The Economics of Regulating Greenhouse Gases: Command & Control, Emissions Trading, and Emissions Taxes

Jonathan Gilligan

EES 3310/5310: Global Climate Change

Contents

List of Figures

Introduction

When we think of government regulations to protect the environment, the most familiar type of regulations are those known as **command and control**, where the regulatory agency specifies in great detail not just the desired outcome of the regulation (limiting air pollution to a certain level, such as 0.08 parts per million of ozone), but also the way the regulated entities (individuals, companies, etc.) must behave to accomplish this outcome. The Clean Air Act uses command-and-control regulations when it tells automobile manufacturers that they must install catalytic converters on all cars to reduce emissions of chemicals that contribute to urban smog. The Department of Transportation uses command-and-control measures when it requires cars to have seat belts and air bags as standard equipment.

A problem with command-and-control regulatory strategies for regulating greenhouse gas emissions is that a one-size-fits-all solution may not work well for different industries and even different factories in the same industry. A factory may find it preferable to reduce its emissions by switching from a carbon-intensive energy source, such as coal, to a cleaner source, such as natural gas. Another factory may find it more economical to keep the same energy source, but cut its total energy use by improving the efficiency with which it uses energy.

Moreover, even if different factories and electric power plants are allowed to pursue individual strategies to reduce their greenhouse gas emissions, some will have an easier time reducing emissions than others. For instance, newer factories may find it easier to install high-efficiency equipment than older ones. Economic studies find that there is a wide range from plant to plant of costs to reduce emissions.

Regulating aggregate emissions

Greenhouse gas emissions are substantially different from many other forms of pollution because it doesn't matter at all to the environment where the gases are emitted. Greenhouse gases mix quickly throughout the atmosphere and what matters is the total atmospheric concentration, not where each particular molecule was released into the atmosphere, so what matters for regulators is not the amount of greenhouse gases any one factory emits, but the total emissions from the entire world. This is very different from pollutants, such as airborne lead or nitric oxide, which stay in the air only a short time and thus affect people who live near the source. Your exposure to airborne lead or nitric oxode depends only on how much is emitted by polluters in Nashville, and isn't affected at all by how much is emitted in Chicago or Shanghai.

In the late 1960s the economist John Dales proposed a different method for regulating emissions, such as greenhouse gases, where all that matters is the total emissions, not where the emissions take place: government regulatory agencies would set a limit on how much total pollution would be allowed and then leave the different polluters to work out among themselves the most efficient way to reduce pollution by buying and selling permits for emitting pollutants.[1] This idea languished in academic obscurity for more than a decade, but in the early 1980s, it was revived and proposed as a serious way to deal with acid rain caused by sulfur compounds emitted by factories and electric power plants that burned coal. One of the early champions of this approach was C. Boyden Gray, who served as counsel to the Presidential Task Force on Regulatory Relief under Ronald Reagan and as White House Counsel under George H.W. Bush. Gray had deeply conservative political views and his support for environmental regulation, even regulation that used market mechanisms, struck his friends as so odd that one later remarked, "I thought he was smoking dope."[2]

[1] For more on the history of tradeable emissions permits, see Richard Conniff, "The Political History of Cap and Trade," Smithsonian Magazine Aug. 2009, `www.smithsonianmag.com/science-nature/Presence-of-Mind-Blue-Sky-Thinking.html`

[2] Conniff, "Political History," *supra*, note 1

A worked example

Suppose that there are four power plants, each emitting 10 million tons of CO_2 per year (see Fig. 1a). The total CO_2 emissions into the bubble are 40 million tons per year. Let's say the government wants to reduce total emissions by 10%, to 36 million tons per year. We could do this by having each plant reduce its emissions by 10%, from 10 million tons to 9 million tons per year, as shown in Fig. 1b.

Now suppose that plants #1, 2, and 3 can sell the electricity they generate for a profit of about \$100 for each ton of CO_2 they emit. Plant #4 is less efficient and it can only sell its electricity for a profit of only \$80 for each ton of CO_2. Before cutting emissions, the total profits of the four power plants is \$3.8 billion per year ($10,000,000 \times (\$100 + \$100 + \$100 + \$80)$). If the only way for each plant to reduce CO_2 emissions is to generate less electricity, the arrangement in Fig. 1b, where each plant cuts its emissions by 1 million tons per year would reduce the total profit to \$3.42 billion, or \$380 million less than before ($9,000,000 \times (\$100 \times 3 + \$80)$).

However, if plants 1, 2, and 3 did not cut their emissions at all but plant 4 cut its emissions by 4 million tons, as shown in Fig. 1c, the total emissions would be reduced by 10% to 36 million tons, but the total profits would be \$3.48 billion ($10,000,000 \times (\$100 + \$100 + \$100) + 6,000,000 \times \$80$), \$60 million more than in the other arrangement. Cutting emissions preferentially at the least efficient plants can be much more economically effective than cutting emissions equally for all operators.

The same reasoning works if the plants pay to add energy-efficiency equipment to reduce emissions without cutting their electricity generation. Suppose the first plant would incur costs of \$20 per ton to reduce CO_2 emissions, while the other three would incur costs of \$24 per ton. If each plants cut emissions by 10%, the total cost would be \$92 million ($1,000,000 \times (\$20 + \$24 \times 3)$). Alternatively, the first plant could cut its emissions by 40%, from 10 million tons to 6 million tons, while the other plants maintain their 10 ton emissions. The total emissions into the bubble would still drop by 10%, from 40 million tons to 36 million tons per year, but the cost would now be \$80 million instead of \$92 million—a significant saving.

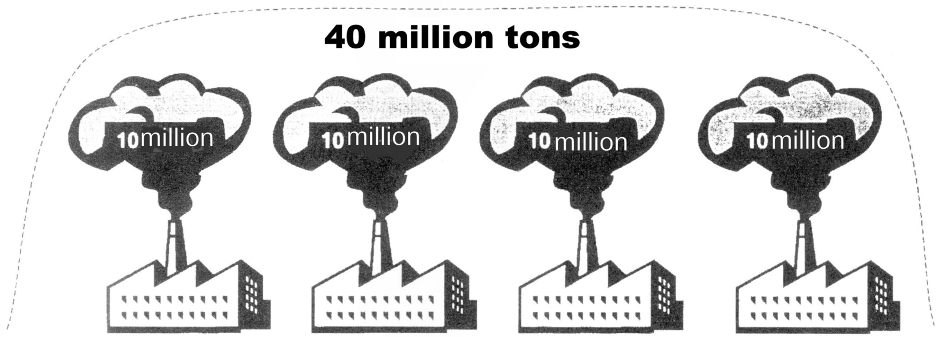
If allocating emissions reduction unequally can improve the efficiency, we might go farther and ask whether some plants might actually increase emissions and offset this with cuts at another, less efficient plant. Fig. 1d shows how this might work: plant #4 shuts down altogether, cutting its emissions to zero. Plants #1, 2, and 3 can now increase their emissions to 12 million tons per year and still remain within the limit of 36 million tons total emission under the bubble. The total profit is now \$3.6 billion, or \$180 million more than if the plants cut emissions equally.

