

1 Introduction

In this section we will begin discussing climate change policies. We will first talk about the problems (in economic terms) associated with climate change. Then we will show these problems graphically. We will then talk about specific types of policies, then show these on a graph. We will then use the computational DICE model for more 'real world' policy analysis.

2 Problems with climate change

There are two main economic problems associated with climate change, externalities and use of a common pool resource.

2.1 Externalities

We have already talked a bit about externalities. We know that they arise when one person's actions affect the utility of another person. Or, when the costs or benefits of an action do not accrue entirely to the actor. We see this directly with firm emissions. It is necessary for firms to emit in order to produce. They get some benefit from emissions, mainly revenue from selling their product. Society (you and me) also get benefits from emissions. We like to consume things, which means we also get benefits from firms emissions.

The problem arises because the costs of emissions go beyond the costs of production or the cost of buying the good. We are all aware of the adverse effects of emissions - on health, and specifically for this course, on radiative forcing and in turn through climate change. Firms do not bear these costs when they make their production decisions and consumers do not pay these costs as part of the price of the good. The result is that too much is produced.

Let's make this a little more formal with some economic jargon:

Benefits from emissions: Because we value the goods we buy, there are benefits to emissions. For private goods (such as electricity, cars, etc.) the benefits are reflected in the price of the good. So marginal benefits of emissions can roughly be represented by willingness to pay for the good, or the demand curve. If we are looking at it from the firm's perspective, marginal benefits of emissions are essentially the firm's marginal revenue curve. We usually assume that these curves are downward sloping. Note that if we can estimate demand curves we can perfectly measure the benefits associated with emissions.

Private costs from emissions: We need to distinguish between private and social costs of an action. Private costs are the costs actually born by the actor. Social costs are total costs to society. We have a market failure when private costs do not equal social costs.

Private costs associated with emissions are usually the costs of production. If there are any environmental regulations imposed then these will be included in the private cost of emissions. Marginal cost of emissions is thus the marginal cost of production plus any added disposal or regulatory fees. We usually assume marginal costs are either upward sloping or constant.

Social costs and externalities: Carbon emissions go into the atmosphere and hang around for a long time. Increases in greenhouse gases cause an increase in radiative forcing. Radiative forcing is the tendency of the atmosphere to reflect heat back towards the Earth, causing global temperatures to rise. Because there

are costs associated with climate change, there are additional costs associated with emissions, costs the firm does not have to pay. This additional cost is an externality. Social costs are the cost of production to the firm plus the value of the externality. Social marginal costs are the sum of the firm's marginal cost and the marginal value of the externality. We often write this as

$$SMC = MC + EXT \tag{1}$$

Let's do this graphically..

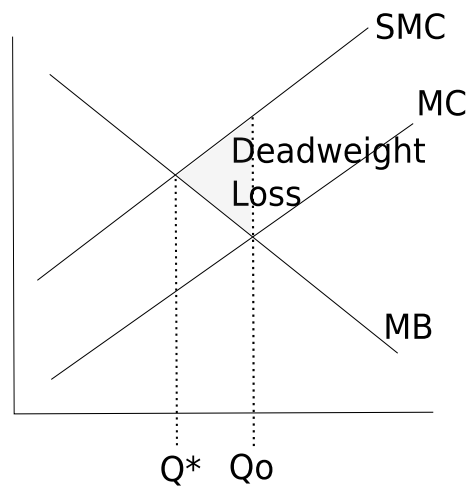


Figure 1: Deadweight Loss

There are a few things worth pointing out:

1. competitive solution
2. optimal solution
3. deadweight loss

And now a numerical example: Revenues at an unregulated power plant depend on the amount of emissions it produces, where output is increasing in emissions. Let the marginal revenue of the firm be $MR = 100 - Q$.

The firm can reduce emissions at a constant marginal cost of $MC = 50$. It is estimated that the emissions cause an additional social cost of 10.

2.2 Open-Access / Common Good

Externalities arise from production decisions because the environment is an open-access good. Specifically, the environment as a place to dump by-products of production is an open-access, it is commonly owned, which is the same as saying that nobody owns it. Until fairly recently, firms were free to dump as much as they wanted into the waters and air. Water sources have been regulated for a long time; emissions into the air are finally catching up.

The following table is useful for identifying types of goods;

Table 1: Taxonomy of Goods

	Excludable	Non-Excludable
Rivalrous	Private Goods	Common Goods
Non-rivalrous	Club Goods	Public Goods

Private goods are the type of goods we usually think of, such as an apple. I can keep you from consuming my apple (excludable), and if I eat the apple you cannot (rivalrous). Club goods are goods often managed by clubs, for example golf courses. They are excludable because you can charge an entry fee, put up a fence, etc. They are non-rivalrous in that if I golf on the course, so can you. Note that this is only true up to a point. If enough people show up to golf we have *congestion*.

Let's consider the problem from the view of a specific firm. Imagine first that a firm owns the air surrounding it, or maybe that its smokestacks empty inside the factory. The firm produces a good valued by society. In order to produce the good it must produce emissions. Because the firm can sell the good in the market, there are benefits associated with emissions. We usually assume that these benefits are quadratic, or upside down u-shaped. The upward sloping segment of the u comes from the fact that benefits from emissions are positive, but diminishing returns exist. So each additional unit of emissions adds to the total benefit, but in a slightly smaller increment, perhaps because of diminishing returns in the actual production process and perhaps because the smoke stacks are inside and workers are beginning to get sick. Eventually the smoke will get so thick that benefits of emitting an extra unit are actually negative and total benefits will begin to fall. If they fall far enough they will eventually reach zero.

