

# Lecture 06

## Tradable Permits

---

Dana Andersen  
ECON 467

# Roadmap

1. How do tradable permit systems work in theory and in the real world?
2. What happens under a tradable permit system?

# Tradable permits

---

# Tradable permits

How do tradable permit systems work?<sup>1</sup>

<sup>1</sup> Tradable permit systems are also called cap and trade systems.

# Tradable permits

How do tradable permit systems work?<sup>1</sup>

First, recall a regular emission standard: we set  $\bar{E}$  at the point where  $MAC = MD$

<sup>1</sup> Tradable permit systems are also called cap and trade systems.

# Tradable permits

How do tradable permit systems work?<sup>1</sup>

First, recall a regular emission standard: we set  $\bar{E}$  at the point where  $MAC = MD$

This is easy with one firm, but what if we have several, or hundreds?

<sup>1</sup> Tradable permit systems are also called cap and trade systems.

# Optimal policy with multiple firms

Suppose the regulator chooses emissions for  $N$  firms:  $E_1, \dots, E_N$

# Optimal policy with multiple firms

Suppose the regulator chooses emissions for  $N$  firms:  $E_1, \dots, E_N$

Let firm  $i$ 's compliance/abatement cost be  $C_i(E_i)$

# Optimal policy with multiple firms

Suppose the regulator chooses emissions for  $N$  firms:  $E_1, \dots, E_N$

Let firm  $i$ 's compliance/abatement cost be  $C_i(E_i)$

Let total damages depend on aggregate emissions:

$$D = D\left(\sum_{i=1}^N E_i\right)$$

# Optimal policy with multiple firms

Suppose the regulator chooses emissions for  $N$  firms:  $E_1, \dots, E_N$

Let firm  $i$ 's compliance/abatement cost be  $C_i(E_i)$

Let total damages depend on aggregate emissions:

$$D = D\left(\sum_{i=1}^N E_i\right)$$

Planner problem:

$$\min_{E_1, \dots, E_N} \sum_{i=1}^N C_i(E_i) + D\left(\sum_{i=1}^N E_i\right)$$

# Optimal policy with multiple firms

Take one FOC for each firm  $i = 1, \dots, N$ :

$$\frac{\partial}{\partial E_i} \left[ \sum_{j=1}^N C_j(E_j) + D \left( \sum_{j=1}^N E_j \right) \right] = 0$$

$$C'_i(E_i) + D' \left( \sum_{j=1}^N E_j \right) = 0$$

# Optimal policy with multiple firms

Take one FOC for each firm  $i = 1, \dots, N$ :

$$\frac{\partial}{\partial E_i} \left[ \sum_{j=1}^N C_j(E_j) + D \left( \sum_{j=1}^N E_j \right) \right] = 0$$

$$C'_i(E_i) + D' \left( \sum_{j=1}^N E_j \right) = 0$$

$$\underbrace{-C'_i(E_i)}_{MAC_i} = \underbrace{D' \left( \sum_{j=1}^N E_j \right)}_{MD}$$

# Optimal policy with multiple firms

$$\underbrace{-C'_i(E_i)}_{MAC_i} = D' \underbrace{\left( \sum_{j=1}^N E_j \right)}_{MD}$$

# Optimal policy with multiple firms

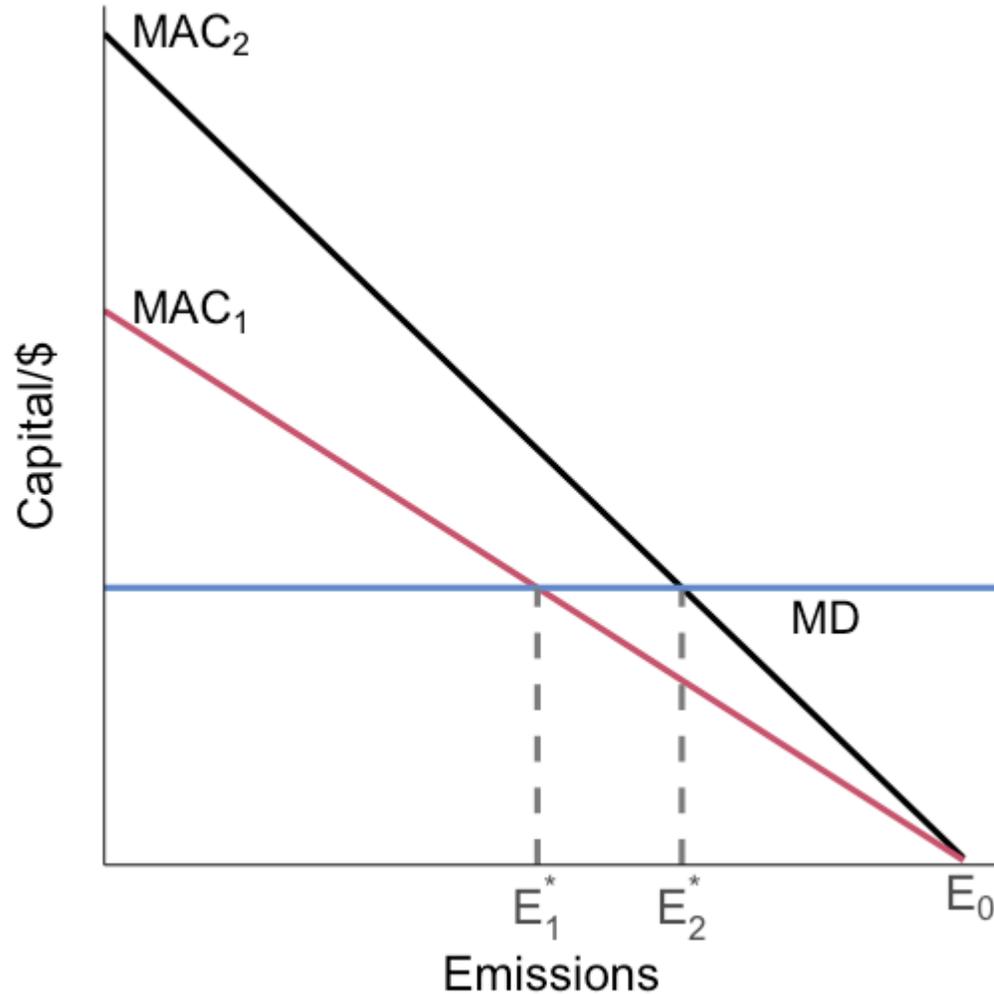
$$\underbrace{-C'_i(E_i)}_{MAC_i} = D' \left( \underbrace{\sum_{j=1}^N E_j}_{MD} \right)$$

At the optimum:

$$MAC_1 = MAC_2 = \dots = MAC_N = MD$$

This gives the target condition that permit markets try to decentralize

# Optimal policy with multiple firms



Firm #2 is 'dirty': has higher MAC

Firm #1 is 'clean': has lower MAC

If we use a regular emission standard: it has to be firm-specific!

Mandate  $E_1^*$  for 1 and  $E_2^*$  for 2

This requires **a lot** of info and political capital on behalf of the regulator

# Tradable permit systems

So how do these systems make standards more flexible?

# Tradable permit systems

So how do these systems make standards more flexible?

They allow firms to trade their emission allowances

# Tradable permit systems

So how do these systems make standards more flexible?

They allow firms to trade their emission allowances

E.g. if firms are restricted to  $\bar{E}_1$  and  $\bar{E}_2$ , we can allow the firms to trade

# Tradable permit systems

So how do these systems make standards more flexible?

They allow firms to trade their emission allowances

E.g. if firms are restricted to  $\bar{E}_1$  and  $\bar{E}_2$ , we can allow the firms to trade

If firm 1 sells an allowance/permit to firm 2, their new restrictions are:  $\bar{E}_1 - 1$   
and  $\bar{E}_2 + 1$

# Tradable permit systems: example

The US Acid Rain Program is the classic example

# Tradable permit systems: example

The US Acid Rain Program is the classic example

Permit = license to create 1 ton of SO<sub>2</sub>

# Tradable permit systems: example

The US Acid Rain Program is the classic example

Permit = license to create 1 ton of SO<sub>2</sub>

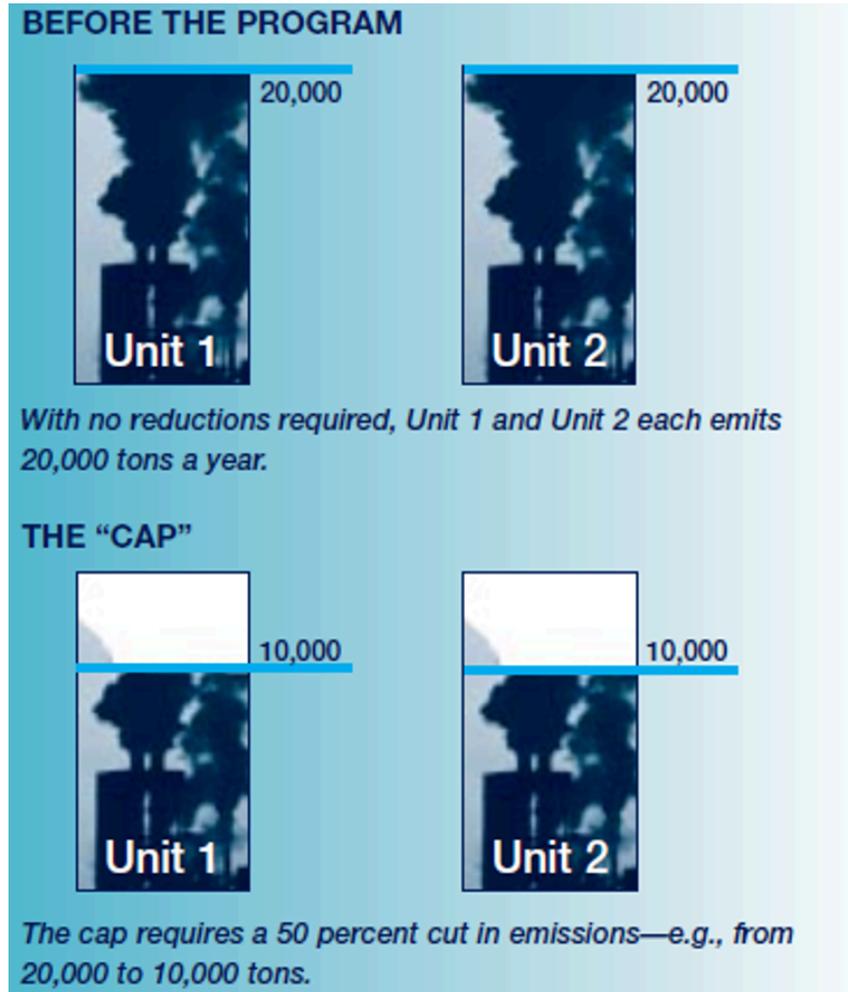
Phase I (1995-2000):

- 6.3 million permits issued per year
- affected 263 generating units at 110 dirtiest power plants

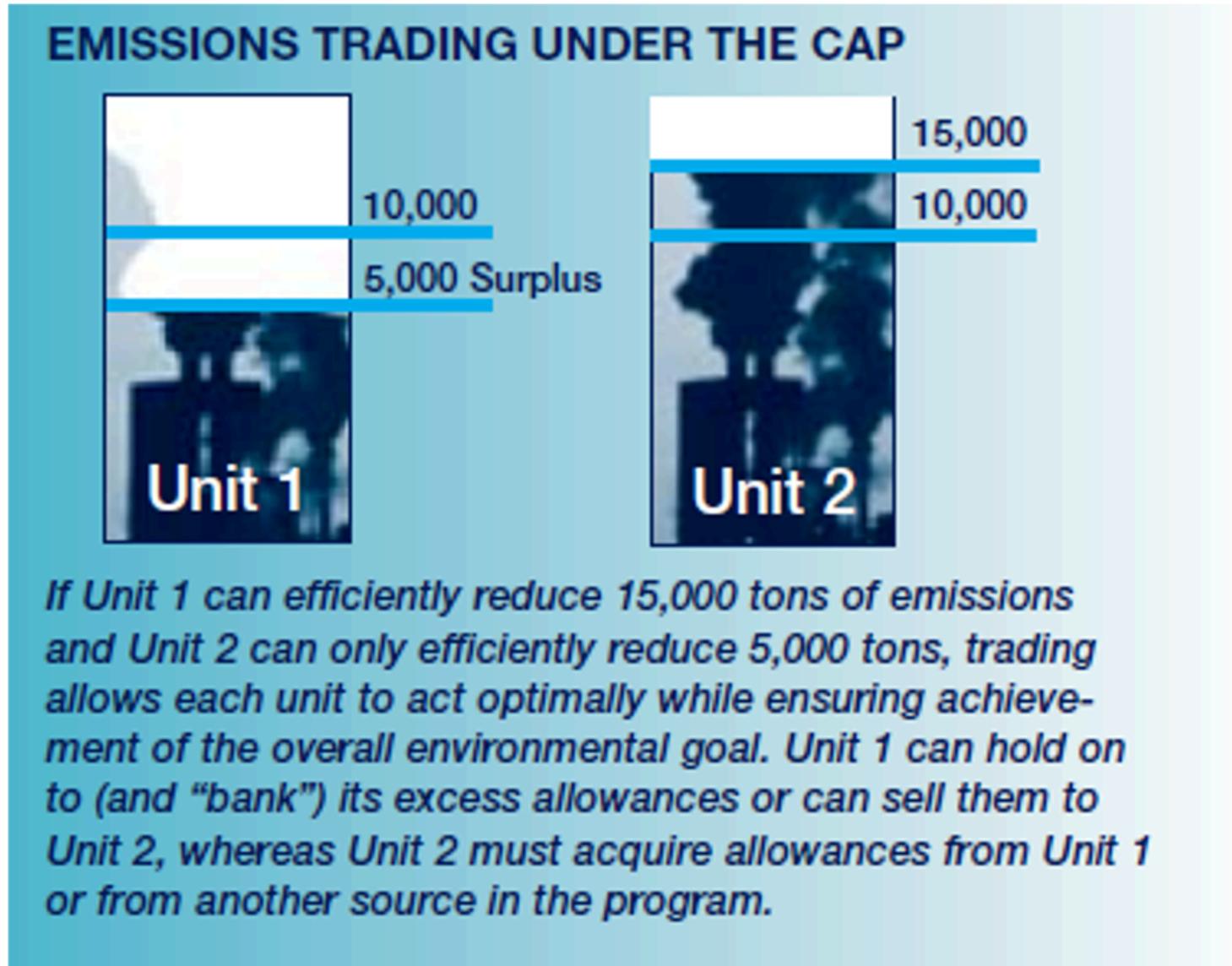
Phase II (2000+):

- 9 million permits issued per year
- affects all power plants over some minimum size

# Tradable permit systems: example

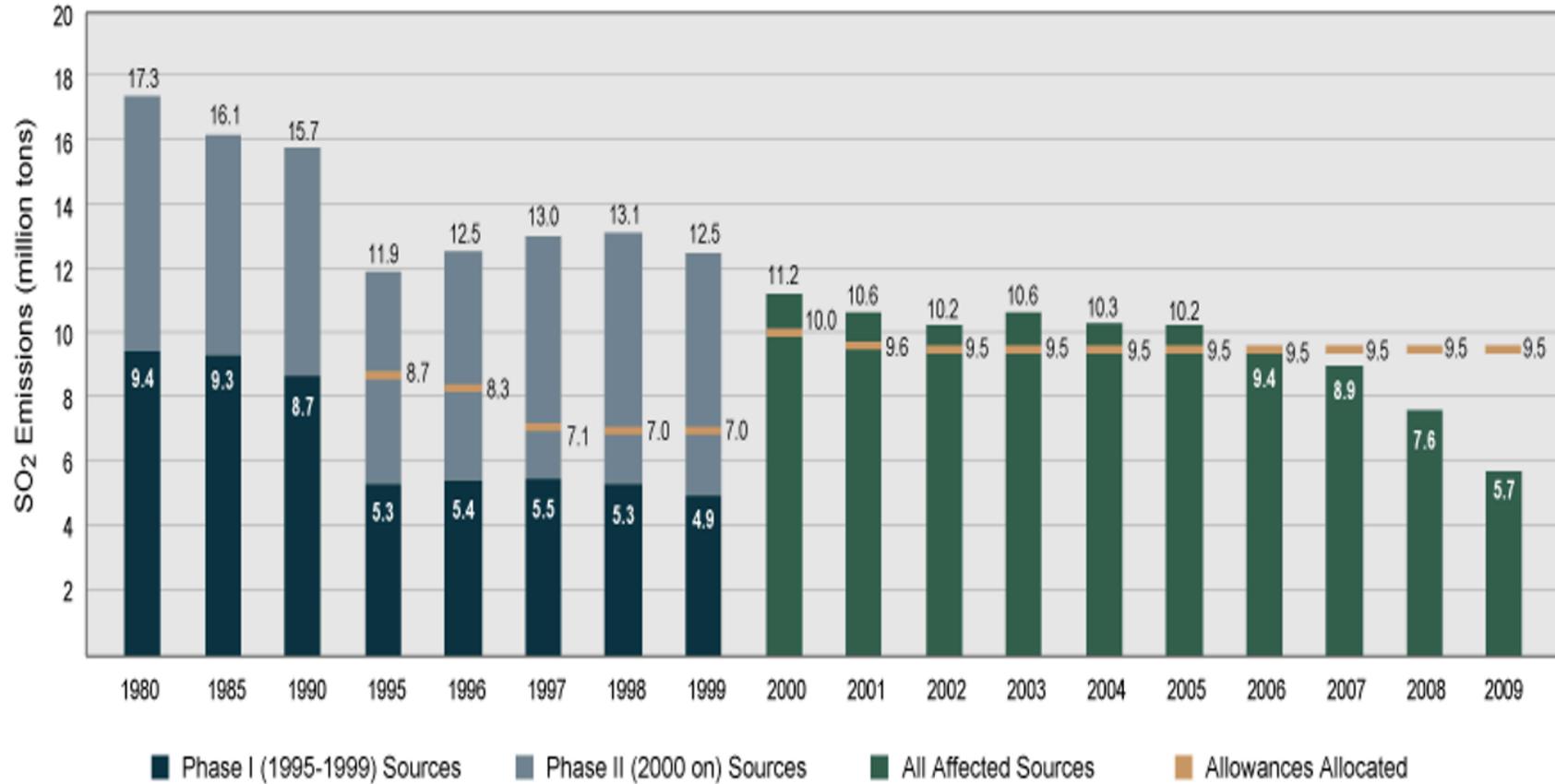


# Tradable permit systems: example



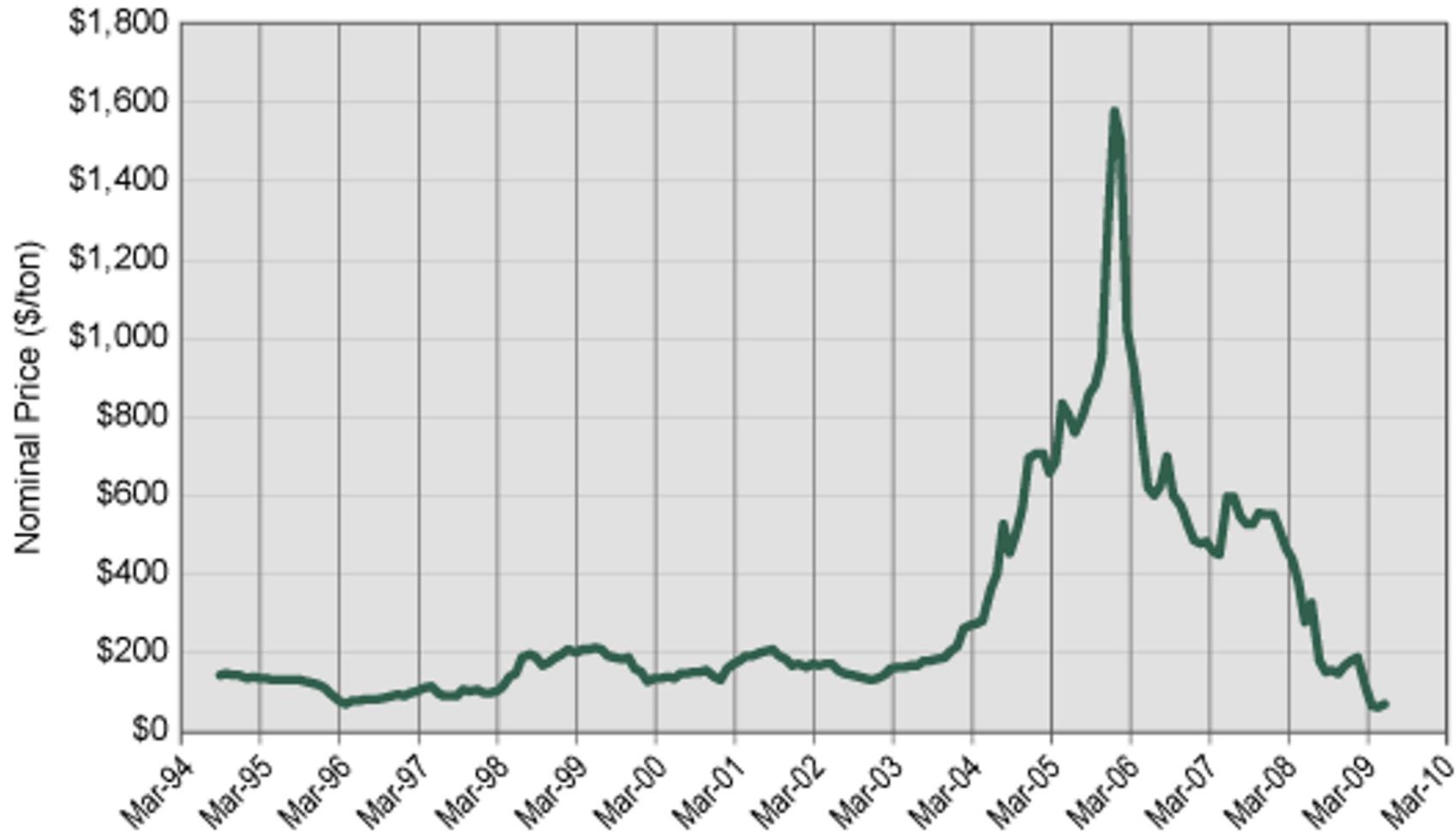
# Tradable permit systems: example

SO<sub>2</sub> Emissions from Acid Rain Program Sources, 1980-2009



Source: EPA, 2010

# Tradable permit systems: example



# Tradable permit systems: example

---

## Quantified benefits\*:

<b>PM<sub>2.5</sub> mortality (U.S. and southern Canada)</b>	<b>\$107,000</b>
<b>PM<sub>2.5</sub> morbidity (U.S. and southern Canada)</b>	<b>\$8,000</b>
<b>Ozone mortality (eastern U.S.)</b>	<b>\$4,000</b>
<b>Ozone morbidity (eastern U.S.)</b>	<b>\$300</b>
<b>Visibility at parks (3 U.S. regions)</b>	<b>\$2,000</b>
<b>Recreational fishing in NY</b>	<b>\$65</b>
<b>Ecosystem improvements in Adirondacks (NY residents)</b>	<b>\$500</b>

---

<b>Total annual quantified benefits</b>	<b>\$122,000</b>
---	------------------

---

## Quantified costs for U.S. power generation:

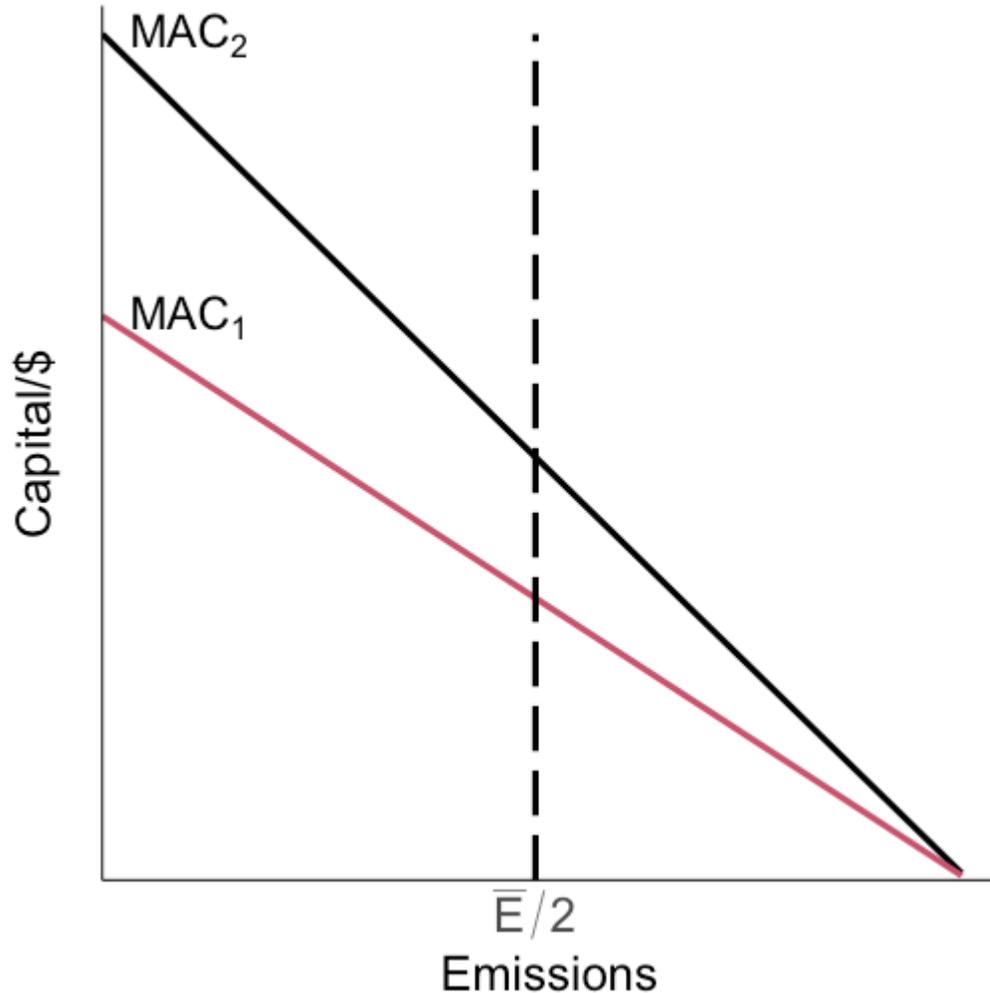
<b>SO<sub>2</sub> controls</b>	<b>\$2,000</b>
<b>NO<sub>x</sub> controls</b>	<b>\$1,000</b>

---

<b>Total annual quantified costs</b>	<b>\$3,000</b>
--------------------------------------	----------------

---

# Tradable permits: graphical



Suppose we want to limit to  $\bar{E}$  total emissions so each firm gets  $\bar{E}/2$  permits, but can't trade them

**This can't be efficient** (i.e. maximize social welfare given some MD curve)

**It also can't be cost-effective:** it doesn't minimize the cost of achieving  $\bar{E}$  total emissions

# Tradable permits: cost-effectiveness

For cost-effectiveness, we need total costs to be minimized for achieving a given level of emissions:

$$\min_{E_1, E_2} C_1(E_1) + C_2(E_2) \text{ subject to: } E_1 + E_2 = \bar{E}$$

This is the same problem as:

$$\min_{E_1, E_2} C_1(E_1) + C_2(\bar{E} - E_1)$$

which has a solution where:

$$-C'_1(E_1^*) = -C'_2(\bar{E} - E_1^*)$$

# Tradable permits: cost-effectiveness

Cost-effectiveness requires:

$$-C'_1(E_1^*) = -C'_2(\bar{E} - E_1^*) \leftrightarrow MAC_1 = MAC_2$$

That marginal abatement costs are equal across all emitters

# Tradable permits: cost-effectiveness

Cost-effectiveness requires:

$$-C'_1(E_1^*) = -C'_2(\bar{E} - E_1^*) \leftrightarrow MAC_1 = MAC_2$$

That marginal abatement costs are equal across all emitters

If firms have different MAC curves, giving them the same amount of emissions/permits cannot be optimal

# Tradable permits: cost-effectiveness

Cost-effectiveness requires:

$$-C'_1(E_1^*) = -C'_2(\bar{E} - E_1^*) \leftrightarrow MAC_1 = MAC_2$$

That marginal abatement costs are equal across all emitters

If firms have different MAC curves, giving them the same amount of emissions/permits cannot be optimal

How do we fix this?

