EC1340 Topic #8

Mitigation

Matthew A. Turner
Brown University
Fall 2025

(Updated July 29, 2025)

Outline I

Subject to lots of uncertainty about everything and a choice of discount rate, we can do a ‘back of the envelope’ calculation of the social cost of C emissions.
As we’ll see, this is enough to calculate the optimal tax.
To arrive at a better calculation of this tax, and determine other types of regulation, we need a better model. For this, we need to know how rapidly emissions fall as we raise the price of C .
This ‘mitigation cost curve’ is our first topic for today.
After that we’ll turn to calculating optimal policy.

Mitigation costs I

To understand how to do this calculation, let's set up the theory to make sure that we calculate the opportunity cost of mitigation.
For industries $i = 1, \ldots I$,

- L_i is labor for industry i.
- K_i is capital for industry i.
- E_i is emissions for industry i.
- Y_i is output i, with $Y_i = F(K_i, L_i, E_i)$.

w, R, T, p are the prices of labor, capital, emissions, and output.
Note that in practice, $T = 0$, so positive prices are hypothetical.
Each industry maximizes profits,

Mitigation costs II

$$\max_{K_i, L_i, E_i} pY_i - RK_i - wL_i - TE_i$$
$$\text{s.t. } Y_i = F(K_i, L_i, E_i)$$

which gives us a profit function $\pi_i(w, R, T, p)$ which we'll write $\pi_i(T)$ to make things easier, i.e., assume all other prices fixed. This optimization also gives us factor demand equations (profit maximizing demand for inputs). In particular, $E_i(w, R, T, p)$, which we'll write $E_i(T)$. We can now ask what happens when we change

Mitigation costs III

the price of emissions, E from $T_0 = 0$ to $T_1 > 0$.

- profits fall, $\pi_i(T_0) \geq \pi_i(T_1)$
- emissions fall, $E_i(T_0) \geq E_i(T_1)$
- unit/average cost of emissions reduction $\frac{\pi_i(T_0)-\pi_i(T_1)}{E_i(T_0)-E_i(T_1)}$

We need to be careful in how we account for TE_i, the CO_2 revenue. It's really a transfer, not a cost.

Mitigation costs IV

We want an economy wide aggregate, so sum over industries:

$$\%\Delta E(T_1) = \frac{\sum_{i=1}^{I} E_i(T_0) - E_i(T_1)}{\sum_{i=1}^{I} E_i(T_0)} \times 100$$

$$\%\Delta \pi(T_1) = \frac{\sum_{i=1}^{I} \pi_i(T_0) - \pi_i(T_1)}{\sum_{i=1}^{I} \pi_i(T_0)} \times 100$$

If we evaluate these two quantities for a sequence of carbon prices, $T_1 = 1\$/GtC, 2\$/GtC, ..., 100\$Gt/C$, we get a bunch of pairs

$$[(\%\Delta E(T_1 = 1), \%\Delta\pi(T_1 = 1)) \\ , ..., (\%\Delta E(T_1 = 100), \%\Delta\pi(T_1 = 100))]$$

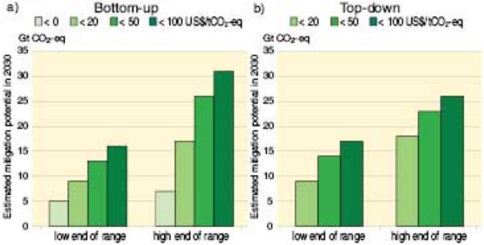
If we plot these pairs, we get a schedule showing the total cost, in % of total profits for a given % reduction in emissions

Mitigation costs V

Issues:

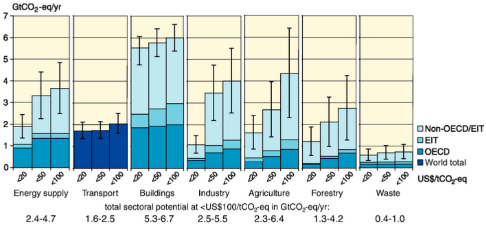
- Really, most industries use energy rather than emissions, so we need to look at emissions per unit of energy to do this calculation. This is complicated because there are many sources with different C emissions rates
- partial equilibrium (bottom-up) versus general equilibrium (top-down) which allows substitution from emissions intensive goods (and so should give lower costs).
- This calculation is a huge mess because there are so many industries, energy sources and emissions types.