Let's suppose this is a constant return to scale production process so marginal (private) costs of emissions are constant. This corresponds to a constantly upward sloping total cost curve.

Ok.. now suppose that the smoke stacks are outside and there are an infinite number of very small firms producing and emitting. The marginal benefits curve is still an upside-down u, for mostly the same reasons. At certain levels of pollution the benefits of polluting turn negative - maybe because the smoke gets so thick workers can't see what they are doing, climate change reaches a point that extreme weather events make it impossible to do business, etc. The total cost curve will be the same.

This is called the **Tragedy of the Commons** and is quite possibly the most 'famous' result in natural resource economics.

In the following figure you should be able to find the market or competitive outcome and the socially optimal

outcome. At each location you should be able to identify the total benefits society gets from emissions.

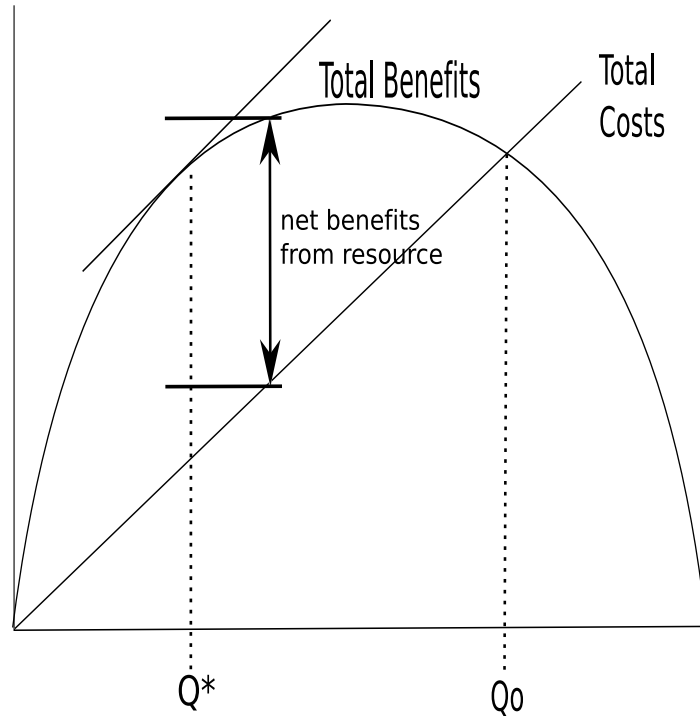


Figure 2: Tragedy of the Commons

3 Policies to Correct Externalities

Reconsider the 'marginal' graph for externalities, figure 1 above. The next section shows the mathematical equivalent.

3.1 Unregulated Firm

An unregulated firm chooses the amount of emissions e to maximize profits π . Emissions are the only input to the production process, where quantity of output is $f(e)$ and the price of the good is p . The per unit cost of emissions is w .

$$\pi = pf(e) - we \tag{2}$$

The first order conditions for the firm are

$$pf'(e) - w = 0 \tag{3}$$

or

$$pf'(e) = w \tag{4}$$

A profit maximizing firm chooses to the production level that sets marginal revenue product $pf'(e)$ equal to marginal cost of production w .

3.2 Social Optimum

We now solve for the social optimal amount of emissions and compare it to the level chosen by the firm. We would like to maximize social welfare W , which is equal to firms profits π minus total climate change damages $D(e)$.

$$W = \pi - D(e) = pf(e) - we - D(e) \tag{5}$$

which gives the following first order condition

$$pf'(e) - w - D'(e) = 0 \tag{6}$$

or

$$pf'(e) = w + D'(e) \tag{7}$$

The socially optimal level of emissions sets marginal revenue product $pf'(e)$ equal to social marginal costs, that is the sum of the firms marginal costs w and the marginal environmental damages $D'(e)$. This corresponds to Q^* in figure 1.

There are two parts to the problem that arises: (1) too much is produced and/or (2) the price is too low. Solutions will, therefore, be along the lines of (1) policies directly aimed at adjusting the quantity produced and/or (2) prices aimed at adjusting the cost of production.

3.3 Command and Control

The first type of policy we consider is *command and control*. Command and control assumes there is an all-knowing regulator that specifies the exact amount of emissions each firm should produce. The regulator simply says you may emit X and the firm must do it. Alternatively, the regulator could specify steps firms must take to solve the problem, such as which production technologies must be used. Early environmental policies were all command and control and newer climate change policies in the EU seem to be heading that way.

