Environmental Efficiency of Four Emission-Reducing Instruments: Emission Tax, Emission Cap, Hybrid, and (General) Indexed Quantity

Hsiao-Chi Chen and Shi-Miin Liu

Department of Economics, National Taipei University

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Literature Review

- Weitzman (1974) compares the price and quantity controls over a monopoly firm in a model with cost and benefit uncertainties. He finds that price control is preferred when the marginal cost function is relatively steeper than marginal benefit function. In contrast, the quantity control is better if the marginal benefit function is relatively steeper.

- By regarding an emission tax as a price control and an emission cap as a quantity control, the outcomes of Weitzman (1974) can be used to compare the social welfare of emission tax and emission cap.

- Precisely, if the damages rise sharply as the emission control level is relaxed, but the marginal control costs do not differ greatly, it is more important to get the quantity of emission right, hence the emission cap is preferred. In contrast, if damages are not sensitive to current emissions, but the costs rise sharply as emissions increase, then it is important to get the price of emission right, hence the emission tax is preferred.

- However, the emission tax is often politically unappealing especially in US even though it is more efficient than the emission cap (see Pizer (1999, 2002)). On the other hand, the emission cap could lead to high compliance costs due to uncertainty even though it is politically appealing. Two other types of policy instruments arise.

- (General) indexed quantity in which the regulator sets firm's emission limit proportional to some index variables such as GDP or firm's outputs (plus some constant).

(a) Ellerman and Wing (2003) show that an indexed quantity performs better than an emission cap.

(b) Jotzo and Pezzey (2007) reach similar conclusions when comparing the emission cap and indexed quantity in a setting of international greenhouse gas emission trading.

(c) Comparing the welfare impacts of emission tax, emission cap, and indexed quantity, Quirion (2005) shows that either emission tax or emission cap yields a higher expected welfare than an indexed quantity.

(d) Newell and Pizer (2008) compare two types of indexed quantity policies with emission tax and emission cap. They show that a general indexed quantity is always preferred to an emission cap, while the relative advantage of general indexed quantity and emission tax depends on the correlation between the index variable and cost shock, as well as the relative slopes of marginal cost and marginal benefit of emissions. In contrast, the indexed quantity policy is preferred to the emission cap when the ratio of the coefficient of variation in index variable and the coefficient of variation in the ex post optimal quantity level is less than twice of their correlation.

- Hybrid policy is a policy instrument combining both price and quantity controls. Under a hybrid policy, an emission cap is set through distributing firms free emission permits, and firms are allowed to buy unlimited amount of permits from the regulator at a predetermined (or trigger) price if their emissions exceed the allocated permit amounts.

  (a) Pizer (2002), Jacoby and Ellerman (2004), McKibbin and Wilcoxen (2002) display that the hybrid policy could outperform either emission tax or emission cap policy.

(b) Webster et al. (2010) compare emission cap, hybrid, and (general) indexed quantity. In our limited knowledge, Webster et al. (2010) is the first piece to provide an analytical solution of hybrid policy. They find that the superiority of the general indexed quantity and hybrid depends on the correlation between cost shocks and index variables, relative slopes of marginal benefit and cost of firms' emissions, and the probability of the hybrid policy being triggered. Moreover, given the probabilities of hybrid policy being activated, Webster et al. (2010) derive the minimum correlation level between cost shock and index variable required for an indexed quantity outperforming a hybrid. Their simulation results show that these minimum correlation levels are so high that the hybrid policy is more practical for the regulator.

Our Motivations

- All the works above analyze these policy instruments from the view of maximizing net benefit of emissions.

- As the global warming problems become more and more serious, the irregular climate has appeared more frequently, and devastated many countries by bring large scale of flood and/or drought.

- On the other hand, the international negotiation of reducing greenhouse gas emissions of most countries seems to face deadlocks.

- Thus, how to effectively reduce firms' pollutant emissions in a short time has become an emergent and unavoidable question for all countries. Thus, this paper tries to explore the environmental efficiency of the above policy instruments. Precisely, we like to find which of these instruments can induce firms' smallest emissions.

- Garvie and Keeler (1994) and Macho-Stadler and Perez-Castrillo (2006) also adopt this criterion to analyze regulator's auditing policy. But our paper is the first attempt to analyze the environmental efficiency of the above instruments.

Our Findings

- Unlike in Weitzman (1974), an emission tax is always preferred to an emission cap.

- Unlike in Newell and Pizer (2008), an emission tax is always preferred to a general indexed quantity.

