

*Tradable Permits versus Effluent Charges under Cost Uncertainty and
Fuel Price Volatility*

Abdi H. Ali
(6970487)

Major paper presented to the
Department of Economics of the University of Ottawa
in partial fulfillment of the requirements of the M.A Degree
Supervisor: Professor M. Leslie Shiell

ECO 6999

Ottawa, Ontario
August 2013

Abstract

This paper compares price-based and quantity-based environmental regulation policies on efficiency grounds when the regulator is uncertain about the future price of fossil fuels and the firms' marginal abatement costs (MAC). In doing so, two key issues are considered. First, it investigates whether assuming complementarity between fossil fuels and emissions in the face of volatile oil prices alters the Weitzman results. Secondly, it examines how the choice between permits and taxes is affected if innovations in the marginal abatement costs are unidirectional. With regards to the first issue, Weitzman's analysis remains intact. As for the second issue, it is found that uncertainty in the marginal abatement cost does not affect instrument choice. The paper thus provides new theoretical insights on the insignificance of the MAC uncertainty for the choice of market-based environmental policies when innovations in MAC are unidirectional.

Acknowledgement

I am greatly indebted to Professor Leslie Shiell for his insightful advice and unwavering support in completing this Major Paper. I could not have asked for a better supervisor.

Table of Contents

I. Introduction.....	1
II. Literature Review.....	4
III. Fuel Price Volatility and the Case where $E(u) = 0$	8
IV. Fuel Price Volatility and the Case of Unidirectional Innovations in the MAC	13
V. Conclusion	16
Appendix	19
Reference List	20

I. Introduction

Economic theory has long established that in the presence of competitive markets and perfect certainty, it does not matter whether a regulatory body announces a price for the regulated substance or orders a quantity limit, as both instruments will lead to the same social welfare (Weitzman, 1974; Baumöl and Oates, 1988). Nevertheless, in an environment of uncertainty and incomplete knowledge, the two regulatory instruments generate different expected welfare. In a seminal paper, Weitzman determined that, under uncertainty, the choice between price-based and quantity-based instruments depends on the relative slopes of the underlying curves; with price-based instruments selected if the marginal cost curve is relatively steeper. Conversely, a quantity-based policy is selected if the slope of the marginal benefits curve is greater than that of the marginal costs.

The goal of this paper is twofold. First, it evaluates the relative desirability of the two instruments when fuel prices are volatile. In doing so, it is assumed that emissions and fuel inputs are perfect complements, an assumption that is not considered in the literature, but plausible given that greenhouse gas emissions are a by-product of fossil fuel inputs. It thus seeks to answer the policy question; does complementarity of fossil fuels and emissions alter the Weitzman results given the volatile nature of fuel prices?

Prices of fossil fuels have behaved erratically since the oil crises of the 1970s (Figure 1 in the Appendix) and are generally believed to be more volatile than other commodities (Bookout, 1990; Verleger, 1994). In fact Regnier (2007) finds that, from 1986, crude oil, refined petroleum and natural gas prices were more unstable than the prices for about 95% of commodities produced in the US. In such a volatile environment, the expectation is that firms will substitute away from fuel inputs when fuel prices are rising and increase their use in the production process

when prices are falling. Correspondingly, many studies have shown that consumers respond to rising gasoline prices by driving less and increasing their demand for fuel-efficient cars (Busse, Knittel & Zettelmeyer, 2009; Gillingham, 2012).

Given that greenhouse gas emissions are directly proportional to fossil fuel combustion, it is anticipated that volatile fuel prices have important implications for environmental policies aimed at curbing GHG emissions. When fuel prices are higher, agents in the market respond by reducing their consumption of fossil fuels. Consequently, emission levels are expected to decline. The reverse is anticipated when prices are lower. Given this effect of fuel price volatility on emissions, one would think that, between the two instruments examined in this paper, emission taxes are excessive when fuel prices are rising and inadequate when they are falling.

On the contrary, permits are thought to deliver offsetting price adjustments in the face of volatile fuel prices. For instance, decreasing emission levels under high fuel prices shifts demand for permits inward, pushing permit prices down. This flexibility is lacking under emission taxes, yet in 2008 when oil prices were highly volatile, jurisdictions such as the province of British Columbia adopted a carbon tax as an environmental policy. In the summer of 2008, oil prices surged to a record high of US\$136 (in 2013\$) per barrel before sharply plummeting to less than US\$40 a barrel by the end of that year. The analysis in the present paper hence provides insights into whether such carbon tax policy is justifiable in the face of volatile oil prices.

The second objective of this paper is to investigate choice between the two instruments when the stochastic components of the marginal abatement cost are unidirectional. Weitzman assumes that both positive and negative innovations in the marginal abatement costs are possible, yet there is a vast literature that models technical change as reduction in the marginal abatement

costs (Downing and White, 1986; Milliman and Prince, 1989; Montero, 2002a; Rosendahl, 2004). Moreover, several studies have shown that end-of-pipe technologies such as Scrubbers and smokestacks lead to a uniform downward shift of the marginal abatement cost curve (Bauman, Lee & Seeley, 2008; Amir, Germain & Steenberghe, 2008). Nevertheless, these studies also show that technical changes in production process may in fact increase abatement costs. In line with most literature, the second goal of the present paper is to evaluate the case where innovations in the marginal control costs are always negative.

