Lecture 3:
The Economics of Pollution Control (I)

ECON7720: Ecological and Environmental Economics

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Semester 2, 2026 | Required reading: Tietenberg & Lewis, Ch. 7

Recap of Lecture 2

- Externalities are the core market failure for pollution: emitters ignore the damage they impose, so the market delivers too much pollution. A Pigouvian tax can close the wedge between private and social cost.
- The Coase theorem: with clear property rights and low transaction costs, bargaining reaches the efficient outcome regardless of who holds the right, but in practice, transaction costs are high for diffuse pollution.
- Courts and liability can internalise damages, but founder on harms that are diffuse, continuous, and hard to attribute.
- Other failures such as CPRs, public goods, market power, asymmetric information compound the problem.

Lecture Outline

1. A pollutant taxonomy: stock vs fund, uniform vs non-uniform mixing
2. Marginal damage (MD) and marginal abatement cost (MAC)
3. How much pollution? The efficient level (MD=MAC)
4. Cost-effectiveness and the equimarginal principle

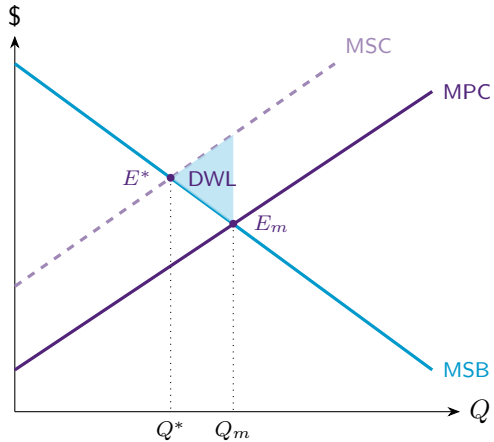
A Pollutant Taxonomy

Recap from Lecture 2 — a negative production externality

A negative externality opens a wedge:

- $MEC = MSC - MPC$.
- Market settles at Q_m ($MSB = MPC$).
- Efficiency wants Q^* ($MSB = MSC$).
- The deadweight loss is the shaded triangle over $[Q^*, Q_m]$.

Today we tackle the pollution directly.



From the goods market to the pollution market

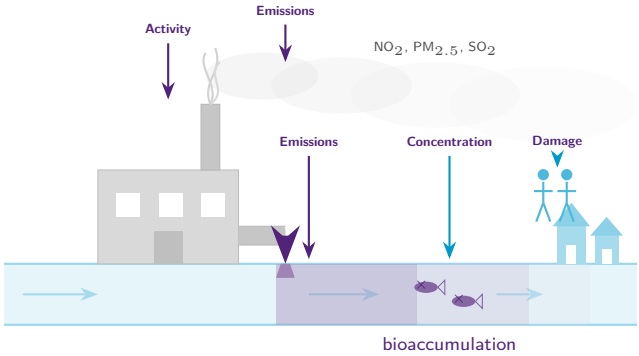
A change of focus

In Lecture 2 we limited a negative externality by cutting *output* of the good. But pollution can be reduced in many ways without simply producing less:

- change the input mix (low-sulfur coal, cleaner feedstock);
- adopt cleaner technology or processes;
- add end-of-pipe controls (scrubbers, filters, treatment);
- recycle or recover the residual.

So we model the pollution market directly: choose the level of emissions (or, equivalently, the level of abatement), not just the level of output.

The pollution pathway



- Activity → emissions: *abatement* breaks this link (cleaner inputs, technology, end-of-pipe controls).
- Emissions → concentration: governed by location and dispersion.
- Concentration → damage: the dose–response relationship (health, ecosystems, materials).

Example — artisanal and small-scale gold mining in the Amazon (1/2)

- ∼30,000 artisanal miners extract alluvial gold using liquid mercury to amalgamate fine particles.
- ∼180 tonnes of Hg released per year into rivers and air.
- Globally, ASGM is the largest single source of anthropogenic mercury (∼38% of total; ∼2,000 t/yr).
- Over 100,000 hectares of rainforest destroyed.

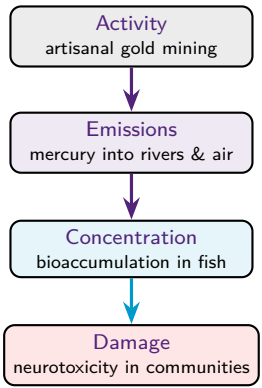
How does mercury released by miners end up damaging the health of communities downstream?



Astronaut photograph (ISS, 24 Dec 2020). Gold prospecting pits appear as bright scars carved into the Amazon rainforest along the Inambari River, Madre de Dios.

Source: NASA/JSC (2020), ISS064-E-16203. Public domain.

Example — artisanal and small-scale gold mining in the Amazon (2/2)

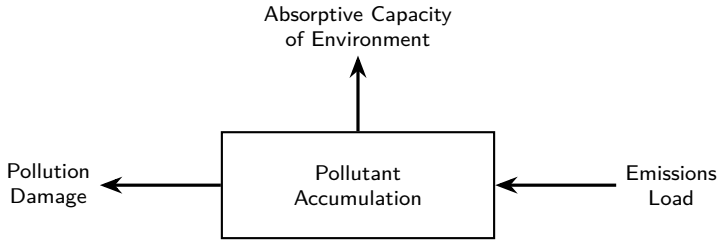


- Activity → Emissions: miners wash mercury into rivers; vapour released when amalgam is burned.
- Emissions → Concentration: mercury bioaccumulates up the aquatic food chain.
- Concentration → Damage: communities eat contaminated fish. Effects include tremor, memory loss, and developmental harm in children.

Mercury is a stock pollutant (persistence: decades–∞) and non-uniformly mixed: damage depends on proximity to the source.

Sources: Ashe (2012, *PLOS ONE*); Diringer et al. (2015, *Environ. Sci.: Processes Impacts*); UNEP (2019), *Global Mercury Assessment*.