Plots of $E(T_1) - E(T_0 = 0)$ as T_1 varies, bottom-up and top-down



IPPC 2007 Mitigation fig sp 5ab: Global economic mitigation potential in 2030 estimated from bottom-up (Panel a) and top-down (Panel b) studies relative to year 2000 GHG emissions of 40.8 GtCO2-eq exclusive of emissions of decay of above-ground biomass that remains after logging and deforestation and from peat fires and drained peat soils

Plots of $E(T_1) - E(T_0 = 0)$ by sector as T_1 varies (bottom-up)



IPPC 2007 Mitigation Figure SPM.6: Estimated sectoral economic potential for global mitigation for different regions as a function of carbon price in 2030 from bottom-up studies, compared to the respective baselines assumed in the sector assessments.

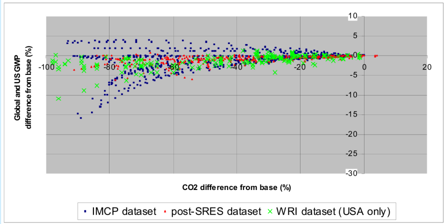
Plot of

$$\{(\%\Delta E(T_1 = 1), \%\Delta\pi(T_1 = 1)), ..., (\%\Delta E(T_1 = 100), \%\Delta\pi(T_1 = 100$$

from various studies:

Figure 10.1 Scatter plot of model cost projections

Costs of CO_2 reductions as a fraction of world GDP against level of reduction



Source: Barker et al. (2006)

Stern 2008, fig 10.1

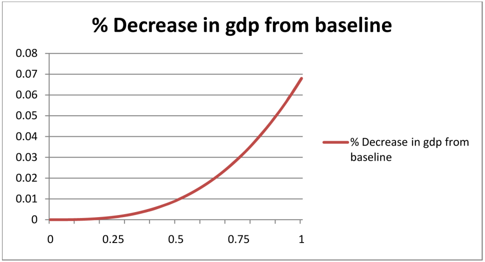
Nordhaus uses data like these to estimate his mitigation cost function,

$$\Lambda = c_0 \mu^{c_1}$$

where

- μ is percentage reduction in emissions (from specified baseline)
- Λ is $\frac{\text{total cost of reduction}}{\text{gnp}}$ (Note that denominator is gnp, not gdp, to exclude trade.)

(From Nordhaus 1991)$c_0 = 0.68$ and $c_1 = 2.889$. Actually, in ‘Question of balance’, μ is time varying, and c_0 decreases over time. Here is what this Λ looks like:



My calculations

Issues 1: Backstop technology I

If you can make energy without C then the whole global warming problem basically goes away.
The question is, how much does it cost to make carbon free energy? Alternatively, how much would C have to cost, before you didn't use it? This is the 'backstop' technology price.
For airplanes, it's a big number. For electricity, guess when nuclear, solar, wind etc. can outcompete coal, or when carbon capture and storage (CSS) becomes viable.
Nordhaus chooses a big number, about 1000$/ton C , but lets it decrease over time. This is the cost of replace C where it is hard to find substitutes, e.g., aviation fuel, plastics(which are made from oil) or lubricants (which evaporate).

Issues 2: Cost of first unit and implied cost of others I

Firms solve

$$\max_{K_i, L_i, E_i} pF(K_i, L_i, E_i) - RK_i - wL_i - TE_i$$

This gives us first order conditions:

$$p\frac{\partial F}{\partial K} = R$$
$$p\frac{\partial F}{\partial L} = w$$
$$p\frac{\partial F}{\partial E} = T$$

but $T = 0$ implies that $p\frac{\partial F}{\partial E} = 0$. That is, marginal revenue product of first unit of C is zero! First unit of mitigation should be free.

Issues 2: Cost of first unit and implied cost of others II

Also, for given E^* the implied price of emissions is $\frac{\partial \pi}{\partial E}\Big|_{E=E^*}$. This is how the ‘price of C ’ is often calculated.

