Quantitative Climate Finance

Lecture - Summer 2013

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Agenda

Economics of Climate Change

- CO_2 emissions and global warming
- Assessment via Environmental Economics
- Policy Instruments

Emission Trading Schemes

Equilibrium Models

Reduced Form Models

Flexible Mechanisms under the Kyoto Protocol

Capital Market and Renewable Energy Projects

United Nations Framework Convention on Climate Change

Background from United Nations Framework Convention on Climate Change can be found

`http://unfccc.int/essential_background/items/6031.php`

Greenhouse Gas Emissions and Climate Change

- Greenhouse Gas Emissions (GHG) are seen as a major reason for global climate change. Since CO_2 emissions are the main source of GHG emissions, GHG are measured in terms of CO_2 equivalents, CO2e.
- In 2010 we observed for the first time in many years an increase in GHG emissions, which makes it increasingly unlikely to met the World Climate Conference (Cancún 2010) target of a 2^o Celcius temperature increase by 2050.

Greenhouse Gas Emissions and Climate Change

- The climate change will lead to an increase of the probability and frequency of storms, floods, draughts according to the Intergovernmental Panel on Climate Change (IPCC).
- The overall stock of CO2e in the atmosphere is relevant. In 2007 CO2e were around 430 parts per million (ppm) rising around 2,5 ppm per year.
- Targets may be a certain temperature increase or a certain stock (with different flow paths)

Probabilities of Temperature Increases

Stabilisierungsniveau (in ppmv CO2e)	2°C	3°C	4°C	5°C	6°C	7°C
450	78	18	5	1	0	0
500	96	44	11	3	1	0
550	99	69	24	7	2	1
650	100	94	58	24	9	4
750	100	99	82	47	22	9

Wahrscheinlichkeiten (%) ein Temperaturniveau im Gleichgewicht zu übersteigen[4]

Figure : Probability of Temperature Increase higher than

Carbon Target

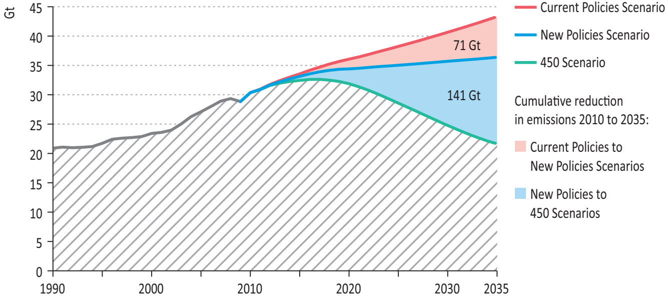

Figure : World energy-related CO2 emissions by scenario

Consequences of Climate Change - Scenario 1

1) No change in policy towards climate change

- Global temperatures could rise by 6-7 Celsius this century - well above the 2 Celsius 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 may die off

Consequences of Climate Change - Scenario 2

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

- Sea levels will rise and low-lying land such as Tarawa, Kiribati 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

Consequences of Climate Change - Scenario 3

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

- World will warm by no more than 2 Celsius by mid-century and thereafter temperatures may start to decline
- Hottest parts of the world will suffer serious declines in crop yields, 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

GHG Emissions are Externalities

- GHGs are global in origin and impact
- Some effects are long-term and governed by a flow-stock process
- There are great uncertainties in most steps of the scientific chain
- Failure to act may have large, possibly irreversible effect.

Challenges

- Economics of risk and uncertainty have to be used
- Links between economics and ethics have to be considered
- International economic policy plays an important role

Risks

- Relation between stock of GHG and temperature increase has to be considered: climate sensitivity
- General Circulation Models (GCM) of climate science produce via Monte Carlo Analysis probability distributions of outcome
- By design: high sensitivity to parameter values