- Unlike in Webster et al. (2010), a hybrid policy is always preferred to the general indexed quantity policy.

- Among the policy instruments of emission tax, emission cap, hybrid, and general indexed quantity, the hybrid policy is the most efficient in reducing firm's emissions.

- Moreover, we show that emission-permit trading is a perfect substitute of emission tax when it is politically infeasible.

- Finally, we investigate the superiority of emission tax, emission cap, hybrid, and indexed quantity. We derive the conditions under which the indexed quantity is the most efficient one. In the remaining situations, the hybrid policy remains the best one. Our conditions could be different from Webster et al.’s (2010). Moreover, we find that an indexed quantity performs better than a hybrid policy in more situations.

The Models

- There are one regulator and one firm.

- Denote e the firm's pollutant emissions.

- Following Weitzman (1974), we adopt the ensuing quadratic functions of abatement cost of emissions.

$$C(e,\varepsilon)=c_0-c_1e+\frac{c_2}{2}e^2-\varepsilon e \qquad (1)$$

where c_i, $i=0,1,2,$ are positive parameters, and ε represents cost shock with zero mean and variance σ_ε^2. Denote $f(\varepsilon)$ the probability density function (pdf) of ε over the range $[-\underline{\varepsilon},\underline{\varepsilon}]$ with $\underline{\varepsilon}>0$.

- Positive ε will reduce firm's abatement cost, while negative ε will raise it. The above equation implies a strictly convex and linear marginal abatement cost as follows.

$$C'(e,\varepsilon)=-c_1+c_2e-\varepsilon.$$

To have $C'(e,\varepsilon)<0$ for all e and ε, we assume $c_1>c_2e_b+\underline{\varepsilon}$.

Equilibrium Emission Tax Policy

Our sequential game proceeds as follows. The regulator first announces an emission tax, t^*, to minimize her expected firm's emission subject to firm's expected abatement cost not exceeding a upper limit $\bar{c} > 0$. That is, t^* is the solution of the following problem.

$$\min Ee \quad \text{s.t.} \quad EC(e) \leq \bar{c}, \tag{2}$$

where E is the expectation operator taken over ε Then, a value of cost shock (ε) is realized and revealed to the firm. In the second stage, given t^* and ε, the firm chooses optimal emission level e_T^* to minimize its total cost

$$TC_t \equiv C(e,\varepsilon)+te\,.$$

- By backward induction, we can derive the following subgame perfect equilibrium (hereafter SPE), (t^*, e_T^*).

Proposition 1. *Suppose* $\frac{\sigma_\varepsilon^2}{2(c_0-\bar{c})} < c_2 < \frac{c_1^2+\sigma_\varepsilon^2}{2(c_0-\bar{c})}$. *Then the SPE of emission tax policy is* $(t^* = \sqrt{c_1^2+2c_2(\bar{c}-c_0)+\sigma_\varepsilon^2}, e_T^* = \frac{c_1-t^*+\varepsilon}{c_2})$. *At equilibrium, the expected firm's emission*

$$Ee_T^* = \frac{c_1-t^*}{c_2} = \frac{c_1-\sqrt{c_1^2+2c_2(\bar{c}-c_0)+\sigma_\varepsilon^2}}{c_2} > 0. \qquad (3)$$

- At optimal emission level, firm's marginal cost of emissions ($-C'(e_T^*, \varepsilon)$) equals the emission tax (t^*). Moreover, firm's optimal emissions decrease with emission tax.

- The regulator will choose the optimal emission tax at which the expected firm's abatement cost equals the upper bound ($\bar{c}$). Moreover, the equilibrium emission tax will increase as the variance of cost shock increases.

Equilibrium Emission Cap Policy

- Our sequential game proceeds as follows. The regulator first announces an emission cap, $\bar{e}_Q^*$, to solve the problem defined in (2). Then, a value of cost shock is realized and revealed to the firm. In the second stage, given $\bar{e}_Q^*$ and ε, the firm chooses emission level e_Q^* to solve the problem of

$$\min_{e} \ C(e,\varepsilon) \quad \text{s.t. } e \le \bar{e}_Q^*.$$

- Again, by backward induction, we can get the ensuing SPE, $(\bar{e}_Q^*, e_Q^*)$.

