On Compartmentalized Environmental Regulation of Multiple Pollutants

Yusen SUNG

National Taiwan University Department of Economics
Taipei, Taiwan
(E-mail) ysung@ntu.edu.tw
(Tel) 886-910-211-221 (Fax) 886-2-2351-1826

August 3, 2013

Abstract

We model in this paper the regulation of two pollutants generated by a single firm, yet controlled by two indepent government regulatory agencies. A typical real-world example is the emission of greenhouse gases (GHG) and sulfur dioxide (SO_2) of a power plant during the production process. As the two regulators aim to maximize social welfare independently in their own jurisdiction, final emission levels may hing on the institutional regulation arrangement.

We consider two possible regulation regimes in our analysis: *centralized* versus *compartmentalized regulation*. In the centralized setting, a single government authority is responsible for regulating both pollutants. In the compartmentalized one, regulation of different pollutants are assigned to independent authorities. In the latter case, we further compare two regulation scenarios: *simultaneous-move Nash regulation game* as opposed to *sequential-move Stackelberg regulation game*.

It is shown in our analysis that, when firm cost function and pollution damage function are both separable, equilibrium compartmentalized regulation policies (both Nash and Stackelberg) are exactly the same as the centralized ones, which are by definition efficient. Otherwise, compartmentalization in pollution regulation will result in different firm output and pollution emissions from the efficient levels.

(JEL classification: H23, Q58)
Keywords: compartmentalized regulation, emission cap policy, Stackelberg game

1 Introduction

This paper considers a situation in which multiple pollutants generated by a single firm are jointly controlled by different government authorities. In reality, compartmentalized regulation by media by separate units of the Environmental Protection Agency (EPA) is quite common. In other cases, these regulators in question may be the central EPA versus local government bureau. As a real-world example, particulate matters such as sulfur dioxide (SO_2) and carbon dioxide (CO_2, also known as the green-house gas, GHG) are often discharged at the same time in industrial combustion processes. In the US, regulation of these pollutants is often divided across different authorities.[1]

We investigate in this paper how division in responsibility of control among different authorities affects pollutant levels of firms. We first model the case of simultaneous regulation, in which regulator of SO_2 (hereinafter s-regulator) and regulator of the GHG (hereinafter g-regulator) decide their policy simultaneously, engaging in a Nash game. Possible policies we consider here include emission caps (discharge standard) and emission fee (or tax). In addition, we also analyze the case of sequential legislation, in which s-regulator determines its policy first, in the presence of subsequent regulation by another authority, the g-regulator, engaging in a Stackelberg game.

Notably the issue of multiple pollutant control has long been recognized in the literature (Ayres and Kneese [1969]). Most researches, however, consider only a single regulator (Beavis and Walker [1979], Hahn [1989]). Lave [1984] and Hendrickson and McMichael [1985] examines the contradictory goals of different regulators in general, not particularly in the pollution control context. Burtraw *et al.* [2012], loosely related to our model, consider the instrument choice (pollution tax or emission cap) of a regulator who faces uncertainty caused by subsequent regulation by another regulator Our goal, in contrast with all above, aims at investigating how environmental quality are affected by compartmentalized stove-piping of environmental regulation.

This paper is organized as follows: The analytical framework is first laid out in Section 2. The third section compares the unregulated firm choice and the socially optimal resource allocation. The fourth section then considers the simultaneous-move policy decision game and its Nash equilibrium. We then turn to the sequential-move policy decision Stackelberg game and its subgame-perfect equilibrium in Section 5. The final section concludes and summarizes our findings.

[1] See U.S. EPA 2009, slide 45.