Relationship between emissions and pollution damage



- Emissions load flows *into* the environmental stock.
- The environment's absorptive capacity removes some naturally (decay, dilution, chemical breakdown).
- The remaining accumulation determines pollution damage.

Source: Tietenberg, T. & Lewis, L. (2024), *Environmental & Natural Resource Economics*, 12th ed., Routledge, Figure 7.1.

Pollution is a residual, and a stock or a flow

Two kinds of pollutant

- Fund (flow) pollutants: the environment has some absorptive capacity. If emissions stay below it, they do *not* accumulate. *Examples:* conventional air and water pollution.
- Stock (cumulative) pollutants: little or no absorptive capacity; they build up over time. *Examples:* greenhouse gases, heavy metals, nuclear waste.

Stock pollutants shift the burden onto future generations (today's emissions raise tomorrow's stock and damage).

Atmospheric persistence

Pollutant	**Main sources**	**Atmospheric lifetime**
SO_2 (sulphur dioxide)	coal combustion, smelters	hours–days
NO_x (nitrogen oxides)	vehicles, power plants	hours–days
BOD (organic waste)	sewage, agriculture	days–weeks
O_3 (tropospheric ozone)	secondary (NO_x + VOCs)	weeks
CH_4 (methane)	agriculture, fossil fuels	$\sim$12 years
N_2O (nitrous oxide)	agriculture, industry	$\sim$114 years
CFCs (chlorofluorocarbons)	refrigerants	50–100 years
CO_2 (carbon dioxide)	fossil fuels, land-use change	300–1,000 years
Pb, Hg (lead, mercury)	mining, industry	decades–∞
Nuclear waste	reactors, weapons	10^3–10^5 years

The dividing line is the environment's absorptive capacity: fund pollutants decay fast enough that steady-state concentrations stabilise; stock pollutants accumulate because natural removal is slow relative to emission rates.

Sources: IPCC AR6 WG I (2021), Table 7.15; EPA *Air Quality Criteria* documents; Seinfeld & Pandis (2016), *Atmospheric Chemistry and Physics*, 3rd ed.

Where the pollutant goes?

- Uniformly mixed pollutants: damage depends on *total* emissions, not on *who* emitted or *where*. One tonne is one tonne. *Example:* greenhouse gases.
- Non-uniformly mixed pollutants: damage depends on the location of the source relative to people. *Examples:* ground-level ozone/smog, particulates, industrial wastewater.

Classifying pollutants

Pollutant	Primary harm	Scale
CO_2, CH_4, N_2O (carbon dioxide, methane)	climate change	global
CFCs, HFCs (chloro-/hydrofluorocarbons)	stratospheric ozone depletion	global
SO_2 (sulphur dioxide)	acid deposition, respiratory disease	regional
NO_x, O_3 (nitrogen oxides, ozone)	photochemical smog, asthma	regional
$PM_{2.5}$, PM_{10} (particulate matter)	cardiovascular & lung disease	local
Industrial wastewater	aquatic ecosystem degradation	local
Noise	sleep disruption, hearing loss	local

Sources: Tietenberg & Lewis (2024), Ch. 7; WHO (2021), *WHO Global Air Quality Guidelines*; IPCC AR6 WG I (2021), Ch. 6–7.

- For uniform pollutants, a single price (tax or permit) works everywhere.
- For non-uniform pollutants, *where* a tonne is emitted matters, requiring location-specific instruments.
- The classification guides instrument design.

Designing a pollution policy

1. How much? What is the appropriate *total* level of the waste flow (emissions)?
   $\rightarrow$ answered by the efficiency criterion: MD = MAC.
2. Who abates? How should the required reduction be *allocated* across the many sources?
   $\rightarrow$ answered by the cost-effectiveness criterion: equalise MAC.

How Much Pollution? The Efficient Level

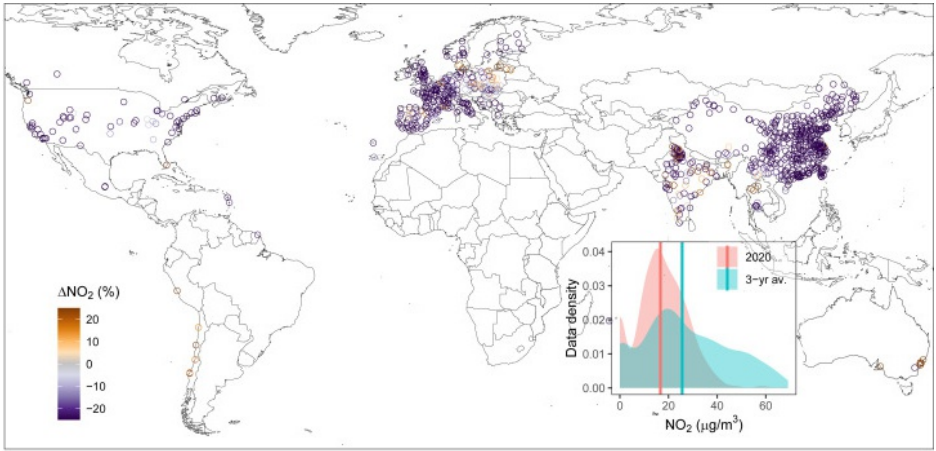
COVID-19 — what does "zero pollution" cost?

In 2020, lockdowns shut down the global economy. Air quality improved dramatically, but at enormous cost.

- Air quality gains: NO_2 fell 23–60%, $PM_{2.5}$ fell 15–31%, global CO_2 fell 6.3%.
- Health gains: $\sim$49,900 avoided premature deaths; $\sim$89,000 fewer paediatric asthma ER visits globally.
- Economic cost: global GDP fell -3.1% (deepest since the Great Depression); hundreds of millions of jobs lost; 97 million pushed into extreme poverty.

Sources: Venter et al. (2020, *PNAS*); Liu et al. (2020, *Nature Comms*); He et al. (2020, *Nature Sustainability*); IMF (2024).