Tradeable Permits: Creating a Market for Emissions

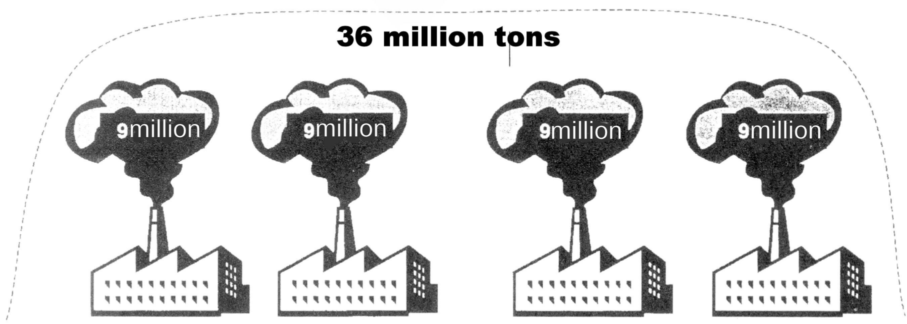
We have not yet addressed the way in which different companies would work out who would reduce emissions under a bubbled or netted regulation. Clearly everyone would prefer for someone else to reduce their emissions, so there must be incentives for someone to act. If the owner of plant #4 in the previous example had to absorb all the lost profits, he would not want to shut down his power plant even though it would produce the best overall outcome. This is accomplished by creating property rights and establishing a market, similarly to the libertarian suggestions of Ronald Coase or Friedrich von Hayek.

The first large-scale test of emissions markets occurred in the United States under the 1990 amendments to the Clean Air Act to limit acid rain that resulted from sulfate pollution from factories and electric power plants that burned coal. These amendments called for the Environmental Protection Agency to issue permits that would allow factories, power plants, and other polluters to emit sulfur compounds into the air. One permit would allow the holder to emit up to one ton of sulfur during the coming year. Anyone emitting more sulfur than he had permits for would pay a substantial fine (around \$1000 per ton). Permits would be sold at auction and total emissions would be controlled by limiting the number of permits available for sale. Permits would expire at the end of the year, so companies could not hoard them for use in the future. Environmental interest groups would be free to reduce pollution further than the law required by buying permits and not using them.

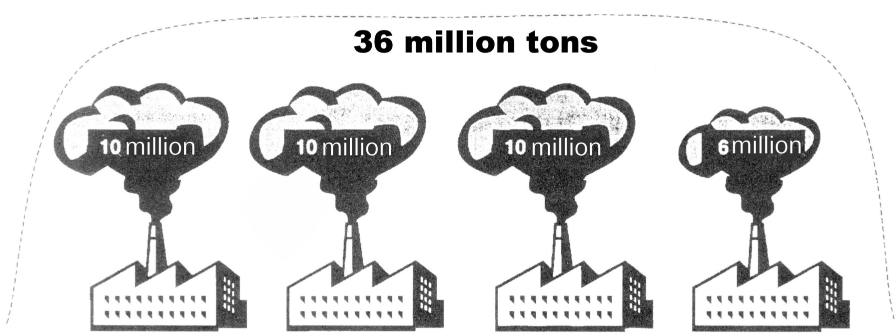
After permits were sold, some companies might find that they had more permits than they needed while other companies might find that they didn't have as many as they wanted. The EPA established



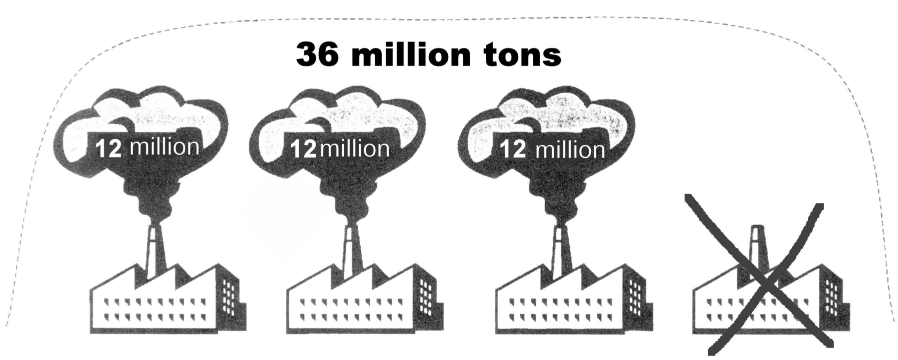
(a) Original emissions



(b) Equal reductions



(c) Unequal reductions: optimum allocation of reductions



(d) Optimum allocation: optimum allocation when both increases and reductions are allowed.

Figure 1: Different ways to reduce emissions by 4 million tons.

rules under which companies could freely buy and sell permits among themselves. The total number of permits would not change, but companies could exchange them at whatever price they could agree on. In a similar market for CO_2 emissions, the owners of plants #1, 2, and 3 in the first example might buy permits from the owner of plant #4. Suppose the owner of each plant starts with 9 million permits, for a total of 36 million tons of CO_2 emissions. The owner of plant #4 can make $80 profit for each permit he uses, but the owners of the other three plants can make $100 profit for each permit. If the owner of plant #4 offers to sell his permits for $90 each he will make more money selling the permits than he could earn using them. The owners of the other three plants could earn more money from each permit than it would cost them to buy it, so each of them would eagerly buy a permit from plant #4 and we achieve the optimal outcome illustrated in Fig. 1d where the maximum profit is earned.

This system is known as "**cap and trade.**" There are many other variations on market-based emissions-trading regulations, but they are largely similar to this one.

Tradeable Permits in Practice

When tradeable permits were first introduced in 1990, there was a lot of suspicion and skepticism. Industry interest groups were suspicious that the regulations would be too stringent and would have too great an economic cost, even with the efficiencies that permit trading would introduce. Environmentalists were suspicious that in selling the right to pollute to the highest bidder, the EPA was abandoning its mission to protect the environment and was confirming their deepest suspicions that a Republican administration was selling out the environment to big business. Some environmental groups denounced the proposed emissions trading program as a "license to kill."[3]

The plan was to start by reducing sulfur emissions by 37% during the 1990s and introduce more significant cuts in 2000 that would bring sulfur emissions 70% below 1990 levels.