2 The Model

Consider a polluting firm in a competitive market. During the production process for output y, it generates at the same time two kinds of pollutants: sulfur dioxide (SO_2) as well as carbon dioxide (CO_2), also known as the green-house gas (GHG). We use s and g to denote their emission levels, respectively. Assume that the firm's production cost function takes the form:

$$C(y, s, g)$$

with increasing marginal production costs and increasing marginal clean-up costs:

$$C_y > 0,\ C_{yy} > 0;\ C_s < 0,\ C_{ss} > 0;\ C_g < 0,\ C_{gg} > 0;\ C_{ys} < 0,\ C_{yg} < 0$$

And its revenues in the competitive output market are simply:

$$R(y) \ = \ p \cdot y$$

with p being the competitive output price. Further, assume that marginal external damages of pollutants s and g are increasing:

$$D(s, g),\ \ D_s > 0,\ D_{ss} > 0,\ D_g > 0,\ D_{gg} > 0$$

with non-negative cross effect:

$$D_{sg} \ \geq \ 0$$

2.1 The Unregulated Firm Choice

Without government regulation, the risk-neutral profit-maximizing firm would try to:

$$\max_{y,s,g} \ \ \Pi^0 \ \equiv \ R(y) \ - \ C(y, s, g)$$

The necessary first-order conditions for its unregulated choice (y^0, s^0, g^0) are then:

$$C_y(y^0, s^0, g^0) \ = \ p$$

$$-C_s(y^0, s^0, g^0) \ = \ 0$$

$$-C_g(y^0, s^0, g^0) \ = \ 0$$

The emission levels (s^0, g^0) are often called the firm's *natural emissions*, as it has no incentive by itself to clean up any of the pollutants. And, $-C_s$ and $-C_g$ (> 0) are simply the marginal abatement costs of respective pollutants.

2.2 Centralized Regulation: Social Optimum

For a single authority (e.g., the EPA) responsible for regulating emissions of both pollutants, its goal would be to pursue maximal social welfare:

$$\max_{y,s,g} \; W \;\equiv\; R(y) \;-\; C(y,s,g) \;-\; D(s,g)$$

As such, the first-order conditions for socially desired (y^*, s^*, g^*) are:

$$C_y(y^*, s^*, g^*) \;=\; p \tag{1}$$

$$-C_s(y^*, s^*, g^*) \;=\; D_s(s^*, g^*) \;>\; 0 \tag{2}$$

$$-C_g(y^*, s^*, g^*) \;=\; D_g(s^*, g^*) \;>\; 0 \tag{3}$$

The conditions simply dictate that marginal abatement costs of each pollutant should be equal to its marginal external damages. We can also easily verify that optimal emissions (s^*, g^*) are lower than the unregulated firm choice (s^0, g^0), given $C_{ss} > 0$ and $C_{gg} > 0$.

2.3 Compartmentalized Regulation

In the following sections, we consider the cases when regulation of the two pollutants are divided across two un-coordinated government authorities: the *s-regulator* and the *g-regulator*. They are assumed to be concerned only with the pollution damages in their own jurisdiction. Therefore, their respective regulator objective is in general (with proper modifications in the following text): For the s-regulator, given (y, g), its objective would be:

$$\min_{s} \;\; D(s,g) \;+\; C(y,s,g) \tag{4}$$

whereas for the g-regulator, given (y, s), it will try to:

$$\min_{g} \;\; D(s,g) \;+\; C(y,s,g) \tag{5}$$

3 The Simultaneous-move Emission-Cap Game

We first analyze the simultaneous-move regulation scenario, in which both s- and g-regulators use emission cap (or discharge allowance) as the policy instrument. Let the emission caps adopted by the regulators be $\bar{s}$ and $\bar{g}$, respectively. To make an interesting case, we assuming that both caps are *binding*, i.e., they are lower than the firm's initial un-regulated natural emissions:[2]

$$\bar{s} < s^0, \;\; \bar{g} < g^0$$

3.1 The Nash Emission-Cap Game Γ^N

We model the interaction among the two regulators and the firm as a two-stage game:

- In Stage 1, both s- and g-regulators set their cap requirements simultaneously, thus engaging in a Nash-type interaction:

$$(\bar{s}^N, \; \bar{g}^N)$$

- In Stage 2, the compliant firm (with $s = \bar{s}^N$ and $g = \bar{g}^N$) decides its output $\bar{y}$.

