10th Winter School– Energy Markets

Lecture 4
An Introduction to Emission Trading Schemes

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26. January 2011

1. CO_2 emissions and global warming

2. Approaches in environmental legislation
   - Policy Responses
   - ETS and Tax
   - ETS and Flexibility
   - The EU ETS

3. Deterministic Equilibrium Model

4. Stochastic Equilibrium Model

Agenda

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Carbon Target

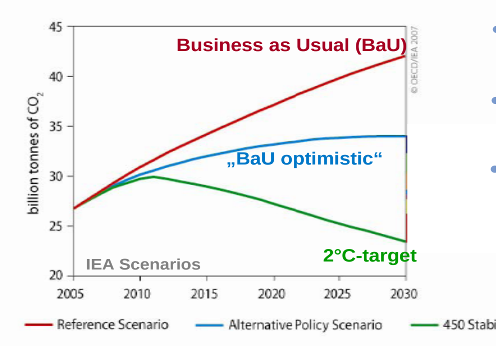
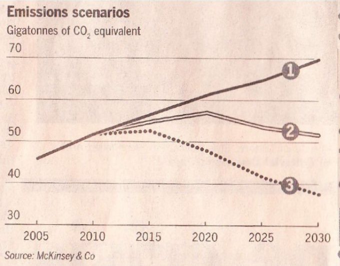


Figure: Global CO2 Emmissions.

Consequences of Climate Change



1 No change in policy towards climate change

- Global temperatures could rise by 6-7°C this century – well above the 2°C scientists regard as the safety limit
- Sea level rises will overwhelm 1-2bn people living in low-lying areas
- 4bn people could be put at risk of water shortages
- The ice caps will melt entirely
- The Amazon rainforest (above) may die off

2 Developed world takes the lead, with $350bn per year investment by 2030

- Sea levels will rise and low-lying land such as Tarawa, Kiribati (above) will be at risk
- Hunger will increase, but more slowly
- Northern areas such as Canada and northern Europe will become more agriculturally productive
- Substantial increase in 'extreme weather events': more droughts, more heatwaves, more floods and more intense storms

3 Global action, with $565bn per year investment by 2030

- World will warm by no more than 2°C by mid-century and thereafter temperatures may start to decline
- Hottest parts of the world will suffer serious declines in crop yields (above), but increase in fertility in other areas will offset this
- Ice at the poles will diminish, but some reduced ice cover could remain
- Increase in floods, droughts and storms, but damage manageable
- Tropical diseases will spread, but not too far

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Pollution control problem

A region faces some kind of environmental pollution and its policymakers want to reduce the pollution level.
Desired characteristics of the policy response to the pollution problem are

- effectiveness (law should ensure that the targeted pollution level is achieved)
- manageable control effort
- minimal costs from a macroeconomic perspective

Possible policy responses I

- **Emission standards ("'Command-and-Control"')**
  Legal limit on the amount of the pollutant an individual source is allowed to emit Problem: Standards ensure the required reduction but in practice it is not achieved in a cost-effective way (sources are usually allocated for an equal reduction)
- **Emission charges**
  Pollutor has to pay a fee on each unit of pollutant emitted
  Problem: Does not necessarily lead to a lower pollution level

Possible policy responses II

- **Product charges**
  Control authority taxes the commodity that is responsible for the pollution instead of the pollutant. This is easy to administer Problem: not every unit of the taxed product may have the same impact on the environment.
- **Emission trading**
  All sources are allocated allowances to emit either on the basis of some criterion such as historic emissions or by auctioning the allowances off to the highest bidder. The control authority issues exactly the number of allowances needed to produce the desired aggregate emission level. The allowances are freely tradeable. Advantage: Leads to a cost-effective allocation