# Tradable permits: cost-effectiveness

Cost-effectiveness requires:

$$-C'_1(E_1^*) = -C'_2(\bar{E} - E_1^*) \leftrightarrow MAC_1 = MAC_2$$

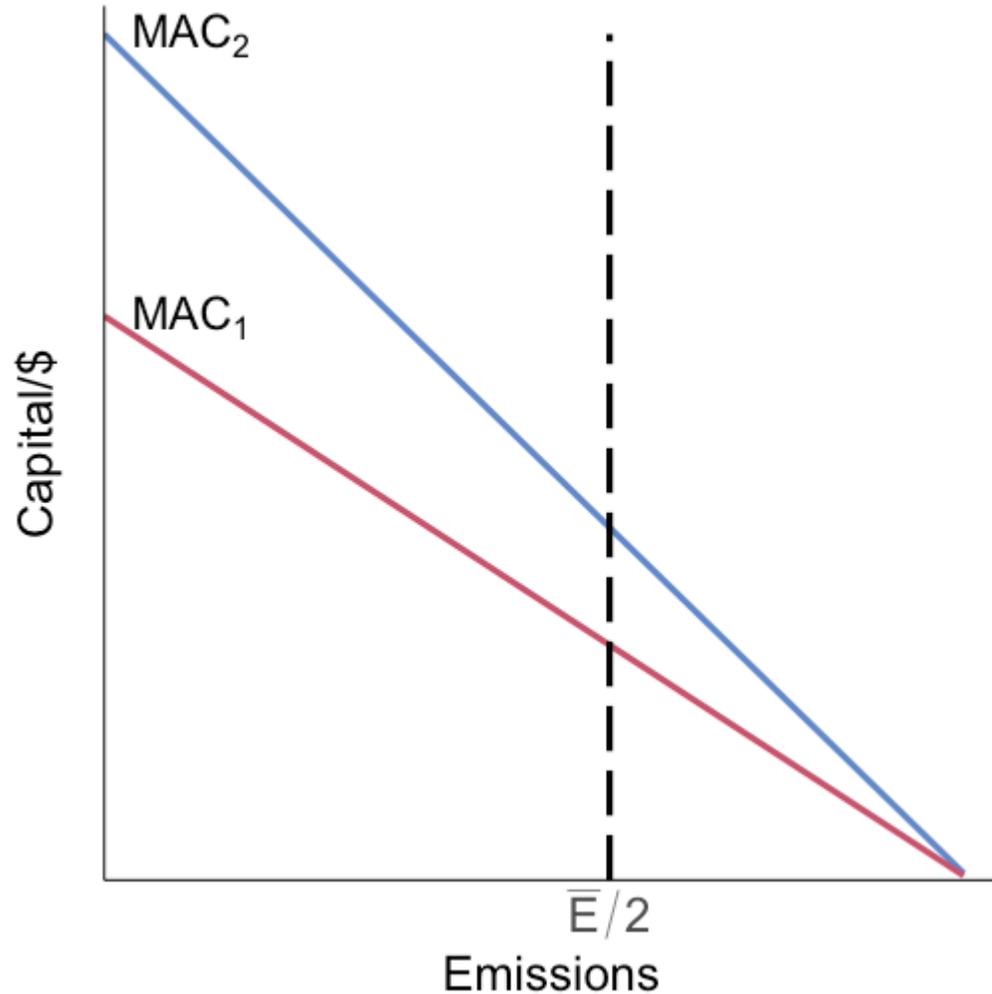
That marginal abatement costs are equal across all emitters

If firms have different MAC curves, giving them the same amount of emissions/permits cannot be optimal

How do we fix this?

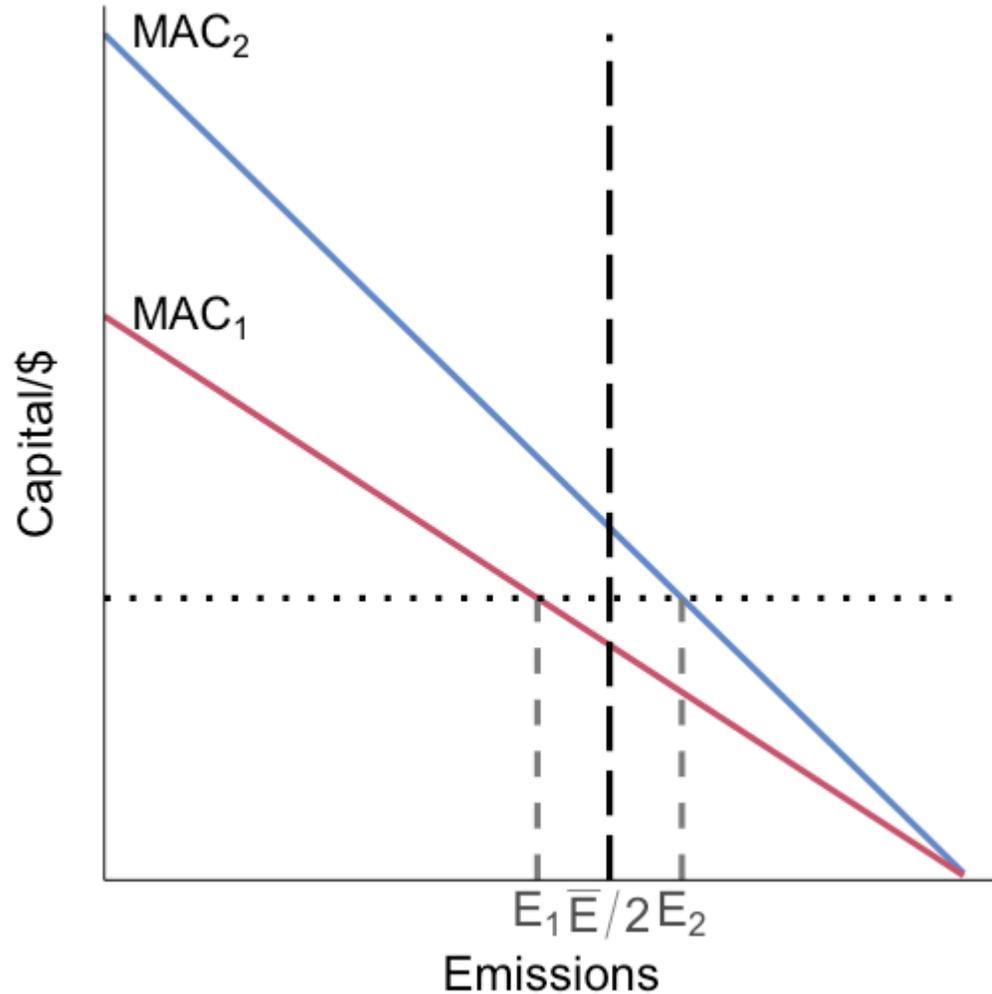
Let them trade the permits

# Tradable permits: graphical



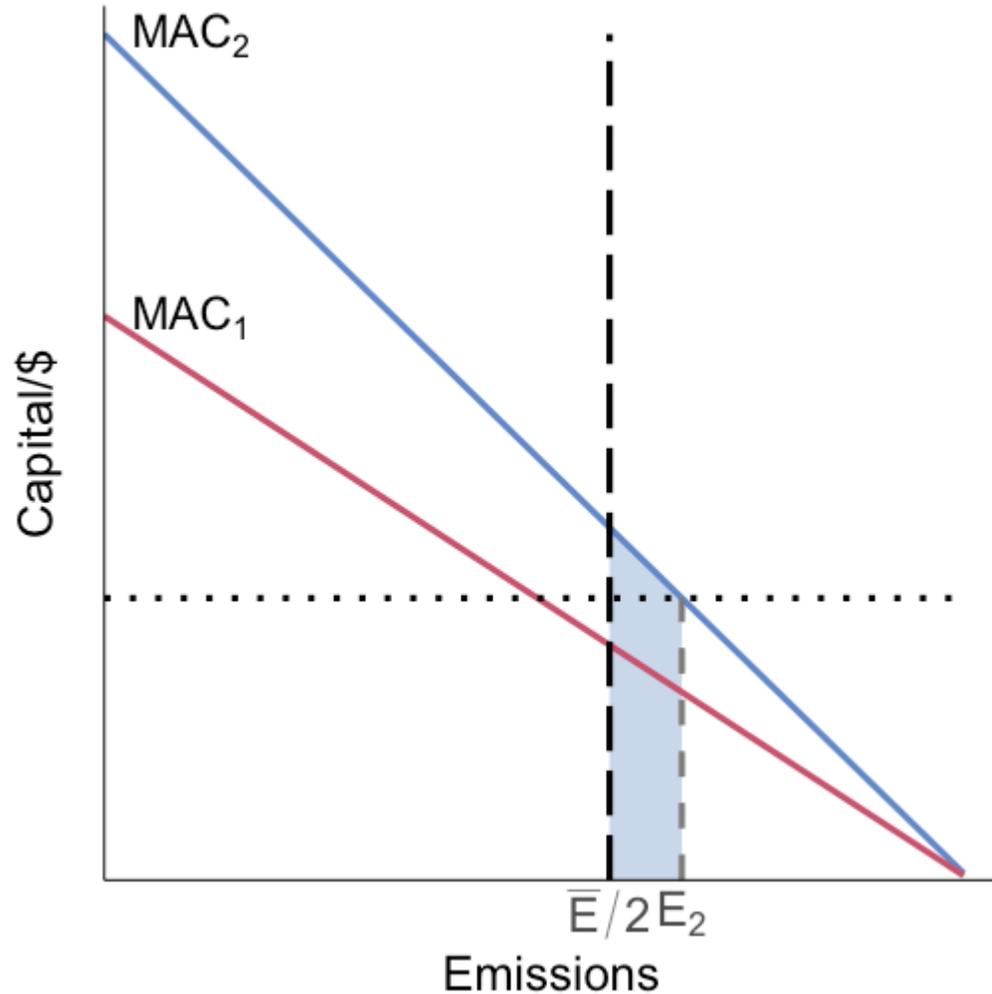
We can reduce costs by increasing abatement at which firm, and decreasing abatement at which firm?

# Tradable permits: graphical



We can reduce costs by increasing emissions at high MAC firm 2 and decreasing emissions at low MAC firm 1 until they are equal

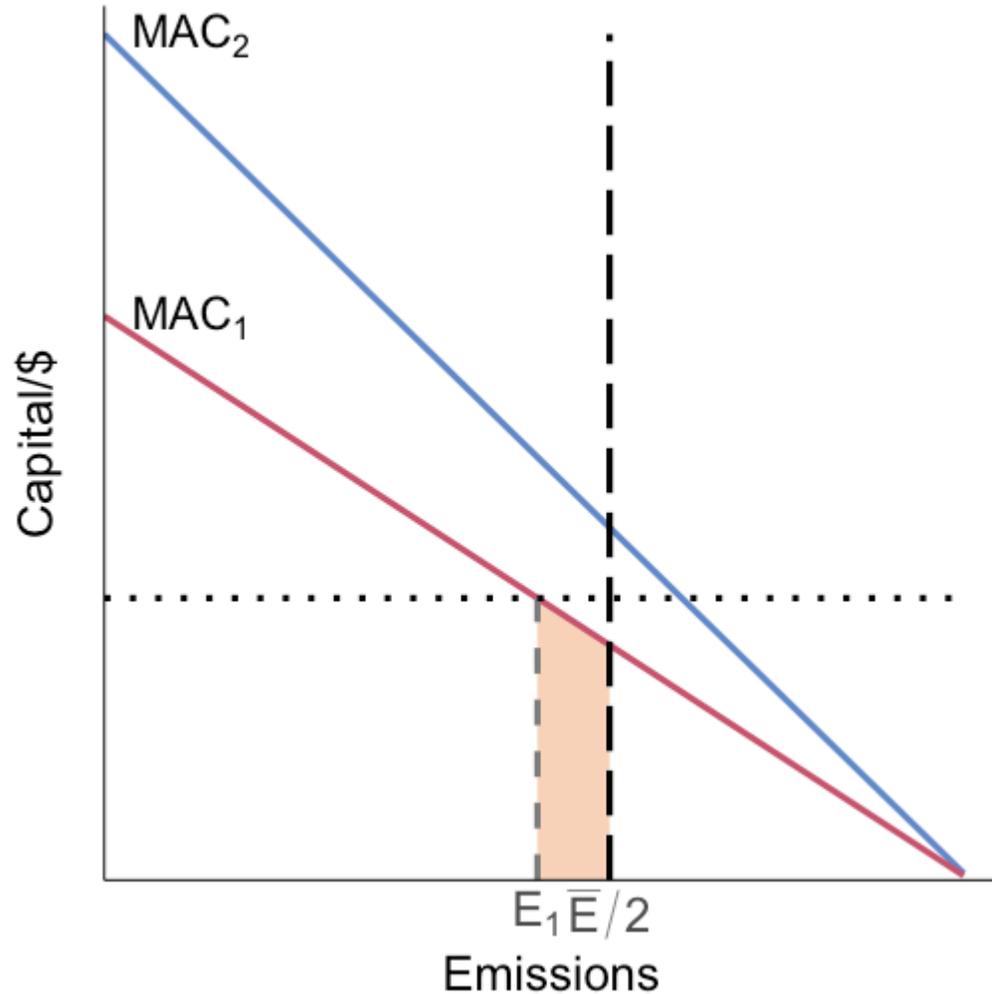
# Tradable permits: graphical



Step 1: allow firm 2 (high MAC) to emit more, from  $\bar{E}/2$  to  $E_2$

The blue shaded area is firm 2's cost saving

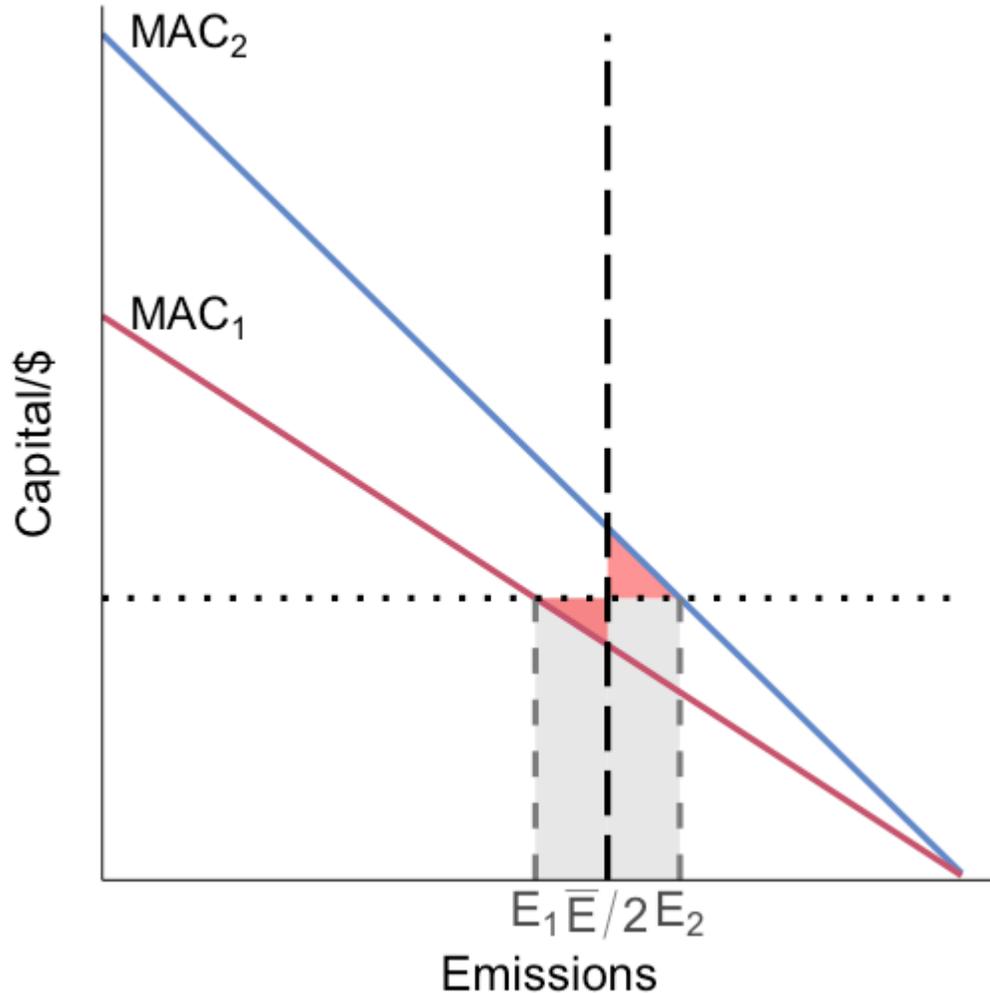
# Tradable permits: graphical



Step 2: firm 1 (low MAC) emits less, from  $\bar{E}/2$  to  $E_1$

The orange shaded area is firm 1's cost increase

# Tradable permits: graphical

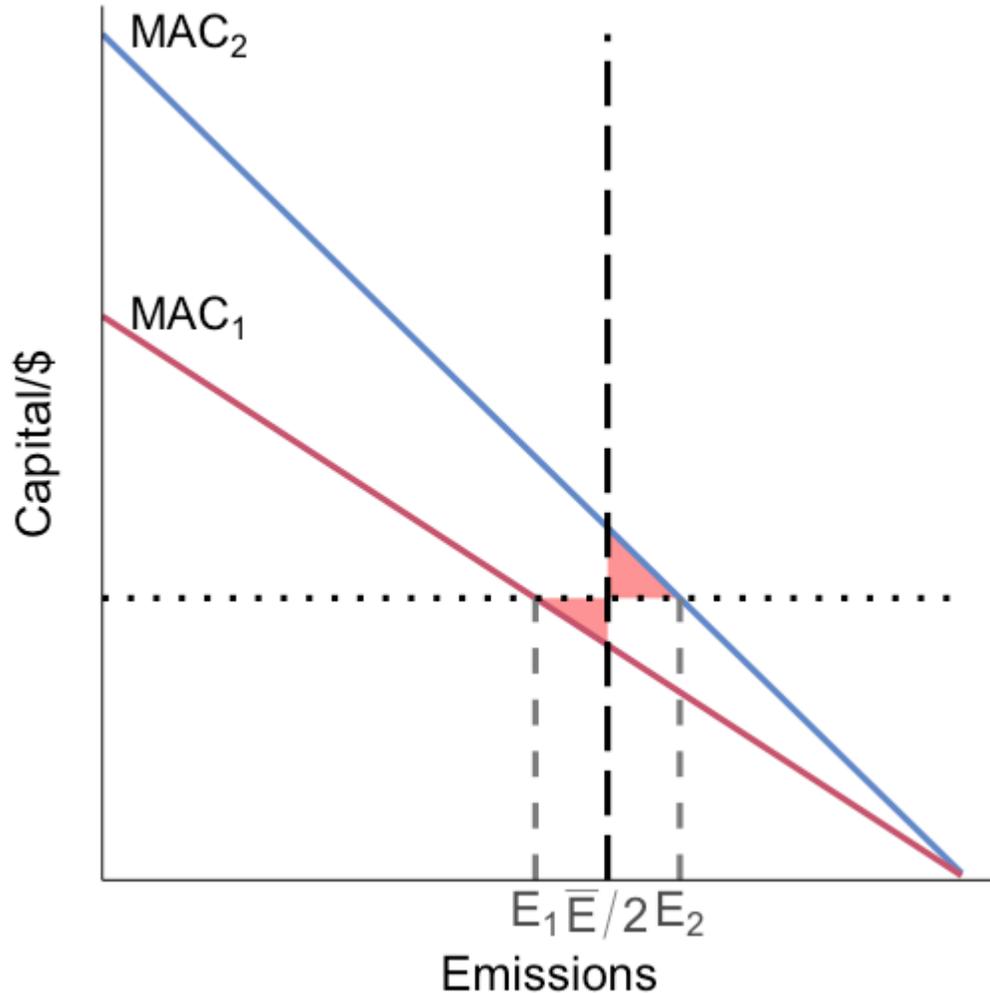


Step 3: net cost change from trading

The grey rectangles are equal (same height and same width  $\Delta E$ ), so they cancel out