Issues 3: Technological progress I

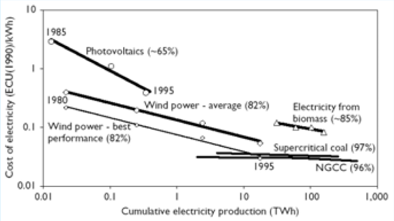
We expect technical progress to affect emissions in three ways

- As income goes up so does consumption, and with it emissions. This is clearly the really important effect right now (e.g., China)
- As technology improves, it takes less energy per dollar of consumption
- As technology improves, it takes less C per unit of energy

Here are some figures describing this process:

Issues 3: Technological progress II

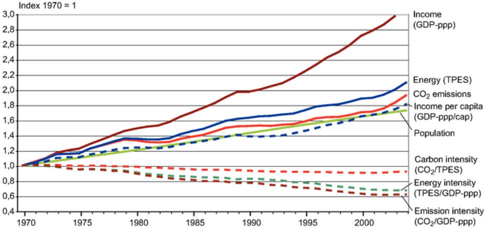
Cost evolution and learning rates for selected technologies



Source: IEA (2000) pp21

Cost decreases as a function of scale in energy generation Stern 2008, box 9.1

Issues 3: Technological progress III



Relative global development of Gross Domestic Product, Total Primary Energy Supply (TPES), CO2 emissions (from fossil fuel burning, gas flaring and cement manufacturing) and Population (Pop). In addition, in dotted lines, the figure shows Income per capita (GDPppp/Pop), Energy Intensity (TPES/GDPppp), Carbon Intensity of energy supply (CO2/TPES), and Emission Intensity of the economic production process (CO2/GDPppp) for the period 1970-2004. IPCC 2007 mitigation, fig. spm 2

Issues 3: Technological progress IV

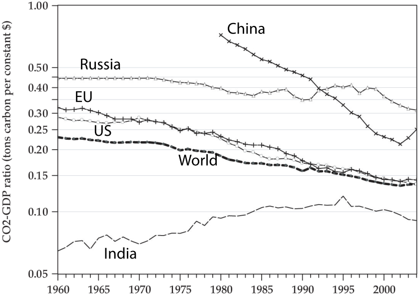


Figure 3-1. Historical ratios of CO_2 emissions to GDP for major regions and globe, 1960–2004. Trends in the ratio of CO_2 emissions to GDP for five major regions and the global total. We call the decline in this rate "decarbonization." Most major economies have had significant decarbonization since 1960. The rates of decarbonization have slowed or reversed in the last few years and appear to have reversed for China. With the changing composition of output by region, the world CO_2-GDP ratio has remained stable since 2000. Note that "W C Eur" is Western and central Europe and includes several formerly centrally planned countries with high CO_2-GDP ratios.

The importance of participation rates I

Let Y_0 and E_0 denote world gdp and emissions. Then,given a mitigation function like:

$$\Lambda = c_0 \mu^{c_1}$$

the cost of reducing emissions by the share μE_0 is $\Lambda Y_0 = c_0 \mu^{c_1} Y_0$. Now suppose that we have two countries, A and B, and that country A is responsible for fraction α of Y_0 and E_0, with country B responsible for the rest. Thus,

$$\begin{aligned} Y_A &= \alpha Y_0 \\ E_A &= \alpha E_0 \\ Y_B &= (1 - \alpha) Y_0 \\ E_B &= (1 - \alpha) E_0 \end{aligned}$$

The importance of participation rates II

Suppose we want to accomplish a $\mu_0 E_0$ reduction of emissions by reducing emissions in country A alone (and $E_A = \alpha E_0 \geq \mu_0 E_0$).

The importance of participation rates III

How much more does this cost than if we were to accomplish this emissions reduction from the whole world?
We want μ_A such that

$$\begin{aligned}
&\mu_A E_A = \mu_0 E_0 \\
\implies &\mu_A \alpha E_0 = \mu_0 E_0 \\
\implies &\mu_A = \mu_0/\alpha
\end{aligned}$$

The cost of this reduction is zero to country B.
The cost to country A is $Y_A c_0 \mu_A^{c_1} = Y_A c_0 \left(\frac{\mu_0}{\alpha}\right)^{c_1}$.
The cost of this mitigation effort for the whole world is $Y_0 c_0 \mu_0^{c_1}$.