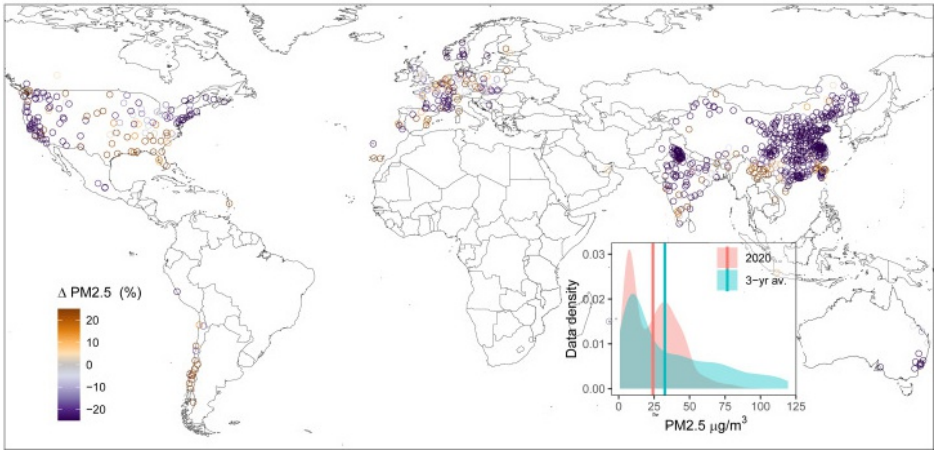
The evidence — NO_2 collapsed worldwide



Ground-station data from 34 countries show lockdowns reduced NO_2 by -23 to -60%. Reductions in transport emissions drove most of the anomaly.

Source: Venter et al. (2020), *PNAS* 117(32), Fig. 1A.

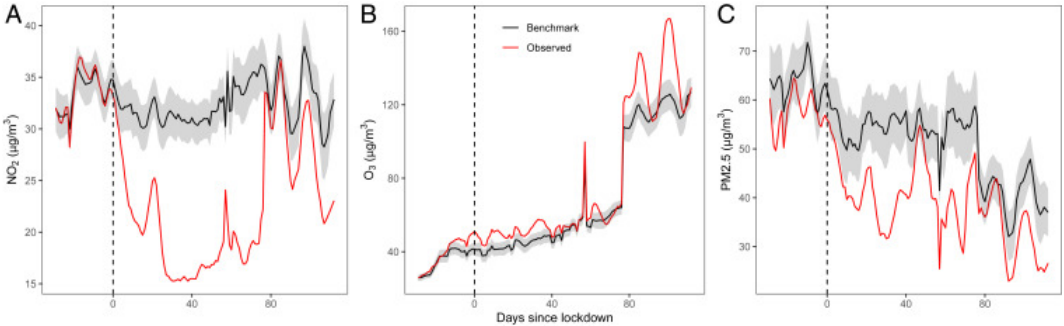
The evidence — $PM_{2.5}$ also fell



Lockdowns also reduced $PM_{2.5}$ by approximately -31%. The effect was smaller than for NO_2 because $PM_{2.5}$ has more diverse sources (agriculture, wildfires, dust).

Source: Venter et al. (2020), *PNAS* 117(32), Fig. 1C.

The evidence — pollution fell with mobility



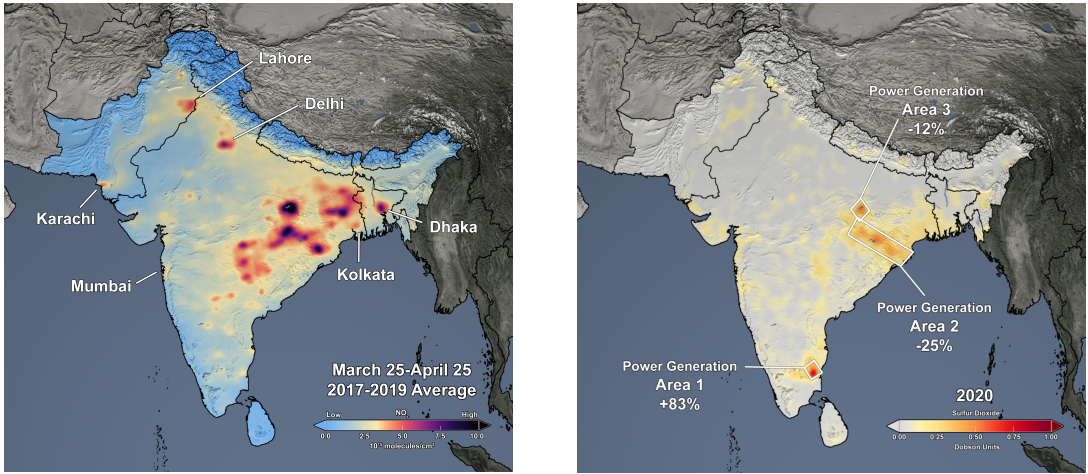
Population-weighted NO_2, $PM_{2.5}$ and O_3 (ozone) before and after lockdowns (red) vs the weather-benchmark prediction (black). NO_2 drops sharply at lockdown; $PM_{2.5}$ falls more slowly; ground-level O_3 *rises* in some cities because lower NO_x.

Source: Venter et al. (2020), *PNAS* 117(32), Fig. 2. Open access (CC BY-NC-ND 4.0).

The evidence — satellite images of NO_2 over South Asia

Baseline (2017–2019 average)

During lockdown (2020)

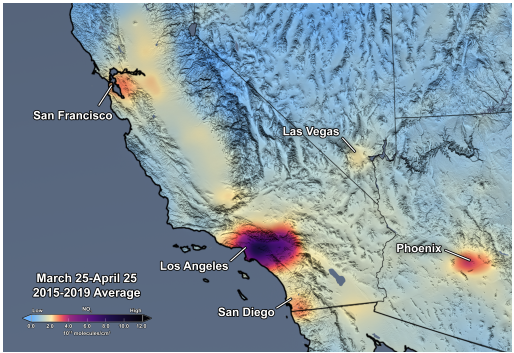


NO_2 concentrations over India fell 30–60% after the nationwide lockdown (March 2020). Satellite: NASA Aura OMI.