Abatement Costs

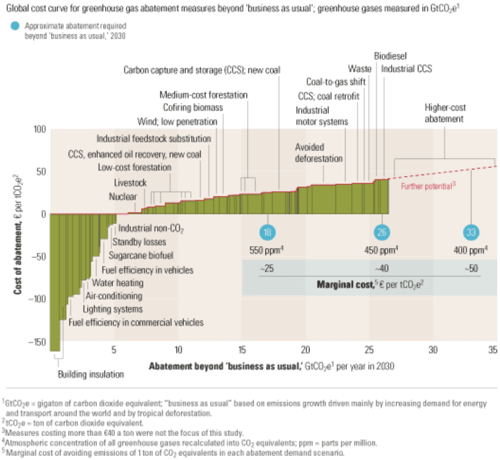

Figure : Abatement Costs

Cost Comparison

- Compare cost of abatement with social cost of carbon (SCC)
- Calculation SCC in a time interval $[0, t]$
  - marginal social utility of consumption at time $\tau \in [0, t]$
  - impact on consumption at τ on all relevant preceding temperature changes
  - impact on relevant temperature increases of increases in preceding carbon stock
  - the impact of all relevant stocks of an increase in carbon emissions in τ

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Ethics

- How to value benefits accruing to different people at different times?
  - intratemporal distribution (between different people at the same time)
  - intertemporal distribution (between generations)
- The discussion focuses on appropriate discount factors and utility functions to capture values
- Utility functions need to take environment, health, type of consumption into account
- Technological progress has to be taken into account.

Instruments

- Price for GHG emissions (externalities are market failures)
- Technology and acceleration of its development
- Energy efficiency (in terms of information and transaction costs)
- International framework and collaboration

EU Roadmap 2050

Headline Target for the EU to be achieved by 2020 relating to energy and climate change aims are

- reducing greenhouse gas emissions (GHG) by 20%,
- increasing the share of renewables in the EU's energy mix to 20%,
- achieving the 20% energy efficiency target.

Emission target

- To keep climate change below 2 Celcius, the European Council reconfirmed in February 2011 the EU objective of reducing greenhouse gas emissions by 80-95% by 2050 compared to 1990.
- The EU Emission Trading System (ETS) is supposed to play a key role by generating a sufficient carbon price, which is long-term predictable.
- The EU considers taxation and technological support as additional measures.

FAZ on Emissions 11. April 2012

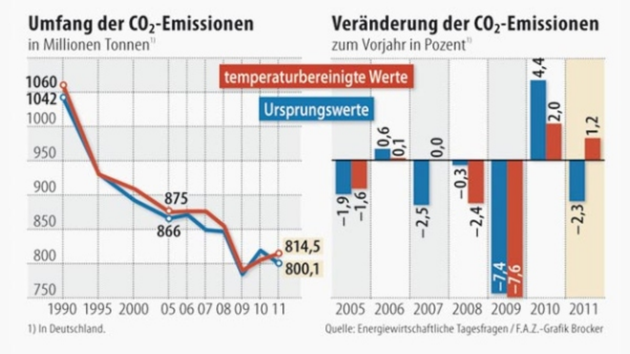


Figure : Emissions 2011

Putting a Price on Carbon

- taxation
- carbon trading on the basis of allocation and auctioning
- implicit, via regulation and standards.

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 an equal reduction).
- **Taxes: 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

- **Taxes: Product charges**
  Control authority taxes the commodity that is responsible for the pollution instead of the pollutant. Problem: They are easy to administer. However, 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.

Agenda

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€

Overview of different emission trading systems

- SO_2 **(US)**
  Acid rain is mostly caused by human emissions of sulfur dioxide (fossil fuel fired power plants). It harms plants, aquatic animals and damages infrastructure (buildings, monuments). The SO_2 emission trading system under the framework of the 1990 Clean Air Act Amendments started in 1995 and is expected to reduce SO_2 by 50% (2010 vs. 1980).
- CO_2 **(EU)**
  A lot of researchers (among them the Intergovernmental Panel on Climate Change, IPCC) conclude that global warming is mainly caused by anthropogenic greenhouse gases (GHG) such as CO_2. Global warming will amongst other effects lead to rising sea levels and more extreme weather events.