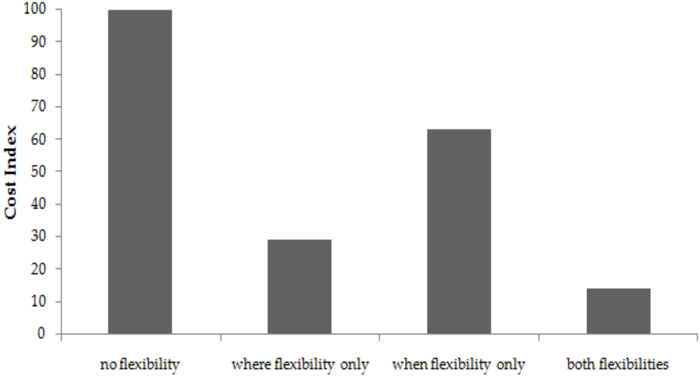
ETS vs Tax: Generalities

- Since compliance costs are uncertain the choice of instrument depends on the relative curvatures of the marginal benefit curve and the marginal abatement costs curve.
- In case of CO2, where damage does not depend on the flow of emissions but on their accumulation in the atmosphere, scientific results suggest that a carbon tax is more economically efficient under uncertainty than emissions trading.
- In practice, however, the analysis of efficiency under uncertainty has had little influence on the choice of policy instruments. The preference for carbon trading over carbon taxes is driven largely by powerful political economy concerns. Trading systems are easier to implement politically.

ETS vs Tax

- The market for emission reductions has a demand schedule, which is determined by the marginal abatement costs of regulated agents, and a supply schedule, which is determined by policy.
- Under a pure tax system, the supply of allowances is infinitely elastic. The market is effectively supplied with as many allowances as agents wish to buy at a fixed price (the tax rate).
- Under a pure allowance system, supply is completely inelastic as the amount of allowances is exogenously fixed.
- Hybrid systems create a supply curve that is neither fully flat (a pure tax) nor fully vertical (pure cap-and-trade) but (stepwise) upward sloping.

ETS and flexibility: *When* and *Where*

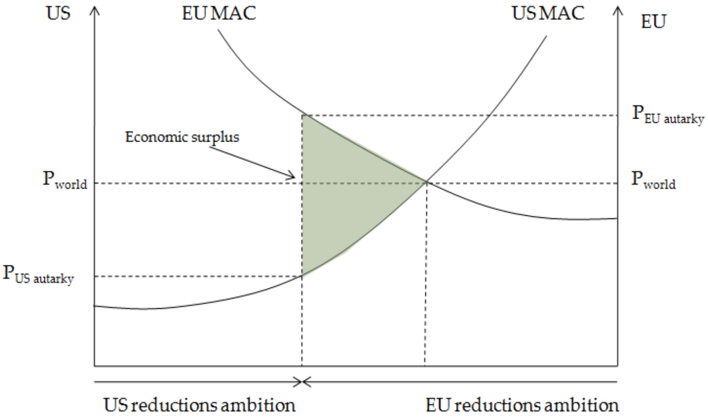


Source: Richels et al (1996)

Where **flexibility**

- The ambition should be a global market. However, there are various constraints such as policy differences, differences in the traded good, etc.
- Linking different national and regional trading systems can approximate a global market.
- Linking markets increases liquidity and thus reduces the cost of trading.
- However, different designs of schemes have to be taken into account.

Where flexibility: Gains from Trade



When **flexibility – Banking**

- effectively increases the depth and liquidity of the market, reducing price volatility by making current prices a function of a longer time span of activity, rather than being entirely determined by events today;
- creates an incentive for firms to take early action;
- firms with banked allowances have a vested interest in higher prices and the continuation (and success) of the system, to maximise the value of their allowance assets;
- banking can also prevent a price collapse between commitment periods;

When **flexibility – Borrowing**

- the regulator may not be well-equipped to assess the credit worthiness and solvency of firms who borrow allowances, who thereby become debtors;
- borrowing enables firms to delay action if they assume that targets will prove too onerous and will subsequently be softened;
- firms with borrowed allowances have an active interest to lobby for weaker targets, or even for scrapping emissions trading altogether, so that their debts are cancelled.
- the political desire to (be seen to) act early, and potential benefits of early action, also imply that politicians may prefer to place constraints on borrowing

When **flexibility**

- banking is usually allowed between periods (Exemption EU ETS Phase I);
- there is typically no borrowing (or only very limited);
- when there are limits on borrowing between periods, the length of the commitment period is relevant to "when" flexibility and to market efficiency.
  - investments to reduce emissions may require many years for investors to recover their costs
  - in case of short periods, investors have to guess the emissions caps set by future governments, and attempt to anticipate changes in the underlying structure of the carbon trading framework.