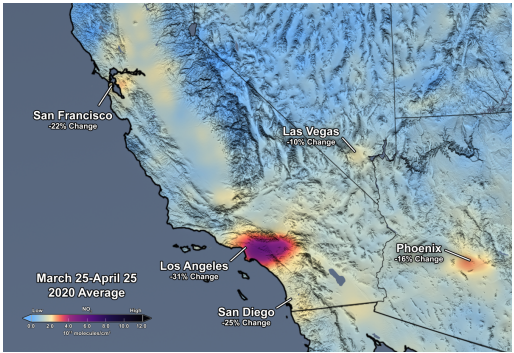
Source: NASA Air Quality, airquality.gsfc.nasa.gov/before-after.

The evidence — satellite images of NO_2 over Los Angeles

Baseline (2015–2019 average)



During lockdown (2020)



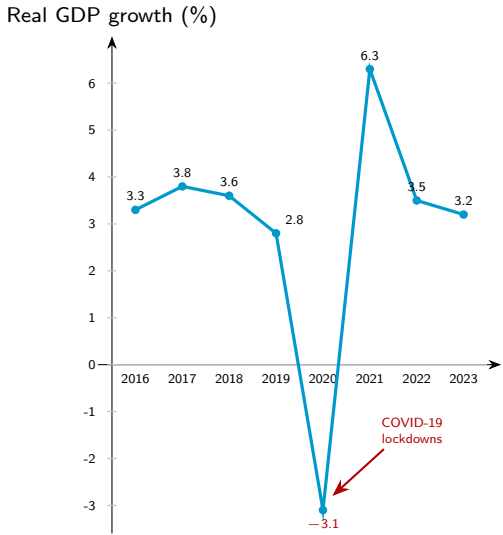
California's stay-at-home order led to a $\sim$31% decrease in NO_2 in the Los Angeles basin. The change was visible from space within days.

Source: NASA Air Quality, `airquality.gsfc.nasa.gov/before-after`. Satellite: Aura OMI.

The cost

The cleaner air came from shutting down the economy:

- Global GDP fell -3.1% in 2020. The deepest contraction since the Great Depression.
- Advanced economies: -4.5%; emerging markets: -2.1%.
- $\sim$255 million full-time equivalent jobs lost worldwide (ILO).
- An additional 97 million people pushed into extreme poverty.



Source: IMF, *World Economic Outlook* (April 2024).

The damage side — the marginal damage curve

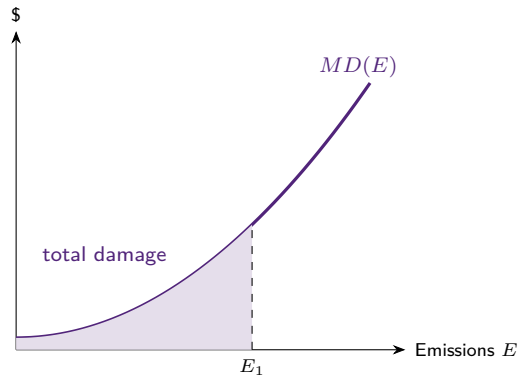
Marginal damage (MD)

MD = the dollar value of the harm done by *one more* unit of emissions. The area under MD up to E = total damage.

Why might MD curve upward? Common reasons:

- Assimilative capacity: at low loads the environment absorbs the residual.
- Thresholds: beyond a critical load, harm accelerates.

But convexity is not universal: for some pollutants (e.g. $PM_{2.5}$) marginal damage is steepest at *low* concentrations and flattens at high levels.



Measuring marginal damage in practice

Where the numbers come from

MD is not handed to us; it must be estimated. Methods (covered in T&L Ch 4):

- Dose–response / damage-function: physical effects (mortality, crop loss) $\times$ unit values (e.g. the value of a statistical life).
- Hedonic: infer the price of clean air from house prices.
- Stated preference: surveys eliciting willingness to pay (contingent valuation, choice experiments).

Estimates are uncertain and sometimes contested. For now we take $MD(E)$ as given.

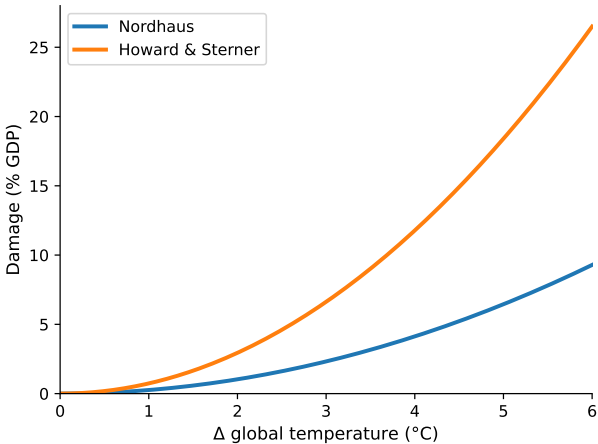
Example: climate damage functions

From warming to GDP loss

Both functions are convex (quadratic): each extra degree does *more* damage than the last.

- Nordhaus: ∼1% GDP at 2°C, ∼9% at 6°C.
- Howard & Sterner: ∼3% at 2°C, ∼27% at 6°C.
- At 1°C the gap is <1%; at 6°C it exceeds 17 percentage points.

Which function you use matters enormously for the social cost of carbon and hence for policy.