To conduct this analysis, standard micro-economic tools are employed. Assumptions in the Weitzman model such as risk neutral agents, linear marginal benefits and marginal cost curves, and additive error terms are maintained. Both forms of uncertainty (technological and fuel price) are assumed to be uncorrelated, with their true probability distributions known to the regulator. It is also postulated uncertainty exist only on the part of the regulator and not at the firm level. As in Heuson (2010), environmental regulation can be thought of as a Stackelberg game with two phases. In the first phase the regulator selects the instrument and in the second, polluters respond to the policy choice. Firms will therefore utilize in their decisions new information that is observed in the time lag between the first and second stages.

With regards to the first goal, it is found that Weitzman's key proposition remains intact. However, under fuel price volatility, the magnitude of the relative advantage coefficient is amplified and proportionately increases with the variance of fuel prices. The key finding of the second exercise is that, if innovations in the marginal abatement costs are unidirectional and fuel and emissions are not modelled as complements (as in Weitzman), both instruments would yield the same expected welfare. Consequently, the Weitzman analysis would collapse.

The next section reviews the literature on “prices versus quantities”. Section III presents the extended price versus quantities model and characterizes the relative advantage of effluent charges over permits for the case where both positive and negative innovations in marginal abatement costs are possible. In Section IV, the analysis is extended to the case where innovations in the marginal abatement costs are unidirectional. Section V concludes the paper.

II. Literature Review

Weitzman (1974) investigated the choice between prices and quantities as planning instruments in the presence of uncertainty. Under the assumptions of linear marginal benefits and marginal costs, risk neutral agents and additive shocks, he found that when marginal costs are unknown to the regulator, the choice is contingent on the relative slopes of the marginal benefit and the marginal cost curves. When the latter is steeper than the former, a price instrument yields larger expected welfare. Conversely, a quantity instrument is preferred when the marginal benefit curve is steeper than the marginal cost curve. Uncertainty in the benefit function is shown to affect both instruments equally as firms respond to the regulator’s decisions along the cost curve. It is therefore deemed irrelevant in the choice between price and quantity instruments.

Adar and Griffin (1976) and Fishelson (1976) have independently explored the topic from an environmental regulation perspective and found similar results. Adar and Griffin also considered firm attitude towards risk when genuine uncertainty exists both at the agency and the firm level. Alluding to Sandmo (1971), they note that when permit prices are uncertain, risk averse firms abate emissions where the expected permit price is greater than the marginal control costs¹. Consequently, the relative advantage of one instrument over the other will, besides the relative slopes of the underlying curves, depend on the firms’ degree of risk aversion. However,

¹ If instead these firms are uncertain about the MAC, they abate emissions where $t >$ expected MAC

pertaining to risk aversion, the authors do not stipulate a systematic approach that ranks the two instruments on efficiency grounds. In contrast, decisions of risk neutral firms do not depend on the degree of uncertainty and hence preference between permits and effluent charges will still be based on the relative slopes criterion.

Baldursson and Von der Fehr (2004) similarly studied risk aversion and uncertainty at the firm level. When markets are imperfect, permit prices may vary randomly in a cap-and-trade regime. Risk aversion may thus influence firms' behaviour vis-à-vis investments in abatement technology to mitigate exposure to price volatility. Prospective permit buyers will invest more while sellers will invest less in abatement technology, eventually limiting permit trade. As marginal control costs will not be equalized across polluters due to the limited permit trade, environmental standards will not be attained at the least cost. As a result, the relative performance of tradable permits² is greatly reduced.

Laffont (1977) argued that the central planning problem involves comparison of three policy options: ordering a fixed production at the least cost, announcing a price to the producer, and announcing a price to the consumer with the consumer's reaction communicated to the producer. He articulated that, by limiting his analysis to the first two options, Weitzman in effect utilized only half of his model. Laffont demonstrated that a relatively steeper marginal benefits curve - a justification for cap-and-trade in Weitzman - is in fact in favour of announcing prices to the consumer; effectively reducing the comparison to using prices on the production side and using prices on the consumption side. Nonetheless, the relative advantage of one price instrument over the other still rests on the relative slopes of the underlying curves.

² Tradable permits, cap-and-trade and permits are used interchangeably in this paper

Yohe (1978) extended Weitzman's framework by including an additional source of uncertainty. Unlike Weitzman, he presupposes that under the cap-and-trade system, firms do not achieve the target set by the regulator with absolute certainty. With this assumption, the choice between prices and quantities largely depends on the relative sizes of quantity variation associated with each instrument. For this reason, a relatively larger variation under effluent fees shifts preference towards cap-and-trade. Yates (2012) introduced non-constant tax and non-constant permit supply functions into the canonical prices versus quantities model. He established that, under these circumstances, the cap-and-trade system unambiguously dominates the fee system.