Permit price in the EU ETS during the first phase

Figure: EUA-Dec07 futures price (22 April 2005 - 17 December 2007).

Price ceilings and price floors

- a price ceiling and floor provide significantly greater clarity to investors to deliver dynamic efficiency (in the form of optimal investment over longer time frames).
- the price floor would guarantee a certain minimum return on investment in low-carbon technologies, reducing the risk faced by innovating firms.
- the price ceiling may enhance policy credibility. Because it caps the costs of compliance, a ceiling reduces the risk of a policy reversal if abatement costs turn out to be injuriously high.

Price ceilings and price floors

- a price ceiling can be established through an unlimited commitment from the regulator to sell allowances onto the market at the price ceiling
- drawback: compliance with the emissions cap is sacrificed
- a price floor can be established through an unlimited commitment from the regulator to buy back allowances from the market at the price floor
- drawback: the floor would be achieved at the risk of imposing a liability on the public balance sheet.

Multiple Instruments

- Emission regulation is directed at internalizing externalities and economic theory indicates that only one instrument is needed to internalize one externality.
- Policy often involves multiple instruments such as command-and-control regulation, subsidies, taxes, trading schemes, etc.
- This process reflects an ad-hoc policy-accretion process driven by the multiplicity of national institutions or ...
- the temptation of politician to fix everything.

Characteristics of EU ETS (CO_2)

- EU ETS is split up into three phases
  - Phase I (2005-07)
  - Phase II (2008-12) coinciding with commitment period of Kyoto protocol
  - Details of Phase III (2013-20) will be decided at the end of 2009
- Scheme covers approximately 12,000 large emitters in the EU that are responsible for 50% of total CO_2 emissions. Regulated sectors include energy industry, combustion, cement, etc.
- Process steps concerning the distribution of the allowances
  - Each country submits a NAP (National Allocation Plan) to the European Commission (EC)
  - EC adjusts NAPs if necessary and countries distribute EUAs among regulated firms according to the final NAP as approved by the EC

Characteristics of EU ETS (CO_2) II

- At the end of the current phase regulated firms have to pay a fine of 100 Euro (40 Euro for last phase) for each emitted ton of CO_2 that is not covered by an allowance)
- Emission allowances are traded mostly OTC (approx 60 %), bilateral (approx 10 %) and on eight different exchanges (approx 30 %): ECX in London, Nord Pool in Oslo, Powernext in Paris, EEX in Leipzig, The Green Exchange (NYMEX), Sende CO_2, EXAA, New Values Climex

Example for Emission Trading

- Consider two companies A and B each emitting 100 000 metric tons of CO_2 per year
- Each has been allocated 95 000 metric tons under its national allocation plan
- Credits are trading at 10 €per metric ton
- Company A can cut 10 000 metric tons of emission at 5 €per ton (marginal abatement costs, MAC)
- Company B has MAC of 15 €per ton
- Company A receives 50 000 €for its surplus and covers the costs of its own reduction
- Company B meets the cap at cost 50 000 €instead of 75 000€

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Rubin 1996: Firm i's optimization problem

Firm i minimizes its cost by buying/selling an optimal quantity of emissions and by emitting an optimal quantity of emissions, i.e.

$$\min_{\theta_i, e_i} \left\{ \int_0^T e^{-rt} [C_i(e_i(t)) + P(t)\theta_i(t)] dt \right\} \tag{1}$$

$$\text{subject to } \dot{B}_i = S_i(t) - e_i(t) + \theta_i(t) \tag{2}$$

$$B_i(0) = 0 \text{ and } B_i(t) \geq 0 \tag{3}$$

$$e_i(t) \geq 0 \tag{4}$$

Explanation of variables

$e_i(t)$	quantity of emissions
$\theta_i(t)$	quantity of emission permits bought or sold
$S_i(t)$	endowment of emissions
$B_i(t)$	level of emissions in the bank
$C_i(e_i(t))$	abatement cost function where $C_i'(e_i) < 0$ and $C_i''(e_i) > 0$
r	interest rate