Overview of different emission trading systems

- **Other GHG trading systems**
  - New South Wales Greenhouse Gas Abatement Scheme (Australia, launched in 2003).
  - Australian ETS starts in 2014. Currently, tax-based first phase. http://www.climatechange.gov.au/
  - New Zealand ETS (New Zealand, launched in 2008)
  - Regional Greenhouse Gas Initiative (US, launched in 2009)
- **GHG trading system in the US (was planned but is now shelved)**
  Ambitious plan that would lead to the world's largest CO_2 emission trading system (covering about 80 per cent of US output vs less than half in Europe). However, California started an ETS in 2012. http://www.arb.ca.gov/cc/capandtrade/capandtrade.htm
- Overview: http://www.climatechange.gov.au/government/international/global-action-facts-and-fiction/

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
  - **Phase III (2013-20)** inducing significant changes compared to the two previous periods, according to Directive 2009/29/EC
- 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.
- 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.

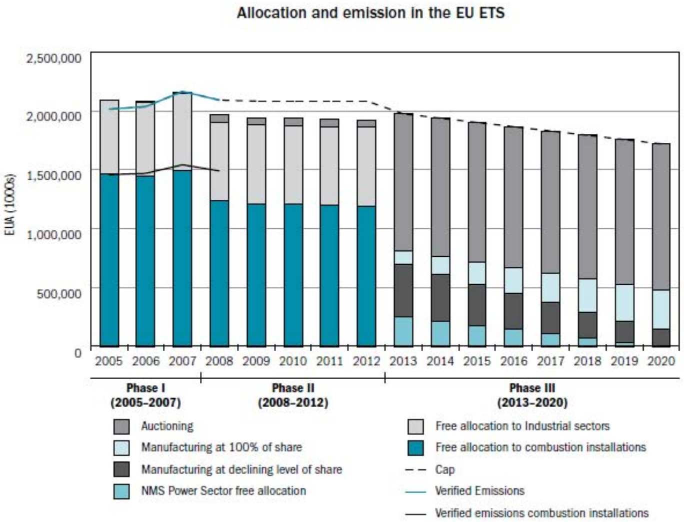
Characteristics of EU ETS (CO_2) - Phases I and II

- Process steps concerning the distribution of the allowances according to Phases I and II:
  - 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
- 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 (excess emissions penalty).

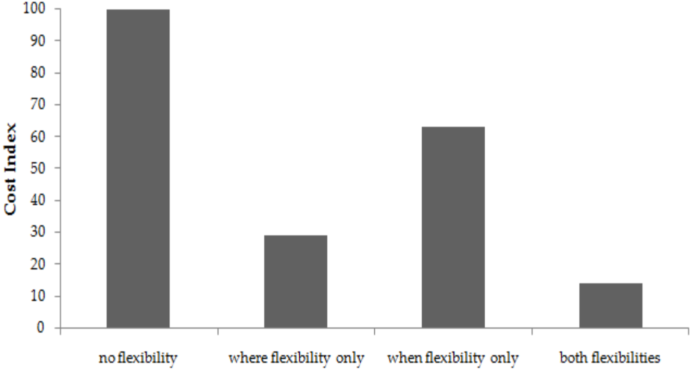
Characteristics of EU ETS (CO_2) - Phase III

- Process steps concerning the distribution of the allowances according to Phase III:
  - NAPs will be abolished
  - From 2013 onwards **Auctioning** will be introduced as default method of initial allowance allocation
  - The initial auctioning share in the power sector will be 100%
  - For all other sectors the initial auction share will be 20% and is to be increased to 70% by 2020 (and to 100% respectively by 2027)
  - Non-auctioned allowances will be distributed on the basis of benchmarks
- The amount of the excess emissions penalty in the upcoming third phase shall be indexed to the annual inflation rate of the Eurozone.