Forms of command and control

1. *Best Available Technology (BAT)* – Best Available Technology regulation specifies the type of equipment a firm must use in the production process. A major advantage of this type of regulation is the ease of which regulators can check compliance. A simple factory tour is often enough to ensure firms are meeting their obligations. Disadvantages to BAT regulation include the lack of incentives for industry to develop newer, better technologies. All R&D must be undertaken by the regulator. It also removes any competitive advantages a firm may have from its production technology; because all firms must use the same production process any competitive edges must come from some other area of business.
2. Quantity targets – Under command and control, regulators may also specify quantity requirements on some aspect of the production process and allow firms flexibility in meeting those requirements. For example, a regulator may directly specify the actual allowable level of carbon emissions a firm may emit. The most common example of quantity targets include fuel efficiency requirements for new vehicles and energy efficiency requirements for new household appliances. The major advantage of quantity targets is that it maintains firm incentives for innovation and least cost way to meet the environmental goals. Major disadvantages include the need to specify quantity targets on a firm by firm or industry by industry basis, it is harder to tell if a firm has met their obligation without testing each unit produces (for example, do all electrical appliance produced by a plant meet the efficiency requirements), and a disconnect between actual level of carbon produced and the regulation (for example, regulating fuel efficiency of cars may reduce greenhouse gases but by how much depends on the characteristics of drivers - upkeep of the vehicle, distance driven, etc).

Regardless of the type of command and control policy actually used, the advantages and disadvantages are as follows:

Advantages of Command and Control:

1. Extreme flexibility in controlling complex environmental problems. Can regulate each individual firm, location, etc. This may not be a big deal in the climate change arena, where location of the source of carbon does not matter.
2. Avoids ambiguity with respect to firm incentives. For example, compared to environmental fees, we don't need to know how the firm will adjust output in response to the regulation. They are told exactly how to adjust output.
3. Monitoring is easy

Disadvantages of Command and Control

1. Restricts the choice of firms with respect to ways of meeting goals
2. Lacks ways of achieving equal marginal control costs across firms, or requires lots of information to achieve equal marginal control costs.
3. Costly to administer. The regulating body must have enough information to effectively determine the best available technology or appropriate control method, which means hiring engineers, accountants, etc.
4. Polluters only pay for emissions controls, not actual damages. This leads to distortions in prices and acts as a subsidy to producers.

4 Market-based Policy Instruments

Command and control is very unpopular among firms and pro-market policy makers that believe the government should not dictate how businesses should handle their affairs. Instead there is a push for market-based instruments that provide rewards to firms to do what is perceived to be in the best interest of the public good.

Economic decisions are made on the margin; thus, to influence firm decisions we must design a policy that directly links emissions with firm costs. Let these new costs, which depend on emissions e be $G(e)$, for 'Government'. The goal of the firm is to maximize profits with the new policy,

$$\pi = pf(e) - we - G(e) \quad (8)$$

The first order condition for the firm is

$$pf'(e) - w - G'(e) \quad (9)$$

or

$$pf'(e) = w + G'(e) \quad (10)$$

Comparing the above equation with the first order condition in the social optimum, it is obvious that any policy should set $G'(e) = D'(e)$. There are numerous ways of doing this, but all market-based instruments for controlling greenhouse gases are either 1) price instruments or 2) quantity instruments.

4.1 Price Instruments

Price instruments are either fees/taxes or subsidies on each unit of firm emissions. In general, a fee will always achieve economic efficiency whereas a subsidy may not achieve economic efficiency. We consider each in turn.

1. *Pigouvian Fee* - A Pigouvian fee, named after Pigou who invented them, is a fee paid by the polluter per unit of pollution exactly equal to the marginal environmental damage caused by pollution when evaluated at the efficient level of pollution. This definition is very important to know. We'll examine each part of the definition:
 - (a) First, fee or tax policies require every firm to pay a per unit fee for each unit of pollution. The firm may pollute as much as it wants provided it pay the associated fee. This will change the firms profit function to $\pi = pf(e) - we - \tau e$ where τ is the per fee per unit of emissions.
 - (b) Second, the fee must be set equal to the marginal environmental damage evaluated at the optimal amount of pollution. This is actually a big deal, because it also says that we don't need to know anything about marginal environmental damages away from the optimal level. Differentiating the firm's profit function under the tax policy gives, $pf'(e) - w - \tau = 0$ All we have to do is set $\tau = D'(e)$ at the social optimum to achieve economic efficiency.

Graphically,

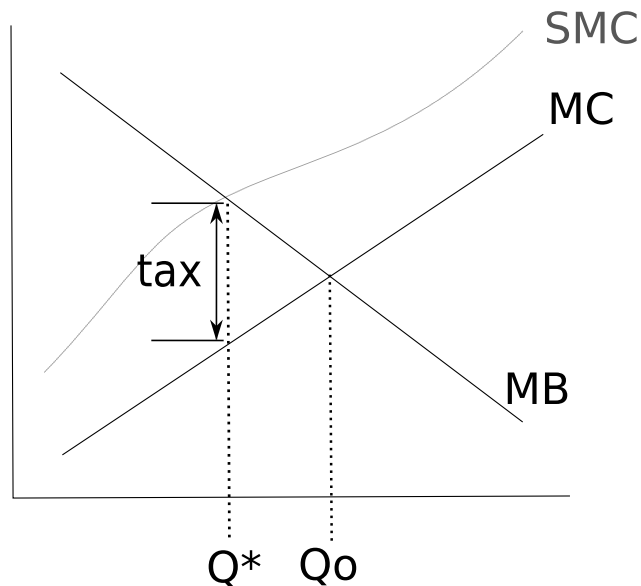


Figure 3: Pigouvian Tax

Firms consider whether the marginal benefits (marginal revenue product or savings from emitting) are greater than marginal costs plus the tax, with profit maximization taking place where marginal benefits equals marginal cost plus the tax. Provided the tax rate is set equal to marginal environmental damages at Q^* , the firm chooses the socially optimal amount.