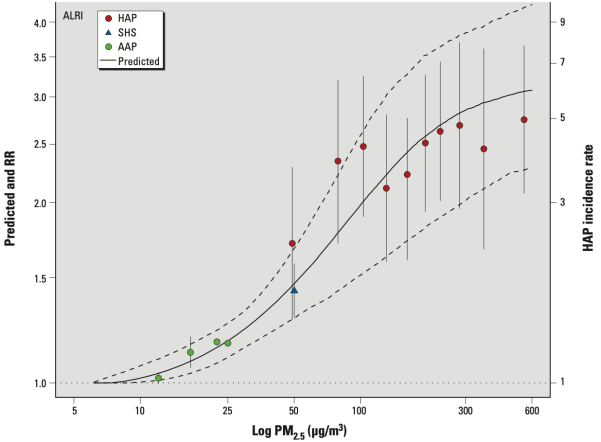
Source: Waidelich, P. et al. (2022), *Environ. Res. Lett.* 17, 094020. CC BY 4.0.

Example: air pollution dose–response ($PM_{2.5}$)

Burnett et al. (2014) estimate the Integrated Exposure–Response (IER) function: how relative risk of disease rises with $PM_{2.5}$ exposure. The figure shows ALRI (acute lower respiratory infection, children <5):

- The curve is S-shaped: steep at moderate concentrations, flattening at high levels.
- At low concentrations, each extra $\mu g/m^3$ causes a larger increase in relative risk.

Translating relative risk into dollars (via the value of a statistical life) gives the MD curve. The shape of MD depends on the pollutant's dose–response relationship.



ALRI = acute lower respiratory infection (children <5). HAP = household air pollution; SHS = second-hand smoke; AAP = ambient air pollution.

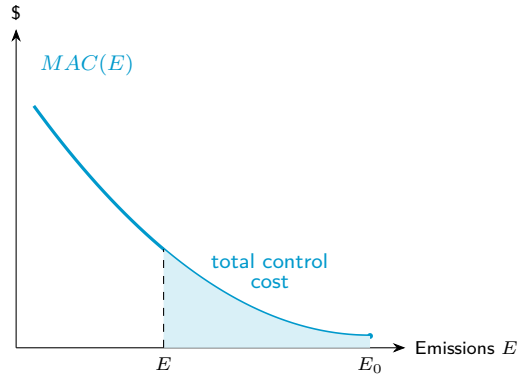
Source: Burnett, R.T. et al. (2014), *Environ. Health Perspect.* 122(4), 397–403. Figure 2.

The cost side — the marginal abatement cost curve

Marginal abatement cost (MAC)

MAC = the cost of removing *one more* unit of pollution: cleaner inputs, capital for scrubbers, lost output.

- Rising in abatement: cheap reductions first, then progressively dearer ones ("low-hanging fruit").
- Read against emissions E, MAC falls as E rises: at high E the next unit of control is cheap; at low E it is expensive.
- At E_0 (uncontrolled) $MAC = 0$. The area under MAC from E to E_0 = total control cost.



Measuring marginal abatement costs in practice

Where the numbers come from

Unlike MD, MAC is rooted in engineering and market data, what does it actually cost to cut one more unit?

- Bottom-up / engineering: rank abatement options from cheapest to dearest (fuel switching, scrubbers, process changes).
- Econometric: estimate cost functions from observed firm behaviour, variation in input prices, output, and abatement across plants could reveal the slope of MAC.
- Market-revealed: in cap-and-trade systems the permit price reveals the marginal cost at the aggregate level.

Firms typically know their *own* MAC, but the regulator does not, a key information asymmetry that shapes instrument choice.

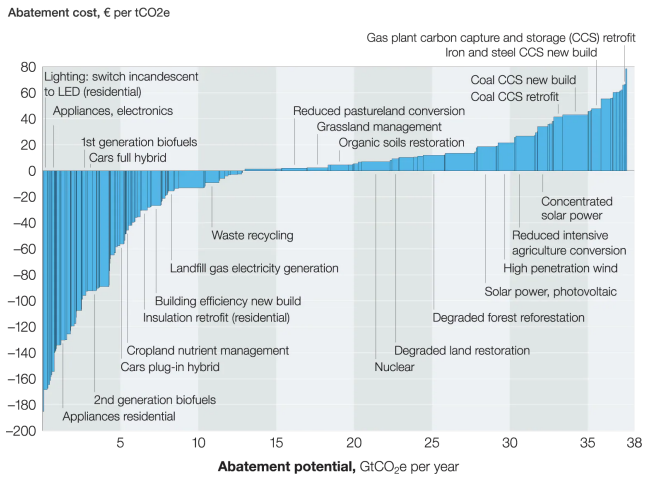
The McKinsey Global GHG Abatement Cost Curve

Each bar is one abatement measure:

- Width = $GtCO_2e$ it can abate.
- Height = cost per tonne (€/tCO_2e).
- Ranked left to right from cheapest to dearest.

Bars below zero *save* money (e.g. insulation, efficient appliances).

Example: nuclear abates ∼2 $GtCO_2e$/yr at ∼€10/t, a low-cost option on paper, yet high upfront capital and political barriers slow deployment.

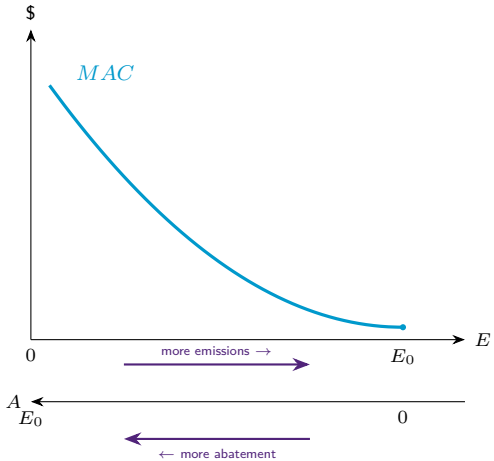


Source: McKinsey & Company, Global GHG Abatement Cost Curve v2.1.

Abatement vs. emissions — two ways to read the MAC

$$A = E_0 - E$$

- When we discuss the efficient level, we plot MAC against E (downward-sloping) so it intersects MD.
- When we discuss the equimarginal principle, we plot MAC against A (upward-sloping) to compare costs across sources.



