Thesis Appendix

Elements of air pollution policy analysis

The National Research Council has pointed out that more ways need to be explored to link scientific research effectively with policy and environmental decision-making[a]. One approach would be to promote interdisciplinary efforts designed to give science graduate students an opportunity to work in a collaborative effort, such as with economists and political scientists, to fulfill a project situating new environmental research within a broader social context. This appendix summarizes the results of work done in collaboration with Profs. Ingela Alger and Frank Gollop in the Economics Department at Boston College. In it we consider elements of air pollution policy analysis, leading to a novel perspective on the effect of permit trading (a popular market mechanism of pollution control) on polluting firms competing imperfectly.

A.1 Introduction

Once science has provided a series of facts revealing the risks associated with atmospheric constituent concentration levels, it becomes the task of governing agencies to design appropriate policies to safeguard citizens against newly revealed threats. The role of government is critical in this aspect as it alone can intervene in the event of a market failure (see below). This discussion of air pollution policy will proceed from a basis of well-accepted market principles, as seen in basic texts on microeconomics[1,2].

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[a] NRC, <u>Opportunities in Applied Research and Development</u>, Washington, D.C.,1997, p.ix.

Supply and demand

If there were no pollution associated with the consumption of energy, the price of energy in a competitive (deregulated) market would reflect the equilibrium point of market supply and demand. We explain that concept here briefly. On the supply side, energy producers generate power at an output that will maximize their profits. On the demand side, energy purchasers consume at a rate that maximizes the utility of energy consumption, subject to budget constraints. In a fully competitive market, demand and supply keep pace with one another, settling at a certain market price. If producers were to over-produce (produce more than the market demands at that price), prices would decrease due to overabundance, forcing firms' profits down and thus motivating a decrease in output. If producers were to under-produce, prices would increase due to scarcity, motivating an increase in output. In either case, convergence on equilibrium output is obtained. It follows that competitive energy prices reflect consumers' willingness to pay for a particular consumption rate. In this way, the price mechanism reflects the aggregate preferences of individuals for a given consumption rate of energy.

A.1.1 Market externalities

A policy designed to safeguard human health therefore does so *in addition* to what consumers have already decided is "healthy" or preferred through the price mechanism. In 1970, the US Congress enacted the Clean Air Act. This was in response to a body of evidence suggesting that buildup of SO_2 from power plant emissions was leading to acid rain that was in turn harming farmlands and buildings. The public knowledge of this fact did not decrease consumption of energy from power plants. The Clean Air Act was necessary because the increased costs imposed on construction, agriculture, and health programs due to energy consumption did not show up explicitly in the price of energy. Such "hidden costs" of consumption are known as *externalities*, negative effects that cannot be mitigated by the price mechanism alone. For such externalities, the free market is unable to maximize social welfare, even when each consumer is aware of what his or her consumption is doing to society as a whole. Epidemiological studies in recent years have shown as many as 50,000 deaths per year in the U.S. can be attributed to urban air pollution,[3] largely a result of emissions from power plants. This apparent loss in social welfare is clearly beyond the reach the price mechanism, and thus constitutes a significant externality of energy consumption.

Such externalities persist in a free market due to the so-called free rider problem, which is associated with public goods such as clean air[4]. Each individual is banking on every other individual acting in the interests of the whole, such that they see themselves as making only a negligible negative effect in acting in their own best interests, without regard to the whole.

When significantly deleterious externalities are present, the government has some options on how to offset the effect. We list them here: 1) A *command and control* strategy is the traditional method of choice. The regulating authority simply issues a control, signs it into law, and enforces it. 2) In addition, *taxes* can be levied on goods whose consumption increases the level of the externality. 3) Government *subsidies* can be issued to help those enterprises whose success would offset the effect of an externality, such as enterprises in renewable energy. 4) A more recent mechanism for controlling externalities involves *trading permits* in which rights to produce the product whose consumption causes the externality are bought and sold on an open market. We discuss this mechanism in detail.