Stranlund and Ben-Haim (2008) compared price and quantity-based policies in situations where the stochastic errors in the cost and benefit functions cannot be modelled with accurate moments of probability distributions. In this study, instead of the traditional expected social welfare, the authors suggest an alternative policy evaluation tool, namely "info-gap robust-satisficing" that "evaluates policies on the basis of robustness to loss when uncertainty is unstructured" (p. 448). In light of this, it is shown that the standard relative slopes tenet ranks the two policies in terms of their robustness to unstructured uncertainty.

When policy variables are fixed over time³, the two market-based instruments are believed to respond differently to exogenous shocks. Butler and Maher (1982) analyzed the relative performance of permits and emission charges in a growing economy and showed that, in the face of increasing pollution sources and inflation, tradable permits perform better than charges in terms of meeting a given emissions control target. This is because, with a fixed allowance, permit prices adjust accordingly, maintaining the overall environmental quality

³ Policy parameters fixed over time is typical of environmental regulation

standards. With a fixed charge, environmental deterioration would result as increasing pollution sources raise abatement costs and inflation lowers the real charge. However, effluent charges are relatively superior in improving environmental quality when there is advancement in abatement technology (Tietenberg & Lewis, 2012).

Price and quantity based instruments have also been compared under incomplete enforcement (Montero, 2002b). Incomplete enforcement of regulation coupled with uncertainty considerably diminishes the relative attractiveness of effluent fees over permits. At the global level, the fee system is also rendered ineffective by offsetting domestic fiscal policies (Wiener, 1999). Rohling and Ohndorf (2012) considered the risk of such fiscal cushioning and found that the level of the marginal benefit curve and the variance of the error term in the cost function determine instrument choice. Below a certain threshold level of the cost variance, the permit system is shown to be strictly preferable.

Many other studies have attempted to compare emission taxes and permits by introducing various assumptions into the Weitzman framework. Heuson (2010) incorporated imperfect competition (Cournot oligopoly) into the model and demonstrated that emission taxes dominate tradable permits. Roberts and Spence (1976) and Mandell (2008) investigated conditions under which a mixed system is welfare-superior to either a tax or a permit regime. Moledina, Coggins, Polasky and Costello (2003) included dynamic effects and discovered that, in steady-state, emission taxes overabate while permits underabate. Newell and Pizer (2003), Hoel and Karp (2002) and Karp and Zhang (2005, 2012) applied the model to stock pollutants such as GHG, and using numerical illustration, showed that effluent charges fare better than permits. Stavins (1996) and Shrestha (2001) demonstrated that if errors in the benefit and cost functions are correlated, the marginal benefit uncertainty can be crucial to identifying the desired policy.

III. Fuel Price Volatility and the Case where $E(u) = 0$

The Weitzman model uses the total benefit and the total cost of abatement functions and takes the stochastic term in the marginal abatement cost to be sufficiently small in order to justify second order approximations to those functions. The quadratic approximations of the total cost and benefit functions accordingly imply linear marginal benefit (MB) and marginal abatement cost (MAC) functions. Adar and Griffin (1976) and Fishelson (1976) on the other hand, postulate linearity of the MB and MAC curves from the outset. The present paper adopts the latter approach with an additive error term in the marginal abatement cost. Additionally, prices of fossil fuel inputs P are assumed to follow a random walk;⁴

$$P_t = P_{t-1} + \theta_t \tag{1}$$

where θ_t represents the stochastic component of fuel prices, unknown to the agency at the time of the regulation adoption.

The specification of marginal benefit function used in this paper has been modified to capture the realities in the current model. It has been augmented to include the price of fossil fuels, effectively introducing uncertainty into the marginal benefits of abatement. Since emissions and fossil fuels are modelled as perfect complements, a unit reduction in emissions also entails a comparable unit decrease in fossil fuel usage. The social marginal benefit of abatement therefore includes marginal environmental benefits plus the opportunity cost of fuel usage (price of fossil fuels). Moreover, it is assumed that the marginal abatement cost curve intercepts the origin; however, this is trivial and does not change the results of this paper.

⁴ Several empirical studies support this view. See, for example, Coimbra and Esteves (2004), Geman (2007) and Hamilton (2008).

$$MAC(q, u) = \delta q + u \quad (2)$$

$$MB(q, \theta) = a - \beta q + P_{t-1} + \theta_t \quad (3)$$

Where $q \geq 0$ represents the level of abatement undertaken by firms and u represents the regulator's error in estimating the firms' marginal control costs. The error terms u and θ_t are uncorrelated, with $E[u] = 0$, $E[\theta_t] = 0$ and $E[u \cdot \theta_t] = 0$.

To achieve the intended environmental quality goal, the regulator announces the control policy (an emission charges or a tradable permit) that seeks to maximize expected social welfare. Essentially, this can be accomplished by either naming an optimal tax t^* and having polluters choose their abatement levels, or ordering polluters to abate q^* through tradable permits. Under complete certainty, both policies would generate the same social welfare.