What remains is the two red triangles: the net cost reduction from reallocation

# Tradable permits: graphical

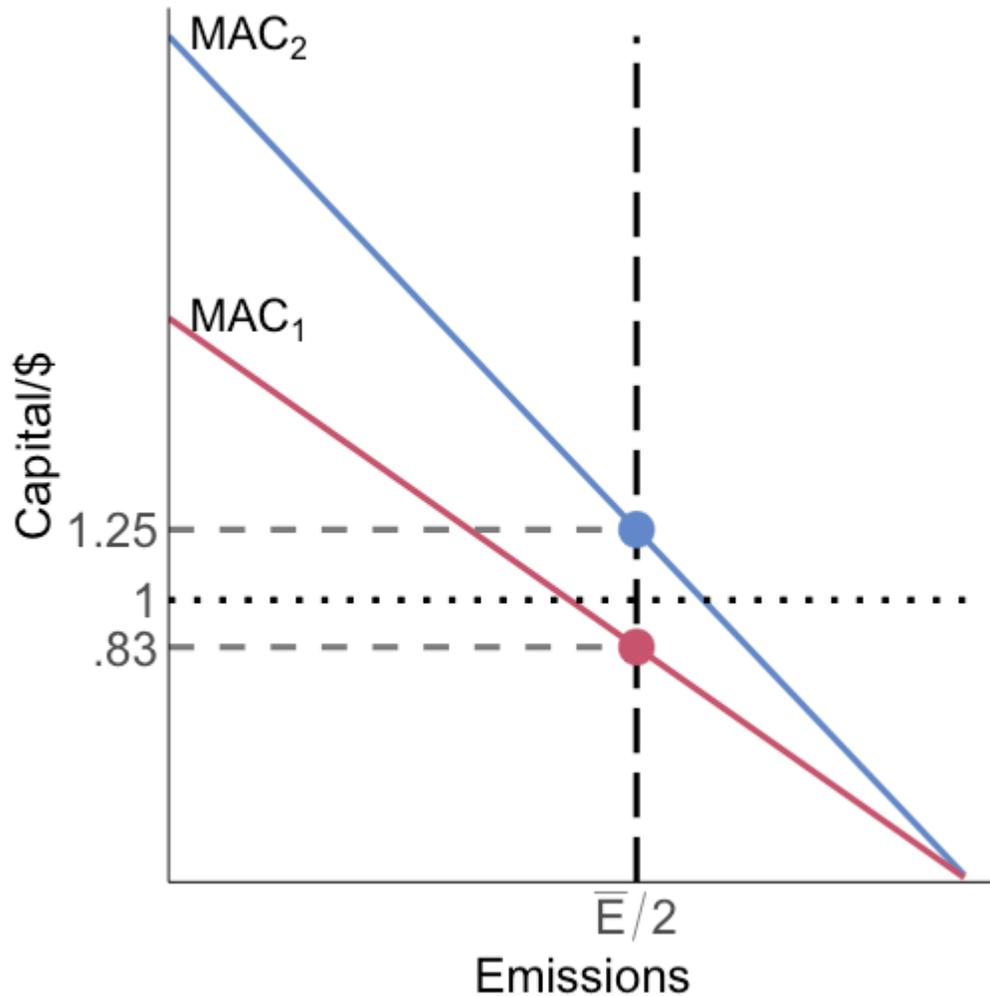


We can reduce costs by increasing emissions at high MAC firm 2 and decreasing emissions at low MAC firm 1 until they are equal

This allows us to recover DWL equal to the red area

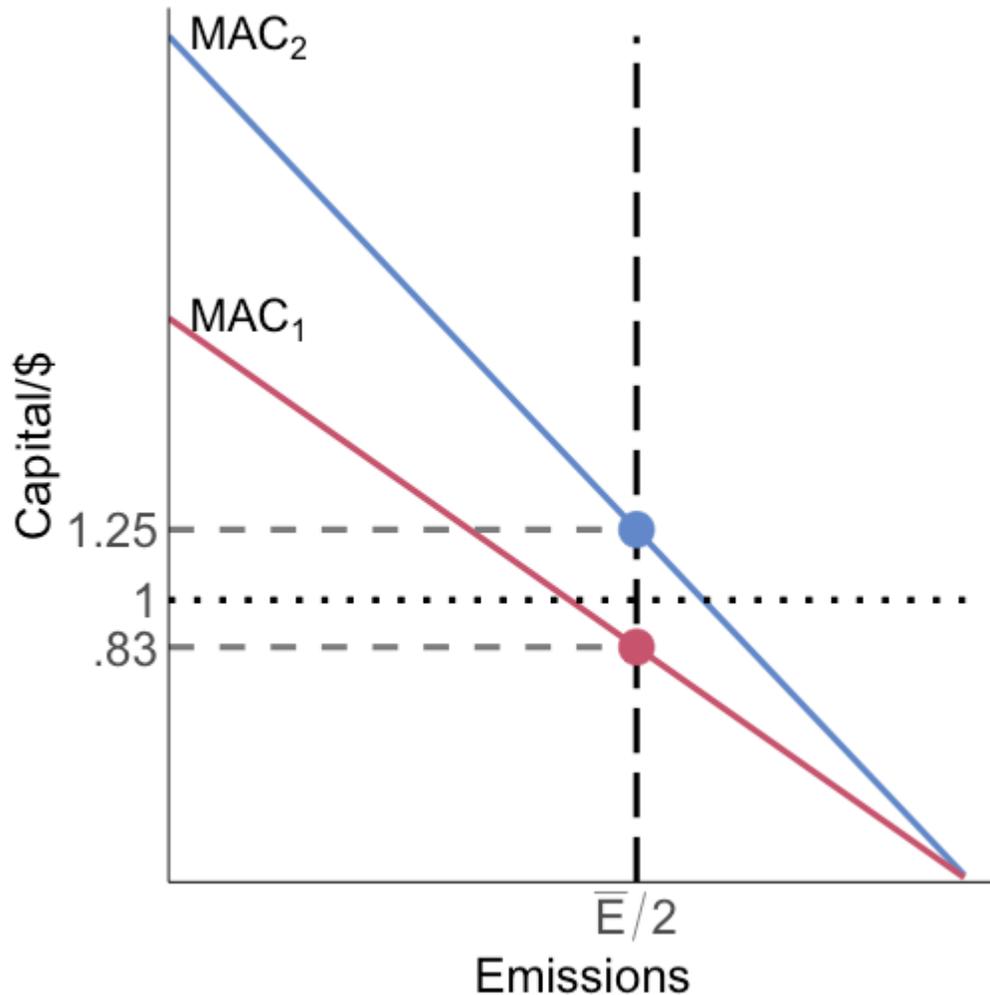
The red area is the difference in areas under  $MAC_2$  and  $MAC_1$  over the range of emissions changes

# Tradable permits: graphical



We want to equalize MACs for cost-effectiveness, but does the permit market cause this to happen?

# Tradable permits: graphical

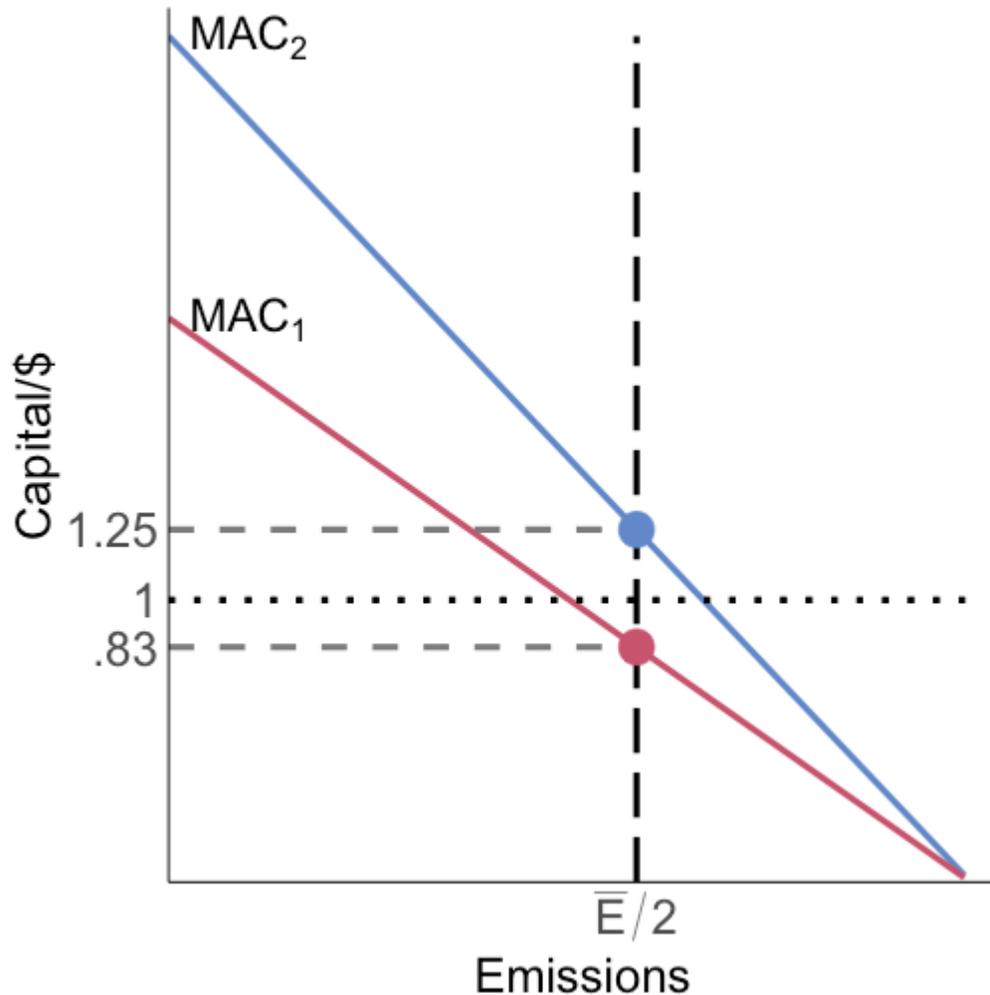


We want to equalize MACs for cost-effectiveness, but does the permit market cause this to happen?

Firm 2 is willing to pay a price up to the blue point (1.25) to be able to emit 1 more unit

Firm 1 can abate 1 more unit at cost equal to the red point (0.83)

# Tradable permits: graphical

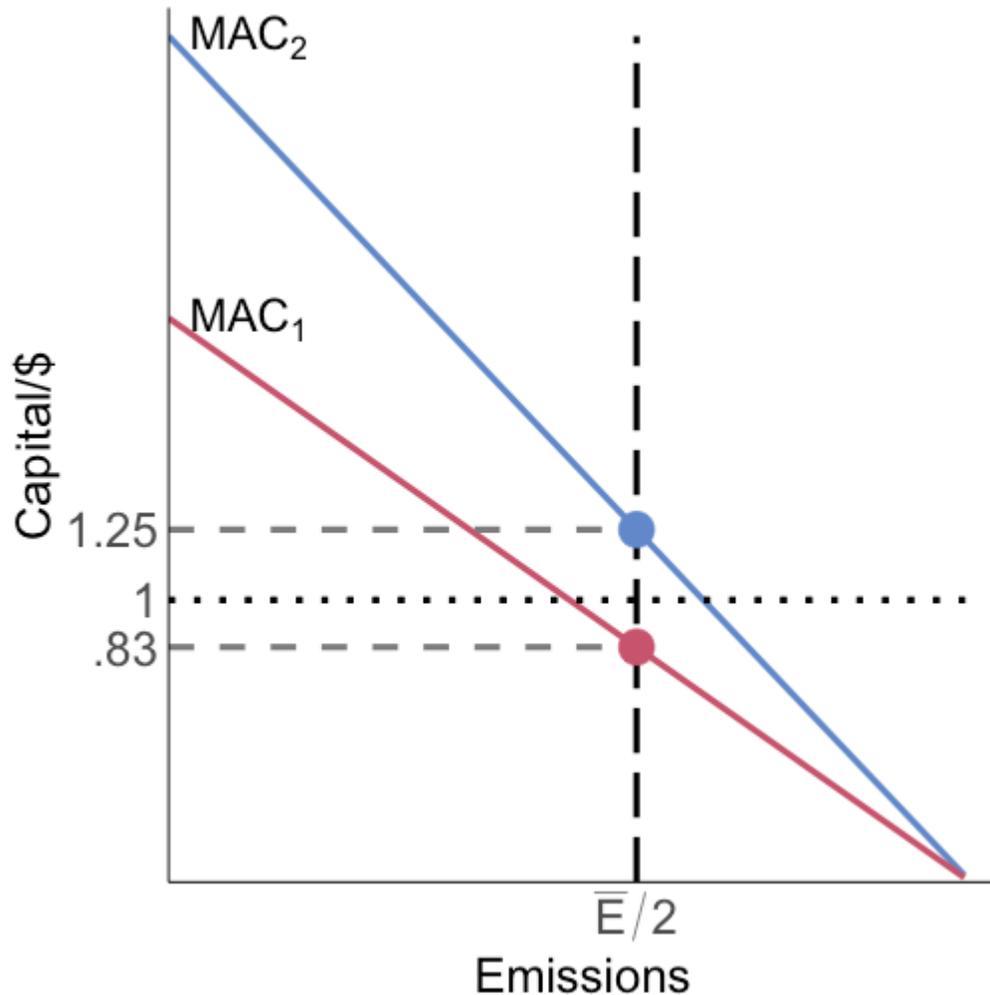


Firm 2 can buy the right to emit 1 unit of pollution from firm 1 for anywhere between 1.25 and 0.83 and **both will be better off** [very Coasean!]

These trades can be done until the MACs are equal at a value of 1

This would be the prevailing permit price in a tradable permit system

# Tradable permits: graphical



An alternative way to think about it:

the prevailing permit price is the MC of freeing up one more permit, the MAC of the selling firm

or it is the MB of freeing up one more permit (avoided MAC), the MAC of the buying firm

# Tradable permits: firm

We can also see this result mathematically

# Tradable permits: firm

We can also see this result mathematically

Suppose there is a permit price  $p$  in the competitive tradable permit market

# Tradable permits: firm

We can also see this result mathematically

Suppose there is a permit price  $p$  in the competitive tradable permit market

Firms are price-takers in the permit market

# Tradable permits: firm

We can also see this result mathematically

Suppose there is a permit price  $p$  in the competitive tradable permit market

Firms are price-takers in the permit market

Let's set up the firm problem: they want to minimize the cost of satisfying the policy

# Tradable permits: firm

The firm's problem is then:

$$\min_E C(E) + pE$$

The firm's first-order condition to minimize costs is:

$$-C'(E^*) = p$$

# Tradable permits: firm

The firm's problem is then:

$$\min_E C(E) + pE$$

The firm's first-order condition to minimize costs is:

$$-C'(E^*) = p$$

The firm minimizes costs by choosing emissions  $E^*$  so that its MAC equals the permit price

# Tradable permits: cost-effectiveness

This makes sense!

# Tradable permits: cost-effectiveness

This makes sense!

The permit price is the MC of emitting, the MAC is the MB of emitting  
(reduced abatement cost)

# Tradable permits: cost-effectiveness

This makes sense!

The permit price is the MC of emitting, the MAC is the MB of emitting  
(reduced abatement cost)

# Tradable permits: cost-effectiveness

This makes sense!

The permit price is the MC of emitting, the MAC is the MB of emitting (reduced abatement cost)

Costs are minimized when these two things are equal

# Tradable permits: cost-effectiveness

What else does firm behavior tell us about permits?

# Tradable permits: cost-effectiveness

What else does firm behavior tell us about permits?

If firms all set their MACs equal to  $p$  then all their MACs are equal to one another, **we have cost-effectiveness:**

$$-C'_1(E_1^*) = -C'_2(E_2^*) = \dots = -C'_N(E_N^*) = p$$

# Tradable permits: cost-effectiveness

What else does firm behavior tell us about permits?

If firms all set their MACs equal to  $p$  then all their MACs are equal to one another, **we have cost-effectiveness:**

$$-C'_1(E_1^*) = -C'_2(E_2^*) = \dots = -C'_N(E_N^*) = p$$

Taxes and permits both achieve cost-effectiveness

# Tradable permits: cost-effectiveness

What else does firm behavior tell us about permits?

If firms all set their MACs equal to  $p$  then all their MACs are equal to one another, **we have cost-effectiveness:**

$$-C'_1(E_1^*) = -C'_2(E_2^*) = \dots = -C'_N(E_N^*) = p$$

Taxes and permits both achieve cost-effectiveness

Why?

# Tradable permits: cost-effectiveness

What else does firm behavior tell us about permits?

If firms all set their MACs equal to  $p$  then all their MACs are equal to one another, **we have cost-effectiveness:**

$$-C'_1(E_1^*) = -C'_2(E_2^*) = \dots = -C'_N(E_N^*) = p$$

Taxes and permits both achieve cost-effectiveness

Why?

Because firms treat permit prices and a tax identically in decisionmaking

# Tradable permits: cost-effectiveness

Tradable permit systems are **always** cost-effective: whatever emissions limit you set, it will be achieved at least-cost<sup>1</sup>

<sup>1</sup> Try to see if you can use the same mathematical derivation to show that taxes are also always cost-effective.

# Tradable permits: cost-effectiveness

Tradable permit systems are **always** cost-effective: whatever emissions limit you set, it will be achieved at least-cost<sup>1</sup>

This does not mean that it is necessarily efficient!

<sup>1</sup> Try to see if you can use the same mathematical derivation to show that taxes are also always cost-effective.

# Tradable permits: efficiency

For efficiency, we also need  $MAC = MD$

# Tradable permits: efficiency

For efficiency, we also need  $MAC = MD$

To keep things simple suppose MD is constant and the same across all firms:  $MD = d$

# Tradable permits: efficiency

For efficiency, we also need  $MAC = MD$

To keep things simple suppose MD is constant and the same across all firms:  $MD = d$

If we can set  $\bar{E}$  such that the equilibrium permit price  $p = d$ , then we also have efficiency

# Tradable permits in practice

Knowing MD is often difficult in practice

# Tradable permits in practice

Knowing MD is often difficult in practice

Tradable permit systems are nice because we can just let politicians choose a  $\bar{E}$  that is politically feasible, and then the permit market ensures that we get the associated emissions reductions at least-cost

# Tradable permits in practice

Knowing MD is often difficult in practice

Tradable permit systems are nice because we can just let politicians choose a  $\bar{E}$  that is politically feasible, and then the permit market ensures that we get the associated emissions reductions at least-cost

What often happens in practice is  $\bar{E}$  starts high, giving us a low  $p$ , and then  $\bar{E}$  gets ratcheted down over time

# Tradable permits: numerical example

Suppose two firms trade permits with total cap:

$$E_1 + E_2 = \bar{E} = 90$$

# Tradable permits: numerical example

Suppose two firms trade permits with total cap:

$$E_1 + E_2 = \bar{E} = 90$$

Abatement cost functions:

$$C_1(E_1) = \frac{1}{2}(90 - E_1)^2, \quad C_2(E_2) = \frac{1}{4}(150 - 2E_2)^2$$

# Tradable permits: numerical example

Suppose two firms trade permits with total cap:

$$E_1 + E_2 = \bar{E} = 90$$

Abatement cost functions:

$$C_1(E_1) = \frac{1}{2}(90 - E_1)^2, \quad C_2(E_2) = \frac{1}{4}(150 - 2E_2)^2$$

So marginal abatement costs are:

$$MAC_1(E_1) = -C'_1(E_1) = 90 - E_1$$

$$MAC_2(E_2) = -C'_2(E_2) = 150 - 2E_2$$

# Tradable permits: numerical example

In a competitive permit market:

$$MAC_1(E_1^*) = p, \quad MAC_2(E_2^*) = p, \quad E_1^* + E_2^* = \bar{E} = 90$$

# Tradable permits: numerical example

In a competitive permit market:

$$MAC_1(E_1^*) = p, \quad MAC_2(E_2^*) = p, \quad E_1^* + E_2^* = \bar{E} = 90$$

Plug in the MAC expressions:

$$90 - E_1^* = p, \quad 150 - 2E_2^* = p, \quad E_1^* + E_2^* = 90$$

# Tradable permits: numerical example

In a competitive permit market:

$$MAC_1(E_1^*) = p, \quad MAC_2(E_2^*) = p, \quad E_1^* + E_2^* = \bar{E} = 90$$

Plug in the MAC expressions:

$$90 - E_1^* = p, \quad 150 - 2E_2^* = p, \quad E_1^* + E_2^* = 90$$

$$E_1^* = 40, \quad E_2^* = 50, \quad p^* = 50$$

# Tradable permits: numerical example

In a competitive permit market:

$$MAC_1(E_1^*) = p, \quad MAC_2(E_2^*) = p, \quad E_1^* + E_2^* = \bar{E} = 90$$

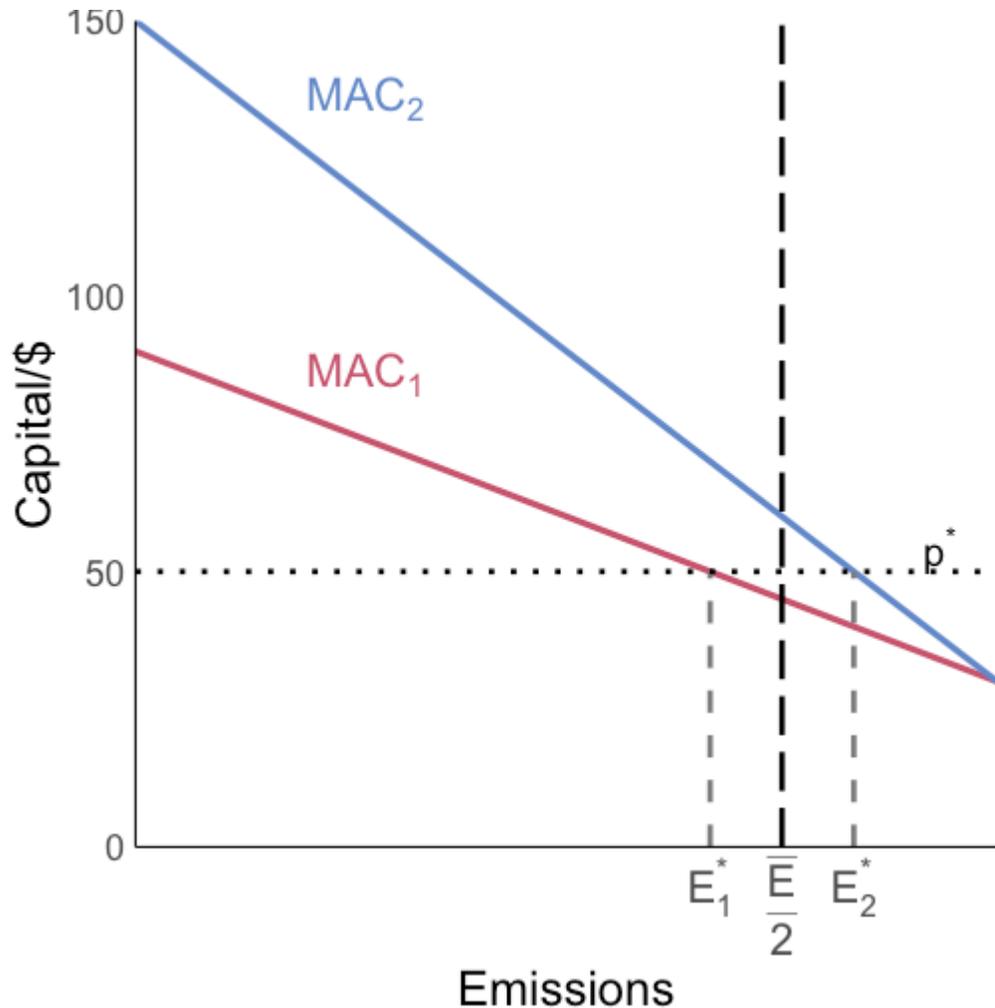
Plug in the MAC expressions:

$$90 - E_1^* = p, \quad 150 - 2E_2^* = p, \quad E_1^* + E_2^* = 90$$

$$E_1^* = 40, \quad E_2^* = 50, \quad p^* = 50$$

Firm 2 has higher MAC at an equal split, so it buys permits and emits more in equilibrium.

# Tradable permits: numerical example



Numerical solution:

$$E_1^* = 40, \quad E_2^* = 50, \quad p^* = 50$$

Starting from equal allocation ( $\frac{\bar{E}}{2} = 45$  each):

- firm 1 sells permits and emits less
- firm 2 buys permits and emits more

# Political economy of permits

Firms are often more willing to accept a higher  $p$  than  $\tau$  because they are often endowed with (some) permits for free

# Political economy of permits

Firms are often more willing to accept a higher  $p$  than  $\tau$  because they are often endowed with (some) permits for free

This means that *in practice*, we might expect to get greater emissions reductions under a permit system than a tax because of these political economy reasons

# Political economy of permits

Firms are often more willing to accept a higher  $p$  than  $\tau$  because they are often endowed with (some) permits for free

This means that *in practice*, we might expect to get greater emissions reductions under a permit system than a tax because of these political economy reasons

This is one of the key reasons the 1990 CAA amendments were able to be passed

# Permit market challenges

**How we do initially allocate permits?**

# Permit market challenges

## How we do initially allocate permits?

**Auction** charge firms for each permit they hold, let price be set by marketplace, revenues can be used in other ways by the government, auction price will be the same as a Pigouvian tax

# Permit market challenges

## How we do initially allocate permits?

**Auction** charge firms for each permit they hold, let price be set by marketplace, revenues can be used in other ways by the government, auction price will be the same as a Pigouvian tax

**Lottery**: Randomly assign permits

# Permit market challenges

## How we do initially allocate permits?

**Auction** charge firms for each permit they hold, let price be set by marketplace, revenues can be used in other ways by the government, auction price will be the same as a Pigouvian tax

**Lottery**: Randomly assign permits

**Grandfathering**: give permits to existing firms based on historical emissions

# Permit market challenges

**How do we set up trading rules?**

# Permit market challenges

**How do we set up trading rules?**

We can decentralize trading market to cut down on transaction costs

# Permit market challenges

## How do we set up trading rules?

We can decentralize trading market to cut down on transaction costs

Do trades need to be validated by central authority to ensure permit validity?

