\frac{m_i}{\rho}. \tag{13}$$

Value of stopping with the options to restart and exit is given by

$$V_2(x) = -\frac{m_i}{\rho} + B_1 x^{\beta_1} + B_2 x^{\beta_2}, \tag{14}$$

where B_1 and B_2 are unknown coefficients and

$$\beta_2 = \frac{-(\alpha - \sigma^2/2) + \sqrt{(\alpha - \sigma^2/2)^2 + 2\sigma^2\rho}}{\sigma^2} > 1. \tag{15}$$

Suppose the firm shuts down the technology, we have

$$V_3(x) = -E_i. \tag{16}$$

Finally, we present boundary conditions. we have the continuity and high-contact conditions at $x = c_i$, and the value-matching and smooth-pasting conditions at exit threshold. At $x = c_i$, we have

$$V_1(c_i) = V_2(c_i), \tag{17}$$
$$V_1'(c_i) = V_2'(c_i). \tag{18}$$

At exit threshold $\hat{X}$, we have

$$V_2(\hat{X}) = -E_i, \tag{19}$$
$$V_2'(\hat{X}) = 0. \tag{20}$$

We find three unknown coefficients and one threshold numerically using four boundary conditions (17)–(20).

3 Duopoly

In this section, we consider a duopoly market where two firms $i \neq j \in \{1, 2\}$ face Cournot competition. Market demand is given by

$$P(X_t, Q) = X_t - \eta Q, \qquad Q = q_1 + q_2, \tag{21}$$

so firm i's best response for given output level of firm j is

$$q_i(q_j) = \frac{X_t - c_i - \eta q_j}{\gamma_i}. \tag{22}$$

Then the Cournot equilibrium is given by

$$q_i^{**} = \left\{ \frac{(\gamma_j - \eta)X_t - \gamma_j c_i + \eta c_j}{\gamma_1\gamma_2 - \eta^2} \right\}^+, \tag{23}$$

$$Q^{**} = \left\{ \frac{(\gamma_1 + \gamma_2 - 2\eta)X_t - (\gamma_2 - \eta)c_1 - (\gamma_1 - \eta)c_2}{\gamma_1\gamma_2 - \eta^2} \right\}^+, \tag{24}$$

and the equilibrium market price is

$$P(X_t, Q^{**}) = \frac{(\gamma_1 - \eta)(\gamma_2 - \eta)X_t + \eta(\gamma_2 - \eta)c_1 + \eta(\gamma_1 - \eta)c_2}{\gamma_1\gamma_2 - \eta^2}, \qquad X_t > \bar{c}_i, \tag{25}$$

where

$$\bar{c}_i = \frac{\gamma_j c_i - \eta c_j}{\gamma_j - \eta}. \tag{26}$$

Then, the firm i's optimal profit is given by

$$\pi(X_t, q_i^{**}) = \frac{\gamma_i((\gamma_j - \eta)X_t - \gamma_j c_i + \eta c_j)^2}{2(\gamma_1\gamma_2 - \eta^2)^2}, \qquad X_t > \bar{c}_i. \tag{27}$$

Suppose firm i produces q_i^{**} and emits forever, we have

$$V_{0i}(x) = \mathbb{E}\left[\int_0^\infty \mathrm{e}^{-\rho t}\pi(X_t, q_i^{**})\mathrm{d}t\right] = \frac{\xi_{1i}x^2}{\rho - 2\alpha - \sigma^2} + \frac{\xi_{2i}x}{\rho - \alpha} + \frac{\xi_{3i}}{\rho}, \qquad x > \bar{c}_i, \tag{28}$$

where

$$\xi_{1i} = \frac{\gamma_i(\gamma_j - \eta)^2}{2(\gamma_1\gamma_2 - \eta^2)^2}, \tag{29}$$

$$\xi_{2i} = -\frac{\gamma_i(\gamma_j - \eta)(\gamma_j c_i - \eta c_j)}{(\gamma_1\gamma_2 - \eta^2)^2}, \tag{30}$$

$$\xi_{3i} = \frac{\gamma_i(\gamma_j c_i - \eta c_j)^2}{2(\gamma_1\gamma_2 - \eta^2)^2}. \tag{31}$$