Rubin 1996: Market equilibrium

An intertemporal market equilibrium in emission permits over a T-period horizon consists of

$P^*(t) \geq 0$ (permit price)
$\theta^*(t) = (\theta_1^*(t), \dots, \theta_N^*(t))$ (vector of optimal trading volumes)
$E^*(t) = (e_1^*(t), \dots, e_N^*(t))$ (vector of optimal emission levels)

such that for a given $P^*(t)$
$\theta^*(t)$ and $E^*(t)$ minimize each firm's costs subject to each firm's constraints as given in (2) - (4) and
the following two conditions hold

- Market clearing condition on permits
  $\sum_{i=1}^{N} \theta_i^*(t) = 0$
- Terminal stock condition
  $P^*(T) \sum_{i=1}^{N} B_i^*(T) = 0$

Rubin 1996: Joint optimization problem

A fictitious central planner minimizes total costs by choosing optimal quantities of emissions, i.e.

$$\min_{e_1,\ldots,e_N} \left\{ \int_0^T e^{-rt} \sum_{i=1}^{N} C_i(e_i(t))dt \right\} \tag{5}$$

$$\text{subject to } \dot{B}(t) = \sum_{i=1}^{N} (S_i(t) - e_i(t)) \tag{6}$$

$$B(0) = 0 \text{ and } B(t) \geq 0 \tag{7}$$

$$e_i(t) \geq 0 \quad \text{for all } i = 1, \ldots, N \tag{8}$$

Explanation of variables

$S_i(t)$	firm i's endowment of emissions
$B(t)$	sum of emissions banked by the firms at time t
$C_i(e_i(t))$	firm i's abatement cost when emitting $e_i(t)$ where $C_i'(e_i) < 0$ and $C_i''(e_i) > 0$
r	interest rate

Rubin 1996: Theorem (Market equilibrium and joint optimization problem)

(a) There exists an intertemporal market equilibrium in emission permits over a T-period horizon

(b) The market equilibrium solution is at least as inexpensive as the result of the joint cost optimization

Rubin 1996: Theorem (Permit price)

(a) The permit price equals the marginal abatement costs

$$P(t) = -C_i'(e_i)$$

(b) The permit price

- grows at the risk-free rate if banking/borrowing are allowed
- grows at a rate less than the interest rate r if there are restrictions on borrowing

$$\frac{\dot{P}}{P} = \begin{cases} r & \text{if } \Phi_i = 0 \\ r - \frac{e^{rt}\Phi_i}{P} & \text{if } \Phi_i > 0 \end{cases}$$

where Φ_i is the adjoint variable of the borrowing constraint

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Carmona et al. 2008: Firm i's optimization problem

For given forward permit price A and prices of the produced goods S the firm i maximizes its expected terminal wealth by buying/selling an optimal number of permits and producing an optimal quantity of goods, i.e.

$$\sup_{\theta^i,\xi^i} \mathbb{E}\left[\underbrace{S^i(\xi^i) - C^i(\xi^i)}_{production} + \underbrace{T^i(\theta^i)}_{trading} - \underbrace{\Pi\left(\varepsilon^i + e^i(\xi^i) - \Delta^i - \theta^i_T\right)^+}_{penalty}\right] \tag{9}$$

Variables

$S^i(\xi^i) = \sum_{t=0}^{T-1} \sum_{j,k} S_t^k \xi_t^{i,j,k}$	revenues from selling the produced goods
$C^i(\xi^i) = \sum_{t=0}^{T-1} \sum_{j,k} C_t^k \xi_t^{i,j,k}$	costs from producing the goods
$T^i(\theta^i) = \sum_{t=0}^{T-1} \theta_t^i (A_{t+1} - A_t) - \theta_T^i A_T$	profit/loss from trading emission permits
$e^i(\xi^i) = \sum_{t=0}^{T-1} \sum_{j,k} S_t^k \xi_t^{i,j,k}$	firm i's emissions in [0,T] from the production
$\Delta^i = \sum_{t=0}^{T-1} \Delta_t^i$	number of emission permits allocated to firm i in [0,T]