The efficient level of pollution

Minimise total social cost

Society bears two costs that move in opposite directions as emissions fall:

$$\text{TSC}(E) \;=\; \underbrace{\text{total damage}(E)}_{\text{falls as } E\downarrow} \;+\; \underbrace{\text{total control cost}(E)}_{\text{rises as } E\downarrow}.$$

The efficiency rule

Total social cost is minimised where the two *marginal* curves cross:

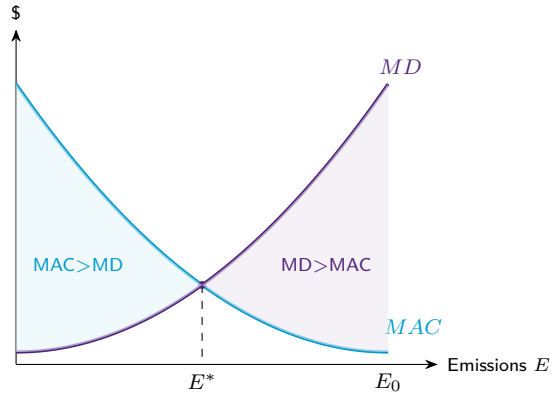
$$MD(E^*) \;=\; MAC(E^*)\,.$$

At E^* the harm from the last unit of pollution just equals the cost of removing it. Cut further and control costs exceed damages avoided; cut less and damages exceed the cost of avoiding them.

The efficient level

The efficient pollution level E^* balances marginal damage against marginal abatement cost.

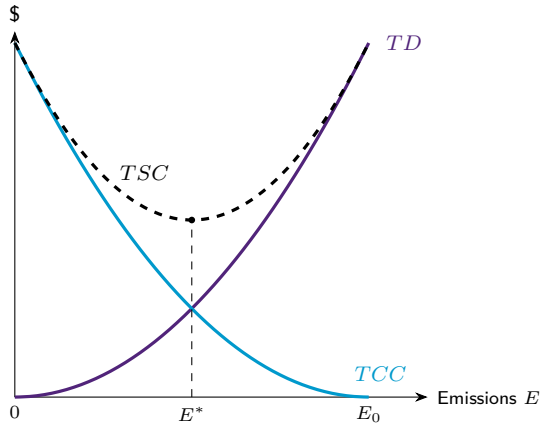
- To the right of E^*: $MD > MAC$, is cheaper to abate than to suffer the damage.
- To the left: $MAC > MD$, the cleanup costs more than the damage it spares.
- Neither $E = 0$ nor $E = E_0$ is efficient.



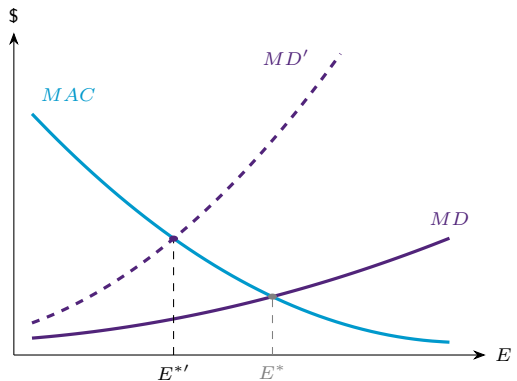
The total social cost

- TD (total damage) rises with emissions.
- TCC (total control cost) falls with emissions, less cleanup needed.
- TSC = TD + TCC is U-shaped: it bottoms out at E^*.
- At E^* the *slopes* of TD and TCC are equal, i.e. $MD = MAC$.

Neither zero pollution (E=0, all cost) nor no control (E=E_0, all damage) minimises total social cost.



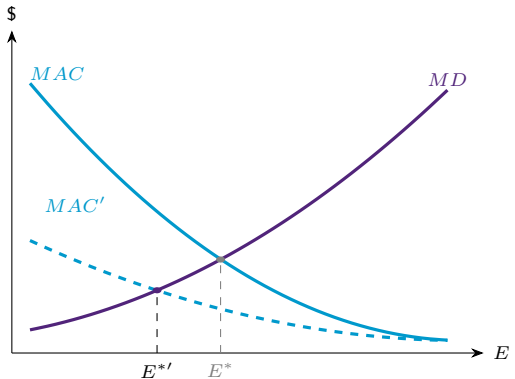
Comparative statics — a rise in marginal damage



More damage discovered

New evidence that pollution is more harmful pivots MD up. The crossing moves left: efficient emissions fall ($E^{*\prime} < E^*$), and the marginal price of pollution rises. Intuition: if each unit hurts more, abate more.

Comparative statics — cheaper abatement



Better control technology

Innovation lowers MAC at every level of abatement. The crossing moves left and down: efficient emissions fall *and* the marginal price falls. Cleaner *and* cheaper. But note: this is the *efficient* response. Under a fixed cap, the same innovation would leave emissions unchanged — a wedge we return to in Lecture 4.

Why the efficient level is not zero

"Some" pollution is efficient

Driving emissions to zero forces society up the steep, expensive top of the MAC curve to abate units whose damage is small.

- At $E = 0$: total control cost is at its maximum, damages are zero;
- At $E = E_0$: control cost is zero, damages are at their maximum;
- At E^*: the sum is smallest.

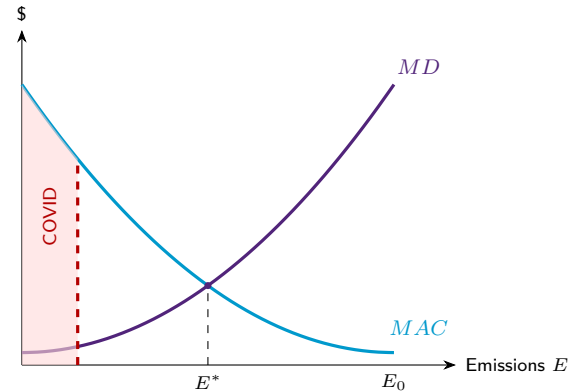
The goal is not a pristine environment at any cost, but the level where the marginal value of a cleaner environment equals the marginal cost of providing it.