# Permit market challenges

**What about transactions costs?**

# Permit market challenges

## **What about transactions costs?**

Transactions costs create a wedge that prevents otherwise surplus-increasing trades from being made

# Permit market challenges

## **What about transactions costs?**

Transactions costs create a wedge that prevents otherwise surplus-increasing trades from being made

Examples?

# Permit market challenges

## **What about transactions costs?**

Transactions costs create a wedge that prevents otherwise surplus-increasing trades from being made

Examples?

Search, information, bargaining, monitoring/enforcement

# Permit market challenges

## What about transactions costs?

Transactions costs create a wedge that prevents otherwise surplus-increasing trades from being made

Examples?

Search, information, bargaining, monitoring/enforcement

Lots of these costs are fixed, prohibit small trades

# Permit systems and heterogeneous MDs

So far we assumed all firms faced the same MD

# Permit systems and heterogeneous MDs

So far we assumed all firms faced the same MD

This is true for things like climate change, less true for things like  $SO_2$  or  $NO_x$

# Permit systems and heterogeneous MDs

So far we assumed all firms faced the same MD

This is true for things like climate change, less true for things like  $SO_2$  or  $NO_x$

How well do permit systems perform with heterogeneous MD?

# Permit systems and heterogeneous MDs

Let's think about a setting with two firms: 1 and 2

# Permit systems and heterogeneous MDs

Let's think about a setting with two firms: 1 and 2

The firms have different MACs:  $MAC_1 < MAC_2$  for all  $E$

# Permit systems and heterogeneous MDs

Let's think about a setting with two firms: 1 and 2

The firms have different MACs:  $MAC_1 < MAC_2$  for all  $E$

And the firms have different marginal damages as well:  $MD_1 < MD_2$  for all  $E$

# Permit systems and heterogeneous MDs

Let's think about a setting with two firms: 1 and 2

The firms have different MACs:  $MAC_1 < MAC_2$  for all  $E$

And the firms have different marginal damages as well:  $MD_1 < MD_2$  for all  $E$

How well does a permit system work?

# Permit systems and heterogeneous MDs

Well we know the following:

# Permit systems and heterogeneous MDs

Well we know the following:

Firms set  $MAC = p$  so we will have  $MAC_1 = MAC_2 = p$

# Permit systems and heterogeneous MDs

Well we know the following:

Firms set  $MAC = p$  so we will have  $MAC_1 = MAC_2 = p$

But for efficiency we also want  $MAC = MD$ :  $MAC_1 = MD_1$  and  $MAC_2 = MD_2$

# Permit systems and heterogeneous MDs

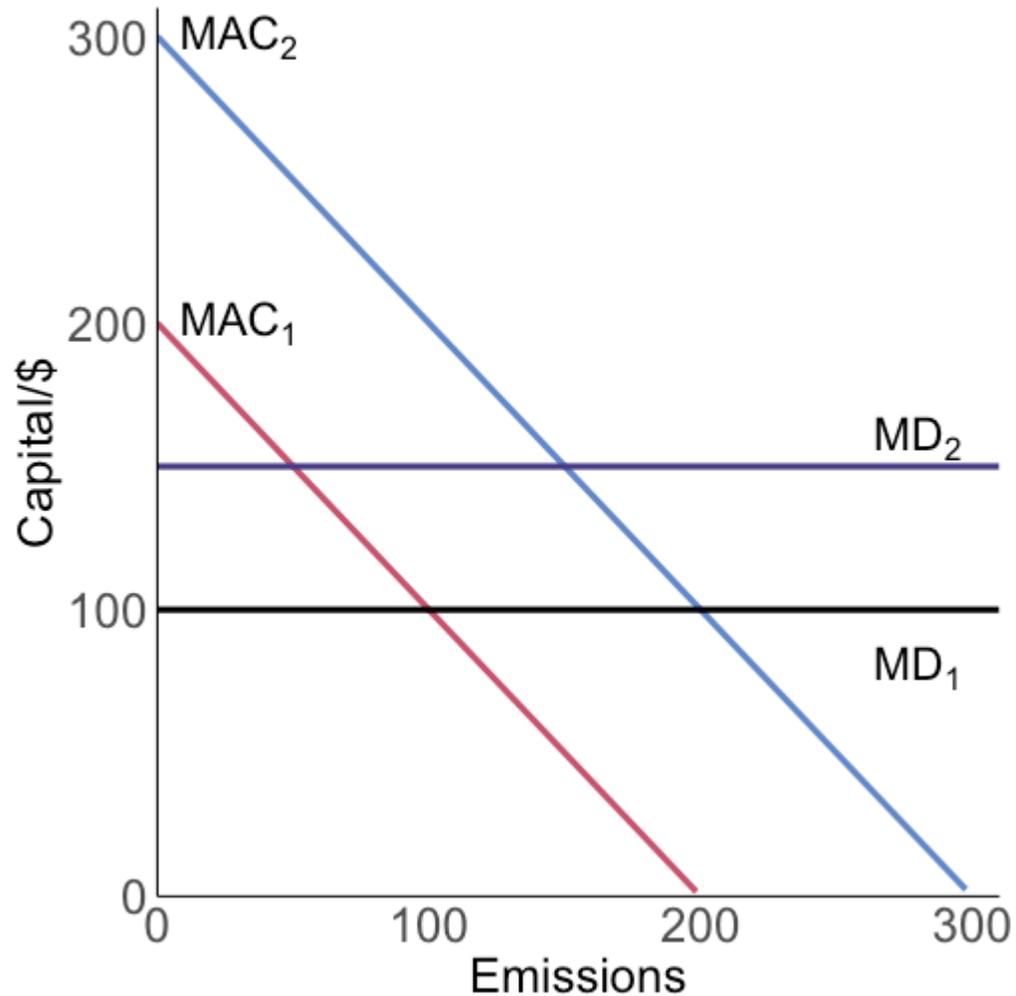
Well we know the following:

Firms set  $MAC = p$  so we will have  $MAC_1 = MAC_2 = p$

But for efficiency we also want  $MAC = MD$ :  $MAC_1 = MD_1$  and  $MAC_2 = MD_2$

If  $MD_1 \neq MD_2$  then the permit system does **not** deliver efficiency!

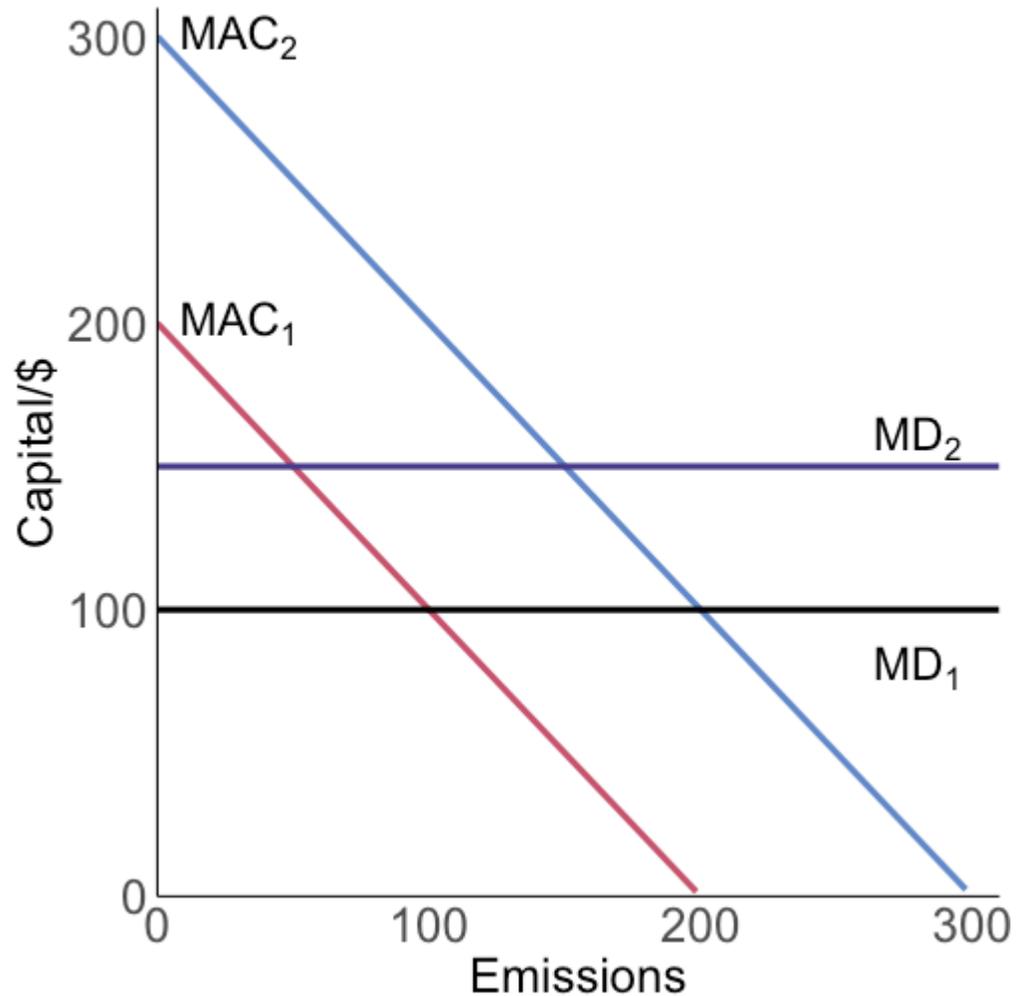
# Permit systems and heterogeneous MDs: graphical



Suppose we have the two firms with different MACs and MDs:

- $MAC_1 = 200 - E_1$
- $MAC_2 = 300 - E_2$
- $MD_1 = 100$
- $MD_2 = 150$

# Permit systems and heterogeneous MDs: graphical



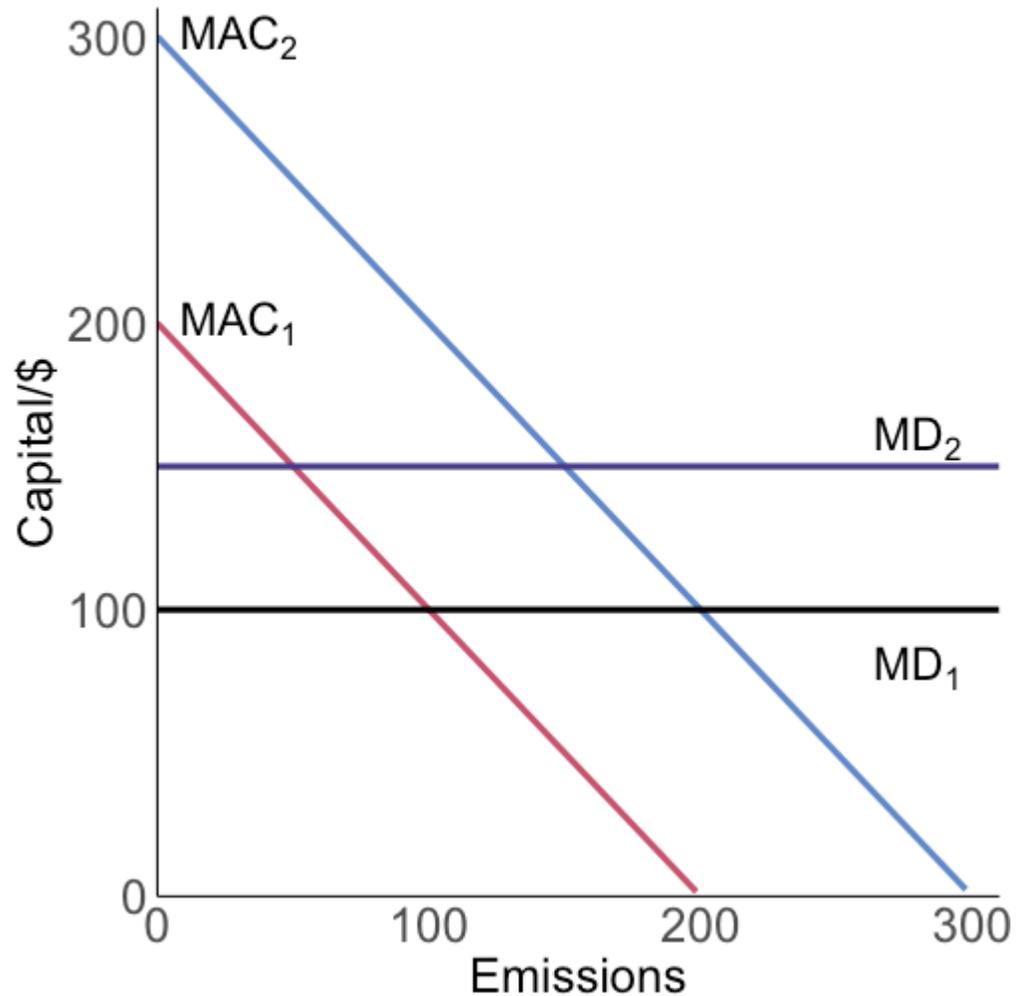
Suppose we have the two firms with different MACs and MDs:

- $MAC_1 = 200 - E_1$
- $MAC_2 = 300 - E_2$
- $MD_1 = 100$
- $MD_2 = 150$

The efficient emissions allocation is:  $E^* = 250 : E_1^* = 100, E_2^* = 150$

The regulator sets  $\bar{E} = 250$

# Permit systems and heterogeneous MDs: graphical



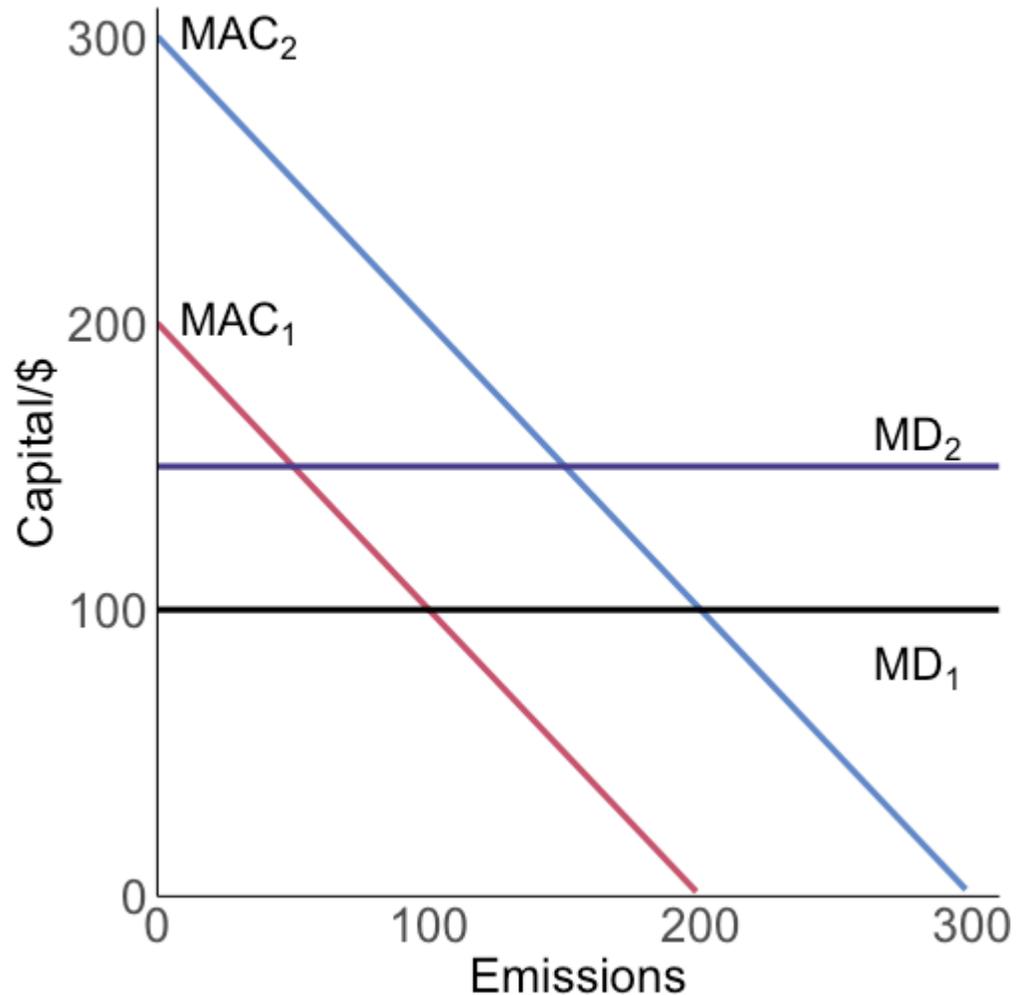
We can solve for the permit market allocation and price using:

$$MAC_1 = MAC_2 \text{ and}$$

$$E_1 + E_2 = 250$$

These two conditions tell us:

# Permit systems and heterogeneous MDs: graphical



We can solve for the permit market allocation and price using:

$$MAC_1 = MAC_2 \text{ and}$$

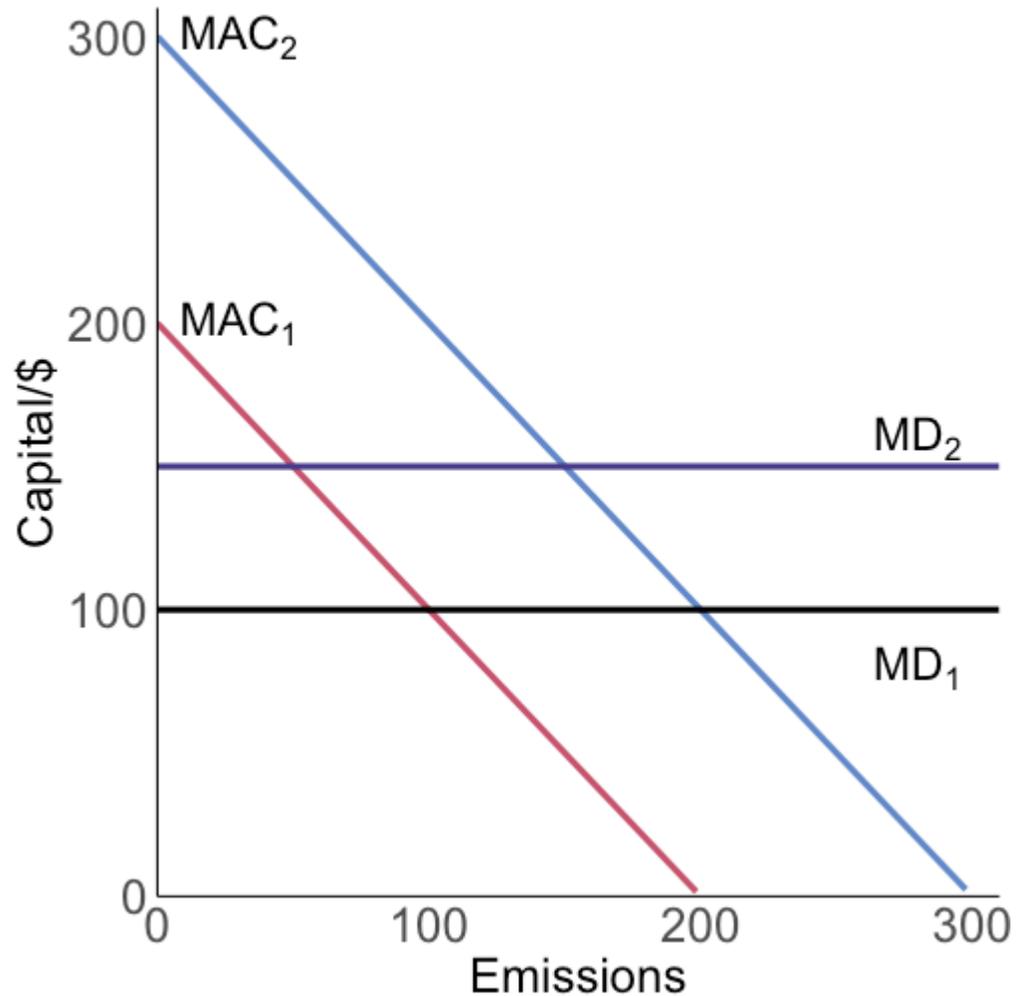
$$E_1 + E_2 = 250$$

These two conditions tell us:

$$E_1^p = 75, E_2^p = 175, p = 125$$

but efficiency is at:

# Permit systems and heterogeneous MDs: graphical



We can solve for the permit market allocation and price using:

$$MAC_1 = MAC_2 \text{ and}$$

$$E_1 + E_2 = 250$$

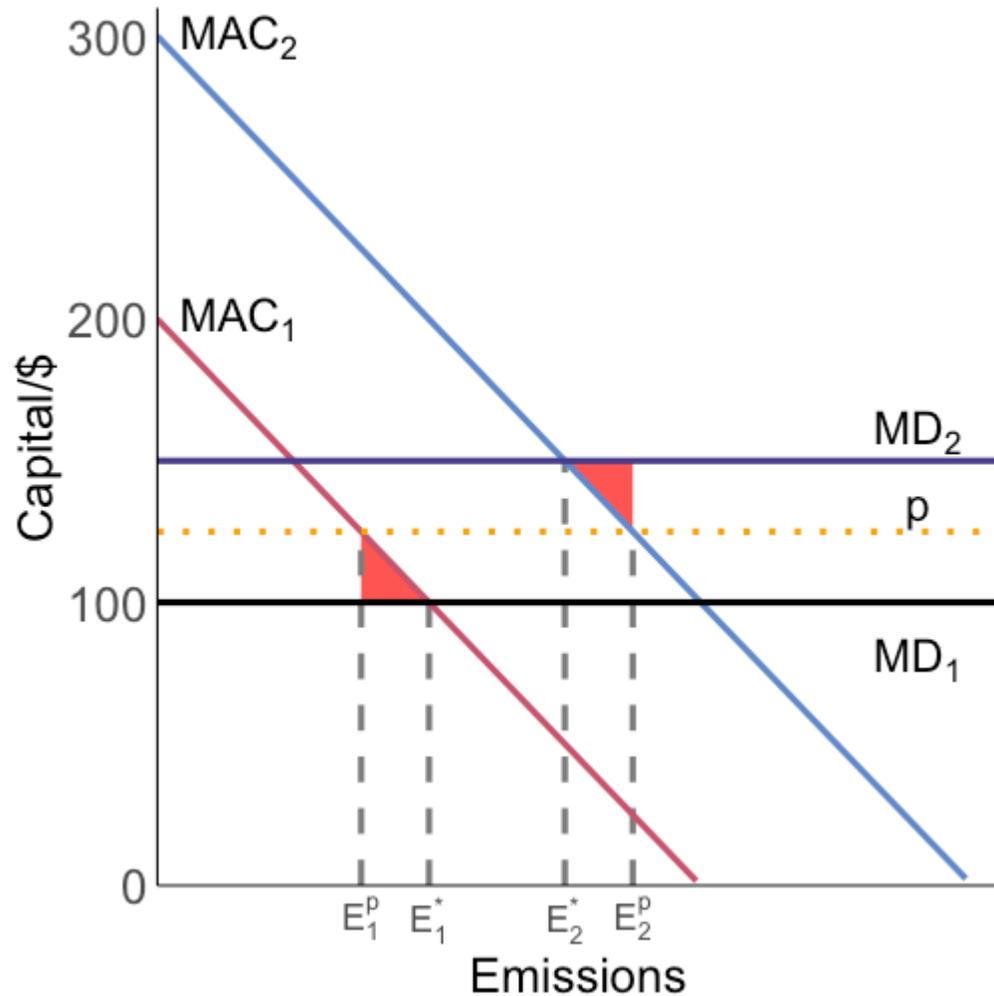
These two conditions tell us:

$$E_1^p = 75, E_2^p = 175, p = 125$$

but efficiency is at:

$$E_1^* = 100, E_2^* = 150$$

# Permit systems and heterogeneous MDs: graphical



We can solve for the permit market allocation and price using:

$$MAC_1 = MAC_2 \text{ and}$$

$$E_1 + E_2 = 250$$

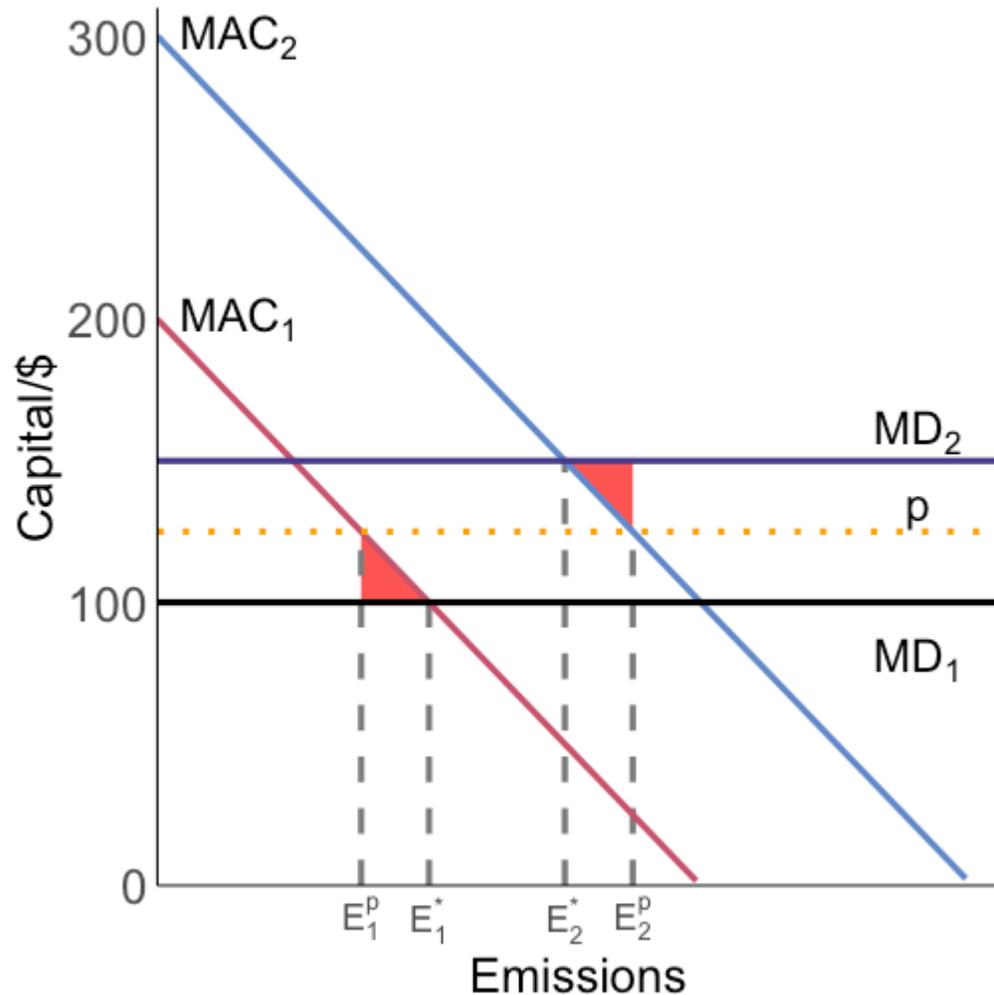
These two conditions tell us:

$$E_1^p = 75, E_2^p = 175, p = 125$$

but efficiency is at:

$$E_1^* = 100, E_2^* = 150$$

# Permit systems and heterogeneous MDs: graphical

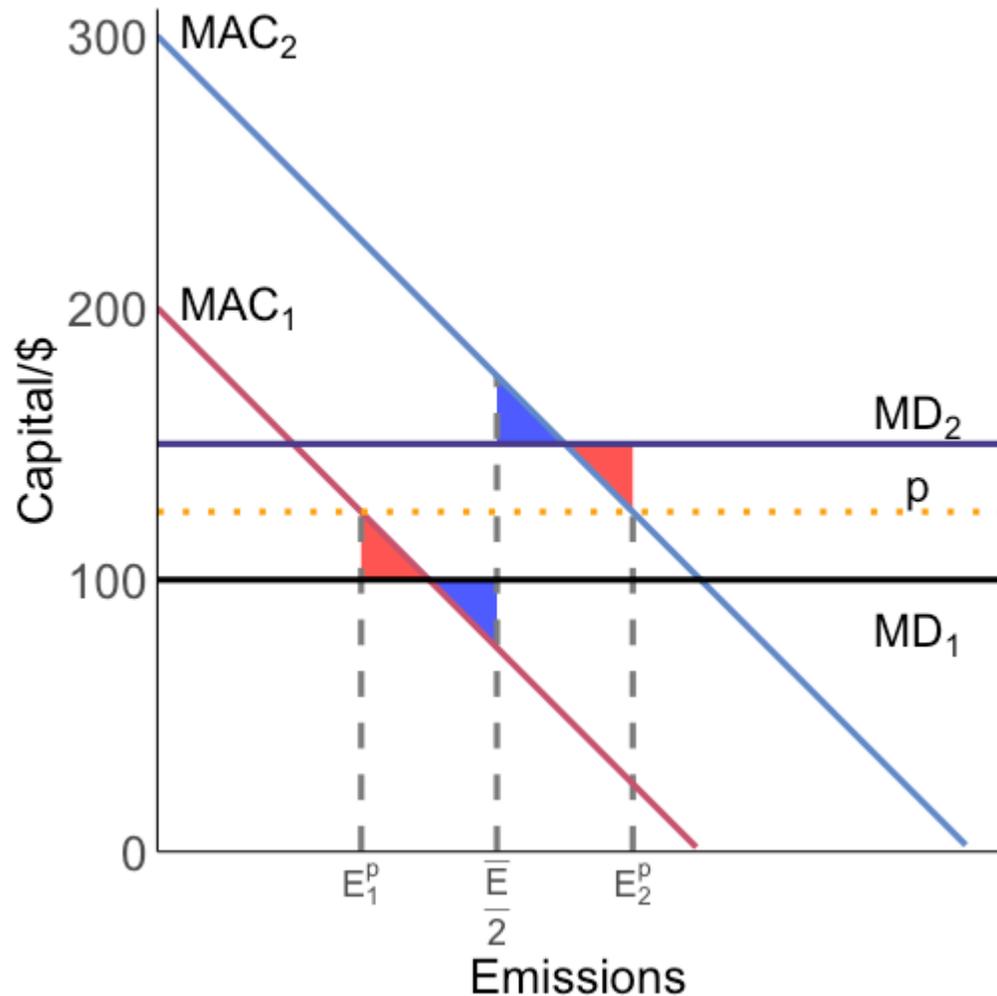


Relative to the optimal allocation, the permit system has DWL equal to the **red area**

The permit allocation is not an **efficient** allocation, but is it a **Pareto improvement** over:

1. No policy?
2. A uniform standard of  $\bar{E}/2$ ?

# Permit systems and heterogeneous MDs: graphical

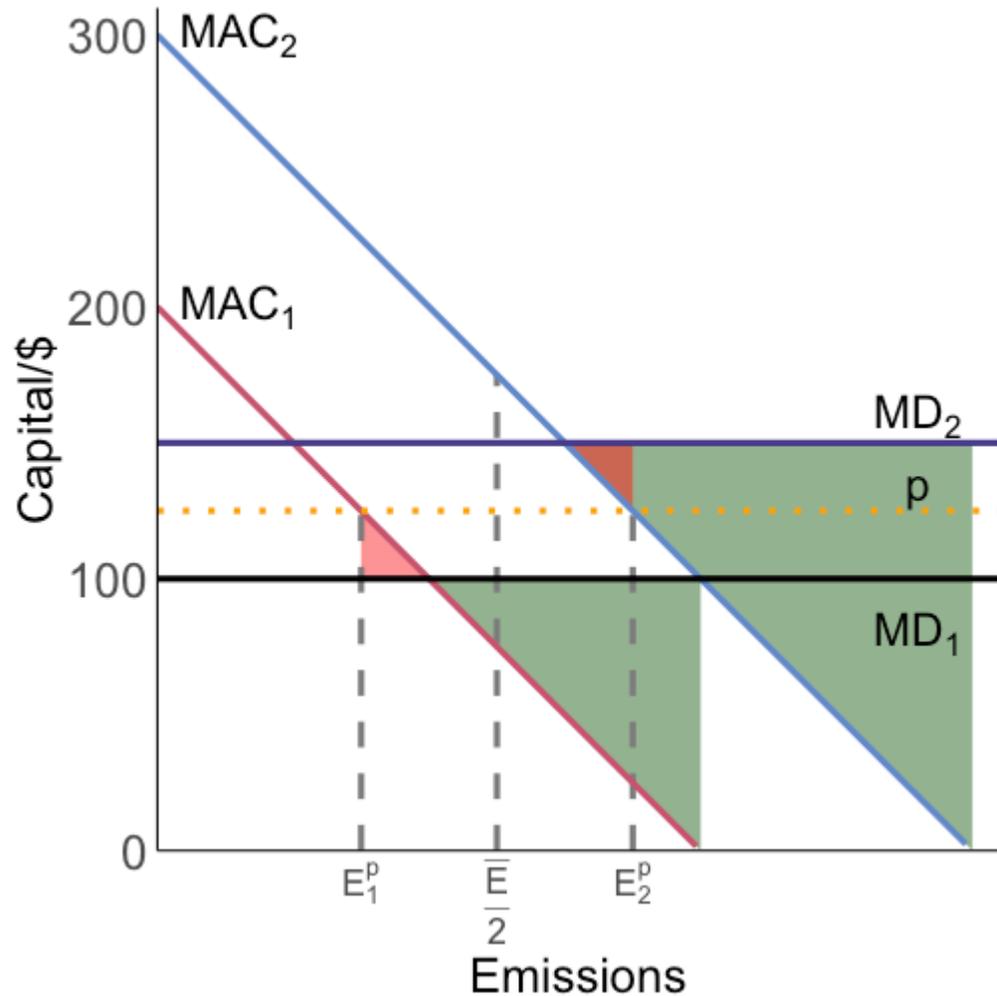


The blue area is the DWL under the uniform standard

**In this specific case,** a uniform standard and the permit system have the same efficiency since the red and blue areas are equal

The only difference is what kind of welfare loss is occurring where

# Permit systems and heterogeneous MDs: graphical

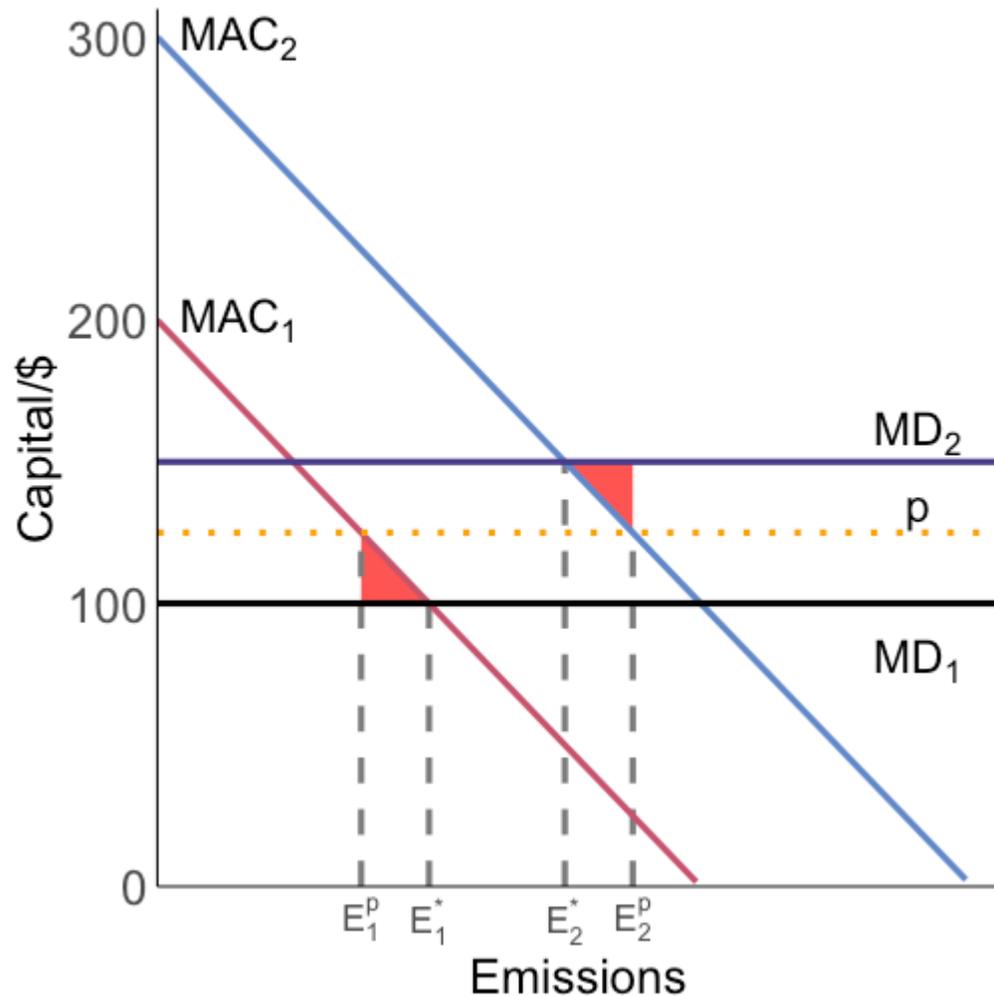


The DWL without any policy is the two large green triangles

These are clearly larger than the DWL under the permit system

The permit system can deliver a welfare improvement

# Permit systems and heterogeneous MDs: graphical



What if the high MAC firm was the low MD firm?

i.e: what if the correlation between MAC and MD was **negative** instead of **positive**?

What might we expect the correlation to be?

# Permit systems and heterogeneous MDs

What is the problem with permit systems and heterogeneous MD?

# Permit systems and heterogeneous MDs

What is the problem with permit systems and heterogeneous MD?

We want to have firms pay a price equal to their MD

# Permit systems and heterogeneous MDs

What is the problem with permit systems and heterogeneous MD?

We want to have firms pay a price equal to their MD

Firms have different MDs

# Permit systems and heterogeneous MDs

What is the problem with permit systems and heterogeneous MD?

We want to have firms pay a price equal to their MD

Firms have different MDs but there's only one common permit price

# Permit systems and heterogeneous MDs

What is the problem with permit systems and heterogeneous MD?

We want to have firms pay a price equal to their MD

Firms have different MDs but there's only one common permit price

This means we can't make all firms correctly account for their externalities

# Permit systems and heterogeneous MDs

What is the problem with permit systems and heterogeneous MD?

We want to have firms pay a price equal to their MD

Firms have different MDs but there's only one common permit price

This means we can't make all firms correctly account for their externalities

One way around this is to use **trading ratios**: firms in high damage areas need to procure more permits for the same amount of emissions

# Permit systems and heterogeneous MDs

What is the problem with permit systems and heterogeneous MD?

We want to have firms pay a price equal to their MD

Firms have different MDs but there's only one common permit price

This means we can't make all firms correctly account for their externalities

One way around this is to use **trading ratios**: firms in high damage areas need to procure more permits for the same amount of emissions

Another way is **zonal trading**: firms can only trade in similar MD areas

# Trading ratios: Acid Rain Program

Below are estimates of efficient trading ratios for the Acid Rain Program

TABLE 3—TRADING RATIOS BETWEEN SOURCES AT EACH QUANTILE FOR SO<sub>2</sub>

Quantile	Source location (county, state)	1 <sup>st</sup>	25 <sup>th</sup>	50 <sup>th</sup>	75 <sup>th</sup>	99 <sup>th</sup>	99.9 <sup>th</sup>
1 <sup>st</sup>	Josephine, OR	1.0	0.4	0.2	0.2	0.1	0.02
25 <sup>th</sup>	Polk, TX	2.5	1.0	0.6	0.4	0.1	0.1
50 <sup>th</sup>	Grant, AR	4.5	1.8	1.0	0.7	0.2	0.1
75 <sup>th</sup>	Marion, SC	6.0	2.4	1.3	1.0	0.3	0.1
99 <sup>th</sup>	Allegheny, PA	19.2	7.7	4.3	3.2	1.0	0.4
99.9 <sup>th</sup>	Hudson, NJ	49.4	19.6	11.0	8.2	2.5	1.0

*Note:* The trading ratio represents the number of tons from the column source required to offset one ton from the row source.

Muller and Mendelsohn (2009)

# PM2.5 damages

Trading ratios are required because damages are heterogeneous across space

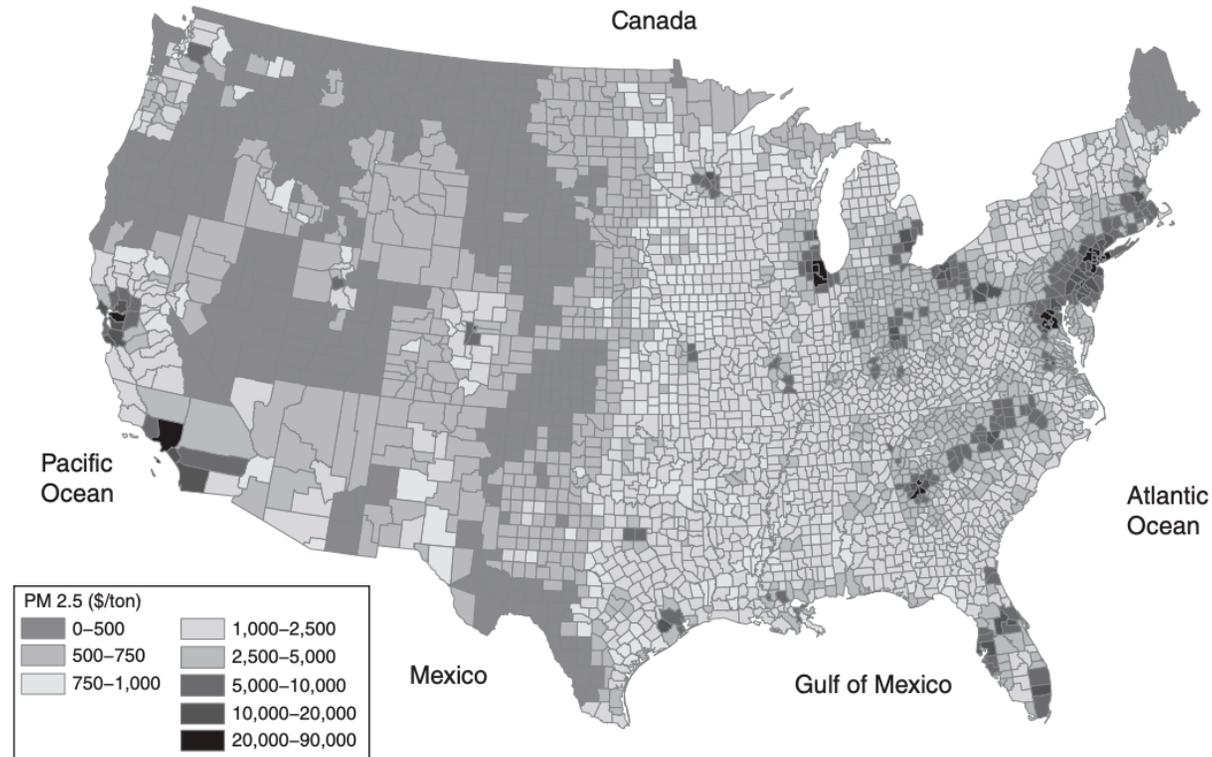
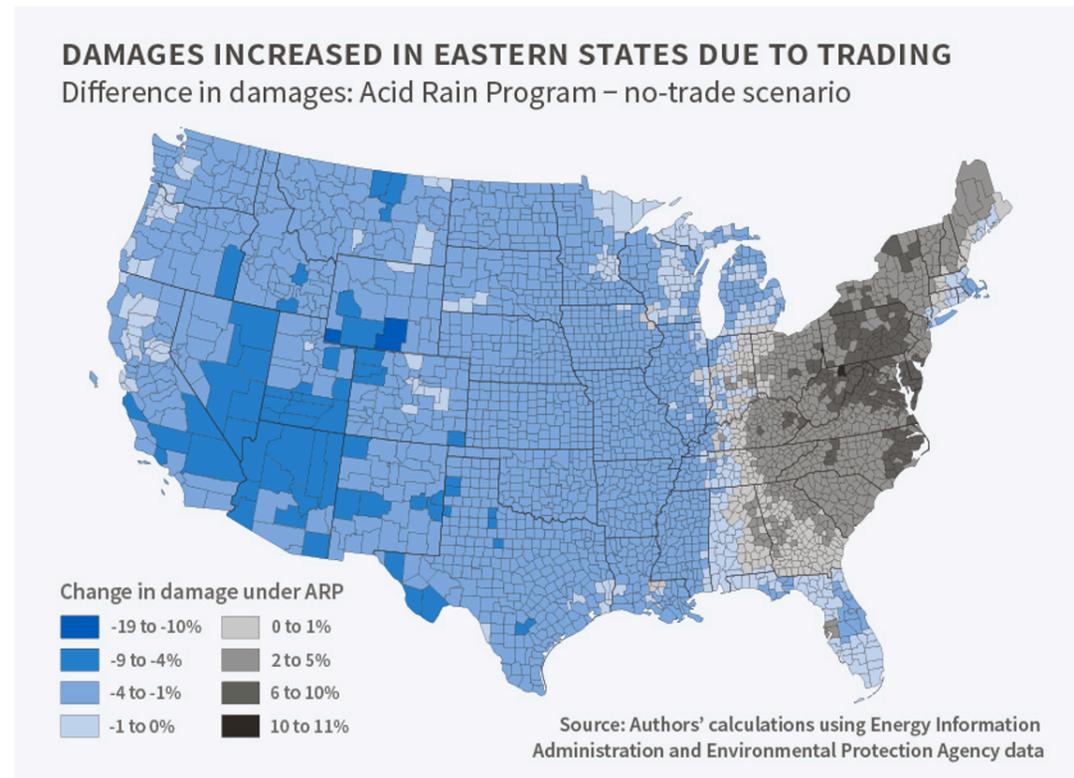


FIGURE 1. MARGINAL DAMAGE OF EMISSIONS FOR GROUND LEVEL SOURCES OF PM<sub>2.5</sub> (\$/TON/YEAR)

# Damages caused by ARP

The Acid Rain Program **increased** damages in the eastern US



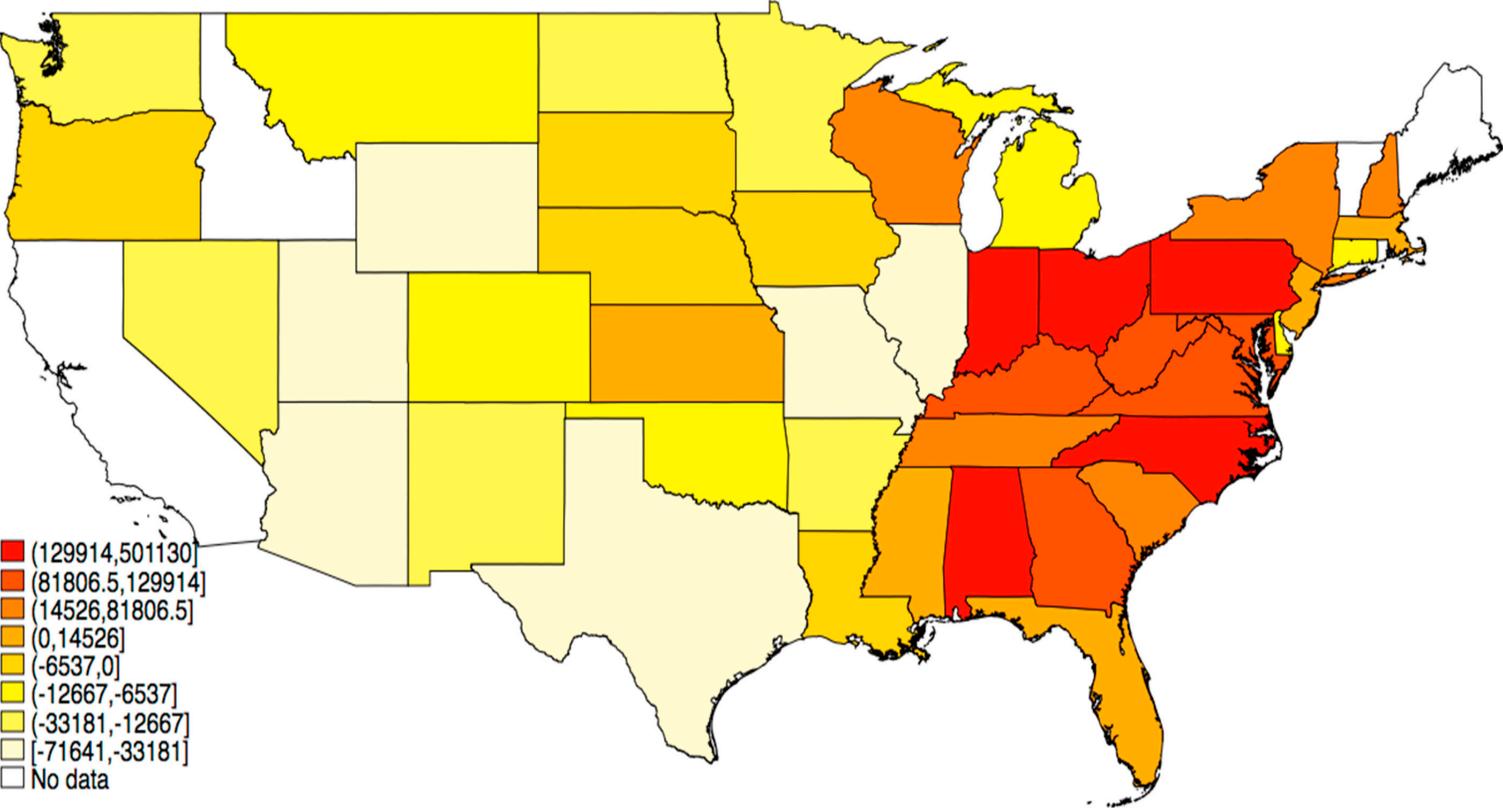
# Damages caused by ARP

Chan et al. (2018) JEEM:

We also compare health damages associated with observed SO<sub>2</sub> emissions from all ARP units in 2002 with damages from a no-trade counterfactual. Damages under the ARP are *2.1 billion(1995)* higher than under the no-trade scenario, reflecting allowance transfers from units in the western US to units in the eastern US with larger exposed populations.