W.l.o.g., we assume $c_1 < c_2$ so that firm 2 suspends and exits earlier than firm 1. Then market supply is as follows:

1. Both firms operate and emit:
   q_i^{**} and Q^{**} are given by (23) and (24), respectively.

2. Firm 1 produces and firm 2 suspends/shuts down:
   $Q^{**} = q_1^*$ and $q_2 = 0$.

3. Both firms suspend/shut down:
   $Q^{**} = 0$.

Table 1: Possible market status for the base case.

		Firm 2		
		Operating	Stopping	Exit
Firm 1	Operating	1**	2*	3*
	Stopping	—	—	4
	Exit	—	—	5

$$1 \underset{\bar{c}_2}{\overset{\bar{c}_2}{\rightleftarrows}} 2 \xrightarrow{\hat{X}_2} 3 \underset{\bar{c}_1}{\overset{\bar{c}_1}{\rightleftarrows}} 4 \xrightarrow{\hat{X}_1} 5$$

Figure 1: Status transition for the base case.

3.1 Base Case

Suppose $\bar{c}_1 < \hat{X}_2 < \bar{c}_2$, possible market status is shown in Table 1. Statuses 1 and 2 are in duopoly, while statuses 3–5 are in monopoly. Then status transition is shown in Figure 1.

Next, we derive value functions of firm 2 which is always in duopoly. The value of operation is given by

$$V_{12}(x) = V_{02}(x) + A_{12}x^{\beta_1}, \tag{32}$$

the value of stopping is given by

$$V_{22}(x) = -\frac{m_2}{\rho} + B_{12}x^{\beta_1} + B_{22}x^{\beta_2}, \tag{33}$$

and value of exit is given by

$$V_{32}(x) = -E_2. \tag{34}$$

We have the continuity and high-contact conditions at $x = \bar{c}_2$:

$$V_{12}(\bar{c}_2) = V_{12}(\bar{c}_2), \tag{35}$$

$$V'_{12}(\bar{c}_2) = V'_{22}(\bar{c}_2), \tag{36}$$

and value-matching and smooth-pasting conditions at exit threshold $\hat{X}_2$:

$$V_{22}(\hat{X}_2) = -E_2, \tag{37}$$

$$V'_{22}(\hat{X}_2) = 0. \tag{38}$$

We find three unknown coefficients and one threshold numerically using four boundary conditions.

Finally, we derive value functions of firm 1. Firm 1 is in duopoly for statuses 1 and 2, while in monopoly for statuses 3–5. For status 1 where both firms operate, the value function of firm 1 is given by

$$V_{11}(x) = V_{01}(x) + A_{11}x^{\beta_1}. \tag{39}$$

Table 2: Possible market status in case of late exit.

		Firm 2		
		Operating	Stopping	Exit
Firm 1	Operating	1**	2*	3*
	Stopping	—	6	4
	Exit	—	—	5

$$\begin{tikzcd} 1 \arrow[r, shift left, "\bar{c}_2"] & 2 \arrow[l, shift left, "\bar{c}_2"] \arrow[r, shift left, "\bar{c}_1"] & 6 \arrow[l, shift left, "\bar{c}_1"] \arrow[r, "\hat{X}_2"] & 4 \arrow[r, "\hat{X}_1"] \arrow[d, shift left, "\bar{c}_1"] & 5 \\ & & & 3 \arrow[u, shift left, "\bar{c}_1"] & \end{tikzcd}$$

Figure 2: Status transition in case of late exit.