COVID-19 — a natural experiment in "zero pollution"

The lesson for pollution policy

COVID lockdowns pushed emissions toward zero, a global recession was the cost.

- Near $E{=}0$: MAC $\gg$ MD $\Rightarrow$ over-abatement.
- Health benefits were real, but economic cost far exceeded the damage avoided.
- Efficient policy: price the externality at E^*, not shut down the economy.



When zero *is* efficient

Corner solutions

The interior rule $MD = MAC$ assumes the curves cross at a positive E. They may not:

- Extremely toxic / threshold pollutants: if $MD > MAC$ at *every* positive level (damage always exceeds the cost of removal), the optimum is $E^* = 0$, ban it. *Examples:* certain persistent toxics, ozone-depleting CFCs (phased out under the Montreal Protocol).
- Harmless residuals: if $MD < MAC$ everywhere, the optimum is to not abate at all ($E^* = E_0$).

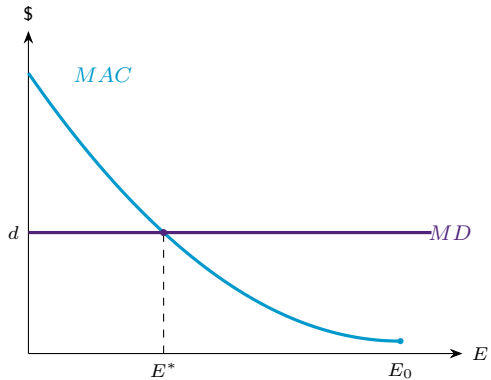
Special case — constant marginal damage

A flat MD

Sometimes marginal damage is roughly constant over the relevant range (e.g. a global pollutant whose local increment is tiny): $MD(E) = d$, a horizontal line.

- Efficiency: $d = MAC(E^*)$, the efficient price is simply d.
- A tax of $t = d$ is the natural instrument: it *is* the marginal damage.

This flat-MD case is the intuition behind pricing carbon at the social cost of carbon, a constant \$/tonne.



Efficient vs "acceptable" levels

The $MD = MAC$ optimum is the environmental-economics answer: trade damages off against costs at the margin.

- Ecological economics is often uneasy with it: damages may be uncertain, irreversible, or involve incommensurable values (a species, a sacred river) that resist a dollar MD.
- It leans instead on safe minimum standards or precaution: set a physical limit (a critical load, a planetary boundary) *first*, then use economics to meet it cheaply.

Notice the bridge: a precautionary target + cost-effective delivery combines both traditions.

Cost-Effectiveness & the Equimarginal Principle

The second question — who abates?

Same target, many sources

Suppose policy has fixed a target: cut total emissions to $\bar{E}$. Sources differ in their abatement costs (old vs new plant, process, fuel). The required cutback can be shared among them in countless ways.

- Cost-effectiveness: achieve the given target at the lowest total abatement cost.
- This is a *weaker* requirement than efficiency: efficiency also fixes the right *target*; cost-effectiveness just hits whatever target is set, cheaply.

Even a regulator who is *unsure* of the efficient $\bar{E}$ should still want to hit its chosen target at least cost. Cost-effectiveness is the minimal ask.

The equimarginal principle

The least-cost rule

A given total reduction is achieved at minimum cost if and only if the marginal abatement cost is equalised across all sources:

$$MAC_1 = MAC_2 = \cdots = MAC_n.$$

The reallocation argument

Suppose $MAC_1 > MAC_2$. Shift *one* unit of abatement from source 1 to source 2, holding total abatement fixed:

$$\text{cost change} = \underbrace{-MAC_1}_{\text{source 1 saves}} + \underbrace{MAC_2}_{\text{source 2 pays}} < 0.$$

Total cost falls. Keep going until $MAC_1 = MAC_2$: only then is no profitable reshuffle left. The same logic for every pair of sources.

The equimarginal principle — a formal derivation

Let source i have total abatement cost $C_i(a_i)$ with $C_i' = MAC_i$. Minimise total cost subject to hitting a required total abatement A:

$$\min_{a_1,\ldots,a_n} \sum_i C_i(a_i) \quad \text{s.t.} \quad \sum_i a_i = A.$$

Lagrangian and first-order conditions

$$\mathcal{L} = \sum_i C_i(a_i) + \lambda\left(A - \sum_i a_i\right), \qquad \frac{\partial \mathcal{L}}{\partial a_i} = C_i'(a_i) - \lambda = 0.$$

Hence for *every* active source

$$MAC_i(a_i) = \lambda \quad \text{for all } i.$$

The multiplier λ is the common marginal cost of the last unit of abatement and, we will see, exactly the tax or permit price that decentralises the solution.

Equal MAC

Why λ is a shadow price

Think of abatement as a task to be sourced at least cost.

- If two suppliers quote different marginal costs, you re-source the marginal unit from the cheaper one, and keep doing so.
- At the optimum every supplier quotes the same marginal cost λ: there is no arbitrage left.

This is the same logic as a competitive market clearing at one price. It is why a single price signal (a tax, or a permit market) is enough to coordinate many heterogeneous firms without the regulator knowing any firm's costs.

Cost-effectiveness is weaker than efficiency

Two distinct questions

- Efficiency answers *how much*: it sets the target at $MD = MAC$ — and needs the damage function.
- Cost-effectiveness answers *how*: it hits *whatever* target is chosen at least cost — and needs only the cost side.