Pollution permit trading

An important market-based approach to offsetting externalities was introduced in 1968 by J. H. Dales. He proposed a system of pollution permits where the regulatory authority decides on a maximum emission level for which a representative number of permits is issued. Each permit represents a right to emit a certain quantity of pollutant over a given period of time. These permits can be bought and sold on an open permit market. On the supply side, the total number of permits is decided by the regulating authority and does not change with price. The EPA, for example may decide that 1 ton of SO_2 per month is the maximum level of pollution allowable in the US. Polluting firms would thus be required to purchase pollution permits for the amount of pollutant they emit in a given month, with the total output of all firms automatically capped at 1 ton. This would lead to effectively higher production costs for dirtier firms compared to their cleaner competitors, driving down their profits. Such firms would respond by decreasing output or investing in clean emission technology, or both.

A.1.2 Market inefficiencies due to imperfect competition

In a perfectly competitive market, a permit trading system as described above can function to offset the effect of externalities such as those associated with energy consumption. This concept has been developed and demonstrated theoretically in the literature[6,7]. However, markets are rarely perfectly competitive, and a permit trading system may lead to some non-intuitive effects on markets where the number of energy producers is small enough that an oligopoly[b] is in place. To explore some potential consequences of a permit system when perfect competition does not prevail, we will look at the case of a duopoly, considering the strategic interactions between firms as they choose outputs so as to maximize profits in permit trading conditions. To our knowledge such strategic implications of permit trading have not been treated in the literature. Because the number of energy firms serving a region is typically small, oligopolistic effects can be expected to play a role, such that predictions based on competitive models may be inadequate. We will explore such oligopolistic effects by considering the limiting case of two firms. For this, we introduce the notion of a Cournot duopoly.

The Cournot duopoly model

The 19th century French engineer, Cournot, made an important advance in the theory of imperfect competition. We briefly describe the Cournot theory here, before applying it to predict the outcome of oligopolistic effects under permit trading. Consider two firms producing energy for a small region. Firm 1 is an older firm using mostly coal. Firm 2 uses a combination of coal and wind from nearby wind farms. Firm 1's marginal costs of production are less than that of Firm 2, but we will assume their total cost functions, $c(y)$ have similar functional dependence on output, y. In this discussion c_i is the total cost for ith firm for production of output y_i, where y_i is a power production (i.e. kilowatts) of the firm.

Both firms face the market demand for energy. They may choose output levels, but not prices. We justify that assumption here. Subject to their budget constraints, consumers will only consume energy at a certain rate as a function of its price. An

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[b] An oligopoly exists whenever the number of firms in a market is too small to obtain the competitive supply and demand equilibrium described above.

increase in price leads to a decrease in consumption. The demand curve is the map of prices (dollars/kW) as a function of total power (kW) demanded. Since firms sell everything to maximize revenue, production equals consumption at all times. With consumers' preferences in place, the market demand for energy defines how much will be paid per kW for every output level of the producers. If power production is very low, consumers are willing to pay quite a bit per kW. As output increases, consumers pay less and less per kW. This demand curve is given by $p(y_1,y_2)$, where y_1 and y_2 are the power outputs of Firm 1 and 2 respectively. If at any time firms were to decide to increase prices at a certain output, they would discover that consumers would simply buy less. In this way, prices and quantity demanded are functionally linked. Under this assumption, the role of the firms is then to choose outputs that will maximize their profits.