In fact, the program worked better than anyone had imagined. In 1990, lobbyists for industry estimated that it would cost between $3 and $7 billion per year at the outset, with costs rising to $7–$25 billion per year by 2000 when the more stringent reductions came into force. More careful and optimistic studies by the EPA estimated the cost of compliance to be between $1.9 and $5.5 billion per year and EPA official Joseph Krueger recalls that when he testified before Congress that the annual cost in 2010 would be about $4 billion, "we were roundly criticized for being overly optimistic."[4]

In fact, in the first few years, the cost of compliance turned out to be so cheap that industry began cutting emissions faster than the EPA required. Economists working for industry think tanks, such as the Electric Power Research Institute, found that in the first two years of the emissions-trading program emissions had dropped 35% below the legal limit and the cost of emissions reduction were coming out to around $0.8 billion per year, less than half of even the most optimistic forecasts from the EPA.

The Phase-II reductions scheduled to begin in 2000 were expected to be more expensive, but even these came out to around $1 billion per year—less than one tenth of the more pessimistic industry estimates from the late 1980s and half the EPA's early estimates. Moreover, industry was cutting emissions much faster than the EPA required and had achieved the 1999 goals by 1995.

Why Was Emissions-Trading So Successful?

We can ask why emissions-trading was so much more successful than anyone had imagined when it was introduced. There are a number of explanations. Careful analysis of the history of emissions trading found that what all the analysts had omitted in their initial assessments was the power of the marketplace to stimulate innovation: when companies knew that they had to cut emissions, a new market emerged for pollution-control technology and the market-mechanisms provided enough flexibility for companies to pursue a number of different possibilities. As engineers competed to design and build better scrubbers, the cost of scrubber technology dropped by 40%.

[3] Conniff, "Political History," *supra*, note 1

[4] R. Kerr, "Acid Rain Control on the Cheap," Science **282**, 1024 (1998).

Because power plant operators had flexibility to choose the way they would achieve emission reductions, they could choose among different fuels—switching from high-sulfur coal to natural gas, to low-sulfur coal, or to a mixture of high- and low-sulfur coal together with some level of scrubbing. The Vanderbilt power station does not use scrubbers, but uses both natural gas and ultra-low-sulfur coal to produce electricity and steam to service buildings on campus. By having the flexibility to use either fuel, Vanderbilt can strike good deals with fuel vendors and achieve low emissions of pollution at a reasonable price.

As innovations and deregulation of rail transportation made it less expensive to ship low-sulfur coal for long distances, power plants in the Midwest and Appalachian areas were able to switch from local coal, which had relatively high sulfur content, to low-sulfur coal mined in Wyoming.

Lessons for Cost-Benefit Analysis

One of the striking lessons from the sulfur-emissions trading program is that estimates of the cost of complying with regulations may grossly overestimate the actual cost. This is not unique to sulfur emissions.

When an international treaty to protect the ozone layer went into effect in 1991 experts estimated that it would take 8–9 years to find acceptable substitutes for banned chlorofluorocarbon chemicals for use in refrigerators and that these substitutes would cost around \$3.55 per kilogram. In fact, it took only two years to bring substitute chemicals to market and they cost \$2.45 per kilogram, 30% less than the estimates. In other industries, eliminating chlorofluorocarbons sometimes even turned a profit, as we will see when we study the stratospheric ozone layer next week.

A systematic study of cost-benefit analyses of government regulations found that cost-benefit estimates tend systematically to significantly overestimate the costs of regulations and often underestimate their benefits. Of a sample of 28 regulations studied in depth, 14 cost less than 75% what estimates predicted, 11 cost between 75% and 125% of the estimates, and only 3 cost more than 125% of the estimates.

Estimates of benefits are often similarly skewed to underestimate the benefits of regulating pollution because people don't always know at the outset how dangerous a pollutant may be. Since the EPA revised its standard for $PM_{2.5}$ in 1995, epidemiological studies have found stronger connections between $PM_{2.5}$ and heart disease, so the number of lives saved by the new regulations has turned out to be significantly larger than was estimated when the regulation was enacted.

This doesn't mean that cost-benefit analysis is worthless—just that we need to understand its limitations if we want to use it effectively.

Emissions taxes

Tradeable permits are not the only possible way to harness the innovative power of markets to create efficient regulations. An approach that may be even more powerful is instituting pollution taxes. One weakness of cap-and-trade and cap-and-net schemes is that they require the government to decide what the appropriate level of pollution is. The limitations of cost-benefit analysis give a sense of the limits of having government set pollution targets. The government may set these targets too high or too low if it misunderstands the dangers of pollution or the cost of reducing emissions.

An alternate strategy is with **emissions taxes**: imposing a tax on CO_2 emissions equal to the value of the negative externality it creates. If a ton of CO_2 causes \$100 of damage to the environment then the government would impose a \$100 per ton tax for emitting CO_2.[5] This would allow consumers and industry to adjust their behavior to achieve an optimal balance of economic wealth and clean air. Because government would be receiving new revenue from pollution taxes, other taxes could be cut to compensate, leaving government revenues constant.

Many economists predict that pollution taxes would be more efficient than command-and-control regulations or even tradeable permit schemes, but the public aversion to taxes has so far prevented

[5] A tax that exactly balances the value of a negative (harmful) externality is known as a "Pigovian tax" after Arthur Pigou, the founder of Welfare economics, who proposed such policies for dealing with externalities in the early 1900s.

these from being implemented. The economist William Nordhaus wrote that right now, the U.S. is taxing something we want people to do (working and earning money) and not taxing something we don't want them to do (emit CO_2).[6] Removing a tax on goods (valuable things and activities) and replacing it with a tax on bads (harmful things or activities) would make the economy a lot more efficient, so Nordhaus proposes to impose Pigovian taxes on carbon emissions and reduce payroll taxes by an equal amount with the net total tax burden remaining constant. Nordhaus's proposal has been endorsed by Douglas Holtz-Eakin, who was John McCain's chief economic adviser during McCain's 2008 campaign for the presidency.

Weaknesses of Market-Based Regulation

The major weaknesses of market-based regulation have to do with the overhead involved in monitoring compliance and with questions of fairness.

Under a command-and-control regulatory scheme, it is easy to determine who is in compliance. Every year in Tennessee every car must be inspected for compliance with various environmental regulations, such as having a working catalytic converter and a gas cap that makes an airtight seal. There is no need to worry about what the car does in between inspections, so the cost of regulating automobile emissions is relatively small. If a factory must have a government-mandated scrubber and other pollution-control equipment, compliance can be enforced by having an inspector visit the factory from time to time to check the equipment. Again, this can be fairly inexpensive.