# Damages caused by ARP

**Redder:** trading lead to greater emissions vs no trading



# Zonal trading: RECLAIM

Regional Clean Air Management (RECLAIM) Program

# Zonal trading: RECLAIM

Regional Clean Air Management (RECLAIM) Program

California South Coast Air Quality Management District (SCAQMD)

# Zonal trading: RECLAIM

Regional Clean Air Management (RECLAIM) Program

California South Coast Air Quality Management District (SCAQMD)

Started in 1994, goal of cutting NO<sub>x</sub> and SO<sub>x</sub> emissions by 80% by 2003

# Zonal trading: RECLAIM

Regional Clean Air Management (RECLAIM) Program

California South Coast Air Quality Management District (SCAQMD)

Started in 1994, goal of cutting NO<sub>x</sub> and SO<sub>x</sub> emissions by 80% by 2003

RECLAIM is a facility-level tradable permit system

# Zonal trading: RECLAIM

14% of permits allocated to power generators

# Zonal trading: RECLAIM

14% of permits allocated to power generators

Permit prices driven by electricity sector

# Zonal trading: RECLAIM

14% of permits allocated to power generators

Permit prices driven by electricity sector

During 2000 electricity price spikes, lots of very dirty plants brought on-line to meet demand

# Zonal trading: RECLAIM

14% of permits allocated to power generators

Permit prices driven by electricity sector

During 2000 electricity price spikes, lots of very dirty plants brought on-line to meet demand

Permit prices rose dramatically for everyone else

# Zonal trading: RECLAIM

14% of permits allocated to power generators

Permit prices driven by electricity sector

During 2000 electricity price spikes, lots of very dirty plants brought on-line to meet demand

Permit prices rose dramatically for everyone else

\$4,284 per ton of NO<sub>x</sub> in 1999

# Zonal trading: RECLAIM

14% of permits allocated to power generators

Permit prices driven by electricity sector

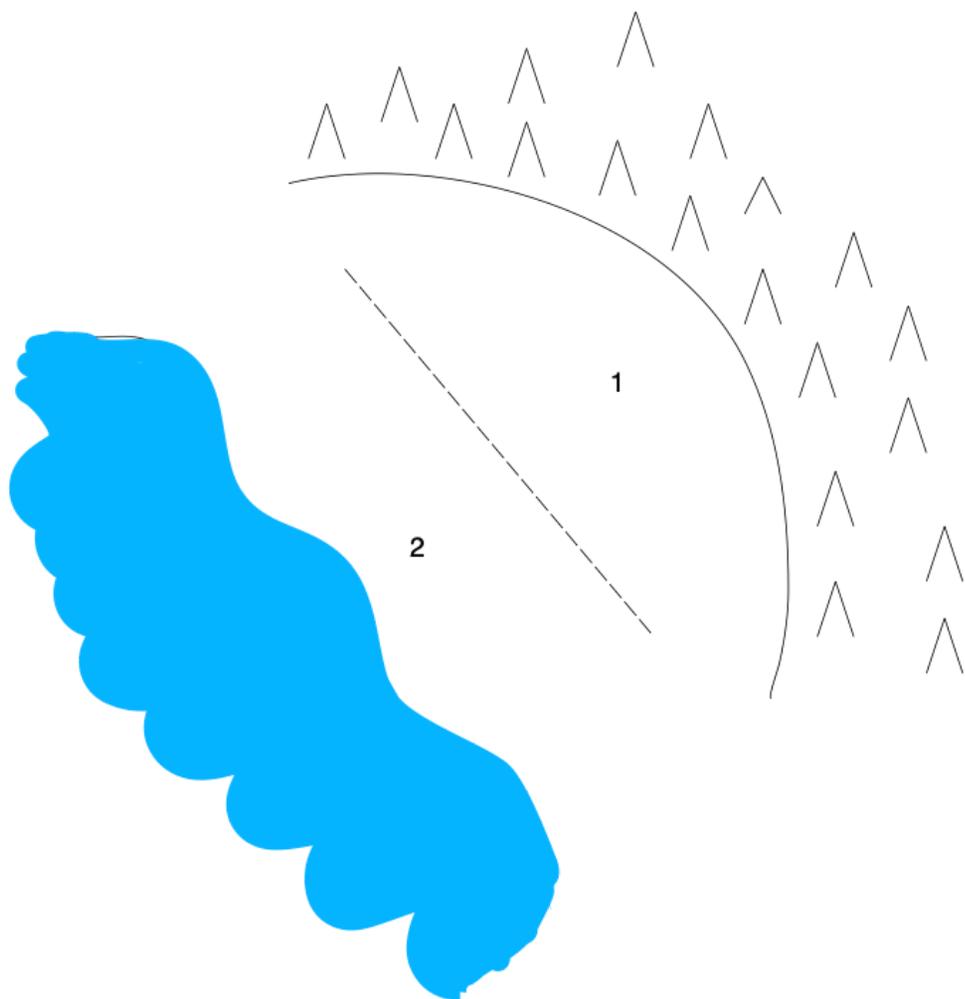
During 2000 electricity price spikes, lots of very dirty plants brought on-line to meet demand

Permit prices rose dramatically for everyone else

\$4,284 per ton of NO<sub>x</sub> in 1999

\$39,000 per ton of NO<sub>x</sub> in 2000

# Zonal trading: RECLAIM



LA Basin has two distinct zones with very different MD's

1. Old heavy industry (high MAC) and mountains trap NO<sub>x</sub> emissions and heat them up → smog (high MD)
2. Newer firms (low MAC) close to the ocean, breezes dissipate pollution before it can turn into smog (low MD)

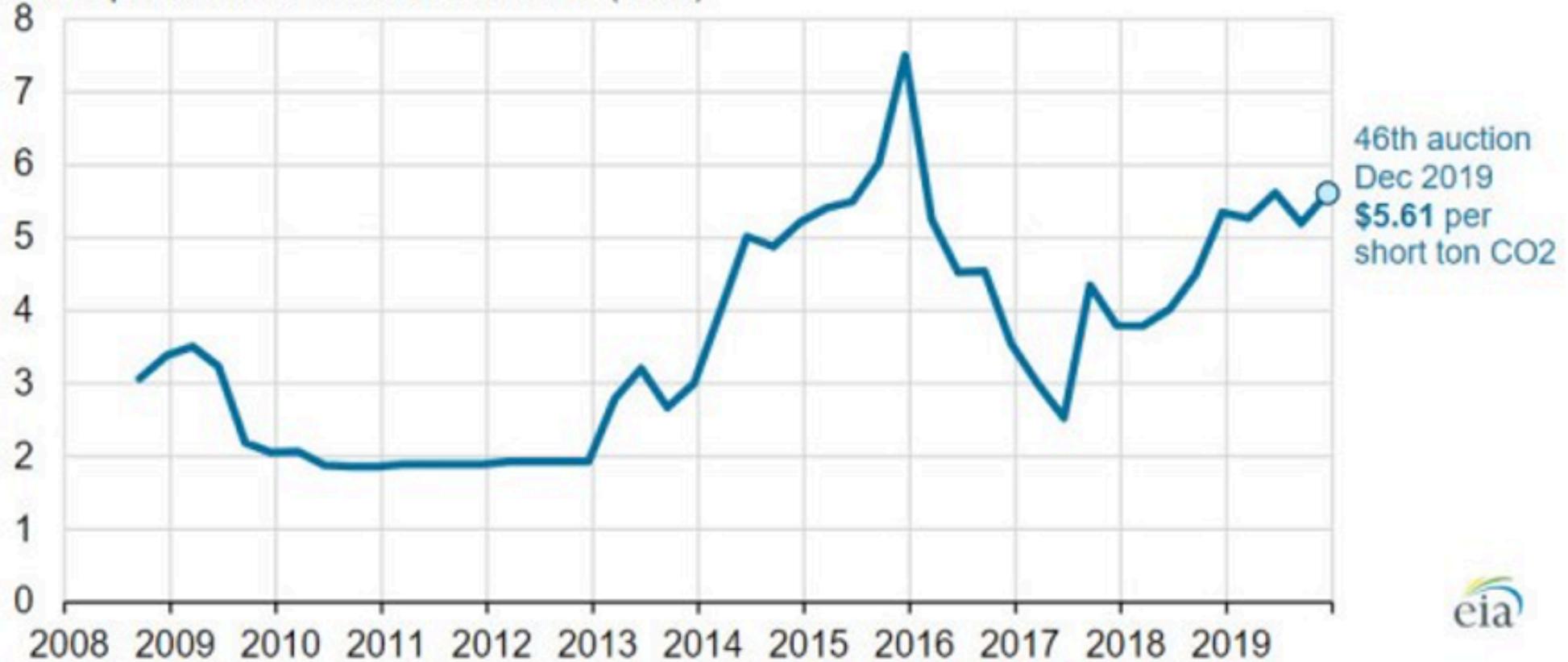
# Other permit market examples

Tradeable permit systems are increasingly common:

1. Acid Rain Program
2. NOx Budget Program
3. Regional Greenhouse Gas initiative
4. California AB32
5. EU Emission Trading System
6. China's National Carbon Cap and Trade

# RGGI

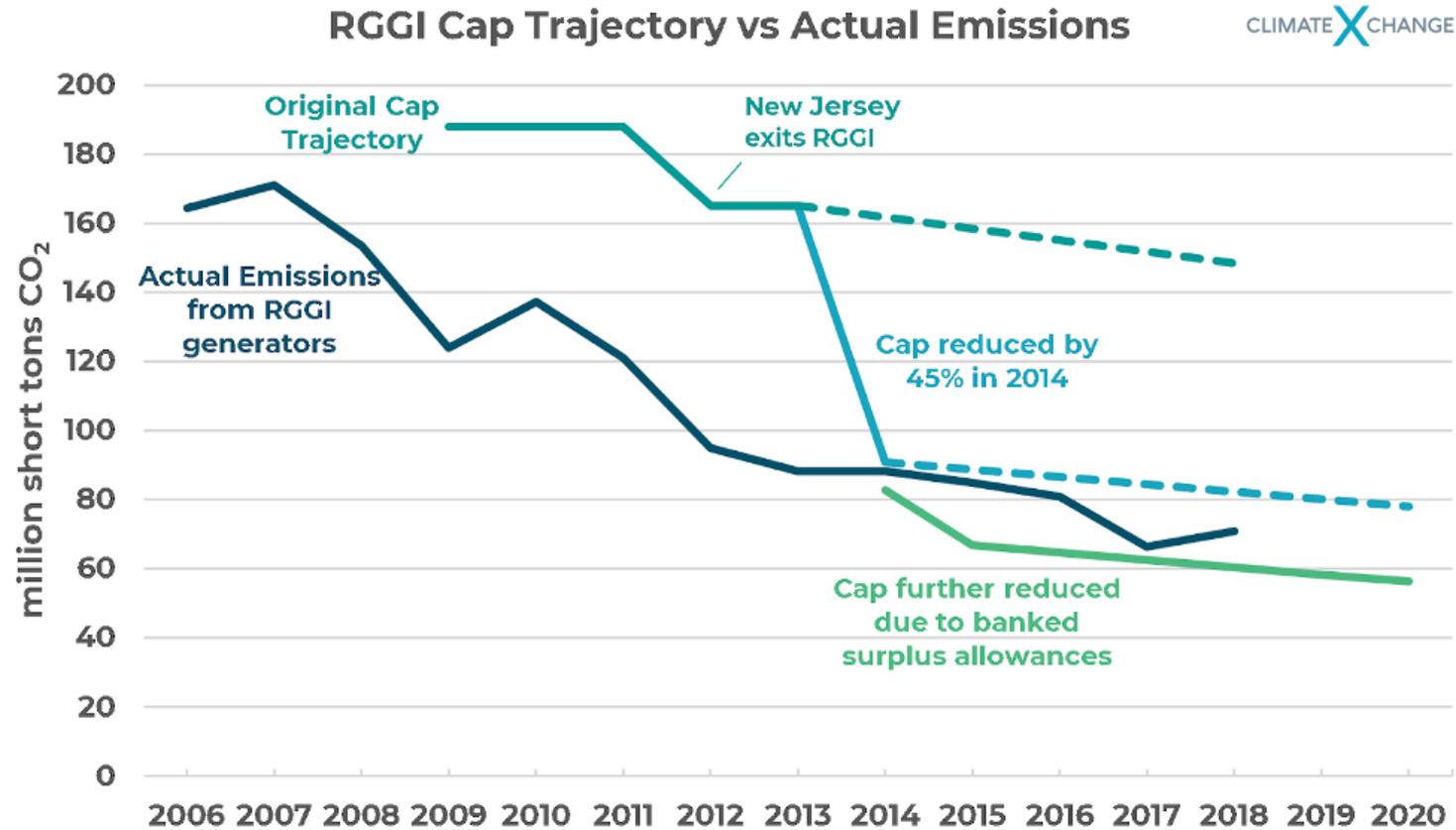
**Regional Greenhouse Gas Initiative (RGGI) allowance clearing price (Jan 2008-Dec 2019)**  
dollars per short ton of carbon dioxide (CO<sub>2</sub>)



Source: U.S. Energy Information Administration, based on [Regional Greenhouse Gas Initiative](#)



# RGGI



# AB32

## CARBON PRICE

\$/Tonne CO<sub>2</sub>e



# EU-ETS

## European carbon credits price

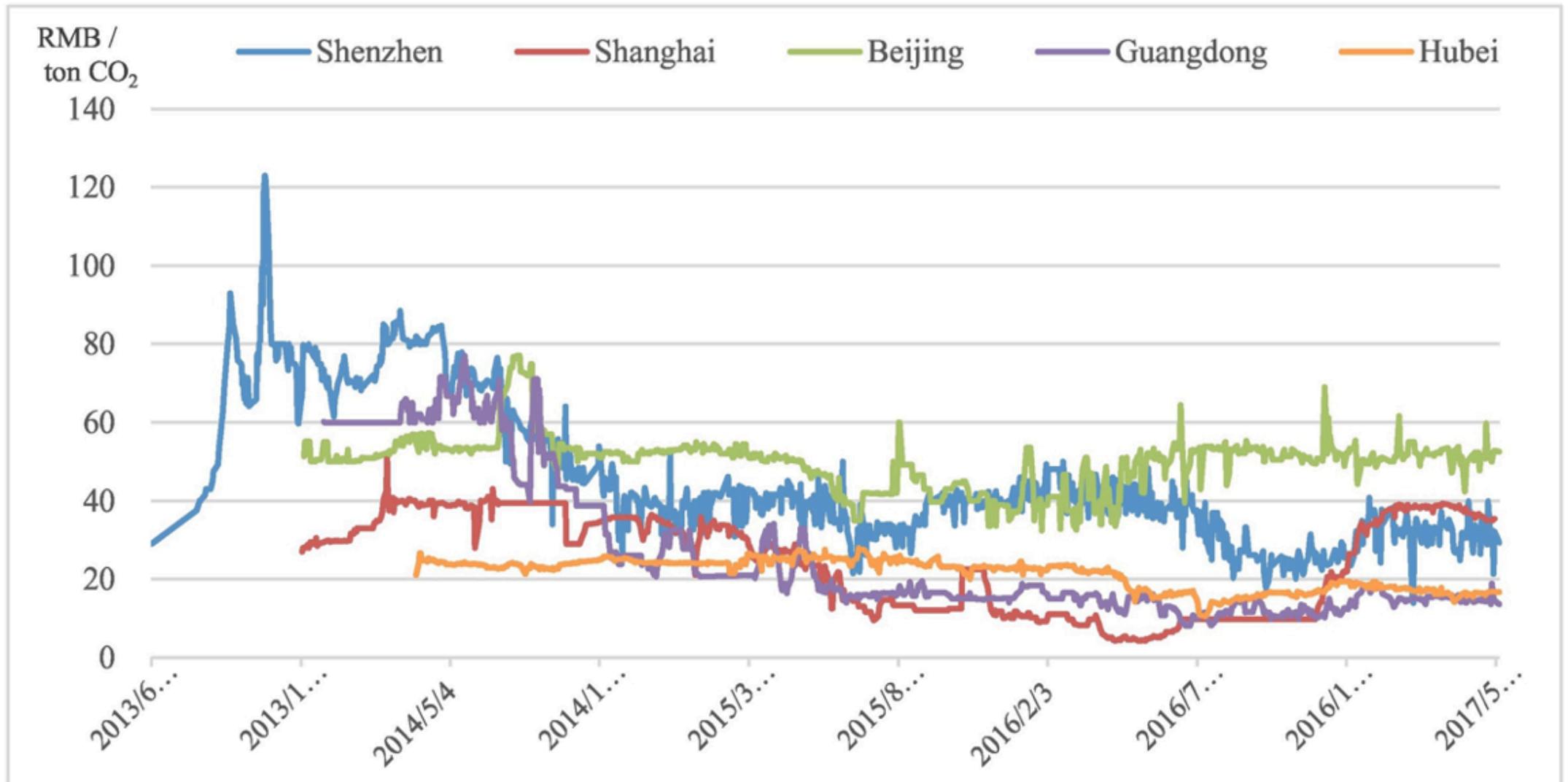
Euros per tonne



Source: Thomson Reuters

© FT

# China ETS



# Banking and borrowing in permit markets

---

# Banking and borrowing in permits

In cap-and-trade, permits may be shifted across time if we allow for banking and borrowing:

# Banking and borrowing in permits

In cap-and-trade, permits may be shifted across time if we allow for banking and borrowing:

**Banking**: save unused permits for future compliance

# Banking and borrowing in permits

In cap-and-trade, permits may be shifted across time if we allow for banking and borrowing:

**Banking**: save unused permits for future compliance

**Borrowing**: use future permits early, then make up the shortfall later

# Banking and borrowing in permits

In cap-and-trade, permits may be shifted across time if we allow for banking and borrowing:

**Banking**: save unused permits for future compliance

**Borrowing**: use future permits early, then make up the shortfall later

Let  $\bar{E}_t$  be permits issued in period  $t$ ,  $E_t$  emissions, and  $B_t$  the end-of-period bank:

$$B_t = B_{t-1} + \bar{E}_t - E_t$$

# Banking and borrowing in permits

In cap-and-trade, permits may be shifted across time if we allow for banking and borrowing:

**Banking**: save unused permits for future compliance

**Borrowing**: use future permits early, then make up the shortfall later

Let  $\bar{E}_t$  be permits issued in period  $t$ ,  $E_t$  emissions, and  $B_t$  the end-of-period bank:

$$B_t = B_{t-1} + \bar{E}_t - E_t$$

Banking only:  $B_t \geq 0$

Borrowing allowed:  $B_t$  can be negative (typically with limits/penalties)

# Banking and borrowing in permits

Two-period cost-minimization benchmark:

$$\min_{E_1, E_2} C_1(E_1) + C_2(E_2)$$

$$\text{subject to: } E_1 + E_2 = \bar{E}_1 + \bar{E}_2$$

# Banking and borrowing in permits

Two-period cost-minimization benchmark:

$$\min_{E_1, E_2} C_1(E_1) + C_2(E_2)$$

$$\text{subject to: } E_1 + E_2 = \bar{E}_1 + \bar{E}_2$$

$$-C'_1(E_1^*) = -C'_2(E_2^*)$$

# Banking and borrowing in permits

Two-period cost-minimization benchmark:

$$\min_{E_1, E_2} C_1(E_1) + C_2(E_2)$$

$$\text{subject to: } E_1 + E_2 = \bar{E}_1 + \bar{E}_2$$

$$-C'_1(E_1^*) = -C'_2(E_2^*)$$

In MAC terms:

$$MAC_1(E_1^*) = MAC_2(E_2^*)$$

# Banking and borrowing in permits

Two-period cost-minimization benchmark:

$$\min_{E_1, E_2} C_1(E_1) + C_2(E_2)$$

$$\text{subject to: } E_1 + E_2 = \bar{E}_1 + \bar{E}_2$$

$$-C'_1(E_1^*) = -C'_2(E_2^*)$$

In MAC terms:

$$MAC_1(E_1^*) = MAC_2(E_2^*)$$

A firm equalizes its MAC over time!

# Banking and borrowing in permits

Intuition:

Standard cap-and-trade allows **within-period trade across firms**

# Banking and borrowing in permits

Intuition:

Standard cap-and-trade allows **within-period trade across firms**

Banking and borrowing add **across-period trade within a firm**

# Banking and borrowing in permits

Intuition:

Standard cap-and-trade allows **within-period trade across firms**

Banking and borrowing add **across-period trade within a firm**

So a firm can effectively "trade with itself over time"

# Banking and borrowing in permits

Intuition:

Standard cap-and-trade allows **within-period trade across firms**

Banking and borrowing add **across-period trade within a firm**

So a firm can effectively "trade with itself over time"

This shifts abatement away from high-MAC periods and toward low-MAC periods

# Banking and borrowing in permits

Why might a firm's MAC change over time?

# Banking and borrowing in permits

Why might a firm's MAC change over time?

1. Fuel and input prices move (e.g., coal vs natural gas prices)

# Banking and borrowing in permits

Why might a firm's MAC change over time?

1. Fuel and input prices move (e.g., coal vs natural gas prices)
2. Output demand changes (business cycle, weather-driven load)

# Banking and borrowing in permits

Why might a firm's MAC change over time?

1. Fuel and input prices move (e.g., coal vs natural gas prices)
2. Output demand changes (business cycle, weather-driven load)
3. Abatement equipment has temporary outages or maintenance

# Banking and borrowing in permits

Why might a firm's MAC change over time?

1. Fuel and input prices move (e.g., coal vs natural gas prices)
2. Output demand changes (business cycle, weather-driven load)
3. Abatement equipment has temporary outages or maintenance
4. New technology adoption lowers future abatement cost

# Banking and borrowing in permits

Why might a firm's MAC change over time?

1. Fuel and input prices move (e.g., coal vs natural gas prices)
2. Output demand changes (business cycle, weather-driven load)
3. Abatement equipment has temporary outages or maintenance
4. New technology adoption lowers future abatement cost
5. Learning-by-doing improves operational efficiency

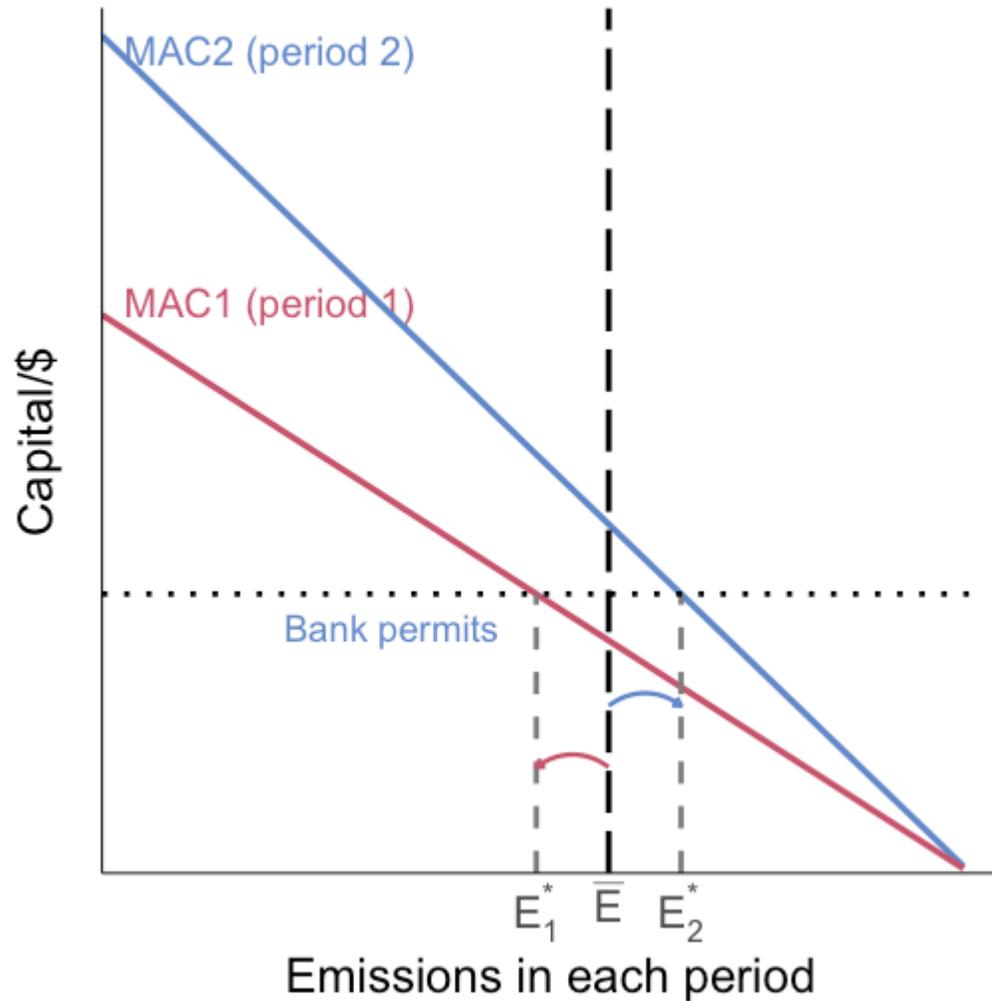
# Banking and borrowing in permits

Why might a firm's MAC change over time?