Proposition 2. *Suppose* $c_2 < \frac{c_1^2}{2(c_0 - \bar{c})}$. *Then the SPE of emission cap policy is* $\left(\bar{e}_Q^* = \frac{c_1 - \sqrt{c_1^2 + 2c_2(\bar{c} - c_0)}}{c_2}, e_Q^* = \bar{e}_Q^*\right)$. *At equilibrium, the regulator's expected firm's emissions*

$$Ee_Q^* = e_Q^* = \frac{c_1 - \sqrt{c_1^2 + 2c_2(\bar{c} - c_0)}}{c_2} > 0. \tag{4}$$

- Since firm's abatement cost will decrease with its rising emissions, it is optimal for the firm to discharge as many emissions as possible. Thus, the emission cap is firm's optimal emission level.

- To reduce firm's emissions, the regulator will set emission cap as low as possible. However, the firm's equilibrium abatement cost will increase as the emission cap decreases. Thus, it is optimal for the regulator to choose the emission cap, at which the expected firm's abatement cost equals the upper bound ($\bar{c}$).

- It is worthy to point out that the equilibrium emission cap is unaffected by cost shocks.

Equilibrium Hybrid Policy

- Our sequential game proceeds as follows. The regulator first announces $(\bar{e}_H^*, p_H^*)$, where $\bar{e}_H^*$ is the permit amount distributed to the firm and p_H^* is the trigger price at which the firm can buy unlimited amount of emission allowance when its emission level exceeds $\bar{e}_H^*$. This hybrid policy solves the problem defined in (2). Then, a value of cost uncertainty is realized and observed by the firm. In the second period, given $(\bar{e}_H^*, p_H^*)$ and ε, the firm chooses the emission level e_H^* to minimize its total cost

$$TC_h = \begin{cases} C(e,\varepsilon) + p(e - \bar{e}_H^*) & \text{if } e \leq \bar{e}_H^*, \\ C(e,\varepsilon) + \min\{p, p_s^*\} \cdot (e - \bar{e}_H^*) & \text{if } e > \bar{e}_H^*, \end{cases}$$

where p is the exogenous permit market price.

- By backward induction, we can derive the SPE, $\{(\bar{e}_H^*, p_H^*), e_H^*\}$, below.

Proposition 3. *There are three possible SPEs of the hybrid policy as follows.*

(i) Suppose $c_1 > p$ *and* $\varepsilon \leq \underline{\varepsilon} - \frac{(p - p_{s1}^*)}{2}$. *Then* $\{(\bar{e}_{h1}^* = \frac{c_1 - p + \varepsilon}{c_2}, p_{h1}^*), e_{h1}^* = \frac{c_1 - p + \varepsilon}{c_2}\}$ *with arbitrary* $p_{h1}^* < p$ *consists of a SPE. At equilibrium, the expected firm's emission is*

$$E(e_{h1}^{*})=\frac{(c_1-p)}{c_2}>0.$$

(ii) *Suppose* $c_1>p+\underline{\varepsilon}$. *Then* $\{(\bar{e}_{h2}^{*}=\frac{c_1-p-\underline{\varepsilon}}{c_2},p_{h2}^{*}),e_{h2}^{*}=\frac{c_1-p+\varepsilon}{c_2}\}$ *with arbitrary* $p_{h2}^{*}>p$ *consists of a SPE. At equilibrium, the expected firm's emission is the same as that in part (i).*

(iii) *Suppose* $c_1>p_{s3}^{*}+\underline{\varepsilon},\frac{\sigma_{\varepsilon}^{2}}{2(c_0-\bar{c})}<c_2<\frac{c_1^2+\sigma_{\varepsilon}^{2}}{2(c_0-\bar{c})}$, *and* $\varepsilon\geq\frac{(p-p_{s3}^{*})}{2}-\underline{\varepsilon}$. *Then* $\{(\bar{e}_{h3}^{*}=\frac{c_1-p_{s3}^{*}-\underline{\varepsilon}}{c_2},p_{h3}^{*}=\sqrt{c_1^2+2c_2(\bar{c}-c_0)+\sigma_{\varepsilon}^{2}}),e_{h3}^{*}=\frac{c_1-p_{s3}^{*}+\varepsilon}{c_2}\}$ *with* $p_{h3}^{*}<p$ *consists of a SPE. At equilibrium, the expected firm's emission is*

$$E(e_{h3}^{*})=\frac{(c_1-p_{h3}^{*})}{c_2}=\frac{c_1-\sqrt{c_1^2+2c_2(\bar{c}-c_0)+\sigma_{\varepsilon}^{2}}}{c_2}>0.$$

- Proposition 3 shows that there are three possible SPEs in hybrid policy. The equilibria in Proposition 3(i) and (ii) cannot occur simultaneously because the firm sells permits to the market in the former equilibria, but buys permits from the market in the later equilibria. Nevertheless, both equilibria lead to the same equilibrium expected firm's emissions. In contrast, at the equilibrium of Proposition 3(iii), the firm purchases permits from the regulator at trigger prices lower than permit market price.