Under emissions-trading, it's necessary to constantly monitor the changing emissions from the factory. In practice, this means that each factory or power plant participating in an emissions-trading program must install multi-million-dollar emissions-monitoring equipment and the EPA must establish a network to constantly monitor the emissions and track who has permits. When pollution is emitted dominantly by a small number of point sources, this sort of monitoring is practical, but it clearly would not work to establish an emissions-trading program to manage pollution from automobiles because the cost of monitoring emissions and tracking permits would become unreasonably expensive. This is a problem for regulating greenhouse gas emissions because roughly one third of the emissions in the United States comes from cars and trucks. One possible way around this problem would be to move the regulation upstream, requiring petroleum refineries to buy permits for the gasoline and diesel fuel they sell. Nonetheless, advocates of taxing emissions argue that even though there are ways to adapt cap and trade to deal with large numbers of small emitters, it is still simpler and more effective to enforce a tax on fossil fuels than to try to monitor and enforce emissions permits.

While emissions trading would ensure that emissions were achieved at the lowest possible cost, that price might still be too high. Many opponents of emissions trading worry that it will cost more than advocates expect to cut emissions and that a cap and trade regulation would raise the price of energy so high that it would seriously damage the economy. To address this, many proposed cap-and-trade policies would include a "safety valve," which would call for the government to issue extra emissions permits if the price of permits rises above some threshold.

There are also disputes about how to issue the permits and what to do with the money they raise. Some policies call for government to simply give businesses permits free, based on the number of tons of CO_2 they have historically emitted, with the number of permits each firm receives dropping by a certain percentage every year. Others call for government to auction the permits, selling them to the highest bidder until all the permits are sold. Some would put the money generated by the auctions into government programs—either the general fund or a special fund to support research on clean energy or to help communities adapt to climate change—while another program, called "**cap and dividend**," where the money raised by the auction would be distributed equally to all citizens in the form of an annual check from the government. Peter Barnes, the author of the original cap and dividend proposal, says that the air belongs to everyone, so if someone's going to pay to alter the atmosphere, the compensation should be shared.

Emissions taxes have two strong advantages over tradeable permits: they would avoid much of the difficulty of verifying and enforcing compliance, and they would remove uncertainty in the price of

[6] W. Nordhaus, *A Question of Balance* (Yale, 2008), p. 26

energy (the added cost of energy would be the cost of the carbon tax, no more and no less).

Microeconomic treatment

The previous section assumed, for simplicity, that for each factory, the cost to cut emissions by one ton of CO_2 was the same regardless whether a plant was cutting by one ton or ten tons. Now let's consider what happens when we use a more realistic description, in which the marginal costs of cutting emissions rise and the marginal benefits fall as we make cut emissions by larger and larger amounts.

Marginal costs and benefits

Before we can calculate costs and benefits, we need to be familiar with the concept of **marginal cost** and **marginal benefit**. I will begin describing marginal costs. Marginal benefits are completely analogous.

MARGINAL COSTS AND BENEFITS FOR INDUSTRIAL PRODUCTION

If you build a factory and produce 1,000 iPods, the average cost per iPod will be high because the cost of inventing the iPod and building the factory will be much larger than the labor and materials that go into the 1000 iPods. If you produce 100,000 iPods at that same factory, the average cost per iPod will be much less because the cost of the factory is spread among many more iPods. It may be possible to use machines to automate the work done by factory workers. If there are few workers, it may not be worthwhile to buy expensive machines to automate production, but if you're producing lots of iPods and have many workers at the factory, the savings on labor costs may justify buying expensive machinery to automate the process. This is an example of an **economy of scale**: the more iPods you make, the less it costs to produce each iPod.

The **marginal cost** of producing a quantity of goods is the cost of producing the very last of those goods: the marginal cost of producing one million iPods is the cost of producing just the millionth iPod. When there are economies of scale, the marginal cost of the one-millionth iPod may be a lot less than the marginal cost of the one-hundred-thousandth iPod, which in turn will be a lot less than the ten-thousandth. Similarly, if a movie costs \$100,000,000 to produce, the marginal cost of showing it in one theater is \$100,000,000, but the marginal cost of showing it in a second theater is somewhere around \$10,000: the cost of making a second print of the movie and mailing it to the theater. Mass-produced consumer goods, such as iPods generally have economies of scale, so the marginal cost drops the more you produce.

On the other hand, there are many other goods where instead of economies of scale, there are **diseconomies of scale**, also known as **diminishing returns**. In those cases, the marginal cost is greater than the average cost, and it rises the more you produce.

MARGINAL COSTS AND BENEFITS OF EMISSIONS REDUCTION

In this section, I will consider the marginal benefits of emitting CO_2. These are the profits or other social goods that people produce with the energy they get from burning fossil fuels. An important point to understand is that **the marginal cost of cutting emissions is equal to the marginal benefit of producing those emissions**: If a factory is emitting 10 tons of CO_2 and the marginal benefit of emitting the tenth ton is \$30, then the marginal cost of cutting emissions is \$30 per ton. What is potentially tricky is that each ton has a different marginal cost.

The marginal benefits to society of pollution reduction also tend to follow diminishing returns: As we saw last week, the social cost of carbon (the social cost of carbon is, for practical purposes, equivalent to the marginal benefit of cutting emissions) is greater when the atmospheric concentration of CO_2 is higher. The amount of harm climate change is likely to cause rises dramatically the more the planet warms, so reducing global warming from four degrees to three degrees is likely to have a much greater benefit than reducing it from three degrees to two degrees. And reducing warming from three degrees to two degrees is likely to have much more benefit than reducing it from two degrees to one degree. This implies that for a factory, reducing emissions from 30 million tons per year to 20 million tons per year generally yields greater benefits to society than reducing it again from 20 million to 10 million tons. Nicholas Stern's economic review of climate change found that if CO_2 were to grow on a "business as usual" trajectory, the social cost of carbon would be around $85 per tonne of CO_2. If we adopted a policy of stabilizing greenhouse gases at concentrations equivalent to 550 parts per million of CO_2,[7] the social cost would only be around $30 per tonne. Figure 2b illustrates marginal benefit falling with increasing emissions and Fig. 2a illustrates the marginal cost (i.e., the social cost of carbon) growing with increasing emissions.

In general, we can justify a regulatory policy on utilitarian grounds if its total net benefit (the total benefit minus the total cost) is positive, meaning that the total benefit of reducing emissions is greater than the total cost of achieving those emissions cuts. However, just because a policy passes the cost-benefit test does not mean it is the best possible policy on utilitarian grounds: there may be another policy with even greater total net benefit.

The marginal costs and benefits come in when we try to find the policy that will have the greatest total net benefit. As long as the marginal benefit of emitting CO_2 is less than the marginal cost (due to the effects of climate change), you can increase the net benefit by decreasing emissions. On the other hand, once the marginal benefit of emissions exceeds the marginal cost, continuing to cut emissions only reduces the net benefit.