The permit system:

Under this emission control policy, the risk neutral regulator orders tradable permits for q reduction in emissions that maximizes the expected social welfare:

$$E[W] = E \int_0^q [MB(q, \theta) - MAC(q, u)] dq \quad (4)$$

Taking the derivative of (4) with respect to q , and setting the resulting expression equal to zero, yields expected marginal benefits equal to expected marginal abatement costs.

$$E[MB(q, \theta)] = E[MAC(q^*, u)] \quad (5)$$

Using the expressions for $MB(q)$ and $MAC(q, u)$ in (2) and (3), (5) becomes:

$$E[a - \beta q^* + P_{t-1} + \theta_t] = E[\delta q^* + u]$$

Solving for q^* in the above equation, the optimal reduction in emissions under the permit system is thus

$$q^* = \frac{\alpha + P_{t-1}}{\beta + \delta} \quad (6)$$

Since $E[u] = 0$ and $E[\theta_t] = 0$.

Substituting the expressions for $MB(q, \theta)$ and $MAC(q, u)$ into (4) and using (6), the expected social welfare under the permit system is obtained by computing:

$$E[W(q^*)] = E \int_0^{q^*} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q + u)] dq \quad (7)$$

The effluent fee system

In this model, emissions and fossil fuel inputs are assumed to be complements ($E = \alpha F$), where α is normalized to unity. A unit reduction in fossil fuel consumption entails a comparable unit decrease in emissions and vice versa. In a competitive equilibrium, profit maximizing firms purchase fuel so that its marginal product equals its total price (emission tax included). Therefore, firms will abate where the marginal control cost of a unit of emissions equals the price of the fuel input plus the emission tax.

Unlike the regulator though, firms in this model know the realized values of the random variables u and θ . Thus, their reaction to any possible tax t involves setting the realized marginal abatement costs equal to the emission tax t plus the realized price of the fuel input ($P_{t-1} + \theta_t$).

$$P_{t-1} + \theta_t + t = MAC(q^*, u) \quad (8)$$

Using (2) the firms' reaction function becomes:

$$q(t, u, \theta) = (P_{t-1} + \theta_t + t - u) / \delta \quad (9)$$

Given $q(t, u, \theta)$ in (9), the risk neutral regulator announces a tax t^* that solves the following maximization problem.

$$\text{Max}_t \quad E \int_0^{q(t,u,\theta)} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q + u)] dq \quad (10)$$

Maximizing (10) with respect to t , setting the resulting expression equal to zero and solving for t yields:

$$t^* = \frac{a\delta - \beta P_{t-1}}{\beta + \delta} \quad (11)$$

Substituting (11) into (9) gives the firms' reaction to the optimal tax t^* announced by the regulator.

$$q(t^*, u, \theta_t) = \left(\frac{a + P_{t-1}}{\beta + \delta} \right) + \frac{\theta_t}{\delta} - \frac{u}{\delta} \quad (12)$$

Using (6), (12) becomes

$$q(t^*, u, \theta_t) = q^* + \frac{\theta_t}{\delta} - \frac{u}{\delta} \quad (13)$$

The realized emissions reduction $q(t^*, u, \theta_t)$ achieved under the tax regime generates the social welfare:

$$W(t^*) = \int_0^{(q^* + \frac{\theta_t}{\delta} - \frac{u}{\delta})} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q + u)] dq \quad (14)$$

Since the policy maker is uncertain about the marginal abatement costs and the future prices of fossil fuels, decisions made *ex ante* have to be based on the expectation of (14):

$$E[W(t^*)] = E \int_0^{(q^* + \frac{\theta_t}{\delta} - \frac{u}{\delta})} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q + u)] dq \quad (15)$$

The relative advantage of emission taxes over tradable permits is given by (15) - (7)

$$\begin{aligned}
E[W(t^*)] - E[W(q^*)] &= E \int_{q^*}^{(q^* + \frac{\theta_t}{\delta} - \frac{u}{\delta})} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q + u)] dq \quad (16) \\
&= E \left[\left[(a + P_{t-1} + \theta_t)q - \frac{(\beta + \delta)q^2}{2} - uq \right]_{q^*}^{(q^* + \frac{\theta_t}{\delta} - \frac{u}{\delta})} \right]
\end{aligned}$$

Evaluating the above expression and using $E[\theta_t] = 0$, $E[u] = 0$ and $E[u \cdot \theta_t] = 0$, the relative advantage of emission charges over tradable permits is given by

$$E[W(t^*)] - E[W(q^*)] = \left(\frac{\delta - \beta}{2\delta^2} \right) [E(u^2) + E(\theta^2)] \quad (17)$$

Equation (17) consists of two additively separable effects. The first effect, the *marginal cost uncertainty effect*, is the fundamental Weitzman result, while the second effect is the *fuel price uncertainty effect*. As evident from (17), the choice between effluent charges and tradable permits solely depends on the relative slopes of the marginal benefits and the marginal abatement cost curves (β and δ respectively). The regulator is indifferent between applying an emission tax and issuing tradable permits when δ and β are equal (in absolute value). Otherwise, emission taxes are preferred to permits if δ is greater β and vice-versa. Thus, in the presence of volatile oil prices, Weitzman's fundamental relative slopes proposition remains intact.