2. Subsidies - Subsidies are per unit payments to firms for reducing their emissions. Subsidies get a lot of political support because every legislator has some firm back home that would like to receive subsidies from the government. Subsidies, however, rarely achieve economic efficiency, due to effects that happen in both the short run and long run.
 - (a) Short run - The short run is defined as a period in which there are fixed costs. And because we are going to be talking about costs to the firm, we need to modify the way we talk about society's objectives and firm incentives. First, it should be pointed out that most of what we have discussed had to do with finding the optimal amount of emissions or output. There is another part of the economic efficiency story that has largely been ignored - that of reaching the optimal amount in the least cost method. If we were to rewrite the Pigouvian fee story from the cost perspective, the firm's objective becomes to minimize costs

$$C(y, e) = V(y, e) + \tau e + FC \quad (11)$$

where total costs $C(y, e)$ and variable costs $V(y, e)$ are a function of output y and emissions e . FC are fixed costs and τe are the firm's payment of the fees. For simplicity we will assume a constant emission to output ration so we can write $e = ay$ and thus

$$C(y, ay) = V(y, ay) + \tau ay + FC \quad (12)$$

which gives first order condition

$$V'(y) + \tau a = 0 \tag{13}$$

where $V'(y)$ is marginal variable costs. The above condition minimizes total costs and is required for firm and social efficiency.

We now compare this to cost minimization with a subsidy s paid to the firm for every unit of reduction in emissions below some predetermined level \hat{e} . We can think of \hat{e} as last period's emissions. Thus, firm costs go down by $s(\hat{e} - e)$. The firm chooses emissions to minimize

$$C(y) = V(y) + FC - s(\hat{e} - e) \tag{14}$$

which can be rearranged as

$$C(y) = V(y) + say + [FC - s\hat{e}] \tag{15}$$

The second term is the opportunity cost of emitting, that is, foregone subsidies from each unit of emissions. The last term in the $[\]$ are total fixed costs. The first order condition for the firm is

$$V'(y) + sa = 0 \tag{16}$$

which provided $s = \tau$ would seem to imply that we can achieve economic efficiency with a subsidy. Unfortunately, this is not true. Recalling our economic principles, we hopefully remember that in the short run firms have the option of shutting down, therefore producing nothing and incurring zero variable costs. If there is a subsidy, we also assume that they cannot receive the subsidy if they shut down, and this is where the problem is. We have firms producing when they should not in order to get the subsidy and cover some of their costs. This is best seen with a graph.

- INSERT GRAPH HERE

Firms will operate provided prices are above marginal variable costs, and since firms produce where marginal revenue (or price in a perfectly competitive industry) equals marginal cost, the supply curve becomes the marginal cost curve above the intersection with the average variable cost curve. Thus, with a subsidy, firms may produce at prices lower than they would without regulation or with a tax. Depending on where demand cuts these curves, output may be too high. At the very least, less efficient firms (firms with higher average variable costs) will be able to operate with a subsidy than would otherwise. And since we would rather less efficient firms not produce, we are not likely to be at efficiency.

- (b) Long run - The long run story is much like the short run story, but instead of firms choosing whether to shut down, they choose entry or exit into the industry. The graph will be exactly like that for the short run except with average total cost curves rather than average variable cost curves. In the long run firms operate at the minimum of their average total cost curve, also where marginal costs intersect the curve. Both a tax and a subsidy shift the MC curve up. However, a tax increases the average total costs whereas a subsidy reduces average total costs; high cost, inefficient firms can survive with a subsidy. Again we have too much production.

4.2 Quantity Instruments

When people say quantity instrument, usually what they mean are tradable permits or carbon credits. A permit allows firms (or individuals or NGOs) to sell or buy the right to emit a specified amount of carbon into the atmosphere. There are three reasons tradable permits work:

1. By allocating permits and allowing trade regulators create a market for emissions, which means they have created market value where there was previously no market value.
2. This market value makes emitting carbon an firm expense which they would like to optimally manage.
3. Not only is there a direct cost associated with emitting, as there would be under a tax, but there is also an opportunity cost of emitting - the foregone revenues from selling the permits.

Example: We offer an example with two firms to illustrate, though what is presented here is equally valid for many firms. A government regulator has decided that \bar{e} is the appropriate amount of emissions that can be released into the atmosphere in a given year. These emissions are to be split between two firms. The regulator allocates permits equal to \bar{e} randomly to the two firms. Let the initial allocation be denoted (e_1^0, e_2^0) where e_1^0 is the initial amount given to firm 1 and e_2^0 is the initial amount given to firm 2. We know that $e_1^0 + e_2^0 = \bar{e}$. Firms emit carbon into the atmosphere because it is cheaper than production methods that do not require carbon emissions. Let the marginal savings from emitting (or marginal net benefits from firm emissions) be given by $MS_1(e)$ and $MS_2(e)$ for the two firms. This setup can be shown on the following graph. The left vertical axis represents marginal savings to firm 1 and the right vertical axis represents marginal savings to firm 2. The horizontal axis measures firm 1 emissions from left to right and firm 2 emissions from right to left.