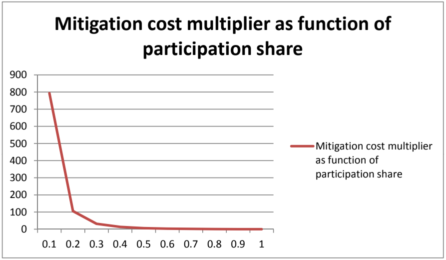
The importance of participation rates IV

Writing the extra cost as a fraction of the world abatement costs, we have

$$
\begin{aligned}
&\frac{Y_A c_0 \left(\frac{\mu_0}{\alpha}\right)^{c_1} - Y_0 c_0 \mu_0^{c_1}}{Y_0 c_0 \mu_0^{c_1}} \\
=&\frac{Y_0 c_0 \mu_0^{c_1} \left(\left(\frac{1}{\alpha}\right)^{c_1} - 1\right)}{Y_0 c_0 \mu_0^{c_1}} \\
=&\left(\frac{1}{\alpha}\right)^{c_1} - 1
\end{aligned}
$$

The importance of participation rates V

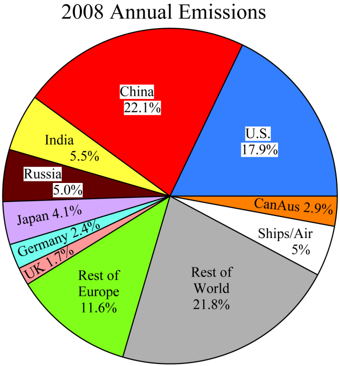
For $c_1 = 2.9$ (Nordhaus' value), this curve looks like this:



So, for example, if 30% of countries try to make a given emissions abatement, it will cost about 30 times as much as if all countries worked at it! This follows immediately from the form of mitigation costs and has immediate and important implications for policy.

The importance of participation rates VI

International agreements to reduce CO_2 without developing world participation are going to be much more expensive...



This is why the Paris Accord is so important.

Metcalf and Stock, 2020

- Rather than theorizing, if we had the right data, we could just look at the way that GDP responded to regulation. This is just what Metcalf and Stock do in their paper, 'The Macroeconomic Impact of Carbon Taxes'.
- In this paper, the authors use data describing the relationship between GDP, emissions, and the level of the carbon tax to do exactly this.

Data

Table 1. EU+ Carbon Taxes

Country	Year of Enactment	Rate in 2018 (USD per metric ton)	Intended Revenue Recycling?	Share of Greenhouse Gas Emissions in 2019 Covered by Tax	Carbon Tax Revenue in 2018 (USD Millions)
Denmark (DNK)	1992	24.92	Yes	40%	543.4
Estonia (EST)	2000	3.65	No	3%	2.8
Finland (FIN)	1990	70.65	Yes	36%	1,458.6
France (FRA)	2014	57.57	No	35%	9,263.0
Iceland (ISL)	2010	25.88	No	29%	44.0
Ireland (IRL)	2010	24.92	No	49%	488.8
Latvia (LVA)	2004	9.01	No	15%	9.1
Norway (NOR)	1991	49.30	Yes	62%	1,659.8
Poland (POL)	1990	0.16	No	4%	1.2
Portugal (PRT)	2015	11.54	Yes	29%	154.9
Slovenia (SVN)	1996	29.74	No	24%	83.1
Spain (ESP)	2014	30.87	No	3%	123.6
Sweden (SWE)	1991	128.91	Yes	40%	2,572.3
Switzerland (CHE)	2008	80.70	Yes	33%	1,177.7
UK (GBR)	2013	25.71	No	23%	1,091.0

Notes: Coverage is the share of a country's emissions covered by the carbon tax. See text for revenue recycling details.

Source: World Bank Group (2019a)

... along with standard data on GDP and CO2.

Econometric Model I

Here is their main estimating equation,

$$100\Delta \ln(GDP_{it+h}) = \alpha_i + \theta_h \tau_{it} + \beta(L)\tau_{it-1} + \delta(L)\ln(GDP_{it-1}) + \gamma_t + u_{it}$$

This is pretty complicated, and the notation is hard. Let's do the easy parts first,

$$i, t \sim \text{country and year indexes}$$
$$\tau_{it} \sim \text{tax rate} \times \text{share of economy affected}$$
$$\alpha_i \sim \text{country fixed effect}$$
$$\gamma_t \sim \text{year fixed effect}$$
$$u_{it} \sim \text{regression residual}$$

Econometric Model II

Now some of the harder parts.