- Webster et al. (2010) investigate the hybrid policy maximizing the social welfare, while we explore the hybrid policy being environmentally efficient. Moreover, Webster et al. (2010) assume that firm's allocated permits are exogenous, but they are endogenous in our model.

- Finally, at equilibria of Proposition 3(i)-(ii), the hybrid policy is not triggered, while it is triggered at equilibria of Proposition 3(iii). Denote π the probability that the hybrid policy is triggered. Accordingly, the expected firm's emission under hybrid policy is

$$E(e_H^*) \equiv \frac{c_1 - [\pi p_{h3}^* + (1-\pi)p]}{c_2}. \tag{5}$$

Equilibrium General Indexed Quantity Policy

- The regulator chooses emission limit $\bar{e}$ as a linear function of another exogenous variable x, such as GDP. That is,

$$\bar{e}(x) = a + rx,$$

where a and r are policy design variables and $E(x) = \bar{x}, V(x) = \sigma_x^2,$ and $Cov(x, \varepsilon) = \sigma_{x\varepsilon}.$

- A two-stage game proceeds as follows. First, the regulator announces $(a^*, r^*),$ which solves the problem defined in (2). Then, a pair random variable (ε, x) is realized and observed by the firm. In the second period, given (a^*, r^*) and (ε, x), the firm chooses emission level e^*_{GIQ} to minimize its abatement cost given the emission cap $(a^* + r^* x)$.

- By backward induction, we can obtain the SPE, $\{(a^*, r^*), e^*_{GIQ}\}$, below.

Proposition 4. *Suppose* $\frac{\sigma^2_{\bar{x}\varepsilon}/\sigma^2_{\bar{x}}}{2(c_0-\bar{c})} < c_2 < \frac{c_1^2+(\sigma^2_{\bar{x}\varepsilon}/\sigma^2_{\bar{x}})}{2(c_0-\bar{c})}$. *Then* $\{(a^* = \frac{(c_1 - \frac{\sigma_{x\varepsilon}\bar{x}}{\sigma^2_{\bar{x}}}) - \sqrt{c_1^2 + 2c_2(\bar{c}-c_0) + (\sigma^2_{\bar{x}\varepsilon}/\sigma^2_{\bar{x}})}}{c_2},$ $r^* = \frac{\sigma_{x\varepsilon}}{c_2\sigma^2_{\bar{x}}}), e^*_{GIQ} = (a^* + r^* x)\}$ *is a SPE of the general indexed quantity policy. At equilibrium, the expected firm's emission*

$$E(e^*_{GIQ}) = a^* + r^*\bar{x} = \frac{c_1 - \sqrt{c_1^2 + 2c_2(\bar{c}-c_0) + (\sigma^2_{x\varepsilon}/\sigma^2_{x})}}{c_2} > 0. \qquad (6)$$

- The higher correlation between x and ε is, the lower expected firm's emissions are. The intuition is similar to Newell and Pizer's (2008). Higher correlation enables the regulator extract more valuable information about cost shocks from the observable index variable. Thus, the regulator could design a more effective policy to lower firm's emissions.

Comparisons of Four Emission-Reducing Instruments

- We first compare the instruments of emission tax, emission cap, and general indexed quantity. By (3) and (4), we have

$$E(e_T^*) - E(e_Q^*) = \frac{\sqrt{c_1^2 + 2c_2(\bar{c} - c_0)} - \sqrt{c_1^2 + 2c_2(\bar{c} - c_0) + \sigma_\varepsilon^2}}{c_2} \leq 0. \qquad (7)$$

- It implies that under cost uncertainty the emission tax policy is always preferred to the emission cap policy.

- This outcome is different from Weitzman (1974), in which the relative advantages of emission tax and emission cap are determined by the relative steepness of marginal benefit and cost of emissions.

- Proposition 1 shows that the equilibrium emission tax under uncertainty is larger than that under no uncertainty, while the equilibrium emission caps under both uncertainty and no uncertainty are the same by Proposition 2. Thus, higher emission tax will induce the firm to discharge fewer emissions under emission tax scheme than that under emission cap scheme in the presence of cost uncertainty.