However, under fuel price uncertainty, the magnitude of the relative coefficient is amplified by a factor of the fuel price variance. If, for instance, δ is greater than β (charges selected in this case), the magnitude of the relative advantage of taxes over permits is greater than in Weitzman. In the context of global climate policy, tax instruments have by and large been justified on the basis that the marginal benefits of pollution control are relatively flat while marginal costs are sensitive to the level of abatement (Pizer, 1999; Nordhaus, 2007). If this is the

case, then (17) shows that complementarity of fuel and emissions does increase the gains from adopting a tax policy. This increase can be more than double if the variance of fuel prices is larger than that of the marginal abatement cost.

Given that the marginal benefits of pollution control are considered flat – and this was rationale behind the 2008 Canadian petition in which over 200 economists urged the federal political parties to adopt a carbon tax as a climate change policy (Laucius, 2008) – then, British Columbia’s adoption of carbon tax in 2008 was in fact the correct policy. It is tempting to think that, under fuel price shocks, emission taxes would be excessive when *ex post* fuel prices are higher and inadequate when they are lower. However, the marginal benefits curve, which is a function of fuel prices, shifts whenever fuel prices change and this moves the socially optimal quantity of abatement to a new level depending on the direction of the fuel price shock.

If, for example, *ex post* fuel prices are higher, the marginal benefits curve (a function of fuel prices) would shift upward increasing the socially optimal level of abatement. If, on the other hand, *ex post* fuel prices are lower, the marginal benefits curve would shift downwards decreasing the socially optimal abatement Level. In effect, emission taxes would not be that excessive under increasing fuel prices and inadequate under falling fuel prices.

IV. Fuel Price Volatility and the Case of Unidirectional Innovations in the MAC

In this section the same analysis as in the previous section is applied, however, it is now assumed that innovations in the marginal abatement costs are unidirectional. In line with the vast literature that associates technological progress with downward shift of the MAC curve, this section considers the case where innovations in the marginal abatement are always negative. Equation (2) is thus modified to capture this unidirectional movement.

$$MAC(q, u) = \delta q - u \quad (18)$$

Where $E[u] > 0$, $u \sim LN$ and $\ln u \sim N(0, \sigma^2)$. As in Section III, $E[u \cdot \theta_t] = 0$

The permit system

In the same manner as in the permit policy in Section III, the regulator orders tradable permits for q reduction in emissions that maximizes the expected social welfare:

$$E[W] = E \int_0^q [MB(q, \theta) - MAC(q, u)] dq \quad (19)$$

Taking the derivative of (19) with respect to q , and setting the resulting expression equal to zero, yields expected marginal benefits equal to expected marginal abatement costs.

$$E[MB(q, \theta)] = E[MAC(q^*, u)] \quad (20)$$

Using (3) and (18), and solving for q^* in the above equation, the optimal reduction in emissions under the permit system is thus

$$q^* = \frac{\alpha + P_{t-1} + E(u)}{\beta + \delta} \quad (21)$$

The expected social welfare under the permit system is then obtained by computing:

$$E[W(q^*)] = E \int_0^{q^*} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q - u)] dq \quad (22)$$

Where q^* is given in (21).

The effluent fee system

In the same manner as in the emissions charge policy in Section III, firms react to any possible tax t by setting the realized marginal abatement costs equal to the emission tax t plus the realized price of the fuel input ($P_{t-1} + \theta_t$).

$$P_{t-1} + \theta_t + t = MAC(q^*, u) \quad (23)$$

Using (18) the firms' reaction function becomes:

$$q(t, u, \theta) = (P_{t-1} + \theta_t + t + u) / \delta \quad (24)$$

Given (24), the policy maker announces a tax t^* that solves the following maximization problem.

$$\text{Max}_t \quad E \int_0^{q(t, u, \theta)} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q - u)] dq \quad (25)$$

Maximizing (25) with respect to t , setting the resulting expression equal to zero and solving for t yields:

$$t^* = \frac{a\delta - \beta P_{t-1} - \beta E(u)}{\beta + \delta} \quad (26)$$

Substituting (26) into (24) gives the firms' reaction to the optimal tax t^* announced by the regulator.

$$q(t^*, u, \theta_t) = \left(\frac{a + P_{t-1}}{\beta + \delta} \right) + \frac{\theta_t + u}{\delta} - \frac{\beta E(u)}{\delta(\beta + \delta)} \quad (27)$$

The expected social welfare achieved under the tax regime is thus given by

$$E[W(t^*)] = E \int_0^{q(t^*, u, \theta_t)} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q - u)] dq \quad (28)$$

The relative advantage of emission taxes over tradable permits is given by (28) - (22)

$$E[W(t^*)] - E[W(q^*)] = E \int_{q^*}^{q(t^*, u, \theta_t)} [(a - \beta q + P_{t-1} + \theta_t) - (\delta q - u)] dq \quad (29)$$