In the absence of government regulation, taxes, subsidies, or permit trading, the profit of the ith firm is given by:

$$\pi_i = p(y_1, y_2)y_i - c_i(y_i) \tag{A.1}$$

Each firm knows that in order to maximize profits, they must satisfy the following at each period:

$$\frac{d\pi_i}{dy_i} = p(y_1, y_2) + y_i \frac{\partial p}{\partial y_i} - \frac{\partial c_i}{\partial y_i} = 0 \tag{A.2}$$

We will always assume that the profit function has negative concavity, such that the second derivative is always negative, and the above can be taken to occur at a global maximum. With the demand curve given by $p(y_1,y_2)$, eq. A.2 can be solved for $y_i(y_j)$, the output that Firm *i* must choose to maximize profits when Firm *j* chooses y_j. This is known as Firm *i*'s *reaction function*, as it predicts the response of Firm *i* to an output choice of Firm *j*. As an example, consider the linear demand function: $p(y_1,y_2) = 1 -$

(y_1+y_2). Consider also the individual supply (cost) functions from the firms' outputs to be given by $c_i(y_i) = m_i y_i^2$. Substituting these expressions into eq. A.1, we can show the reaction function for the i^{th} firm to be:

$$y_i = \frac{1-y_j}{2(1+m_i)} \tag{A.3}$$

Here, $i = 1$ or 2 and $j = 2$ or 1, respectively. This state of affairs enables us to define rules of a *game* wherein the players, Firms 1 and 2, compete with one another to maximize profits. In *game theory*, one makes the assumption that players are fully rational, making choices so as to maximize payoffs. In the case where both firms choose output simultaneously, there exists a pair of outputs for the rational managers of the firms where the maximum payoff is achieved. This occurs when each firm chooses an output that is optimal in the midst of the other firm's optimal choice, a so-called *Nash equilibrium*[5]. The concept of a Nash equilibrium was developed over a hundred years after Cournot, but Nash's discovery revealed the Cournot equilibrium as belonging to a more general type. A Nash equilibrium in a two-player game is obtained whenever each player's strategy is simultaneously a best response to the other's best response, maximizing expected payoffs for both players[6]. There exists a pair of outputs where neither firm will have an incentive to change. Such an optimum output, y^* is defined when both $y_1^*=y_1(y_2^*)$ and $y_2^*=y_2(y_1^*)$, where y_1^* and y_2^* are the *Cournot-Nash equilibrium* outputs for Firms 1 and 2 respectively. This is illustrated graphically in fig. A-1 (as seen in Varian [1992]).