The optimum policy would have both a positive net benefit and zero net marginal benefit (i.e., the marginal cost equals the marginal benefit). Figs. 2c and 2d illustrate the total net benefit of emissions. In the figure, if you emit E tons of CO_2, the total benefit is greater than the total cost, so the net benefit is positive and even greater emissions could be justified as a policy. However, as the emissions increase, once they become greater than the optimal amount ($E*$), the marginal benefit would be less than the marginal cost, and it would be beneficial to cut emissions.The economically optimal change in emissions (either an increase or decrease) would be one that makes the marginal net benefit equal zero (the marginal benefit equals the marginal cost). We find this where the marginal cost line intersects the marginal benefit line, at $E^\star$.

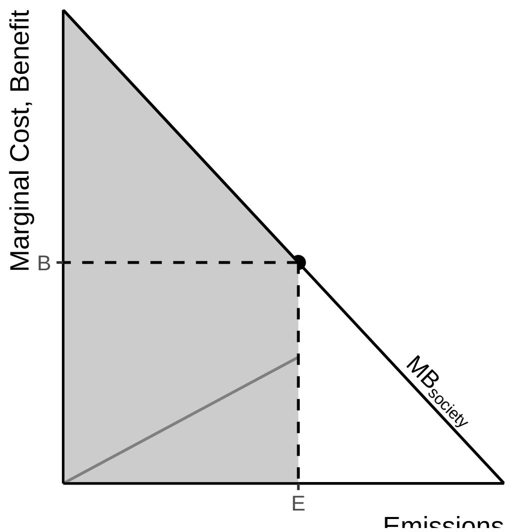
APPLICATION TO PRIVATE FIRMS

The same reasoning applies if you are running a company: if you want to maximize profit (income minus expense) you will find that this occurs when the marginal cost of increasing production equals the marginal price at which you can sell the product. Because of the usual shapes of supply and demand curves, the marginal cost tends to rise as supply rises while marginal price declines.

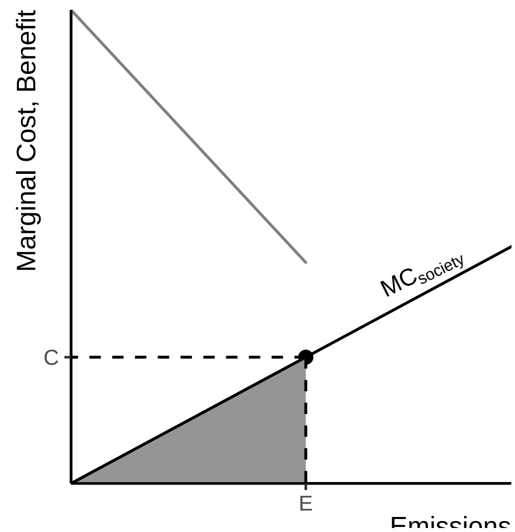
Marginal cost of producing more goods tends to rise because of diminishing returns (which we discussed last week). Diminishing returns apply, in some industries more than others. They apply very strongly in the energy business: if you only want to produce a small amount of coal or oil, you can focus on the places where it's easy to mine or drill. But if you want to produce a lot, you will quickly run out of easily accessible deposits and you'll need to start drilling and mining in more difficult or dangerous places, which makes the cost per ton of coal or per barrel of oil rise.

Marginal prices tend to decline because when there are only a few items to sell, those people who want them the most will pay very high prices, but after those people are satisfied, the next people in line will not be willing to pay as much, so they will only buy at lower prices. Consider this example: if there were only 1000 copies of the new Dan Brown novel available, there might be 1000 people willing to pay an awful lot for it; but if there are a million available, you wouldn't find a million people willing to pay the same amount, so the book will sell for much less than the 1000 most eager customers would be willing to pay.

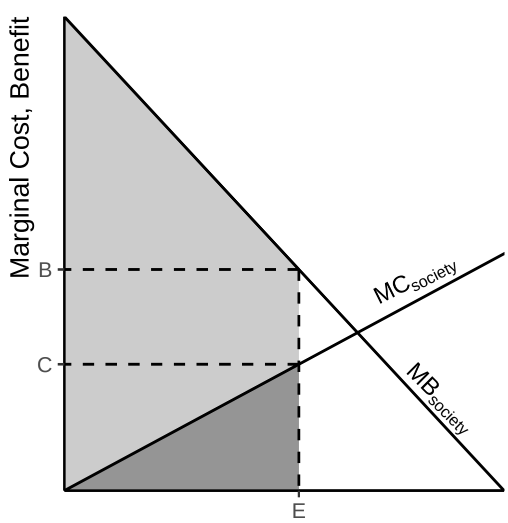
[7] Recall that the **equivalent CO_2 concentration** means the amount of CO_2 in the atmosphere that would produce the same amount of radiative forcing on its own as the sum of all the different greenhouse gases in the atmosphere. We calculate equivalent-CO_2 by adding up the contribution of each greenhouse gas, which we obtain by multiplying the concentration of each greenhouse gas by its **global warming potential**. Mathematically, $\mathrm{CO}_{2,\mathrm{eq}} = \sum_i c_i \mathrm{GWP}_i$, where c_i is the concentration of the i^{th} greenhouse gas and GWP_i is its global warming potential.



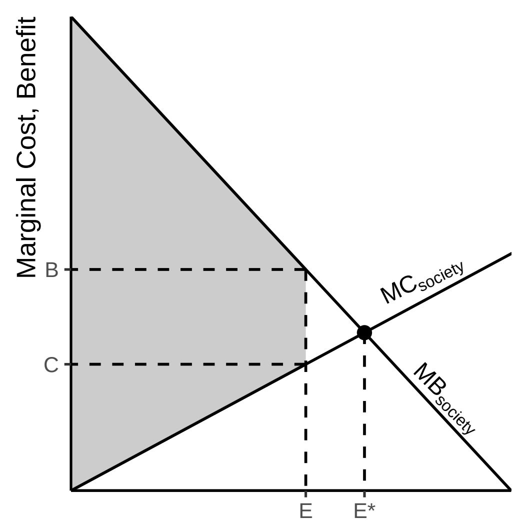
(a) B is the marginal benefit (profit) to society from emitting E tons of CO_2. The area of the gray triangle below the marginal benefit line is the **total gross benefit**.



(b) C is the marginal cost to society (damages from climate change, etc.) of emitting E tons of CO_2. The area of the gray trapezoid below the marginal cost line is the **total gross cost** (i.e., the social cost of carbon) due to the emissions.