Evaluating the above expression and using $E[\theta_t] = 0$ and $E[u \cdot \theta_t] = 0$, the relative advantage of emission charges over tradable permits is given by

$$E[W(t^*)] - E[W(q^*)] = \left(\frac{\delta - \beta}{2\delta^2} \right) E(\theta^2) \quad (30)$$

Even though equation (30) illustrates that the relative slopes of the underlying curves determine the preferred instrument, it is interesting to see that, contrary to the Weitzman conclusion, marginal abatement cost uncertainty vanishes. In the context of Weitzman analysis, if innovations in the MAC are unidirectional, price-based and quantity-based instruments would yield exactly the same expected welfare (abstracting from fuel price shocks). It would therefore not matter whether the policy maker is uncertain about the marginal abatement cost of polluters or not. If evidence shows that MAC decreases with technical progress, and this is indeed the case for end-of-pipe technologies, then a remarkable symmetry is established between price and quantity-based instruments even in the face of uncertain marginal control costs.

Accordingly, the analysis presented here provides new theoretical insights on the insignificance of the marginal abatement cost uncertainty for the choice of market-based environmental policies when innovations in MAC are unidirectional. Under this postulation, the only uncertainty that affects instrument choice is that of fossil fuel prices. If the regulator's errors of the marginal control costs are always negative as in the case of advancement in end-of-pipe technologies, effluent charges and tradable permits would yield the same expected social welfare unless fuel price uncertainty is included in the model (assuming complementarity). Nonetheless, incorporating the complementarity assumption reinforces the relative slopes argument.

V. Conclusion

This paper compared price-based and quantity-based environmental regulation policies on efficiency grounds when the regulator is uncertain about the future price of fossil fuels and the firms' marginal control cost. It extended the canonical prices versus quantities model to include a fundamental complementarity property that is characteristic of pollution abatement. This complementarity property is justified on the basis that, in the real world, greenhouse gas

emissions are directly proportional to fossil fuel combustion. Additionally, the uncertainty on the part of the policy maker can be attributed to the sluggish nature of environmental regulation.

In conducting the analysis, this paper considered two key issues. First, it answered the question; does complementarity of fossil fuels and emissions alter the Weitzman results given the volatile nature of fuel prices? Secondly, it investigated the choice between the two instruments when the stochastic components of the marginal abatement cost are unidirectional. Weitzman assumes that both positive and negative errors in the marginal abatement costs are possible, yet a common understanding of technological change is that innovations are unidirectional. There is a vast body of literature that models technical change as reduction in the marginal abatement costs. Moreover, many studies have shown that end-of-pipe technologies lead to a uniform downward shift of the marginal abatement cost curve. In accordance with these studies, the present paper evaluates the case where innovations in the marginal control costs are always negative.

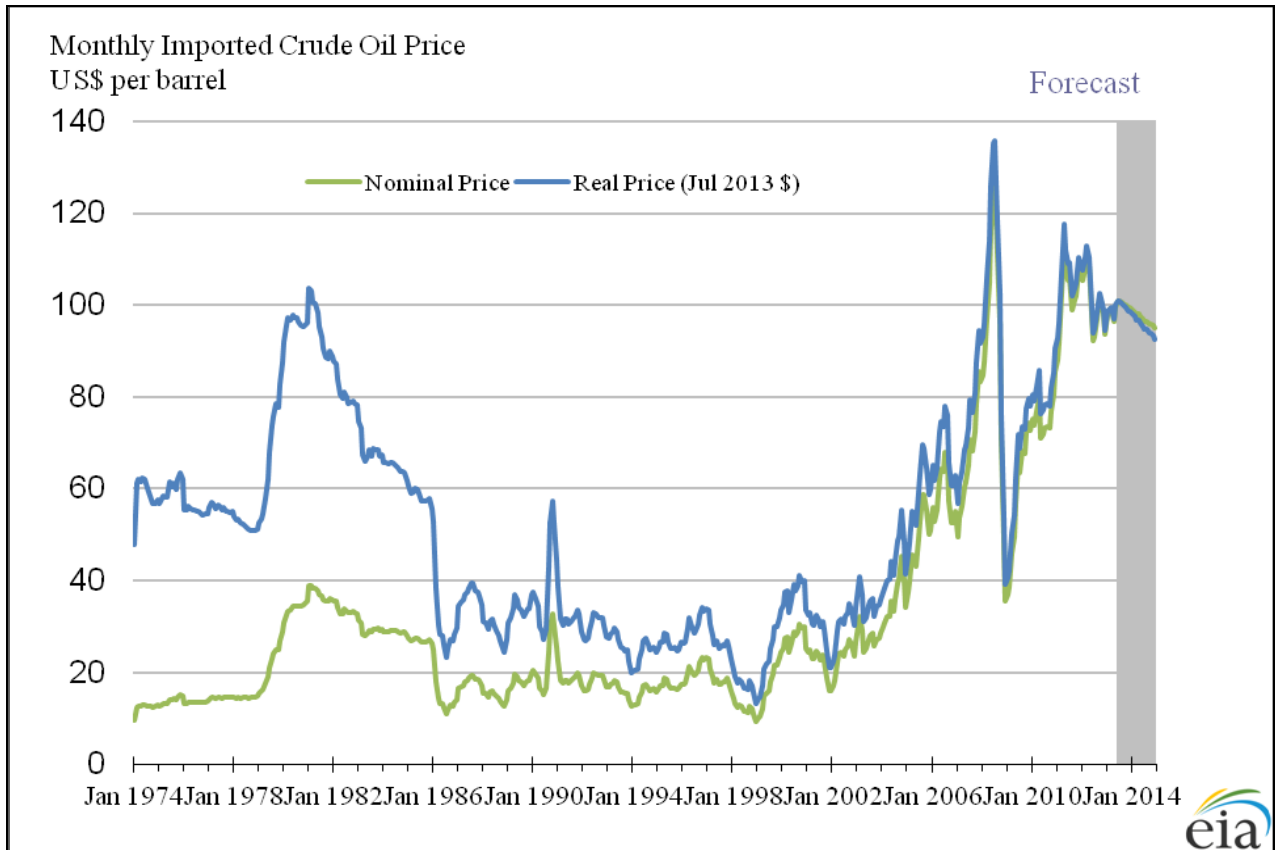
In the first case, the results show that complementarity of fuel and emissions in the face of volatile oil prices does not alter Weitzman's key proposition. The relative slopes criterion still determines the instrument choice, however, the magnitude of the relative coefficient increases proportionately with the variance of fuel prices. The gains from adopting the desired policy are higher than what Weitzman would suggest. Given that the marginal benefits of pollution abatement are considered flat, one could argue that British Columbia's adoption of carbon tax in the face of highly volatile oil prices was in fact the right policy as the gains at stake were higher than thought.