- By (3) and (6), we have

$$E(e_T^*) - E(e_{GIQ}^*) = \frac{\sqrt{c_1^2 + 2c_2(\bar{c} - c_0) + (\sigma_{x\varepsilon}^2 / \sigma_x^2)} - \sqrt{c_1^2 + 2c_2(\bar{c} - c_0) + \sigma_\varepsilon^2}}{c_2} \leq 0 . \tag{8}$$

- It means that an emission tax policy is always more efficient than a general indexed quantity policy. This outcome is different from Newell and Pizer (2008).

- . By (4) and (6), we obtain

$$E(e_Q^*) - E(e_{GIQ}^*) = \frac{\sqrt{c_1^2 + 2c_2(\bar{c} - c_0) + (\sigma_{x\varepsilon}^2 / \sigma_x^2)} - \sqrt{c_1^2 + 2c_2(\bar{c} - c_0)}}{c_2} \geq 0 . \tag{9}$$

- It implies that a general indexed quantity is always more efficient than an emission cap policy.

- Combining (7)-(9) yields

$$E(e_T^*) \le E(e_{GIQ}^*) \le E(e_Q^*). \tag{10}$$

- Under a general indexed quantity, the regulator could collect extra information of cost shock from the index variable. Thus, the regulator does not face the full extent of uncertainty. In contrast, the regulator faces the full extent of uncertainty under an emission tax, but is unaffected by cost uncertainty under an emission cap. Thus, the equilibrium emission tax policy will be the most severe one to offset the adverse effects of cost uncertainty, the equilibrium general indexed policy is the next, and the equilibrium emission cap policy is less severe. Accordingly, the emission tax policy will lead to the smallest firm's emissions on average when compared with the emission cap and general indexed quantity.

- By (3) and (5), we have

$$E(e_H^*) - E(e_T^*) = \frac{(1-\pi)(p_{h3}^* - p)}{c_2} < 0 \quad (11)$$

due to $p_{h3}^* < p$.

- At hybrid policy, the firm will trade permits in the market at price p with probability $(1-\pi)$ and buy permits from the regulator at price p_{h3}^{*} with probability π Since the trigger price (p_{h3}^{*}) is less than market price (p) and equal to the equilibrium emission tax (t^{*}), the average trading price faced the firm under the hybrid policy is greater than the equilibrium emission tax. Accordingly, firm's expected emissions will be smaller at hybrid policy than at emission tax policy. Thus, the hybrid policy is the most effective in reducing firm's emissions.

• Combining (10) and (11) yields the following outcomes.

Proposition 5. *Suppose the regulator considers four policy instruments of emission tax, emission cap, hybrid, and general indexed quantity in reducing firm's emissions. It is further assumed that* $\frac{\sigma_{\varepsilon}^2}{2(c_0-\bar{c})} < c_2 < \frac{c_1^2}{2(c_0-\bar{c})}$. *Then the hybrid policy is the most environmentally efficient among these four policies.*

- Webster et al. (2010) show that the relative advantages of hybrid and general indexed quantity are determined by the correlation of index variable and cost shocks, and the slopes of marginal cost and marginal benefit of emissions. However, in our model, hybrid policy is always more efficient than the general indexed quantity in reducing firm's emissions.

Extensions

● The two-stage game associated with emission permit trading policy is as follows. First, the regulator announces the permit amount, L^*, distributed to the firm. Then, a value of cost shock, ε, is realized. Second, given (L^*, ε), the firm chooses the emission level e_L^* solving the problem of

$$\min_e C(e, \varepsilon) + p(e - L^*),$$

where $p = p(L^*)$ is the permit price at permit amount L^* with $\frac{dp}{dL} < 0$.

Proposition 6. *Suppose* $\frac{\sigma_\varepsilon^2}{2(c_0-\bar{c})}<c_2<\frac{c_1^2+\sigma_\varepsilon^2}{2(c_0-\bar{c})}$. *Then the SPE of emission permit trading policy is* $\{L^*, e_L^*=\frac{c_1-p(L^*)+\varepsilon}{c_2}\}$ *with* $p(L^*)=\sqrt{c_1^2+2c_2(\bar{c}-c_0)+\sigma_\varepsilon^2}$. *At equilibrium, the expected firm's emission*

$$Ee_L^*=\frac{c_1-p(L^*)}{c_2}=\frac{c_1-\sqrt{c_1^2+2c_2(\bar{c}-c_0)+\sigma_\varepsilon^2}}{c_2}>0.$$

- It means that the emission permit trading scheme is a perfect substitute of the emission tax policy.