1. Fuel and input prices move (e.g., coal vs natural gas prices)
2. Output demand changes (business cycle, weather-driven load)
3. Abatement equipment has temporary outages or maintenance
4. New technology adoption lowers future abatement cost
5. Learning-by-doing improves operational efficiency

With these shocks, banking/borrowing lowers compliance cost relative to a rigid period-by-period cap

# Banking and borrowing in permits



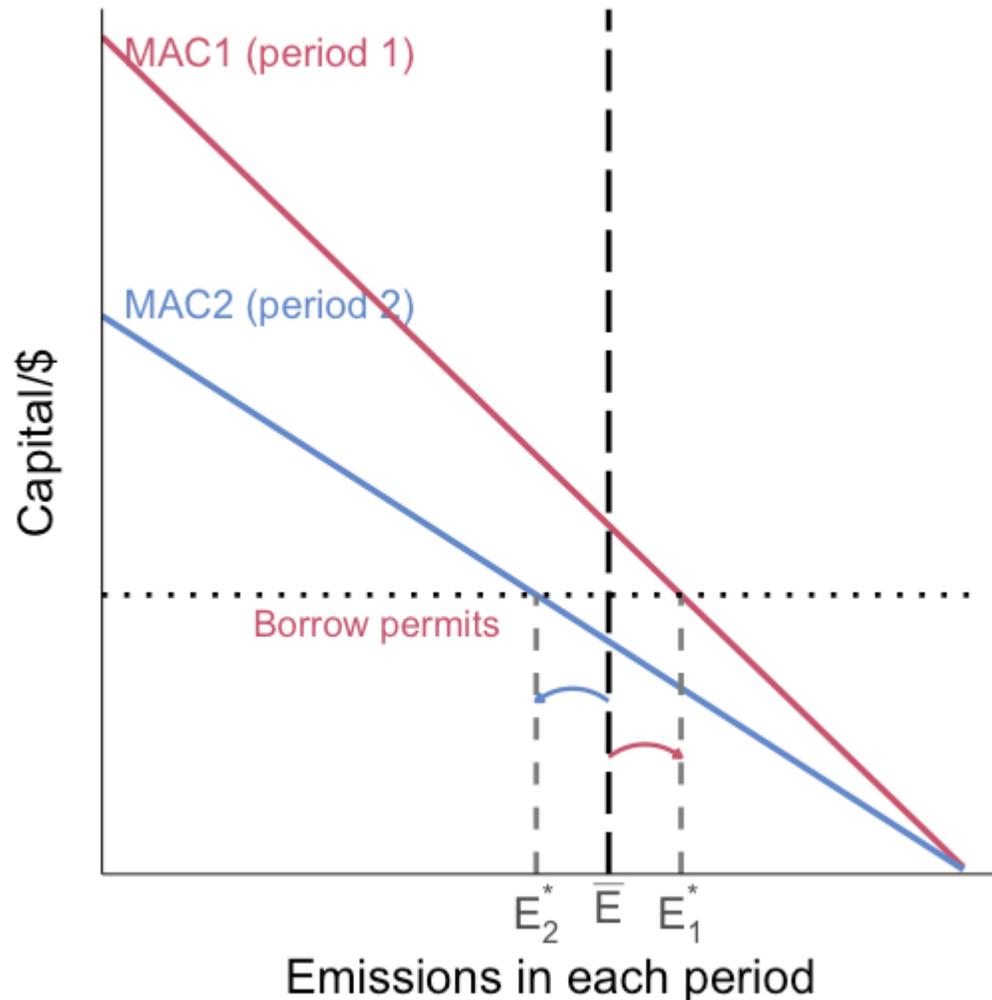
Decision rule at the no-flex caps:

If  $MAC_2(\bar{E}_2) > MAC_1(\bar{E}_1)$ , period 2 abatement is more expensive

Banking is optimal:  $E_1^* < \bar{E}_1$  and  $E_2^* > \bar{E}_2$

If  $MAC_1(\bar{E}_1) > MAC_2(\bar{E}_2)$ , borrowing is optimal

# Banking and borrowing in permits



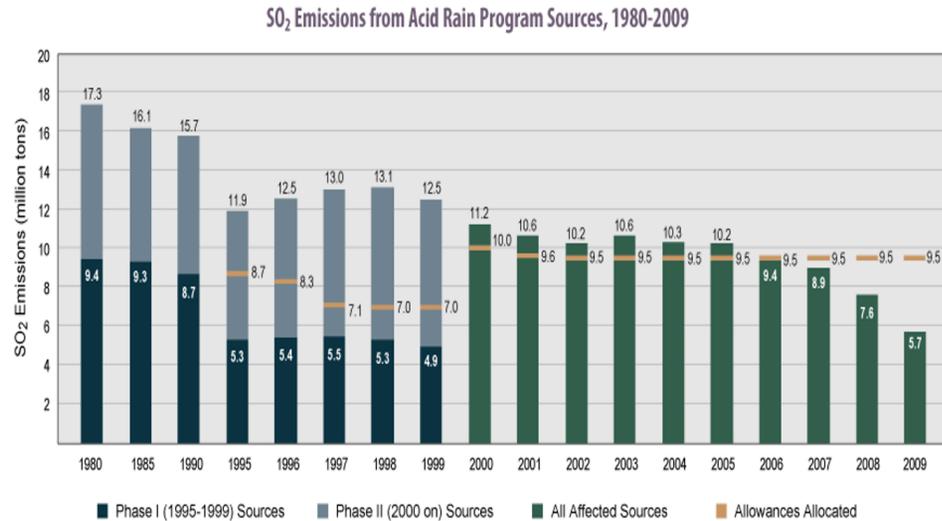
Borrowing case: period 1 starts with the higher MAC at cap

Cost minimization shifts emissions toward period 1 and away from period 2

$$E_1^* > \bar{E}_1 \text{ and } E_2^* < \bar{E}_2$$

Both banking and borrowing are intertemporal permit trade that aligns MACs across time

# Banking and borrowing in practice: Acid Rain Program



Source: EPA, 2010

U.S. SO<sub>2</sub> trading (Acid Rain Program) allowed banking across years

Firms over-complied in the 1990s and built an allowance bank before tighter caps

# Banking and borrowing in practice: EU-ETS

European Union Allowances – Historical price evolution  
(2005 – 2024, in EUR)



Phase I (2005-2007): limited inter-phase banking; surplus allowances led to a price collapse near phase end

From Phase II onward, banking became a key margin for compliance planning

Large cumulative surplus carried forward across phases and affected prices

# Banking and borrowing: design lessons

1. Banking is widely used because it lowers costs while preserving a cumulative cap
2. Borrowing is often constrained because of default, enforcement, and credibility concerns
3. Rules on banking/borrowing strongly affect allowance price dynamics
4. Without banking across phase boundaries, end-of-phase price volatility can be severe

# Comparison of standards, taxes, permits

---

# What do we know so far

So far we have seen that:

1. Standards, taxes, and tradable permits can all achieve the efficient allocation
2. Taxes and tradable permits are cost-effective **no matter what**
  - (all firms set  $MAC = \tau$  and  $MAC = p$ )

# What do we know so far

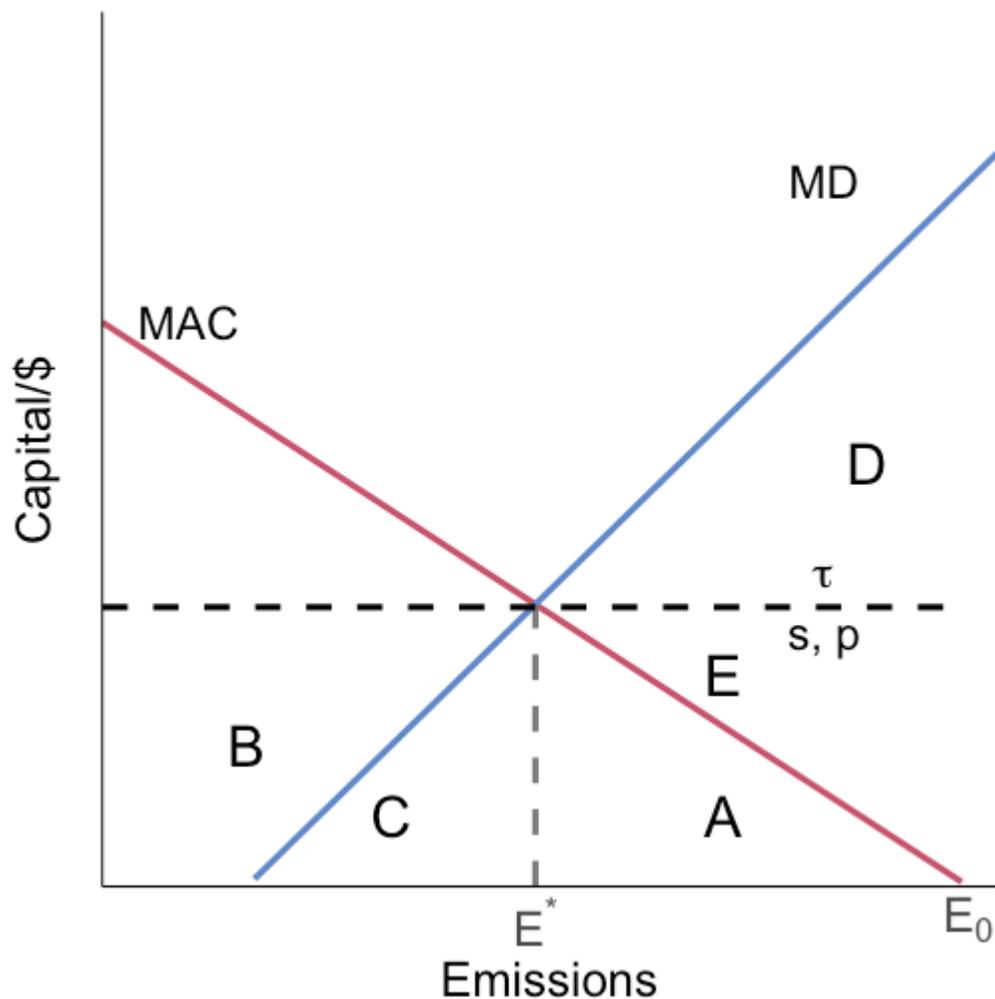
So far we have seen that:

1. Standards, taxes, and tradable permits can all achieve the efficient allocation
2. Taxes and tradable permits are cost-effective **no matter what**
  - (all firms set  $MAC = \tau$  and  $MAC = p$ )

This still leaves a few questions to answer:

1. What are the equity effects?
2. What are the output effects?
3. What are the administrative burdens?
4. What are the **dynamic** incentives under these policies?

# The equity set up

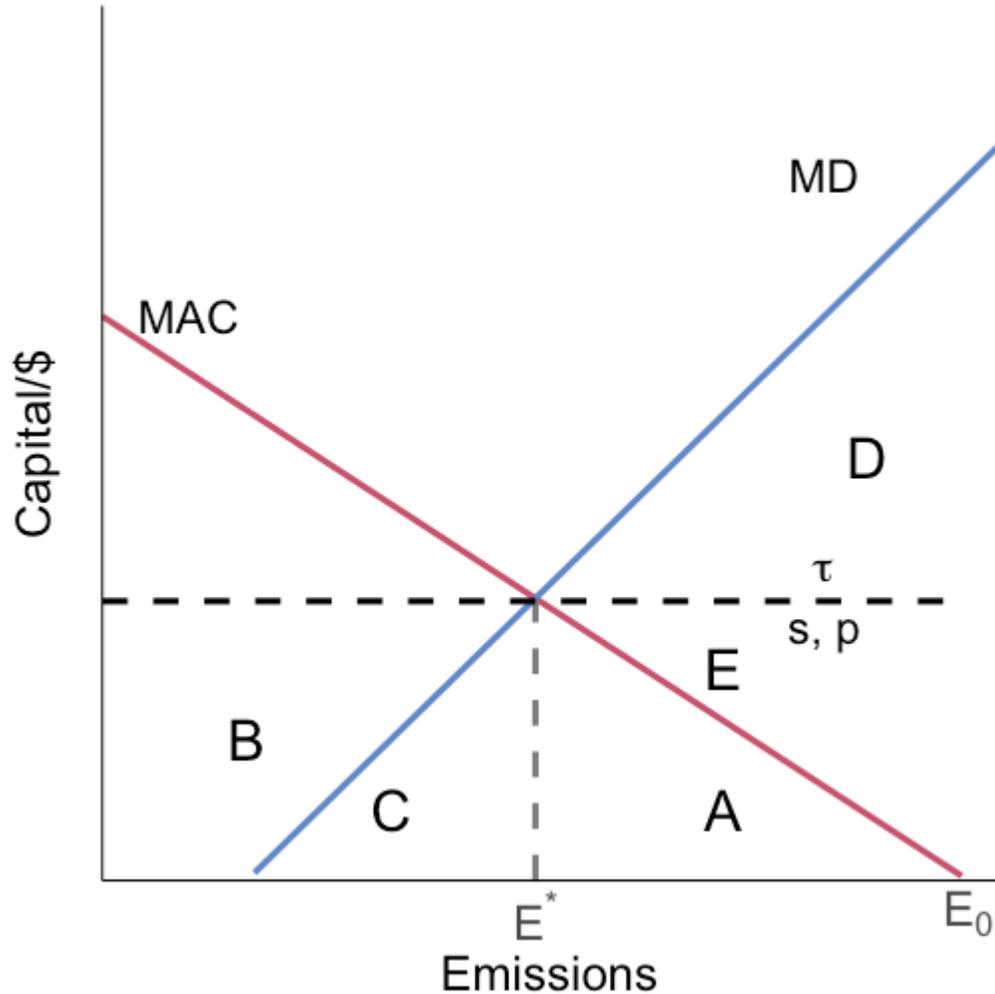


Lets consider this our base set up for 1 firm

The regulator can achieve  $E^*$  through:

- an emission standard of  $E^*$
- a tax of  $\tau$
- an abatement subsidy of  $s$
- "tradable permit" cap of  $E^*$  with auctioned permits at price  $p$

# The equity set up

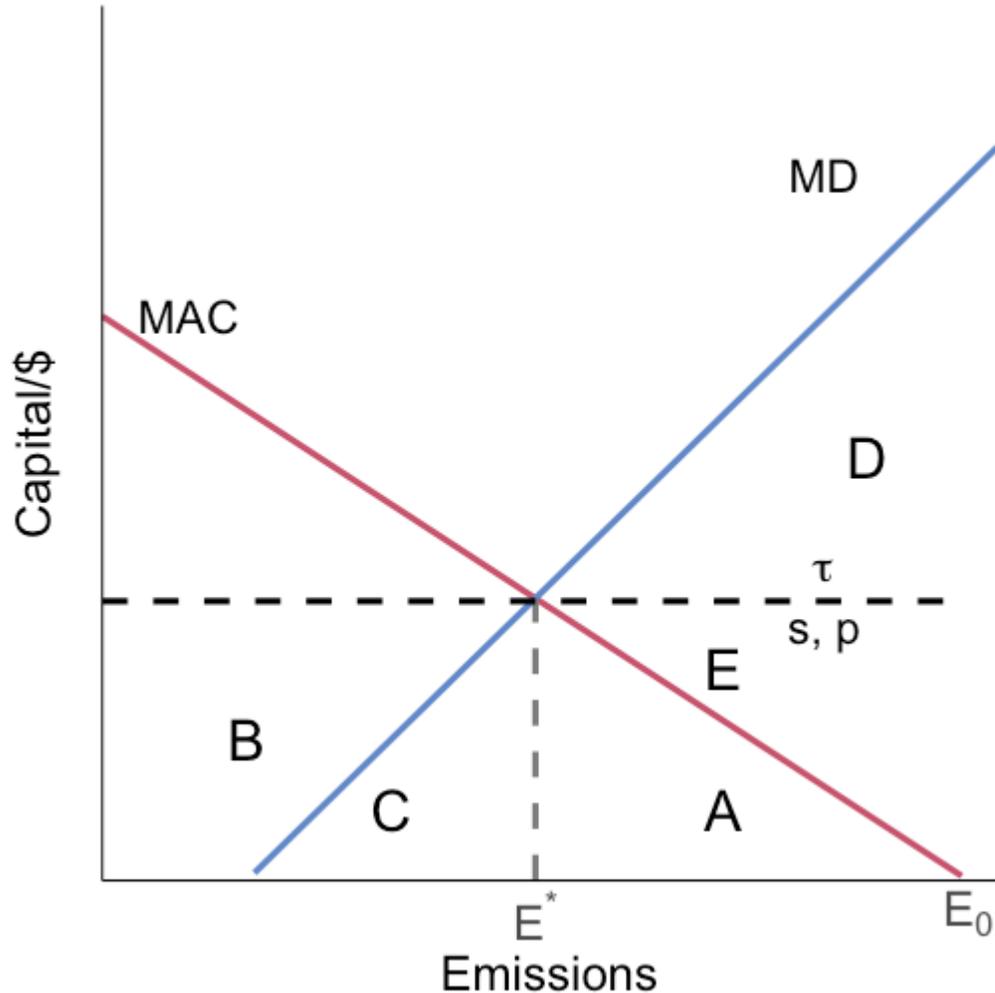


First let's look at **equity**

How do the costs and benefits of the policies fall on different groups?

From here on we will roll the tax and permit system into 1: they are actually identical in terms of their impacts if all permits are auctioned

# The distributional outcomes



	Tax/Permits	Standard	Subsidy	Ranking
Firm	$-(A+B+C)$	$-A$	$E$	Sub > Std > Tax
Households	$A+D+E$	$A+D+E$	$A+D+E$	Indifferent
Government	$B+C$	$0$	$-(E+A)$	Tax > Std > Sub
Total	$D+E$	$D+E$	$D+E$	

The total welfare gain is the same for all policies

The difference is in the **distribution**

The standard strikes a middle ground out of the three

# Output effects

So far we have assumed that actual firm output is not affected by abatement/emission decisions

# Output effects

So far we have assumed that actual firm output is not affected by abatement/emission decisions

This won't always be true in the real world

# Output effects

So far we have assumed that actual firm output is not affected by abatement/emission decisions

This won't always be true in the real world

Key identity:

$$E = \left( \frac{E}{q} \right) \times q$$

Firms can reduce total emissions either by lowering emissions intensity per unit of output  $q$ :  $\left( \frac{E}{q} \right)$ , or by lowering output  $q$

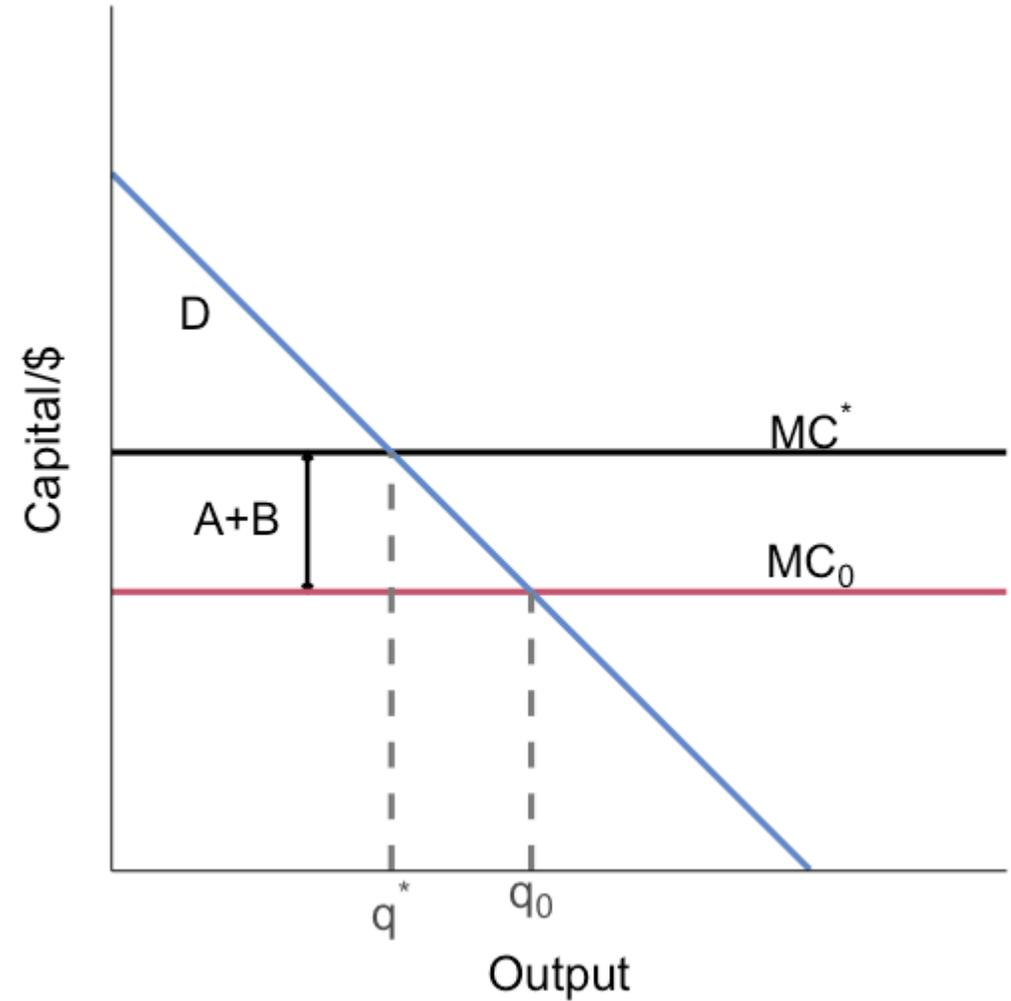
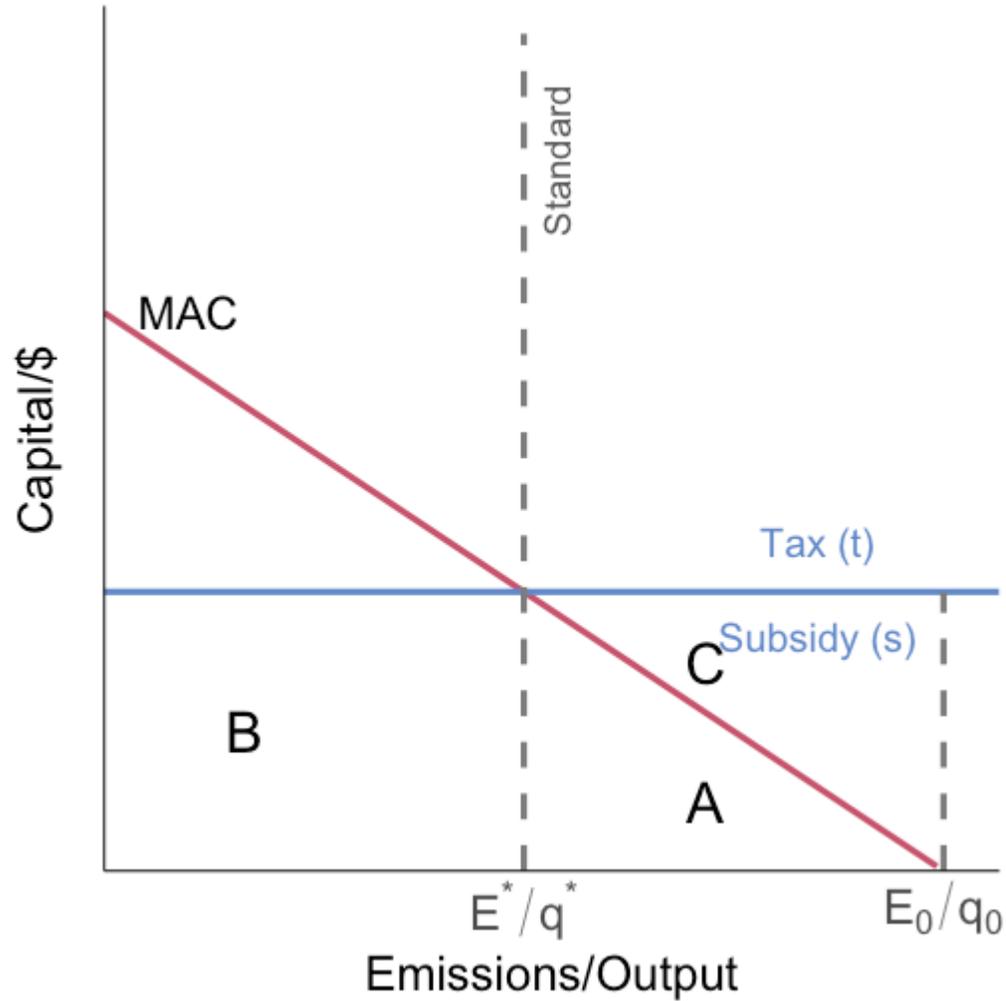
# Output effects

Why can emissions policy reduce output?