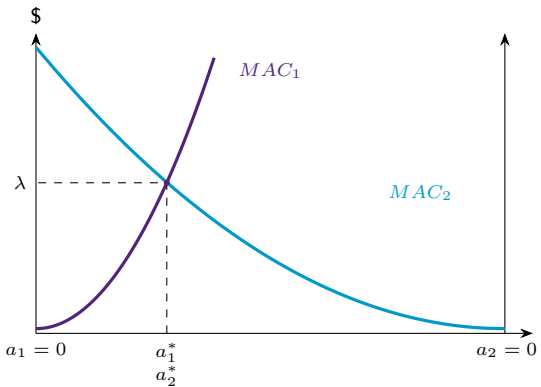
Why the split matters:

- Damages are hard to measure and politically contested; abatement costs are comparatively knowable.
- So regulators often set a target politically (a treaty, an air-quality standard) and then ask economics to deliver it cheaply.
- An instrument can be cost-effective yet aimed at the wrong target — efficient only if the target itself is E^*.

The equimarginal principle — two sources

Total required abatement (width of the box) is split where the two MAC curves cross: $MAC_1 = MAC_2 = \lambda$.

- The cheap abater (flat MAC) does most of the work.
- Any other split pushes one firm up its steep MAC, raising total cost.

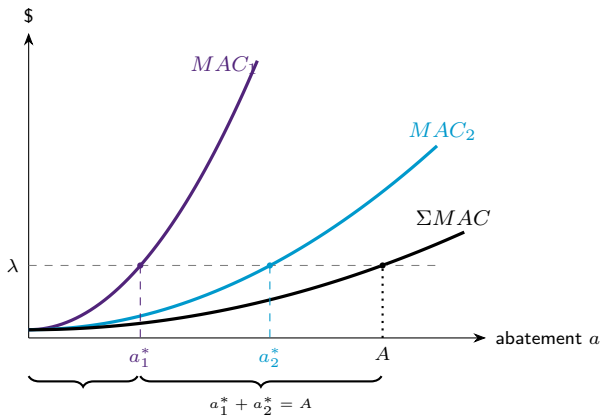


The equimarginal principle

A regulator sets a total abatement target A. Two sources must deliver $a_1 + a_2 = A$.

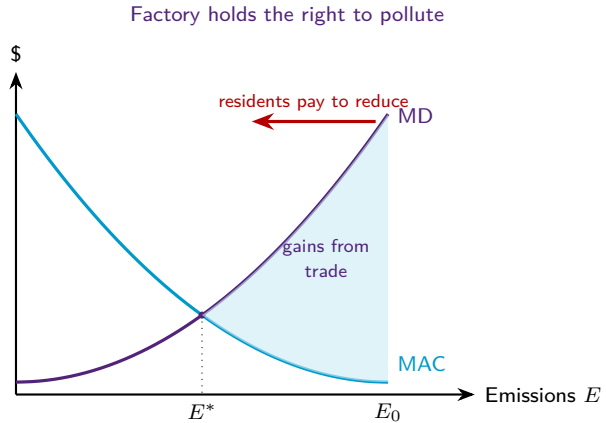
- Read the aggregate MAC at A to find λ.
- Project λ back to each firm's MAC to get a_1^* and a_2^*.
- The target is exactly met: $a_1^* + a_2^* = A$.
- The cheap source (flat MAC) does most of the work.

Any other split raises total cost. The ΣMAC curve is the market "demand to pollute", the basis for the permit market (Lecture 4).



The Coase Theorem with MD & MAC

Coase with MD & MAC — right to pollute

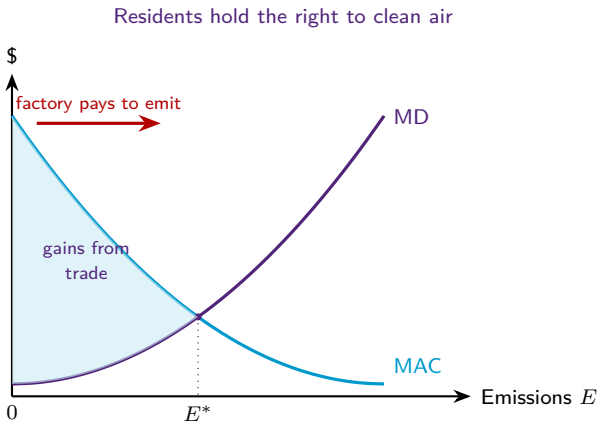


Starting point

Factory runs at E_0. Residents want less pollution.

- For each unit of abatement, residents will pay up to MD (damage avoided).
- Factory demands at least MAC (abatement cost).
- As long as MD $>$ MAC, there is a mutually beneficial deal.
- Bargaining stops at E^* where MD $=$ MAC: the efficient level.

Coase with MD & MAC — right to clean air



Starting point

Factory at $E = 0$. Factory wants permission to emit.

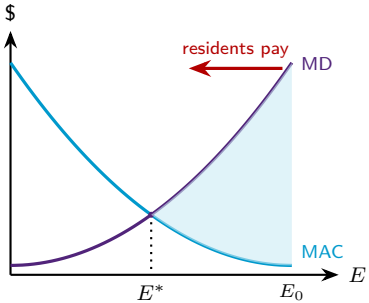
- For each unit of pollution, factory will pay up to MAC (abatement cost saved).
- Residents demand at least MD (damage suffered).
- As long as MAC $>$ MD, there is a mutually beneficial deal.
- Bargaining stops at E^* where MD $=$ MAC: the same efficient level.

Coase confirmed

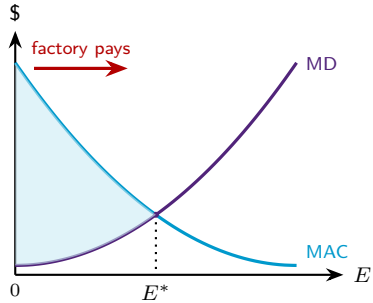
Same E^*, different direction of payment.

The Coase theorem — same E^*, different payment

Right to pollute



Right to clean air



The Coase punchline

- Both panels reach the same E^* where MD = MAC.
- The shaded gains from trade are fully captured in both cases.
- Only the direction of payment differs: who holds the right determines who pays whom, not the efficient outcome.
- Efficiency is invariant; equity is not.

Appendix

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