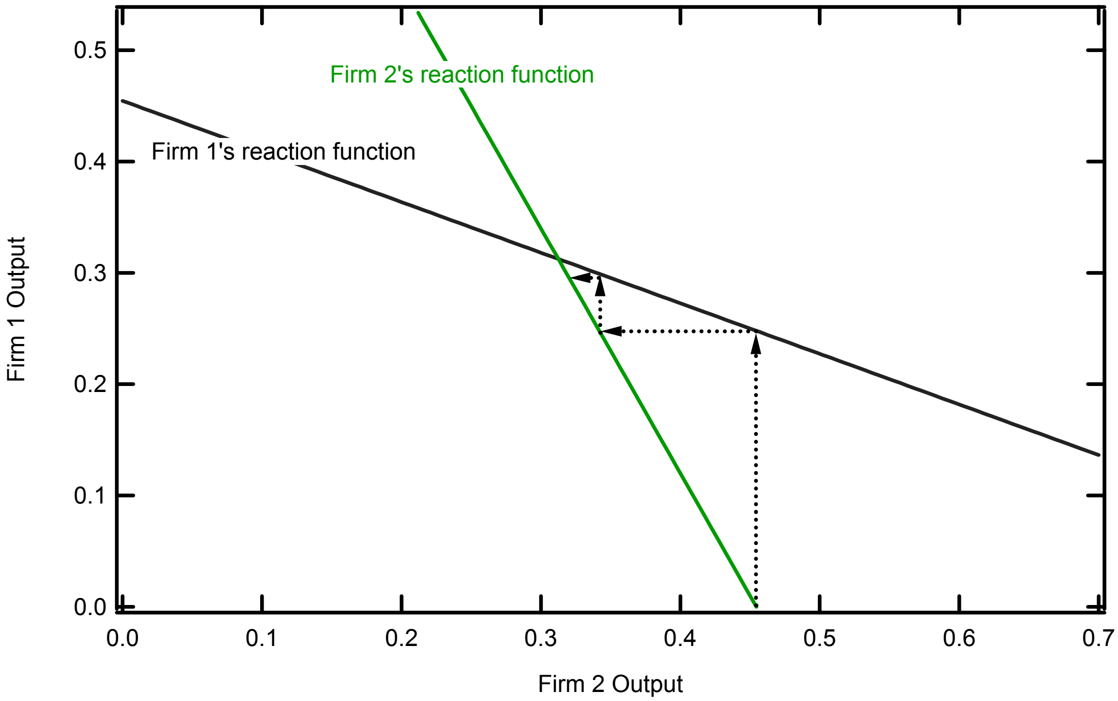

Figure A-1: Any choice of output not at the intersection of both firms' reaction functions provides incentive for one of the firms to change the output choice. For example, if Firm 2 (downward sloping reaction function) were to choose 0.45 as an output, Firm 1 would respond with output choice 0.23, which would provoke Firm 2 to choose 0.33, etc. Both Firms would quickly settle on the Cournot-Nash equilibrium, given by the intersection, where neither would have an incentive to change output.

Applying the ideas outlined above, one can show that the equilibrium outputs will be given by:

$$y_i^* = \frac{2m_j + 1}{4(m_i + 1)(m_j + 1) - 1} \tag{A.4}$$

Since Firm 1 is dirtier, we may assume it costs less for it to produce the same amount of energy as Firm 2, such that $m_1 < m_2$. It follows that $y_1^* > y_2^*$ as expected, since this firm pays less to produce a given output of energy. It can be shown that the duopolists increase their combined producer surplus at the cost of the consumer surplus, resulting in a loss in social welfare when compared to the competitive equilibrium with large numbers of firms.[7]

A.2 Permit trading between duopolists

The efficiency of a system of permit trading in competitive markets is well established[8,9]. In such a market, a permit trading system can function to offset the effect of externalities such as those associated with energy consumption. However, markets are rarely perfectly competitive, and a permit trading system may lead to some non-intuitive effects on markets where the number of energy producers is small enough that an oligopoly is in place. To explore some of the features of a permit system when perfect competition does not prevail, we will look at the case of a duopoly, considering the strategic interactions between firms as they choose outputs so as to maximize profits.

We will begin with the assumption that each firm believes that the regulating authority will check their emissions at each period. If they are found to emit more during a period than their permits allow, they are very heavily fined. For now, we will assume that no firm is willing to chance being caught in violation of regulation mandate. The new profit function of each firm is given by:

$$\pi_i = p(y_1, y_2)y_i - c_i(y_i) - \varepsilon\Delta x_i \tag{A.5}$$

Here, ε is the market price for emission permits, and Δx is the number of permits bought or sold by Firm *i*.

Since the firms are at all times constrained by the regulation, they are required to always own enough permits in a given period as to allow whatever emissions are associated with their energy output during that period. In other words, each firm must satisfy:

$$x_i \geq \omega_i y_i \tag{A.6}$$

Here, ω is a *pollution coefficient* linking a firm's energy output to the amount of harmful emissions (i.e. tons SO_2 / kilowatt hour). In this case, since Firm 2 is newer and getting a fraction of its energy from wind for example, we assume $\omega_2 < \omega_1$.

The profit maximizing permit-trading duopolist must decide two important quantities at each period: the energy output and the number of permits to buy or sell. For now we will assume that each firm is able to buy or sell permits instantaneously, such that they may do so solely to accommodate the chosen output. In such a scenario, if it turns out to be profitable to produce more output in a given period, the firm is not required to have permits in reserve to accommodate the output increase. They buy when they need them and sell when they do not, with no time lag, and thus no risk of being fined by the regulating authority. Since we also assume the price of permits to be fixed, this removes any incentive for firms to save up permits, either as financial investments or as a means of increasing flexibility of energy output.