ε^i	quantity of firm i's emissions in [0,T] that cannot be controlled
θ_t^i	number of forward contracts on emission permits held by firm i at time t
Π	penalty per emission unit
S_t^k	price of product k
$C_t^{i,j,k}$	firm i's marginal production costs of product k using production technology j
$e_t^{i,j,k}$	emission factor of firm i, production technology j and product k

Market equilibrium

A market equilibrium in emission permits consists of

- A^* (one-dimensional stochastic process for forward price on permits)
- S^* (multi-dim. stochastic process for the prices of the products)
- θ^* (multi-dim. stochastic process of optimal trading strategies)
- ξ^* (multi-dim. stochastic process of optimal production strategies)
- such that for given A^* and S^*, θ^* and ξ^* leads to a situation where all the firms are satisfied by their strategy.

Market equilibrium

Formally

$\mathbb{E}\left[L^{A^*,S^*,i}\left(\theta^{*i},\xi^{*i}\right)\right] \geq \mathbb{E}\left[L^{A^*,S^*,i}\left(\theta^{i},\xi^{i}\right)\right]$ for all $\left(\theta^{i},\xi^{i}\right)$

and the following two conditions hold

- Market clearing condition on permits

$$\sum_i \theta_t^{*i} = 0$$

- Supply meets demand for each good

$$\sum_{i,j} \xi_t^{*i,j,k} = D_t^k$$

Global optimization problem

A fictitious central planner minimizes expected total costs by producing an optimal quantity of goods ξ^*, i.e. it faces the optimization problem

$$\inf_{\xi} \mathbb{E}\left[\underbrace{C(\xi)}_{production} - \underbrace{\Pi\left(\varepsilon + e(\xi) - \Delta\right)^+}_{penalty} \right] \tag{10}$$

where

$C(\xi) = \sum_i C^i(\xi^i)$	total production costs
$e(\xi) = \sum_i e^i(\xi^i)$	total emissions from production in [0,T]
$\varepsilon = \sum_i \varepsilon^i$	total emissions in [0,T] that are not controllable
$\Delta = \sum_i \Delta^i$	total emission certificates handed out by the regulato
Π	penalty per emission unit

Theorem: Market equilibrium and joint optimization problem

(a) If (A^*, S^*) is a market equilibrium with associated strategies (θ^*, ξ^*) then ξ^* is a solution of the global optimization problem
(b) There exists a solution $\bar{\xi}$ of the global optimization problem
(c) If $\bar{\xi}$ is a a solution of the global optimization problem then $(\bar{A}, \bar{S})$ is a market equilibrium and the equilibrium allowance price process is almost surely unique

Theorem: Equilibrium prices

Let (A^*, S^*) be a market equilibrium with associated strategies (θ^*, ξ^*) then
Forward prices on permits are almost surely given by

$$A_t^* = \Pi \cdot \mathbb{E}\left[\chi_{\{\varepsilon + e(\xi) - \Delta \geq 0\}} \middle| \mathcal{F}_t\right]$$

Theorem: Equilibrium prices

Spot prices S^{*k} of the goods and the optimal production strategy ξ^{*i} correspond to a merit-order-type equilibrium with adjusted costs $C_t^{i,j,k} + e^{i,j,k} A_t^*$, i.e. at time t and for each good k

- all the production means of the economy are ranked by increasing adjusted production costs
- demand is met by producing from the cheapest production means
- k's equilibrium spot sprice is the marginal cost of production of the most expensive production means used to meet demand D_t^k

$$S_t^{*k} = \max_{i,j} \left\{ \left(C_t^{i,j,k} + e^{i,j,k} A_t^* \right) \chi_{\left\{ \xi_t^{i,j,k} > 0 \right\}} \right\}$$