1. Taxes and standards make cleaner production more costly per unit of output
2. That increases marginal cost of supplying output
3. With downward-sloping demand, higher MC implies lower profit-maximizing output

Even when the policy directly targets emissions, output can move as an indirect equilibrium response

# The output set up



# The output results

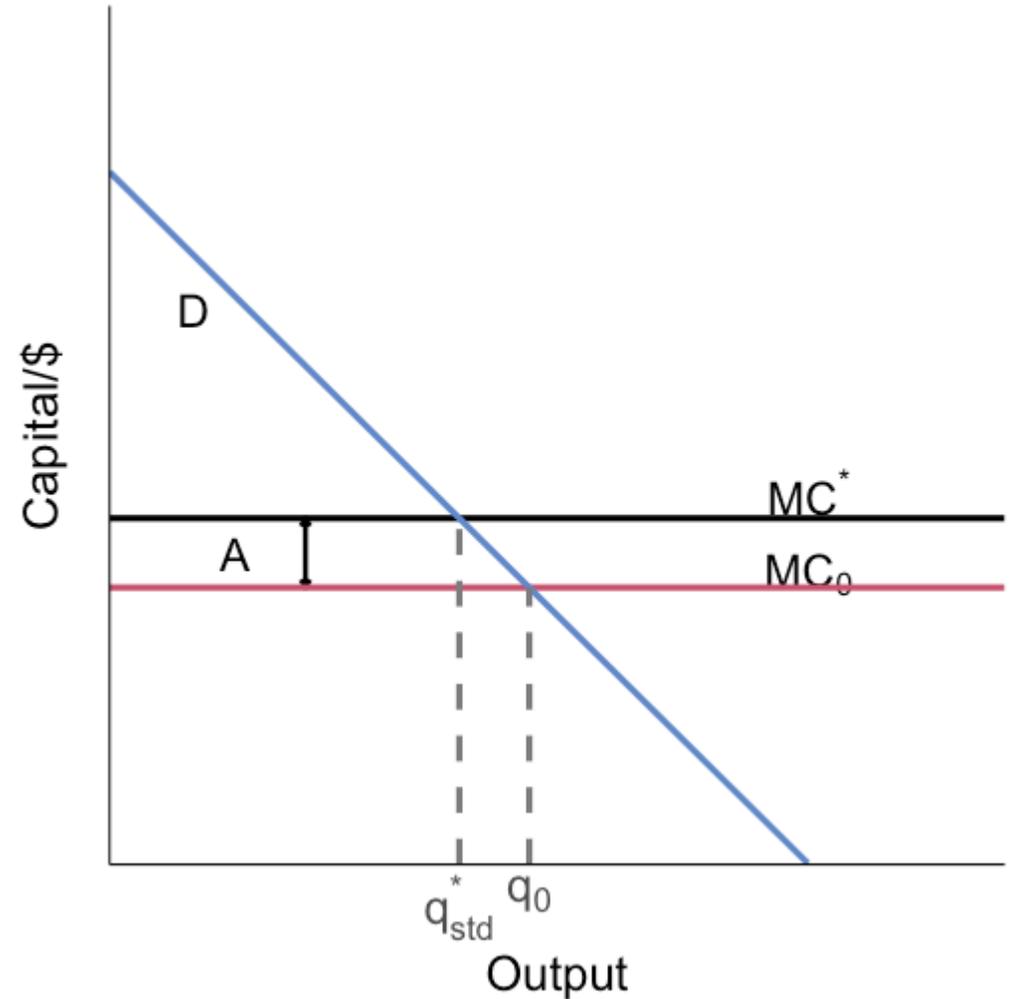
Emission tax:

- Firm chooses  $E^*/q^*$
- Firm pays A+B in tax and abatement cost **per unit of output**
- This raises the MC of production by A+B to  $MC^*$
- Output  $q^*$  falls
- Pollution  $(E^*/q^*) * q^*$  falls even more since the tax lowers the optimal  $E^*/q^*$ , and increased MC lowers  $q^*$

# The output results

Emission standard:

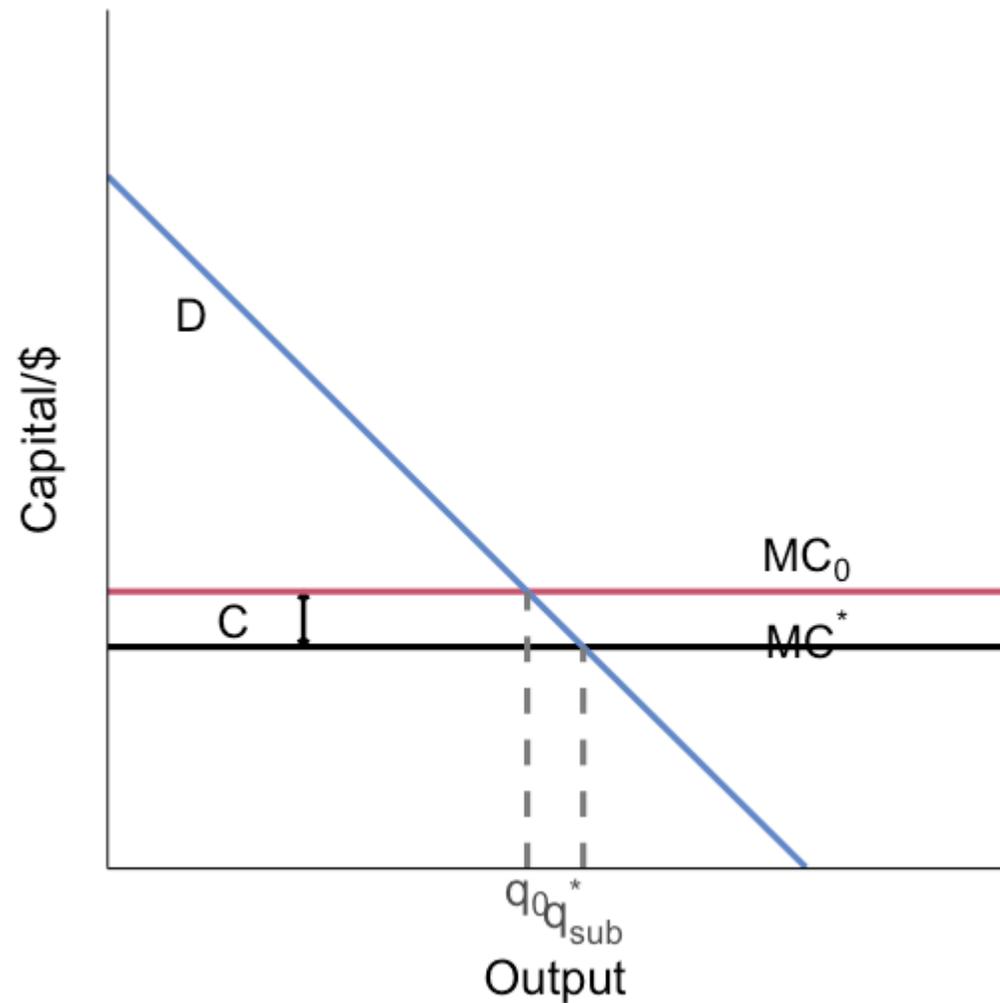
- Firm pays  $A$  in abatement cost per unit of output
- This raises the MC of production by  $A$
- Output and  $(E^*/q^*) * q^*$  fall, but not by as much as under the tax



# The output results

Abatement subsidy:

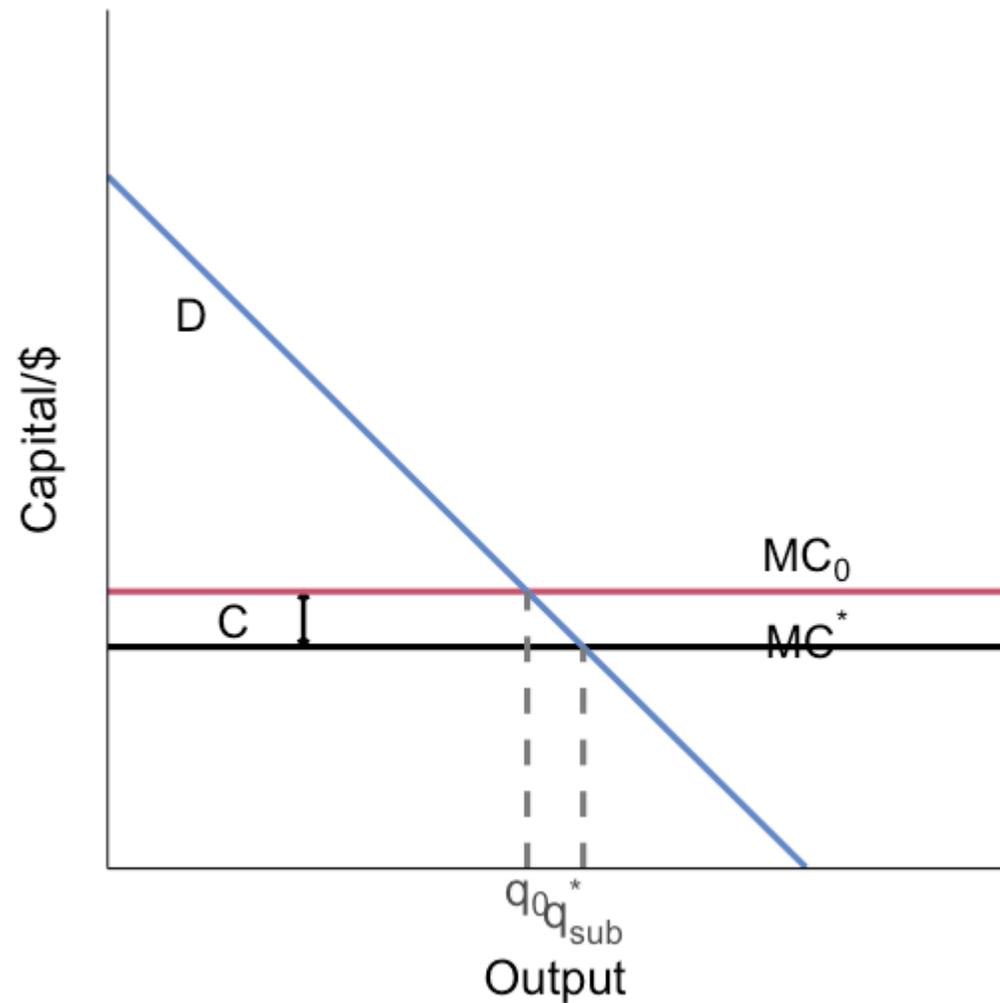
- Reduces firm costs per unit of output by  $C$
- This reduces the MC of production by  $C$
- This **raises** output
- Even though  $E/q$  goes down because the subsidy induces a lower emission intensity, total emissions may go up because  $q$  will rise



# The output results

Abatement subsidy:

- Reduces firm costs per unit of output by  $C$
- This reduces the MC of production by  $C$
- This **raises** output
- Even though  $E/q$  goes down because the subsidy induces a lower emission intensity, total emissions may go up because  $q$  will rise



# Administration

These policies are not equivalent in their cost of implementation

# Administration

These policies are not equivalent in their cost of implementation

Enforcing a technology standard is very easy: you can inspect to see if they have installed the tech or not

# Administration

These policies are not equivalent in their cost of implementation

Enforcing a technology standard is very easy: you can inspect to see if they have installed the tech or not

Emission standards, taxes, subsidies require monitoring of emissions

# Administration

These policies are not equivalent in their cost of implementation

Enforcing a technology standard is very easy: you can inspect to see if they have installed the tech or not

Emission standards, taxes, subsidies require monitoring of emissions

Monitoring systems cost money

# Administration

These policies are not equivalent in their cost of implementation

Enforcing a technology standard is very easy: you can inspect to see if they have installed the tech or not

Emission standards, taxes, subsidies require monitoring of emissions

Monitoring systems cost money

Firms have incentives to try to cheat!

# Administration

Pigouvian policies will not work as well for **non-point sources** like cars or farms

# Administration

Pigouvian policies will not work as well for **non-point sources** like cars or farms

With non-point sources we observe total emissions but not who emitted it

# Administration

Pigouvian policies will not work as well for **non-point sources** like cars or farms

With non-point sources we observe total emissions but not who emitted it

With non-point sources it often makes sense to use technology standards

# Administration

Pigouvian policies will not work as well for **non-point sources** like cars or farms

With non-point sources we observe total emissions but not who emitted it

With non-point sources it often makes sense to use technology standards

Point sources like power plants are much easier to handle with Pigouvian policies like taxes

# Administration

Technology and emission standards typically guarantee some amount of emissions reductions

# Administration

Technology and emission standards typically guarantee some amount of emissions reductions

Taxes and subsidies guarantee firms pay a certain price but doesn't deliver us a guaranteed quantity

# Administration

Technology and emission standards typically guarantee some amount of emissions reductions

Taxes and subsidies guarantee firms pay a certain price but doesn't deliver us a guaranteed quantity

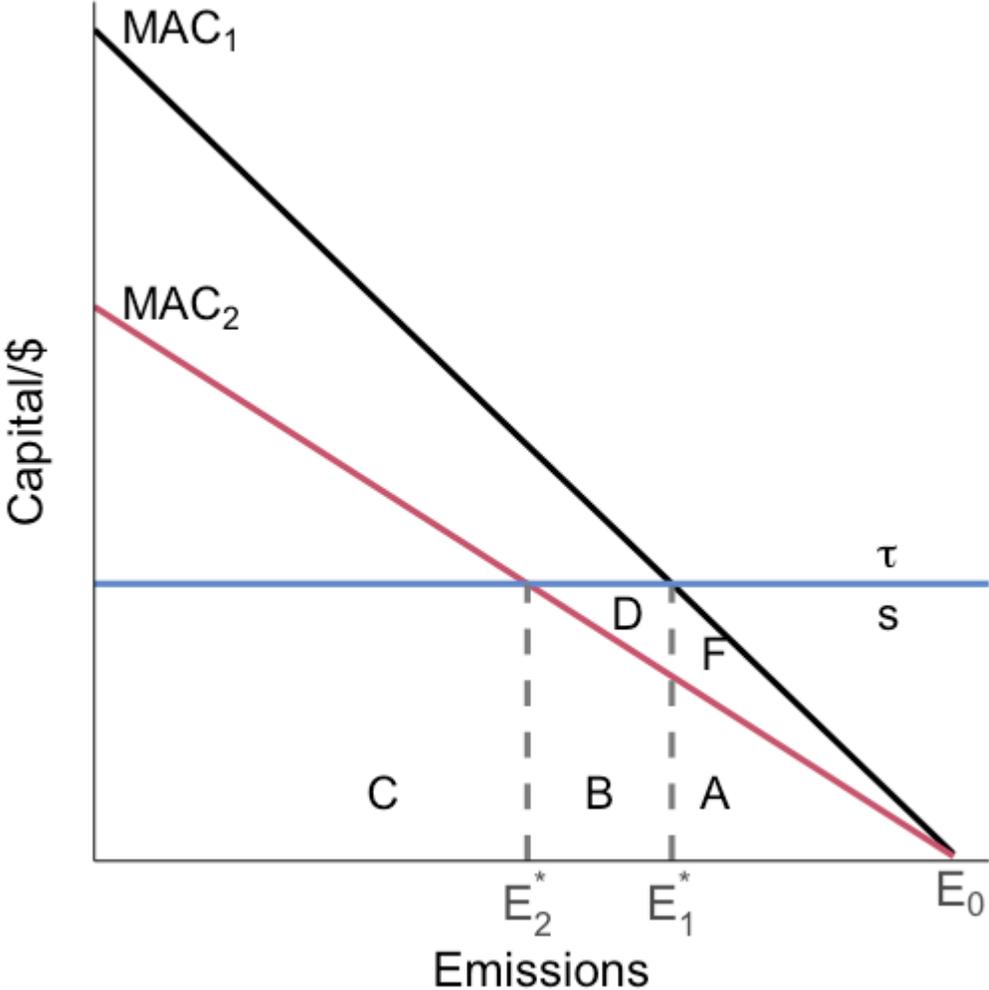
This might make things more politically difficult to pass

# Administration

When does C&C / technology standards make sense?

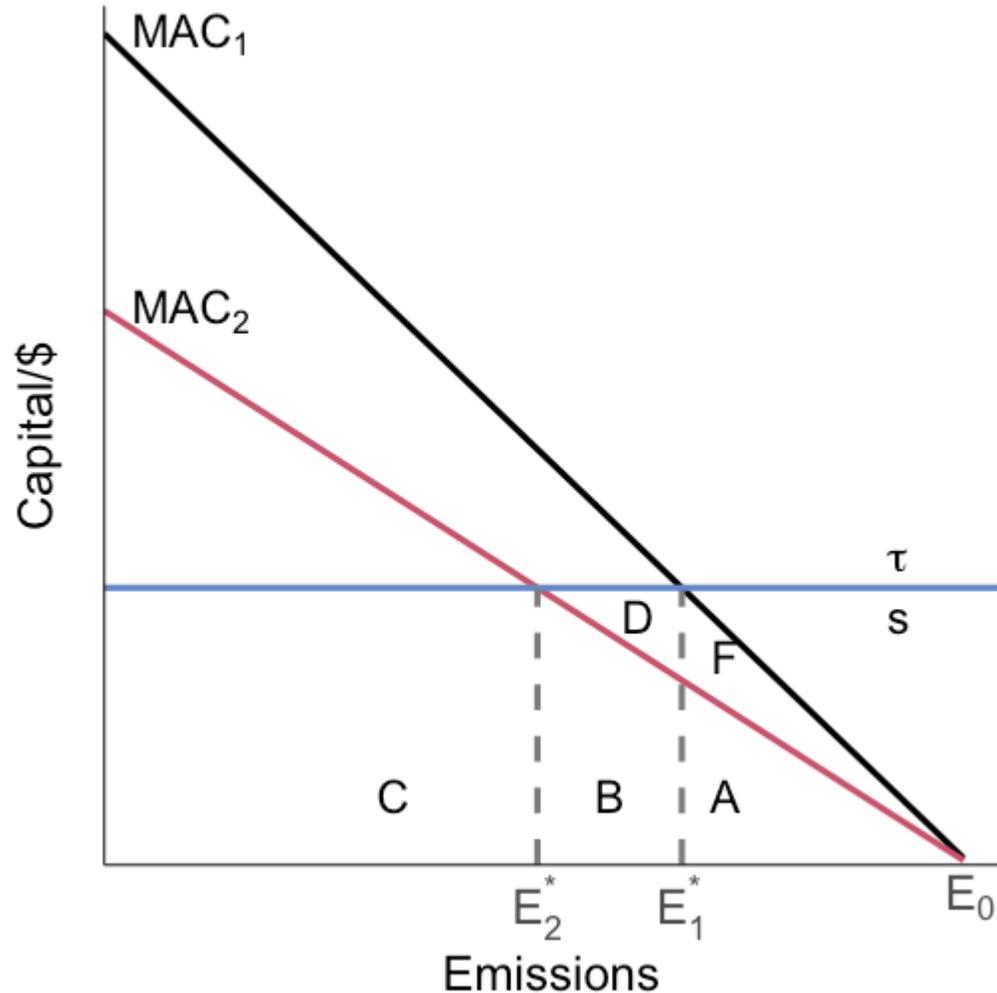
1. If there's a dominant technology where there's benefits to coordination or scale economies from production of the technology
2. High costs of monitoring/enforcement
3. High admin costs and little heterogeneity across firms

# Dynamic incentives



What are the gains to the firm from moving from  $MAC_1$  to  $MAC_2$ ?

# Dynamic incentives



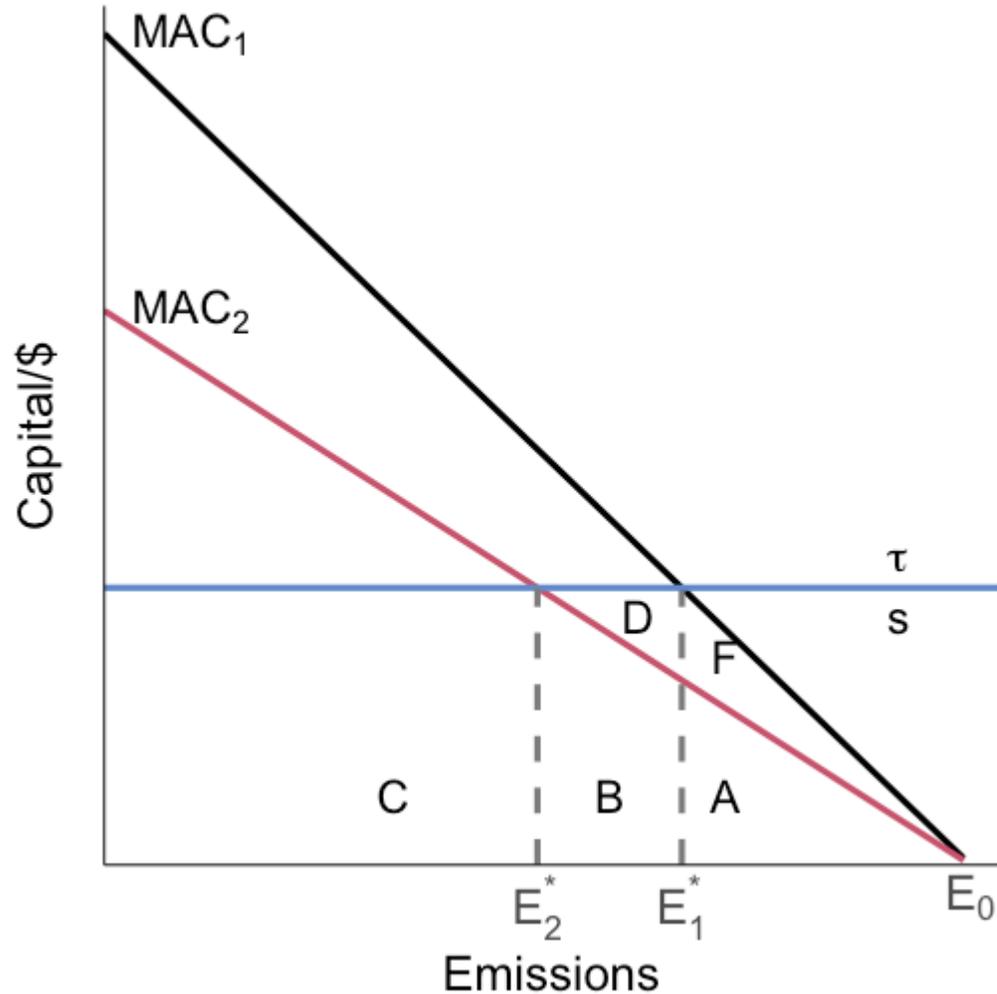
What are the gains to the firm from moving from  $MAC_1$  to  $MAC_2$ ?

**Standard:** F (abatement cost reduction)

**Emission Tax:** F + D (abatement cost and tax payment reduction)

**Abatement Subsidy:** F + D  
(abatement cost reduction and abatement subsidy increase)

# Dynamic incentives



What are the gains to the firm from moving to  $MAC_2$ ?

Taxes and subsidies give greater incentives to innovate!

Once a firm meets a standard, there's no additional incentive beyond reducing abatement costs

Taxes and subsidies give the firm extra benefits for further reductions

# How do carbon markets work?