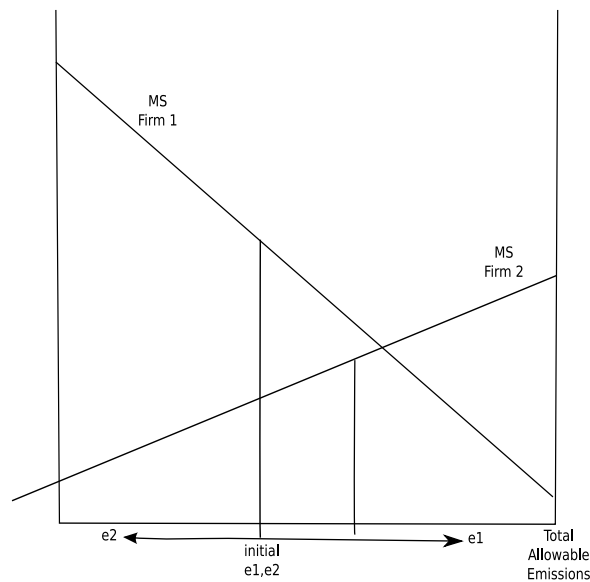


Figure 4: Tradable Carbon Credits

Note that at the initial allocation marginal savings from emitting are higher for firm 1 than for firm 2, meaning firm 1 values carbon permits more than does firm 2. Firm 1 would be willing to buy permits from firm 2 at any price lower than its marginal savings. Because it costs firm 2 less to reduce emissions than firm 1 is willing to buy emission credits for, trade will occur. Firm 1 will continue to buy credits from firm 2 until their marginal savings from emissions are equal. This will determine the equilibrium permit price. In the final equilibrium firm 1 will be emitting at levels above its initial allocation of permits and firm 2 will voluntarily reduce its emissions in order to sell permits to firm 1.

4.3 Coase Theorem

Tradable permits work because of a finding by Ronald Coase, now known as the Coase Theorem. Coase said that if property rights are well-defined and there are no transaction costs, parties will negotiate to the Pareto optimal outcome. Most environmental problems, including climate change, occur precisely because property rights are ill-defined or not defined at all, preventing the creation of a market. By creating tradable permits, regulators have defined property rights for carbon emissions - anyone with a permit has the right to emit. The initial allocation matters for distributional or fairness issues, but does not matter for efficiency.

5 Price vs Quantity Instruments: The role of uncertainty

In a world where regulators have perfect knowledge about everything, price and quantity instruments both achieve the social optimum. However, there are large differences in the two when marginal savings from emissions are unknown to the regulator. Typically this information is only known by the firm, and regulators must rely on firm responses. Of course, firms have a strategic incentive to tell the regulator whichever answer it thinks will lead to more leniency.

5.1 Price Instrument under Uncertainty

Imagine that a regulator is trying to determine the optimal tax rate to impose on firm emissions. The regulator knows that firms will either have 1) low savings associated with emitting denoted MS_L or 2) high savings associated with emitting into the atmosphere denoted MS_H . If the firm gets very little benefits from emitting (marginal savings are low), the regulator would like to impose a strict emissions standard and high fee. However, if the firm benefits associated with emissions are high, costs to control emissions are also high. The regulator may want to impose more lenient environmental policies. Regardless of the actual firm type, therefore, the firm has an incentive to say it is a high control cost firm in order to get the lenient policy.

Faced with such uncertainty, the regulator would like to minimize expected social costs of emissions

$$ExpectedSocialCosts = ExpectedPollutionControlCosts + PollutionDamage \quad (17)$$

The regulator can solve the above minimization problem and set the appropriate emissions fee. We know that firms will emit such that the marginal cost of abatement or the marginal savings from emissions is equal to the tax rate, shown in the following figure.

The regulator sets the emissions fee equal to r . If marginal savings are low, the firm will emit e_1 ; if marginal savings are high, the firm will emit e_2 . The shaded area represent welfare losses associated with each outcome.

5.2 Quantity Instrument under Uncertainty

Alternatively, the regulator could solve the expected cost minimization problem and allocate permits according to the quantity determined. In this case, e is emitted with certainty, but we don't know for sure what the cost of abatement will actually be, as shown in the graph. If the firm is a high savings firm the cost of

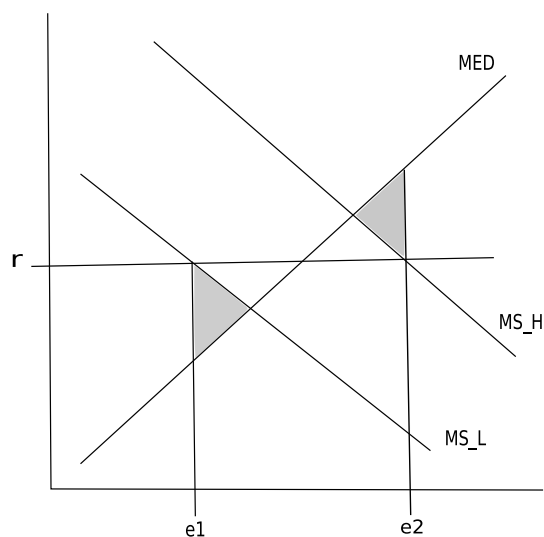


Figure 5: Efficiency Losses Associate with Price Instrument

abatement will be PH, if the firm is a low savings firm the cost of abatement will be PL. The shaded regions denote welfare losses associated with each possibility.