(c) Combined cost and benefit: B is the marginal benefit of emissions and C is the marginal cost. The area of the dark gray triangle below the marginal cost line is the **total gross cost** from the emissions. The area of the trapezoid comprising both the dark gray and light gray regions is the **total gross benefit**, and the area of the light gray trapezoid is the **total net benefit** (the total gross benefit minus the total gross cost).



(d) Net benefit: B is the marginal benefit of emitting E tons of CO_2, C is the marginal cost. The area of the light gray trapezoid is the total net benefit (the total benefit minus the total cost). $E^\star$ represents the optimal emissions.

Figure 2: Cost and benefit of CO_2 emissions of E tons. Since the benefit line is above the cost line at E in fig. 2c and 2d, the marginal net benefit is greater than zero (i.e., the marginal benefit is greater than the marginal cost), which means additional emissions would increase the total net benefit. $E^\star$, where the marginal cost line crosses the marginal benefit line would be the optimum amount of emissions.

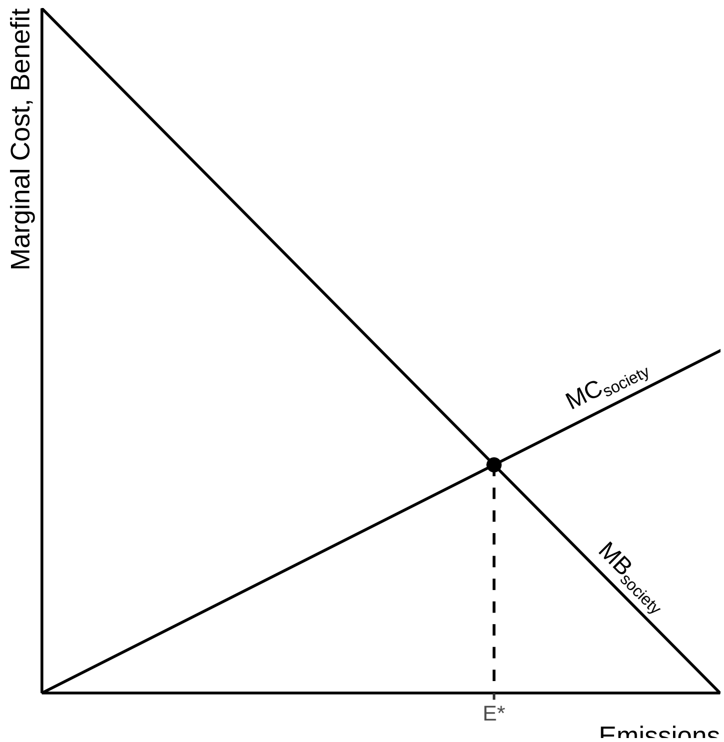


Figure 3: Marginal cost and benefit of greenhouse gas emissions. The optimal emissions is $E^\star$, where the marginal cost equals the marginal benefit.

A rational firm will choose to produce a quantity of goods so the marginal price of production equals the marginal price at which it can sell the good.

Optimal social policy

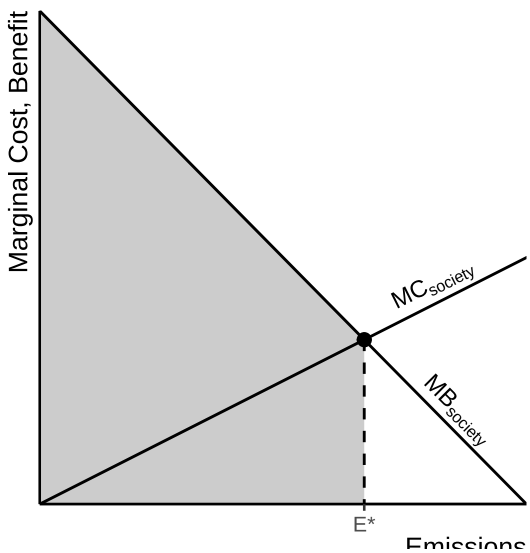
An optimal policy (from a utilitarian point of view) will set the emissions to the level where the marginal benefit or emitting slightly more or less would equal the marginal cost. Figure 3 shows an example of marginal benefit (MB) and marginal cost (MC) for emitting greenhouse gases. In this figure, we can find the optimum emissions reduction where the two curves cross. Let's call this optimum $E^\star$.

We can analyze the cost and benefit of cutting emissions to $E^\star$. Figure 4a shows the benefit to society of cutting emissions by $E^\star$. The **gross benefit** (meaning the raw benefit of cutting pollution, without considering the cost) is just the area under the marginal benefit line, between the y-axis and the vertical line at $E^\star$. There is nothing special about setting the emissions reduction to $E^\star$: if we had set the emissions to some other (non-optimal) amount E, we'd just draw a vertical line at E and the gross benefit of the emissions would be the area under the MB curve from the y-axis to E.

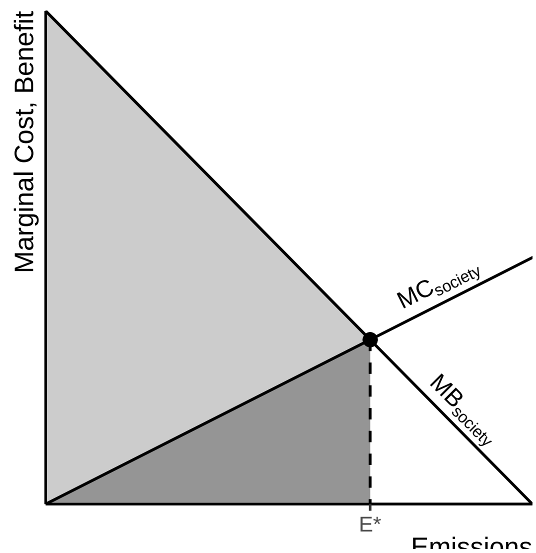
Calculating the cost proceeds the same way: the cost is the area under the marginal cost (MC) curve from the y-axis to $E^\star$, as shown in Fig. 4b. If we subtract the triangle representing cost from the trapezoid representing gross benefit, we find the net benefit to be the area between the MC and MB curves, from the y-axis to $E^\star$.

Suboptimal emissions cuts and deadweight losses

Deadweight losses refer to inefficiencies in government regulatory programs that prevent markets from achieving optimal net benefits. In this example, deadweight losses occur when a regulation results in emissions abatement different from $E^\star$.



(a) Benefit to society of setting emissions to the optimal amount, $E^\star$. The gross benefit is the area under the marginal benefit (MB) curve from the y-axis to the emissions at $E^\star$, indicated by the light gray trapezoid in the figure.



(b) Cost of setting emissions to the optimal amount, $E^\star$. The cost is the area under the marginal cost curve from the y-axis to $E^\star$, indicated by the dark triangle in the figure. The net benefit is the gross benefit minus the cost: the light gray triangle between the MB and MC curves.