3.2 The Nash Regulation Equilibrium

To solve for the equilibrium of the Nash cap game Γ^N, we begin with Stage 2 first, and then Stage 1 backwards.

In Stage 2, the firm's choice of y, given binding $(\bar{s}^N, \bar{g}^N)$ set in Stage 1, is:

$$\max_y \;\; R(y) \; - \; C(y, \bar{s}^N, \bar{g}^N)$$

The necessary condition is simply:

$$p \; - \; C_y(y, \bar{s}^N, \bar{g}^N) \; = \; 0 \tag{6}$$

which defines the optimal firm output implicitly:

$$\bar{y}(\bar{s}^N, \bar{g}^N) \tag{7}$$

The following comparative statics results can be easily obtained:

$$\frac{d\bar{y}}{d\bar{s}^N} \; = \; \frac{C_{ys}}{s.o.c.(-)} \; > \; 0$$

$$\frac{d\bar{y}}{d\bar{g}^N} \; = \; \frac{C_{yg}}{s.o.c.(-)} \; > \; 0$$

[2]Otherwise, the regulation will have no impact on firm choices.

Hence $\bar{y}$ is independent from $\bar{s}^N$ if y and s are separable in $C(y, s, g)$, and is similarly independent from $\bar{g}^N$ if y and g are separable in $C(y, s, g)$.[3]

Next we move up to Stage 1 to analyze the Nash interaction between the two regulators. For the s-regulator, given $\bar{g}^N$, its goal, by (4), is:

$$\min_{s} \ D(s, \bar{g}^N) \ + \ C(\bar{y}(s, \bar{g}^N), s, \bar{g}^N) \tag{8}$$

The Nash reaction function $\bar{s}^N(\bar{g}^N)$ is implicitly defined by the first-order condition:

$$D_s(\bar{s}^N, \bar{g}^N) \ + \ \left[C_y \cdot \frac{d\bar{y}}{d\bar{s}^N} \ + \ C_s(\bar{y}, \bar{s}^N, \bar{g}^N) \right] \ = \ 0 \tag{9}$$

As for the g-regulator, given $\bar{s}^N$, it will, by (5), look to:

$$\min_{g} \ D(\bar{s}^N, g) \ + \ C(\bar{y}(\bar{s}^N, g), \bar{s}^N, g) \tag{10}$$

We can also derive the Nash reaction function $\bar{g}^N(\bar{s}^N)$:

$$D_g(\bar{s}^N, \bar{g}^N) \ + \ \left[C_y \cdot \frac{d\bar{y}}{d\bar{g}^N} \ + \ C_g(\bar{y}, \bar{s}^N, \bar{g}^N) \right] \ = \ 0 \tag{11}$$

We can then solve for ($\bar{s}^N$, $\bar{g}^N$) jointly using the Nash functions (9) and (11).

4 The Sequential-move Emission-Cap Game

Now we turn to the sequential regulation scenario where the s- and g-regulators engage in a Stackelberg-type policy game.

4.1 The Stackelberg Emission Cap Game Γ^K

We assume that s-regulator acts first, followed by the g-regulator. The Stackelberg regulatory game now has three stages altogether.

- In Stage 1, the s-regulator (as *regulation leader*) determines the s-cap $\bar{s}^K$.
- In Stage 2, the g-regulator (as *regulation follower*) decides its g-cap $\bar{g}^K$, after observing the s-cap in effect.
- In the final Stage 3, the firm chooses its optimal output level y^K (in compliance with the cap requirements $s = \bar{s}^K$ and $g = \bar{g}^K$).

[3]Otherwise, $\bar{y}$ will vary with $\bar{s}^N$ if $C_{ys} \neq 0$, and vary with $\bar{g}^N$ if $C_{yg} \neq 0$.