5.3 Comparing the Two Types of Instruments

We have seen that under uncertainty, both price and quantity instruments lead to welfare losses. The question is, which policy yields the least welfare loss. It turns out the answer depends on the relative slopes of the marginal savings and marginal environmental damage lines. Compare the following two pictures showing the welfare losses associated with either a fee set at r or permit policy with e allowable emissions.

The darker areas indicate the loss from the quantity instrument; the lighter areas indicate welfare losses from price instruments. Which policy is better, or leads to smaller welfare losses, depends on the relative slopes of the marginal damages and marginal savings curves. If the marginal damage curve is flatter than the marginal savings curve, price instruments are preferred. If the marginal damage curve is steeper, quantity controls are more preferred. This makes sense. If damages become severe with small changes in quantity, it is more important to get the quantity right. If damages are relatively constant, regulators should pay more attention to managing control costs.

In summary

- With price instruments, costs of controlling emissions are known. Marginal control costs will equal the fee. The actual quantity of emissions is uncertain.
- With quantity instruments, the amount of emissions is known, equal to the level specified by the regulator. The cost of controlling emissions, however, is uncertain.

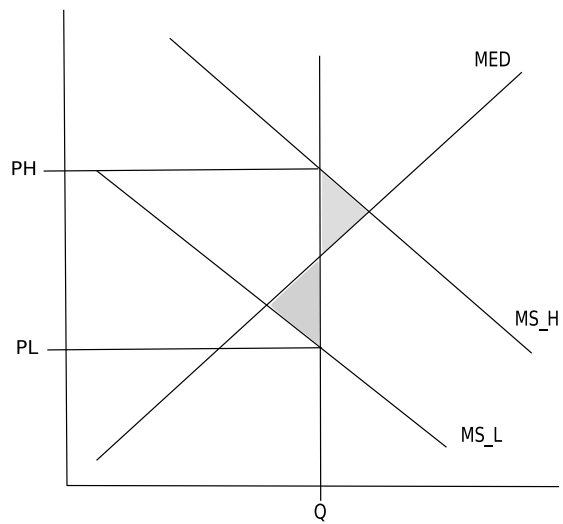


Figure 6: Efficiency Losses Associate with Quantity Instrument

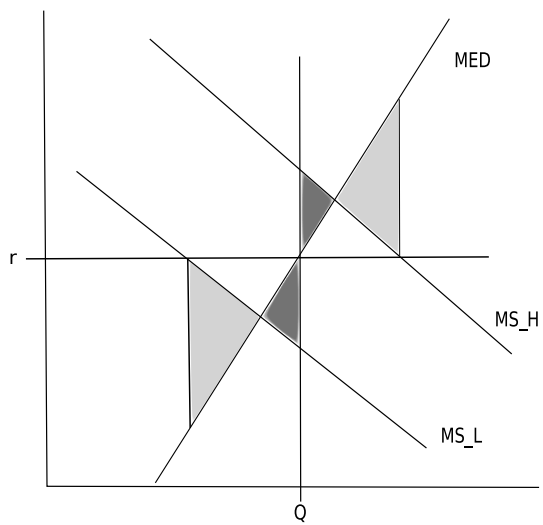


Figure 7: Comparison 1

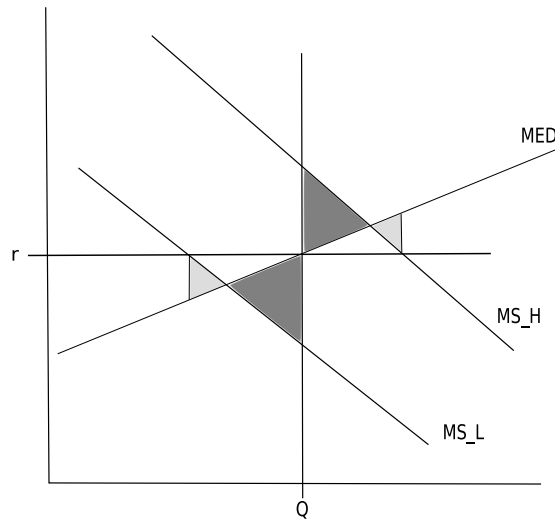


Figure 8: Comparison 2

5.4 Comparing the Two Types of Instruments - take 2

The original question of whether price or quantity instruments are better under uncertainty was set out by Weitzman in the *Review of Economic Studies* in 1974. His setup was slightly different, so students interested in reading his work should be careful. First, he examines the problem from the other angle. Instead of looking at the cost and benefit of emissions, he examines the cost and benefits of better environmental quality, e.g., clean air. In this case, what I earlier referred to as the marginal savings curve of emissions would become the marginal cost curve associated with achieving clean air (or abating pollution). Likewise, the marginal environmental damage function would be transformed to the marginal benefit function for clean air. The picture would look like the following

– insert graph of marginal benefits and marginal cost of better environmental quality –

Timing of the problem is as before. The regulator must choose and set either a price or quantity instrument without knowing the true cost of abatement to the firm. The firm makes its decision after the policy has been made, and after uncertainty has been resolved. In this case, Weitzman comes to the following conclusions:

1. If the benefit function is more sharply curved or the cost function is close to linear, using price controls could be detrimental.
2. If the marginal benefit function is roughly linear, it would be foolish to name a quantity, because in fact, society is indifferent to the quantity.