For status 2 where firm1 operates and firm 2 suspends, we have

$$V_{21}(x) = V_0(x) + B_{11}x^{\beta_1} + B_{21}x^{\beta_2}. \tag{40}$$

Firm 1 in monopoly is already solved, that is, the value function for status 3 is $V_1(x)$, $V_2(x)$ status 4 and $V_3(x) = 0$ for status 5. From Figure 1, we have only value-matching conditions in duopoly at firm 2's restart threshold $\overline{X}_2$:

$$V_{11}(\overline{X}_2) = V_{21}(\overline{X}_2), \tag{41}$$

at firm 2's suspend threshold $\underline{X}_2$:

$$V_{11}(\underline{X}_2) = V_{21}(\underline{X}_2), \tag{42}$$

and at firm 2's exit threshold:

$$V_{21}(\hat{X}_2) = V_1(\hat{X}_2). \tag{43}$$

We find three unknown coefficients numerically using three boundary conditions.

3.2 Late Exit

Suppose $\hat{X}_2 < \bar{c}_1 < \bar{c}_2$. In this case, possible market status and status transition are shown in Table 2 and Figure 2, respectively. Statuses 1, 2 and 6 are in duopoly, while statuses 3–5 are in monopoly. Note that status 6 affects only firm 1's value function. For status 6 where both firms suspend, the value function of firm 1 is given by

$$V_{61}(x) = -\frac{m_1}{\rho} + C_{11}x^{\beta_1} + C_{21}x^{\beta_2}. \tag{44}$$

We have value-matching and smooth-pasting conditions at firm 1's restart threshold $\overline{X}_1$:

$$V_{21}(\overline{X}_1) - K_1 = V_{61}(\overline{X}_1), \tag{45}$$

$$V'_{21}(\overline{X}_1) = V'_{61}(\overline{X}_1), \tag{46}$$

Table 3: Possible market status in case of early eixt.

		Firm 2		
		Operating	Stopping	Exit
	Operating	1**	—	3*
Firm 1	Stopping	—	—	4
	Exit	—	—	5

$$1 \xrightarrow{\hat{X}_2} 3 \underset{\bar{c}_1}{\overset{\bar{c}_1}{\rightleftarrows}} 4 \xrightarrow{\hat{X}_1} 5$$

Figure 3: Status transition in case of early exit.

and at firm 1's suspend threshold $\underline{X}_1$:

$$V_{21}(\underline{X}_1) = V_{61}(\underline{X}_1), \tag{47}$$

$$V'_{21}(\underline{X}_1) = V'_{61}(\underline{X}_1). \tag{48}$$

In addition to value-matching conditions (41) at firm 2's restart threshold $\overline{X}_2$ and (42) at firm 2's suspend threshold $\underline{X}_2$, we have

$$V_{61}(\hat{X}_2) = V_2(\hat{X}_2), \tag{49}$$

at firm 2's exit threshold $\hat{X}_2$.

3.3 Early Exit

Suppose $\bar{c}_1 < \bar{c}_2 < \hat{X}_2$. In this case, possible market status and status transition are shown in Table 3 and Figure 3, respectively. Statuses 1 is in duopoly, while statuses 3–5 are in monopoly.

Note that firm 2 exits before suspends, therefore, status 2 does not exist in this case. We no longer consider the value of suspend for firm 2, and we have value-matching and smooth-pasting conditions in duopoly only at firm 2's exit threshold $\hat{X}_2$:

$$V_{12}(\hat{X}_2) = -E_2, \tag{50}$$

$$V'_{12}(\hat{X}_2) = 0, \tag{51}$$

$$V_{11}(\hat{X}_2) = V_1(\hat{X}_2). \tag{52}$$

4 Conclusion

We have investigated firm's entry-exit under the environmental regulation in Cournot competition where only a cost-advantaged firm can enjoy monopoly. Especially, we consider demand uncertainty, while existing literature do not consider it. Our remainders are welfare analysis and empirical studies. As a future study, it seems important to consider the game theoretic approach in the duopolistic setting. To this end, we need to develop a new equilibrium concept of entry-exit.

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