We will look for a Cournot-Nash equilibrium using the same method as described in sec. A.1.2. We first derive a reaction function for each firm, revealing the optimal choice in output (and permits to own) in response to that firm's beliefs regarding the other firm's output choice.

For a profit function having a parabolic shape such as eq. A.5 (quadratic in y_i), the additional term due to permit trading constitutes a vertical translation of the profit function. As long as firms satisfy eq. A.6, they will choose outputs as described by the classic Cournot duopoly equilibrium, unhindered by the new regulatory constraint. Their profits will be larger since they can sell unused permits, but their choice of output will be the same. If on the other hand, a firm finds that the profit maximizing choice is in violation of regulation (eq. A.6), it must make a new profit maximizing choice. This is shown graphically in fig. A-2. Purchasing new permits allows them to shift the constraint, represented by the vertical line, to the right. Such a purchase however, shifts the profit function down, such that the new profit function (depending on the number of permits bought) creates a new parabola (dashed line).

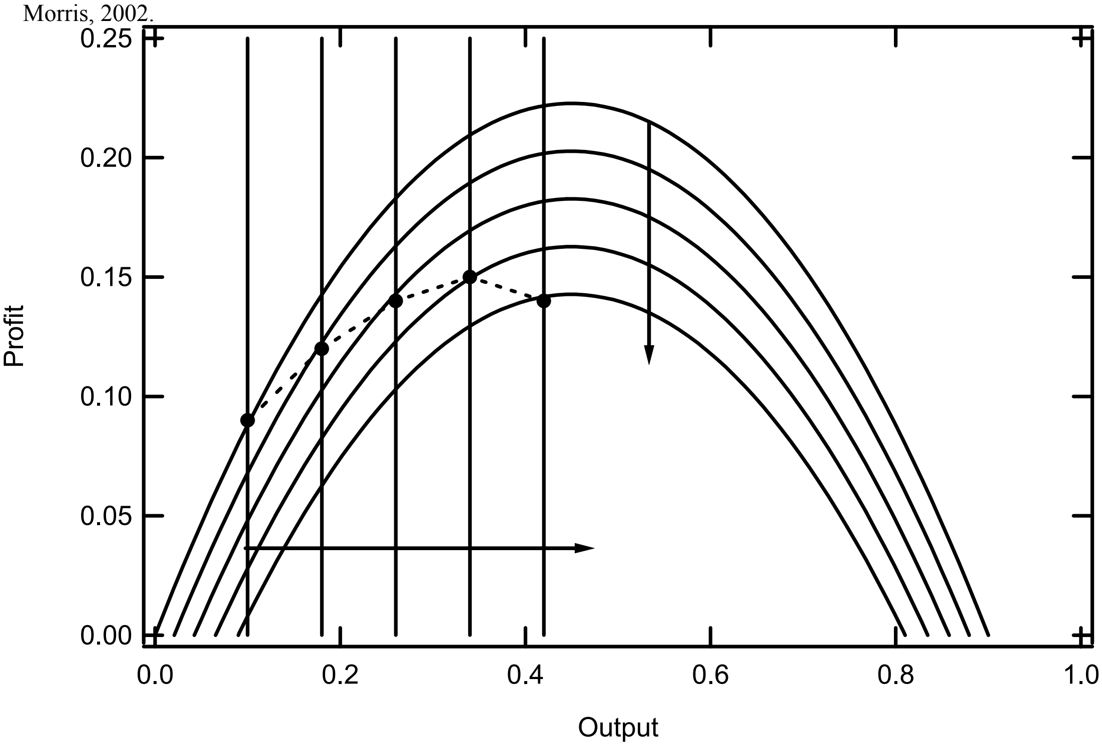

Figure A-2. Permit trading creates a new profit function (dashed line) for firms competing in a duopoly. Both profits and output decrease with the permit trading mechanism in place.