6 Hybrid Policy

The best of all worlds is a policy that combines price and quantity instruments, known as a hybrid policy. A hybrid policy specifies a quantity target but allows firms to emit more than the target provided they pay a per unit fee to emit. If firms emit less than the specified target, they get a per unit subsidy.

Imagine that there are two possible states of the world 1) high marginal savings from emitting and 2) low marginal savings from emitting. The regulator does not know which state of the world is more likely but does know the average marginal savings MS_{AVG} and the marginal damage function MD . With no way to resolve the uncertainty the regulator specifies an amount e^* for the firm to emit. The firm must pay a per unit fee p for any unit above e^* and receives a per unit subsidy s for each unit of reduction below e^* . Thus total payments and subsidies are

- subsidy of $s(e^* - e) = se - se^*$ if $e < e^*$. The subsidy becomes an opportunity cost of emitting for the firm.
- fee of $p(e - e^*) = pe - pe^*$ if $e > e^*$. The fee raises actual cost to the firm.

Graphically,

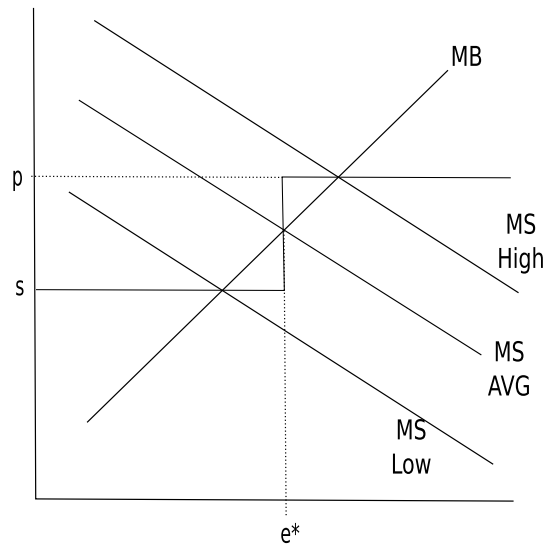


Figure 9: Hybrid Emissions Policy

If savings from emitting are low (i.e., marginal cost of abatement is low) the firm voluntarily reduces emissions and receives the subsidy. If savings from emitting are high (marginal cost of abatement is high) the firm chooses to pay the emission fee. With only two possibilities for cost level we get an efficient outcome. With more than two firms we don't quite get efficiency but it comes closer than either a strict price or strict quantity mechanism.

7 Stock Pollutant

It is important to remember that carbon in the atmosphere is a stock pollutant, meaning it builds up over time. This changes slightly the way we define and talk about marginal damages.

A stock pollutant can be defined by

$$s_t = \delta s_{t-1} + e_t \quad (18)$$

where s_t is the amount of the carbon in the atmosphere at time t . δ is the rate of decay, or the speed of which carbon is naturally absorbed into the deeper oceans, e_t is emissions at time t which add to the amount of carbon in the atmosphere. Looking at only the first period ($t = 1$) emissions, net costs from first period emissions are

$$NetCosts = NC = \sum_{t=1}^{\infty} \beta^{t-1} \{c_t(e_t) + D_t(s_t)\} \quad (19)$$

where $\beta = \frac{1}{1+r}$. Economic efficiency requires net costs to be minimized, which is done by making marginal changes to first period emissions so

$$\frac{dNC}{de_1} = \sum_{t=1}^{\infty} \beta^{t-1} \left\{ \frac{dc_t(e_t)}{de_1} + \frac{dD_t(s_t)}{de_1} \right\} = 0 \quad (20)$$

$$\frac{dNC}{de_1} = \sum_{t=1}^{\infty} \beta^{t-1} \left\{ \frac{dc_t(e_t)}{de_1} + \left[\frac{dD_t(s_t)}{ds_t} \frac{ds_t}{de_1} \right] \right\} = 0 \quad (21)$$

Because $s_t = e_t + \delta e_{t-1} + \delta^2 e_{t-2} + \dots$, $\frac{ds_t}{de_1} = \delta^{t-1}$. The first term in the above equation is marginal costs (or negative of marginal savings) from emissions, thus

$$\frac{dNC}{de_1} = MC(e_1) + \sum_{t=1}^{\infty} \beta^{t-1} \delta^{t-1} MD_t(s_t) = 0 \quad (22)$$

or

$$MS(e_1) = \sum_{t=1}^{\infty} \beta^{t-1} \delta^{t-1} MD_t(s_t) \quad (23)$$

The above equation is the condition for optimality with a stock pollutant. The left side is the same as before, but the right side is a more complicated version of marginal damages that includes effects from several time periods.

8 Exercises

1. *P vs Q* Notice that the Weitzman story is completely about uncertainty about firms' cost of abatement. We have not talked about the role of uncertainty in the environmental damages function in achieving

efficiency, or at least in the difference between price and quantity instruments. Does it matter? Why or why not?