- The game associated with indexed quantity policy is the same as that of general indexed quantity except that $\bar{e}(x) = a + rx$ is replaced with $\bar{e}(x) = rx$ The corresponding SPE,$\{r^{**}, e^{*}_{IQ}\}$, is derived below.

Proposition 7. *Suppose* $c_2 < \frac{(c_1\bar{x}+\sigma_{x\varepsilon})^2}{2(c_0-\bar{c})(\bar{x}^2+\sigma_x^2)}$. *Then,*$\{r^{**} = \frac{(c_1\bar{x}+\sigma_{x\varepsilon})-\sqrt{(c_1\bar{x}+\sigma_{x\varepsilon})^2+2c_2(\bar{c}-c_0)(\bar{x}^2+\sigma_x^2)}}{c_2(\bar{x}^2+\sigma_x^2)}$, $e^{*}_{IQ} = r^{**}x\}$ *is the SPE of indexed quantity policy . At equilibrium, the expected firm's emission is*

$$E(e^{*}_{IQ}) = r^{**}\bar{x} = \frac{(c_1+v_{x\varepsilon})-\sqrt{(c_1+v_{x\varepsilon})^2+2c_2(\bar{c}-c_0)(1+v_x^2)}}{c_2(1+v_x^2)}, \qquad (12)$$

where $v_{x\varepsilon} = \frac{\sigma_{x\varepsilon}}{\bar{x}}$ *is the coefficient of covariance between index variable and cost shock, and* $v_x = \frac{\sigma_x}{\bar{x}}$ *is the coefficient of variation of the index* *variable.*

• By (5) and (12), we have

$$E(e_{IQ}^*)-E(e_H^*)=\frac{(c_1+v_{x\varepsilon})-\sqrt{(c_1+v_{x\varepsilon})^2+2c_2(\bar{c}-c_0)(1+v_x^2)}-(1+v_x^2)[c_1-\pi p_{s4}^*-(1-\pi)p]}{c_2(1+v_x^2)}.$$

Proposition 8. *Suppose the regulator considers four policy instruments of emission tax, emission cap, hybrid, and indexed quantity in reducing firm's emissions. Then, we have the followings.*

(i) *Suppose* $c_1-\sqrt{c_1^2+2c_2(\bar{c}-c_0)(1+v_x^2)}\leq(1+v_x^2)[c_1-\pi p_{h3}^*-(1-\pi)p]$. *Then the indexed quantity policy is preferred for all* $v_{x\varepsilon}$.

(ii) *Suppose* $c_1 - \sqrt{c_1^2 + 2c_2(\bar{c} - c_0)(1 + v_x^2)} > (1 + v_x^2)[c_1 - \pi p_{h3}^* - (1 - \pi) p]$. *Then the indexed quantity policy is preferred for* $v_{x\varepsilon} \geq v_{x\varepsilon}^0$, *and the hybrid policy is preferred for* $v_{x\varepsilon} < v_{x\varepsilon}^0$, *where* $v_{x\varepsilon}^0$ *is defined in the paper.*

- Proposition 8 shows that either hybrid or the indexed quantity policy is the most efficient in reducing firm's emissions among the policy instruments of emission tax, emission cap, hybrid, and indexed quantity.

- We find an indexed quantity performs better than a hybrid in more situations.

Conclusions

- This paper explores the environmental efficiency of four emission-reducing policies: emission tax, emission cap, hybrid, and general indexed quantity.

- For each policy instrument, we construct a two-stage game to characterize the interactions between one regulator and one firm.

- Unlike in Weitzman (1974), an emission tax is always more efficient than an emission cap.

- Unlike in Newell and Pizer (2008), an emission tax is always more efficient than a general indexed quantity.

- Unlike in Webster et al. (2010), a hybrid policy is always more efficient than a general indexed quantity.

- Among these four policy instruments, the hybrid policy is the most efficient in reducing firm's emissions.

- When an emission tax policy is politically infeasible, we show that an emission permit trading policy can completely play the role of emission tax.

- Finally, we compare the policy instruments of emission tax, emission cap, hybrid, and indexed quantity. We find the conditions under which the indexed quantity is the most efficient. In the remaining cases, the hybrid policy still remains the most efficient one.

- In the future, we will extend our model by considering more polluting firms or by considering the *ex post*, instead of *ex ante*, environmental efficiency (or maximum net welfare) of these policy instruments.

Thanks for your attentions!