Mathematically, the optimum number of permits to buy is given by maximizing eq. A.5, subject to the constraint, $x_i = \omega_i y_i$. Substituting the constraint for y_i, a new profit maximum is sought as a function of x_i:

$$\frac{d\pi_i}{dx_i} = p(x_i, y_j)\frac{1}{\omega_i} + \frac{x_i}{\omega_i}\frac{\partial p}{\partial x_i} - \frac{\partial c_i}{\partial x_i} - \varepsilon = 0 \tag{A.7}$$

This leads to a reaction function for Firm *i* as a function of the expected output of Firm *j*. Using the cost and market supply functions from before as an example, we obtain:

$$x_i = \frac{\omega_i(1 - \omega_i\varepsilon - y_j)}{2(1 + m_i)} \tag{A.8}$$

In this case, it is apparent that ω_i plays an important role in determining how many permits a firm will choose to buy. Also, a low marginal cost coefficient, m_i, (reflecting the fact that dirty energy is usually cheaper) will lead to an increase in the permits Firm *i* must purchase.

But in the case where both firms are forced to buy permits, Firm *j*'s choice of output is constrained at $y_j = x_j/\omega_j$, such that we may write the *permit purchase reaction function* or (equivalently) the *output reaction function* of each firm as:

$$x_i = \frac{\omega_i\left(1-\omega_i\varepsilon-\frac{x_j}{\omega_j}\right)}{2(1+m_i)} \tag{A.9}$$

$$y_i = \frac{1-\omega_i\varepsilon-y_j}{2(1+m_i)} \tag{A.10}$$

We can solve either of these for the Cournot-Nash equilibrium as before to show:

$$y_i{}^* = \frac{1+\varepsilon\omega_j+2(m_j-\varepsilon\omega_i-\varepsilon\omega_i m_j)}{3+4(m_i+m_j+m_i m_j)} \tag{A.11}$$

At this equilibrium output[c], neither firm has an incentive to change either the number of permits purchased or the energy produced in a given period.

Discussion

Everywhere in A.11 where one firm's output is affected by the properties of the other firm, we see evidence of strategic interaction serving to couple each firm to the other. In the competitive equilibrium model of perfect competition, the firm need only worry about its own pollution coefficient or production costs in deciding its output. The market

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[c] It should be noted that in the case where only one firm is constrained by permits, there will be a different equilibrium.

would decide the rest. In the case of the duopoly, one firm's choices are explicitly a function of its competitor's pollution/cost properties, as well as its own.

If one were to allow permit prices to vanish, eq. A.11 becomes equivalent to eq. A.4 as expected. Making permits free is identical to not requiring their use, so we recover the no-permit case seen in the first example. From eq. A.11 it is apparent that in the limit of costless permits, the pollution coefficients, ω drop out and the dirtier firm will again produce more. As ε increases however, the importance of the ω-terms increase. To compare outputs of the old and new firms (1 and 2 respectively), we focus our attention on the numerator since the denominator is the same for both. Ignoring the 1 in the numerator, there are 4 terms remaining. For Firm 1, term 1 is low since Firm 2 has a lower pollution coefficient. Thus, Firm 2's low pollution coefficient will have a tendency to drive down Firm 1's output choice. The second term for Firm 1 however is larger than that for Firm 2 since Firm 1's production costs are higher. This term will tend to drive up Firm 1's output as expected. Term 3 for Firm 1 is high however, on account of its very own high pollution coefficient. This counters the 2nd term, driving down output. The final term is high on both accounts (Firm 1's high pollution coefficient and Firm 2's high production costs) and consequently drives Firm 1's output even lower. In summary, this expression shows how production costs drive high outputs for dirtier firms in the limit of very cheap permits, and how pollution coefficients can offset that effect, driving down output (and profits) when permit prices become significant.

Appendix References

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