4.2 The Stackelberg Regulation Equilibrium

Again we solve for the SPE backwards starting with Stage 3. Given the binding caps $(\bar{s}^K, \bar{g}^K)$ of the previous stages, the firm faces the problem:

$$\max_{y} \;\; R(y) \; - \; C(y, \bar{s}^K, \bar{g}^K)$$

and its optimal output

$$\bar{y}(\bar{s}^K, \bar{g}^K)$$

has exactly the same form as $\bar{y}$ in (7) of the Nash game Γ^N.

One step up to Stage 2, the *policy follower* g-regulator has a similar goal as in (10):

$$\min_{g} \;\; D(\bar{s}^K, g) \; + \; C(\bar{y}(\bar{s}^K, g), \bar{s}^K, g) \tag{12}$$

And its Nash reaction function $\bar{g}^K(\bar{s}^K)$ is similarly implicitly defined as in (11) by:

$$D_g(\bar{s}^K, \bar{g}^K) \; + \; \left[C_y \cdot \frac{d\bar{y}}{d\bar{g}^K} \; + \; C_g(\bar{y}, \bar{s}^K, \bar{g}^K) \right] \; = \; 0 \tag{13}$$

Further up to Stage 1, the *policy leader* s-regulator, aware of $\bar{g}^K(\bar{s}^K)$, would like to:

$$\min_{s} \;\; D(s, \bar{g}^K(s)) \; + \; C(\bar{y}(s, \bar{g}^K(s)), s, \bar{g}^K(s)) \tag{14}$$

The necessary optimality condition for $\bar{s}^K$ is hence:

$$\left[D_s + D_g \cdot \frac{d\bar{g}^K}{d\bar{s}^K} \right] \; + \; \left\{ C_y \cdot \left[\frac{\partial \bar{y}}{\partial \bar{s}^K} + \frac{\partial \bar{y}}{\partial \bar{g}^K} \cdot \frac{d\bar{g}^K}{d\bar{s}^K} \right] + C_s + C_g \cdot \frac{d\bar{g}^K}{d\bar{s}^K} \right\} \; = \; 0 \tag{15}$$

5 The Separable Function Case

Following Burtraw (2012),[4] we assume in this section *additive quadratic functional forms* for the cost function

$$C(y, s, g) \; = \; \left[c_y y \; + \; \frac{c_{yy} y^2}{2} \right] \; + \; \left[-c_s s \; + \; \frac{c_{ss} s^2}{2} \right] \; + \; \left[-c_g g \; + \; \frac{c_{gg} g^2}{2} \right] \tag{16}$$

and the pollution damage function

$$D(s, g) \; = \; \left[d_s s \; + \; \frac{d_{ss} s^2}{2} \right] \; + \; \left[d_g g \; + \; \frac{d_{gg} g^2}{2} \right] \tag{17}$$

[4]A major difference between our analysis and his is that he does not incorporate firm output y in his model.

where $c_y, c_{yy}, c_s, c_{ss}, c_g, c_{gg}, d_s, d_{ss}, d_g$, and d_{gg} are all positive parameters. Note that second derivatives

$$C_{ys} = C_{yg} = C_{sg} = 0 \quad \text{and} \quad D_{sg} = 0$$

indicates that there is no cross effect between these varibles in corresponding functions. It can be noted that the *constant marginal damage case*

$$D(s,g) = d_s s + d_g g$$

is simply a special case of the separable damage function (17).

5.1 Social Optimality

Now with the separable functions (16)(17), the optimality conditions (1)(2)(3) dictate:

$$y^* = \frac{p - c_y}{c_{yy}} \tag{18}$$

$$s^* = \frac{c_s - d_s}{c_{ss} + d_{ss}} \tag{19}$$

$$g^* = \frac{c_g - d_g}{c_{gg} + d_{gg}} \tag{20}$$

5.2 The Nash Regulation Equilibrium

With the separable functions (16)(17), firm's output choice y, solved from (6), is:

$$\bar{y} = \frac{p - c_y}{c_{yy}} \tag{21}$$

which is independent from its emission decisions. Furthermore, the regulators' Nash functions (9)(11) become:

$$\left[d_s + d_{ss}\bar{s}^N\right] + \left[-c_s + c_{ss}\bar{s}^N\right] = 0$$

$$\left[d_g + d_{gg}\bar{g}^N\right] + \left[-c_g + c_{gg}\bar{g}^N\right] = 0$$

and the equilibrium emission cap policies of the regulators are hence:

$$\bar{s}^N = \frac{c_s - d_s}{c_{ss} + d_{ss}} \tag{22}$$

$$\bar{g}^N = \frac{c_g - d_g}{c_{gg} + d_{gg}} \tag{23}$$

It can be noted that *these Nash caps $(\bar{s}^N, \bar{g}^N)$ coincide exactly with the socially optimal (s^*, g^*).*

5.3 The Stackelberg Regulation Equilibrium

Now, note first that, given cap combination $(\bar{s}^K, \bar{g}^K)$, firm output choice $\bar{y}(\bar{s}^K, \bar{g}^K)$ is the same as in (21) in the Nash regulation game:

$$\bar{y} = \frac{p - c_y}{c_{yy}} \tag{24}$$

and hence is not affected by the emission caps:

$$\frac{d\bar{y}}{d\bar{s}^K} = 0, \quad \frac{d\bar{y}}{d\bar{g}^K} = 0 \tag{25}$$

Next, given the leader cap $\bar{s}^K$ set in Stage 1, the policy follower g-regulator's reaction function $\bar{g}^K(\bar{s}^K)$ is exactly the same as that in the Nash game:

$$\bar{g}^K = \frac{c_g - d_g}{c_{gg} + d_{gg}} \tag{26}$$

and hence is independent of the leader's cap choice $\bar{s}^K$:

$$\frac{d\bar{g}^K}{d\bar{s}^K} = 0 \tag{27}$$

Finally, we get to the policy leader s-regulator's optimality condition (15) for cap $\bar{s}^K$, which now, given (25)(27), yields:

$$\bar{s}^K = \frac{c_s - d_s}{c_{ss} + d_{ss}} \tag{28}$$

Comparing (22)(23) and (26)(28), we can see that both simultaneous and sequential emission cap games have the same equilibrium regulation when firm cost function and pollution damage function are both separable.

6 Conclusions

In this paper, we consider two different pollution regulation regimes when multiple pollutants are generated during firm production process: *centralized regulation* versus *compartmentalized regulation*. In the former, a single government authority is responsible for regulating all types of pollutants; whereas in the latter, regulation of different pollutants are assigned to independent authorities. In the compartmentalized regulation case, we further compare two possible regulation settings: *simultaneous-move Nash regulation game* versus *sequential-move Stackelberg regulation game*.

It is shown in our analysis that, when firm cost function and pollution damage function are both separable, *compartmentalized regulations (Nash as well as Stackelberg regulation) result in the same performance policies as the efficient centralized regulation.* Otherwise, compartmentalization in pollution regulation will result in different firm output and pollution emissions from the efficient levels.

References

1. Ayres, R.U. and Kneese, A.V. (1969) "Production, Consumption, and Externalities," *American Economic Review*, 59(3), 282–297.

2. Beavis, B. and Walker, M. (1979) "Interactive Pollutants And Joint Abatement Costs," *Journal of Environmental Economics and Management*, 6, 275–286.

3. Burtraw *et al.* (2012) "Robust Instrument Choice When Environmental Regulations Spill Over," paper presented in the *19th Annual Conference of the European Association of Environmental and Resource Economists*, Prague.

4. Hahn, R.W. (1989) "A New Approach to the Design of Regulation in the Presence of Multiple Objectives," *Journal of Environmental Economics and Management*, 17, 195–211.

5. Hendrickson, C.T. and F.C. McMichael (1985) "Controlling Contradictions among Regulators: Note," *American Economic Review*, 75(4), 876–877.

6. Lave, L.B. (1984) "Controlling Contradictions among Regulators," *American Economic Review*, 74(3), 471–475.