As for the case where innovations in the marginal abatement cost are unidirectional, it is shown that, contrary to Weitzman, uncertainty in the abatement costs does not affect the relative advantage coefficient. Without the complementarity assumption, price-based and quantity-based instruments would yield the same expected welfare, whether marginal costs are unknown to the regulator or not. In effect, Weitzman's key proposition collapses. Nevertheless, incorporating complementarity of fuel and emissions would reinforce the relative slopes argument.

One would think that, under fuel price shocks, emission taxes would be excessive when *ex post* fuel prices are higher and inadequate when they are lower. However, Given the complementarity assumption, the marginal benefits curve shifts in direct proportion to fuel prices, increasing (decreasing) the socially optimal level of abatement whenever fuel prices rise (fall). As a potential area of research, it would be interesting to include dynamic effects into these models and extend the analysis. Such extension would certainly reveal a great deal about the relative desirability of these two instruments.

Appendix

Figure 1: US Imported Crude Oil Price Movements



Source: US Energy Information Administration
<http://www.eia.gov/forecasts/steo/realprices/>

Reference List

- Adar, Z., & Griffin, J. M. (1976). Uncertainty and the choice of pollution control instruments. *Journal of Environmental Economics and Management*, 3(3), 178-188.
- Amir, R., Germain, M., & Van Steenberghe, V. (2008). On the impact of innovation on the marginal abatement cost curve. *Journal of Public Economic Theory*, 10(6), 985-1010.
- Baldursson, F. M., & Von der Fehr, Nils-Henrik M. (2004). Price volatility and risk exposure: On market-based environmental policy instruments. *Journal of Environmental Economics and Management*, 48(1), 682-704.
- Bauman, Y., Lee, M., & Seeley, K. (2008). Does technological innovation really reduce marginal abatement costs? Some theory, algebraic evidence, and policy implications. *Environmental and Resource Economics*, 40(4), 507-527.
- Baumol, W. J. & Oates, W. E. (1988). *The theory of environmental policy* (2nd ed.). Cambridge: Cambridge University Press
- Bookout, J. F. (1990). Managing volatility in the oil industry. In J. L. Helm (Ed.), *Energy production, consumption and consequences* (pp. 145). Washington, D.C: National Academy Press.
- Busse, M. R., Knittel, C. R., & Zettelmeyer, F. (2009). *Pain at the Pump: The Differential Effect of Gasoline Prices on New and used Automobile Markets* (No. w15590). National Bureau of Economic Research.