2. *Market Equilibrium with Multiple Agents* The market demand for a good is given by $Qd = 8004P$. There are three price-taking sellers. Sellers 1 and 2 each have a willingness to accept given by: $P = Qs_1$. Seller 3's willingness to accept is $P = (Qs_3)/4$. Determine: The quantity sold by seller 3.
3. *Positive Externality* The marginal benefit of flu vaccines is given by $MB = 100Q$. The marginal cost of flu vaccines is given by $MC = 3Q$. Studies have found that an individual vaccine raises social welfare by 20 per vaccine. Determine: The optimal number of vaccines.
4. *Deadweight Loss* The marginal benefit from local road construction is given by $MB = 100Q$, where Q is days of construction. There is a constant marginal cost of $MC = 50$. It is estimated that the detours from construction add an additional social cost of 10 per day of construction. Determine: The deadweight loss associated with the construction.
5. *Consumer and Producer Surplus* Consider an inverse demand function given by $P = 80 - Q$ and marginal costs of a profit maximizing firm with marginal costs $MC = Q$.
 - (a) Compute consumer surplus and producer surplus if Q is supplied by competitive industry.
 - (b) Compute consumer surplus and producer surplus if Q is supplied by a monopoly firm.
 - (c) Compare price, quantity, producer surplus, consumer surplus between the two scenarios.
6. *Externalities* Suppose two agents are deciding how fast to drive their cars. Agent i chooses speed x_i and gets utility $u_i(x_i) = m_i + \phi(x_i)$, where m_i is money. However, the faster the agents drive the more likely they are to get in a mutual accident. Let $p(x_1, x_2)$ be the probability of an accident. Let $c_i > 0$ be the cost an accident imposes on agent i such that $u_i(x_i) = m_i + \phi(x_i) - c_i$ is utility following an accident.
 - (a) Show each agent has an incentive to drive too fast from the social point of view.
 - (b) If agent i is fined amount t_i , in the case of an accident, how large should t_i be to internalize the externality?
 - (c) If the optimal fines are being used, what are the total costs, including fines, paid by the agents. how does this compare to the total cost of an accident?
 - (d) Suppose now that agent i gets utility $u_i(x_i) = m_i + \phi(x_i)$ if there is no accident and $u_i(x_i) = m_i - c_i$ if there is an accident. What is the appropriate fine in this case?
7. *Recycling Bottles* One important motivation for recycling bottles and cans is to reduce litter. Suppose you are given the following facts about the glass bottle industry:
 - The demand for tons of bottles is given by $Q = 1000 - 10 * P$.
 - The cost of producing bottles from raw materials is \$50 per ton.
 - Litter creates an externality cost of \$20 per ton of bottles produced.
 - Bottles can be recycled at a MC of $\$1 * X$, where X is the tons recycled.

Please answer the following questions:

- (a) Find the market outcome when firms take prices as given and the industry ignores the litter problem. Find the price, the total quantity of bottles consumed, the amount produced from raw materials, and the amount produced by recycling (if any).
- (b) Explain why the outcome in part (1) is not efficient. Use an appropriate graph to illustrate your explanation. Now calculate the efficient outcome and suggest a specific policy that could move the industry toward efficiency.

8. *Electricity Generation with Nuclear Power* Suppose that electricity can be produced by nuclear power at a constant marginal cost of \$10 per unit (that is, $MC = \$10$). A city's demand for electricity from nuclear power is given by the equation: $P = 15Q/1,000,000$. Please determine the market equilibrium price and quantity of electricity.

Suppose each unit of electricity generated produces 1 gram of radioactive waste. The waste remains safely inside the reactor for 20 years. After 20 years, the reactor core is moved to a storage site. From year 21 on (forever), there is a $1/100,000,000$ chance (each year) that a person will come into contact with the waste. If that happens, the damages are \$6 million. Calculate the expected present value of the damages associated with one unit of electricity. Be sure to show all your work. You may assume the interest rate is 5%.

Using your answer to question (2), find the efficient price and quantity of electricity.

9. *Congestion Externalities* The Internet is a prime example of one type of good that is not handled well by an unaided market. Suppose you were given the following information:

- Two types of people use the Internet: business users and home users;
- There are 1 million users of each type;
- Each business user has a willingness to pay for hours of use given by $P = 100 - 10Qb$, where Qb is the number of hours she spends on line;
- Each home user has a willingness to pay for hours given by $P = 4 - Qh/5$, where Qh is the number of hours he spends on line;
- At low levels of traffic, when total user-hours is less than 10 million, the marginal cost of using the network is zero;
- After network traffic reaches 10 million user-hours, each additional user-hour causes \$2 worth of external costs to other people. (That is, $MED = MSC = 2$).

Please answer the following questions:

- (a) If there is no charge for using the Internet, how many total user-hours will business users spend on line? How many total user-hours for home users? Is the efficient? If not, explain in non-technical terms what is wrong with the situation and what features of the Internet create the problem.
- (b) Suppose a fee were charged per user-hour for access to the Internet. What should the fee be? Why? How many user-hours will each type of user spend on line now? How much revenue will the fee generate from each group? How much, in dollar terms, will it reduce the problem from (1)? How will different groups feel about the policy?