$$\begin{aligned}
100\Delta \ln(GDP_{it+h}) &= 100(\ln(GDP_{it+h}) - \ln(GDP_{it+h-1}) \\
&= 100 \ln(GDP_{it+h}/GDP_{it+h-1}) \\
&= 100 \ln(1 + r_{it+h}) \\
&\approx 100 r_{it+h}
\end{aligned}$$

Where we are using $\ln(1 + x) \approx x$ for x small.
Dropping all the fixed effects and writing r_{it} for $\ln(GDP_{it})$, the main estimating equation becomes,

$$100 r_{it+h}) = \theta_h \tau_{it} + \beta(L)\tau_{it-1} + \delta(L) r_{it-1} + u_{it}$$

Econometric Model III

$\beta(L)\tau_{it-1}$ is (bad) shorthand for 'L-lags of τ', and we are told (p14) that $L = 4$, so

$$\beta(L)\tau_{it-1} = \beta_{-1}\tau_{it-1} + \beta_{-2}\tau_{it-2} + \beta_{-3}\tau_{it-3} + \beta_{-4}\tau_{it-4}$$

and

$$\delta(L)r_{it-1} = \delta_{-1}r_{it-1} + \delta_{-2}r_{it-2} + \delta_{-3}r_{it-3} + \delta_{-4}r_{it-4}$$

Why? We are worried that the current tax and GDP may be affected by old tax rates and old GDP, so model this explicitly.

Econometric Model IV

Only h is left. Look what happens when $h = 0, 1, 2$,

$$
\begin{aligned}
100r_{it} &= \theta_0\tau_{it} + \beta(L)\tau_{it-1} + \delta(L)r_{it-1} + u_{it} \\
100r_{it+1} &= \theta_1\tau_{it} + \beta(L)\tau_{it-1} + \delta(L)r_{it-1} + u_{it} \\
100r_{it+2} &= \theta_1\tau_{it} + \beta(L)\tau_{it-1} + \delta(L)r_{it-1} + u_{it}
\end{aligned}
$$

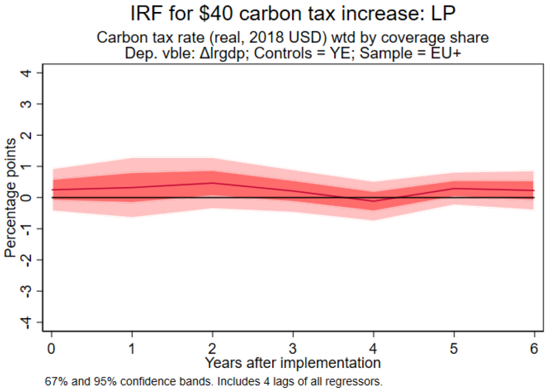
As h in creases, we increase the lag between the when we measure growth rate and the most recent measure of τ. θ_h measures the effect of a change in the carbon tax on GDP growth, h periods in the future.

What is the total effect of the tax on GDP growth k periods in the future? $\theta_0 + \theta_1 + \ldots + \theta_k$, times the tax rate at t.

Econometric Model V

This is pretty complicated, but lets us evaluate the effect of a \$40/ton CO_2 tax applied to 30% of GDP on GDP growth in an average European country over the six years following the implementation of the tax.

GDP vs Carbon Tax

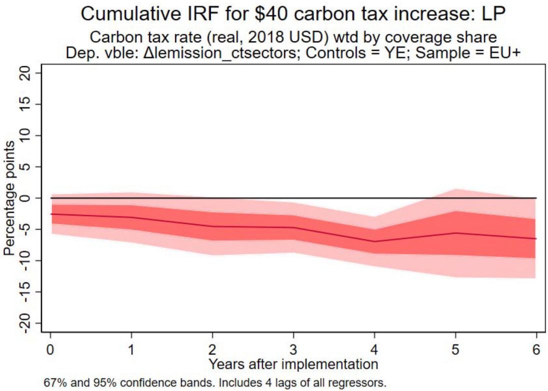


These data tell us the tax has no measurable effect on GDP.

CO2 vs Carbon Tax

Applying the same estimation strategy to CO_2 , we see that the tax leads to about a 5% reduction in CO_2 . That is, the first 5% of CO_2 reduction is close enough to free that we can't distinguish the effect from zero. This is consistent with our intuition from theory.

CO2 vs Carbon Tax



This is really good news.