- Butler, R. V., & Maher, M. D. (1982). The control of externalities in a growing urban economy. *Economic Inquiry*, 20(1), 155-163.
- Coimbra, C., & Esteves, P. S. (2004). Oil price assumptions in macroeconomic forecasts: Should we follow futures market expectations? *OPEC Review*, 28(2), 87-106.
- Downing, P. B., & White, L. J. (1986). Innovation in pollution control. *Journal of Environmental Economics and Management*, 13(1), 18-29.
- Fishelson, G. (1976). Emission control policies under uncertainty. *Journal of Environmental Economics and Management*, 3(3), 189-197.
- Geman, H. (2007). Mean reversion versus random walk in oil and natural gas prices. In *Advances in Mathematical finance* (pp. 219-228). Birkhäuser Boston.
- Gillingham, K. (2012). *Selection on anticipated driving and the consumer response to changing gasoline prices*. Technical Report, Yale University.
- Hamilton, J. D. (2008). *Understanding Crude Oil Prices* (No. w14492). National Bureau of Economic Research.
- Heuson, C. (2010). Weitzman revisited: Emission standards versus taxes with uncertain abatement costs and market power of polluting firms. *Environmental and Resource Economics*, 47(3), 349-369.
- Hoel, M., & Karp, L. (2002). Taxes versus quotas for a stock pollutant. *Resource and Energy Economics*, 24(4), 367-384.

- Karp, L., & Zhang, J. (2005). Regulation of stock externalities with correlated abatement costs. *Environmental and Resource Economics*, 32(2), 273-300.
- Karp, L., & Zhang, J. (2012). Taxes versus quantities for a stock pollutant with endogenous abatement costs and asymmetric information. *Economic Theory*, 49(2), 371-409.
- Laffont, J. J. (1977). More on prices vs. quantities. *The Review of Economic Studies*, 44(1), 177-182.
- Laucius, J. (2008, 7 October). Back carbon tax, leading economists tell politicians; more than 200 experts say policy is best way to fight climate change. *The Ottawa Citizen*.
- Mandell, S. (2008). Optimal mix of emissions taxes and cap-and-trade. *Journal of Environmental Economics and Management*, 56(2), 131-140.
- Milliman, S. R., & Prince, R. (1989). Firm incentives to promote technological change in pollution control. *Journal of Environmental Economics and Management*, 17(3), 247-265.
- Moledina, A. A., Coggins, J. S., Polasky, S., & Costello, C. (2003). Dynamic environmental policy with strategic firms: Prices versus quantities. *Journal of Environmental Economics and Management*, 45(2), 356-376.
- Montero, J. P. (2002a). Permits, standards, and technology innovation. *Journal of Environmental Economics and Management*, 44(1), 23-44.
- Montero, J. (2002b). Prices versus quantities with incomplete enforcement. *Journal of Public Economics*, 85(3), 435-454.

- Newell, R. G., & Pizer, W. A. (2003). Regulating stock externalities under uncertainty. *Journal of Environmental Economics and Management*, 45(2), 416-432.
- Nordhaus, W. D. (2007). To tax or not to tax: Alternative approaches to slowing global warming. *Review of Environmental Economics and Policy*, 1(1), 26-44.
- Pizer, W. A. (1999). The optimal choice of climate change policy in the presence of uncertainty. *Resource and Energy Economics*, 21(3), 255-287.
- Regnier, E. (2007). Oil and energy price volatility. *Energy Economics*, 29(3), 405-427.
- Roberts, M. J., & Spence, M. (1976). Effluent charges and licenses under uncertainty. *Journal of Public Economics*, 5(3), 193-208.
- Rohling, M., & Ohndorf, M. (2012). Prices vs. quantities with fiscal cushioning. *Resource and Energy Economics*, 34(2), 169-187.
- Rosendahl, K. E. (2004). Cost-effective environmental policy: implications of induced technological change. *Journal of Environmental Economics and Management*, 48(3), 1099-1121.
- Sandmo, A. (1971). On the theory of the competitive firm under price uncertainty. *The American Economic Review*, 61(1), 65-73.
- Shrestha, R. K. (2001). The choice of environmental policy instruments under correlated uncertainty. *Resource and Energy Economics*, 23(2), 175-185.

- Stavins, R. N. (1996). Correlated uncertainty and policy instrument choice. *Journal of Environmental Economics and Management*, 30(2), 218-232.
- Stranlund, J. K., & Ben-Haim, Y. (2008). Price-based vs. quantity-based environmental regulation under knightian uncertainty: An info-gap robust satisficing perspective. *Journal of Environmental Management*, 87(3), 443-449.
- Tietenberg, T., & Lewis, L. (2012). *Environmental and natural resource economics* (9th ed.) Pearson Education, Inc.
- U.S. Energy Information Administration. (2013). *Short-term energy outlook, July 2013*. U.S.A: EIA. Retrieved from <http://www.eia.gov/forecasts/steo/realprices/>
- Verleger, P. K. (1994). *Adjusting to volatile energy prices*. Washington, DC.: Institute for International Economics.
- Weitzman, M. L. (1974). Prices vs. quantities. *The Review of Economic Studies*, 41(4), 477-491.
- Wiener, J. B. (1999). Global environmental regulation: Instrument choice in legal context. *The Yale Law Journal*, 108(4), 677-800.
- Yates, A. J. (2012). On a fundamental advantage of permits over taxes for the control of pollution. *Environmental and Resource Economics*, 51(4), 583-598.
- Yohe, G. W. (1978). Towards a general comparison of price controls and quantity controls under uncertainty. *The Review of Economic Studies*, 45(2), 229-238.