Figure 4: Cost and benefit of setting emissions to the optimal level $E^\star$.

To see deadweight losses in action, let's compare the optimal emissions cut to what happens if the EPA makes a mistake. Suppose the EPA makes a underestimates the marginal costs of cutting emissions. This is the same as underestimating the marginal benefits of emissions. This underestimate of the marginal benefits is shown as the gray line labeled "$\text{MB}_{\text{Perceived}}$" in Fig. 5. Underestimating the marginal costs would lead the EPA to call for excessive emissions cuts, which would leave the emissions at E', which is lower than the optimal value $E^\star$.

If the EPA cuts emissions by E', we can figure the cost and benefit to society similarly to the case of $E^\star$. Figures 6a and 6b show these calculations, with the net benefit represented in Fig. 6b by the light gray trapezoid between the MC and MB curves from the y-axis to E'. **Note that these calculations use the real MC curve, not the EPA's perceived curve.**

If we compare the net benefit of setting emissions to E' instead of $E^\star$, we can see that the light-gray net-benefit trapezoid in Fig. 6b is smaller than the net-benefit triangle in Fig. 4b. The difference between these two net-benefit values is the gray triangle in Fig. 7a between the MC and MB curves, bounded by E' and $E^\star$. This triangle represents the net benefit society loses when it cuts emissions to E' instead of $E^\star$. We call this loss a **deadweight loss**. In this case, the deadweight loss occurs because there was too much reduction in emissions, but deadweight losses can also occur if the EPA does not reduce emissions enough.

If the EPA were to *over*estimate marginal costs instead, and set an emissions target greater than $E^\star$, there would also be a deadweight loss because of a region in the graphs where the marginal costs exceeds the marginal benefits and take away from the region where the marginal benefits exceed the marginal costs. This is illustrated in Fig. 7b

Emissions Taxes

Now let's look at an alternate market-mechanism for regulating emissions. Suppose that instead of trying to cap emissions at $E^\star$, we simply impose a price on emissions equal to the marginal cost

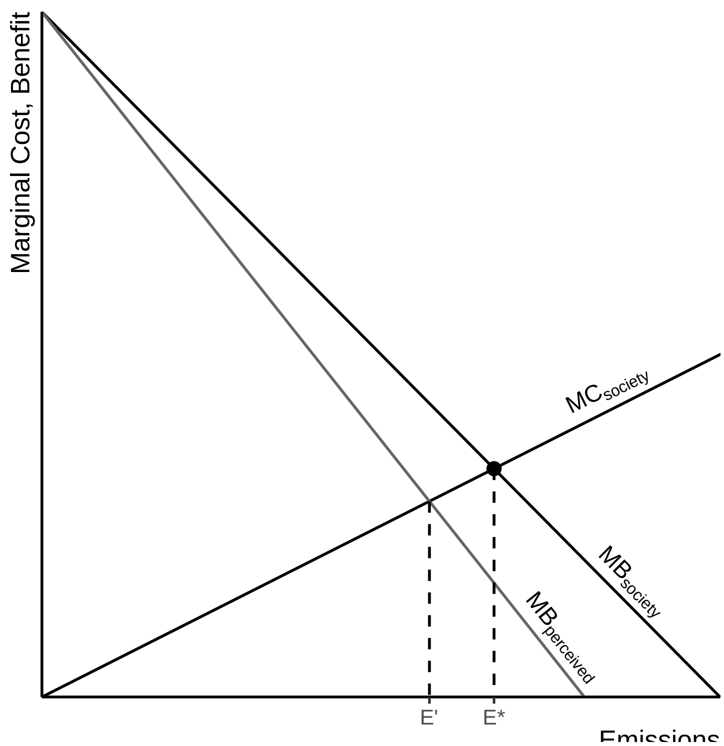
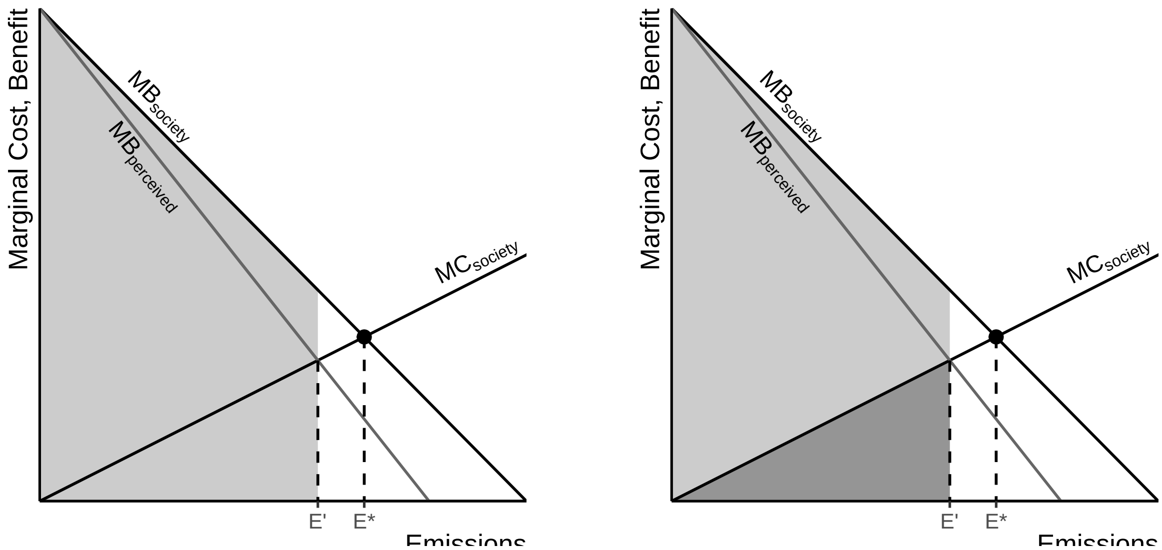


Figure 5: Consequences of underestimating the marginal benefits of emissions. The light-gray line indicates the EPA's erroneous underestimate of marginal benefits and the black line indicates the true marginal benefits. Underestimating MB leads the EPA to set the emissions too low. The optimal emissions is indicated by the black circle at $E^{\star}$ and the EPA's actual emissions target is indicated by the light gray circle at E'.



(a) Benefit to society of setting emissions to E', less than the optimal amount $E^\star$. The gross benefit is the area under the marginal benefit curve, between the y-axis and the emissions at E', indicated by the light gray trapezoid in the figure.

(b) Cost of setting emissions to E', less than the optimal amount $E^\star$. The cost is the area under the marginal cost curve, between the y-axis and the emissions at E', indicated by the dark triangle in the figure. The net benefit is the gross benefit minus the cost: the light gray trapezoid between the MB and MC curves.

Figure 6: Cost and benefit of a sub-optimal emissions reduction to E', which results from the EPA underestimating the marginal costs of abatement.

(the social cost of carbon) at the optimal amount of emissions. As long as the marginal benefit of emissions is less than the cost of paying the tax, then a firm will cut emissions. Thus, a firm that wants to maximize its profits will cut emissions until the marginal cost equals the emissions tax, P, which will put emissions at the optimal level of $E^\star$.

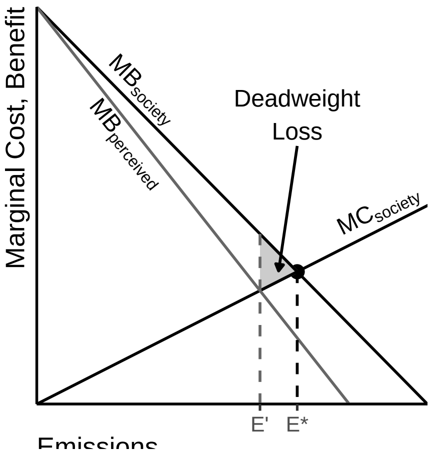
We will assume that we use a revenue-neutral emissions tax: we cut other taxes by the same amount that is collected from emissions taxes. This means that we don't have to consider the impact of the tax payments on the economy, and can analyze this policy purely in terms of the costs and benefits of of cutting emissions.

How do we find the best price, $P^\star$, to charge for emissions? We calculate the optimal price, $P^\star$, the same way we calculated the optimum emissions, $E^\star$: $P^\star$is the price where the marginal cost equals the marginal benefit. If we get both the marginal benefit and the marginal cost curve correct, there is no deadweight loss for either emissions taxes or tradeable permits. However, if we make a mistake, such as underestimating the benefit of emissions, **and** if the marginal benefit line is steeper than the marginal cost line, **then** the deadweight loss due to our error will be smaller for an emissions tax policy than for a tradeable permit policy.

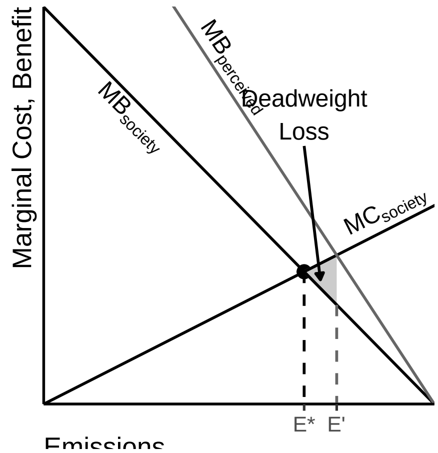
Comparing regulatory strategies

Any regulation in an imperfect world will result in deadweight losses. The existence of deadweight losses does not mean that a regulatory policy is bad, only that it is worse than a perfect policy. Externalities also produce losses, so the obligation of a utilitarian policy analyst is not to reject all regulations with deadweight losses, but to compare the likely deadweight losses of different policies to the losses incurred by externalities in the absence of regulation and to choose the policy likely to produce the smallest deadweight loss.

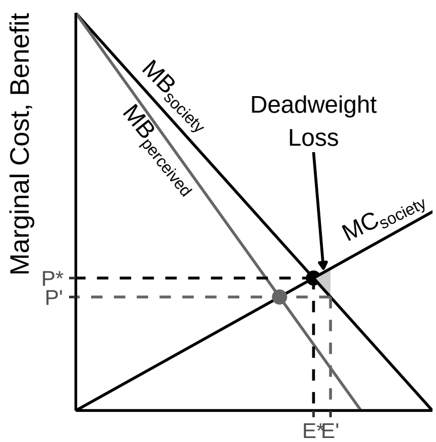
A detailed rigorous analysis of the benefits and limitations of different regulatory strategies is



(a) Deadweight loss for emissions cuts when underestimating the marginal benefit of emissions. This leads to setting emissions to E', which is less than the optimal amount, $E^{\star}$. The deadweight loss is the area of the triangle formed by E' and the marginal cost and benefit curves.



(b) Deadweight loss from overestimating the marginal benefit. This leads to allowing emissions of E', which is more than the optimal cut $E^{\star}$. The deadweight loss is the area of the triangle formed by E' and the marginal cost and benefit curves.



(c) Deadweight loss from emissions taxes when underestimating the marginal benefit of emissions. Note that the deadweight loss for underestimating the marginal cost is smaller when we use carbon taxes than when we use tradeable permits.

Figure 7: Deadweight loss of cutting emissions to E' instead of $E^{\star}$. Whether E' is greater or less than the optimal emissions cut $E^{\star}$. the deadweight loss is the area of the triangle between the MB and MC curves, with a vertex at the black dot (see fig. 4b). The actual net benefit is the trapezoid between the MB and MC curves, bounded by the vertical line at E' (see fig. 6a). The difference between the two is the light gray triangle in this figure. This is called the deadweight loss.

beyond this course. A course on environmental economics would provide such a rigorous analysis and present tools for deciding which kind of regulatory policy would incur the smallest deadweight loss. However, it is worth remembering that a policy with significant deadweight losses may still be preferable to no regulation at all, so long as the deadweight losses are smaller than the losses produced by the externalities it sets out to correct.

Command and control policies produce deadweight losses so long as different firms have different marginal costs for cutting emissions. Even if the government accurately estimates the average marginal cost of emissions reductions, the variations among different firms will lead to deadweight losses when regulations require all the firms to make equal cuts.

Cap-and-trade programs can dramatically reduce the deadweight losses that arise from variation in marginal cost between firms. However, they can still lead to significant deadweight losses if the regulatory agency seriously underestimates or overestimates the marginal cost of reducing emissions.

Moreover, if the marginal benefit of reducing emissions is sharply nonlinear (e.g., if there is some threshold or tipping point above which the consequences of emissions become much worse) cap and trade may be particularly efficient from an economic point of view.

When the marginal cost of reducing emissions is poorly known, but the marginal benefit is well-known and fairly linear, then emissions taxes can produce much smaller deadweight losses than tradeable permits when a regulatory agency under- or over-estimates the marginal cost of reducing emissions.

However, when the marginal benefit of reducing emissions is highly nonlinear, emissions taxes may produce significantly greater deadweight losses than cap-and-trade regulatory programs.

Another difference between tradeable permits and emissions taxes is that with tradeable permits you know in advance what the emissions will be, but you are uncertain about how expensive the policy will be. With emissions taxes, you know in advance the cost of the policy, but you are uncertain about how much it will cut emissions. Which policy is better depends in part on whether you are more concerned about the cost getting out of control, or about failing to cut emissions enough to prevent catastrophe.