Allocation and emissions in the EU ETS



ETS and flexibility: *When* and *Where*



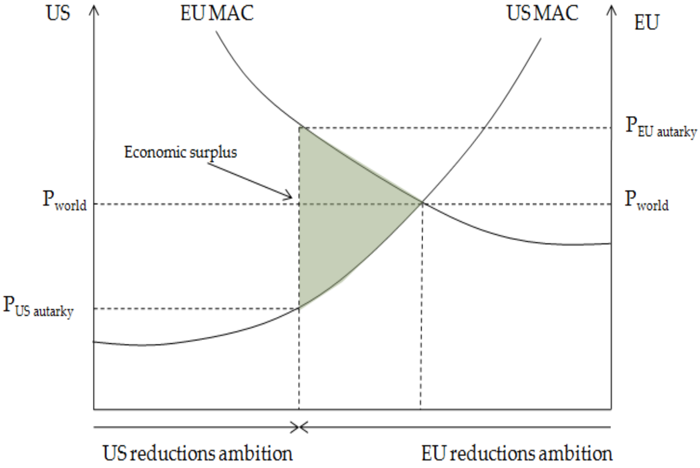
Source: Richels et al (1996)

Figure : Cost reductions from allowing 'where' and 'when' flexibility

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 phases

Figure : EUA - futures prices (1 January 2005 - 15 August 2011).

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.

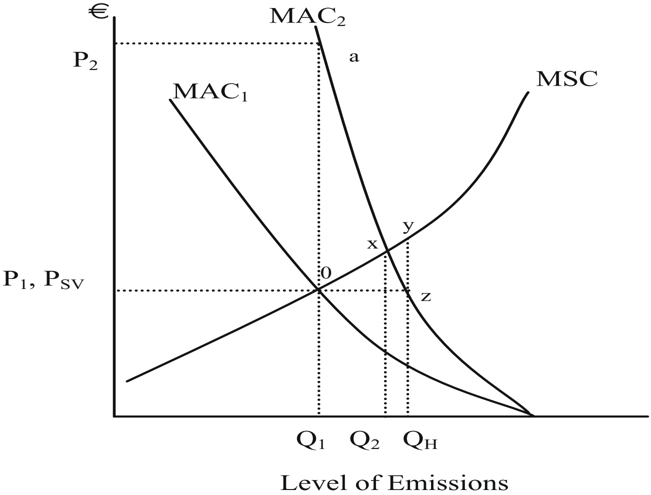
Price ceilings and price floors

- 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.

Hybrid System with Safety Valve



Ecological Effectiveness

- Emission trading systems sets a cap, which in theory establishes precisely the level of emissions which is desired (100% effectiveness)
- Tax system cannot guarantee an exact amount of emissions as an outcome. The tax level is set under uncertainty about the marginal abatement costs.
- Hybrid systems reach the target value as long as the system is in its trade area. As soon as the trigger level is reached the ecological target becomes diluted due to the additional certificates.

Political Feasibility

Political feasibility is the level of acceptance a policy has in the public. A major factor is the number of people affected.

- Emission trading systems have a good political enforceability since costumers feel no direct effect by government action.
- Price rises are blamed on companies, especially in case allocation is free. In case of auctioning extra government revenues can be used for redistribution.
- Tax systems are generally met with scepticism (especially in the US). Additional costs on emissions will effect consumers more directly via cost increases.
- Hybrid systems also generate an extra revenue after the trigger is met, which may be viewed positively.

Financial Impact

Financial impact relates to how consumers in a country with a regulation policy are affected in monetary terms.

- In emission trading systems with free allocation companies have integrated the costs (price) for certificates as real costs and prices have increased (pass-through rates of cost between 60% and 100% in Germany).
- High windfall profits for companies in the power sector (around 5 Mrd Euro).
- Tax systems will also increase costumer costs.

Multiple Instruments I

- 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.

Multiple Policy Instruments II

- Combinations of permit trading schemes, carbon taxes, technology-specific subsidies and regulatory standards
- Taxes introduced by Sweden, Norway, Denmark, Ireland
- Subsidies for renewable energy by Germany, Spain
- Academic literature gives justification for multiple instruments used in a complimentary way, i.e. hybrid systems. Justification in terms of presence of multiple market failures, asymmetric information, principle-agent relation

Tax and Trade

- Carbon tax t (Euro per tonne)
- Cap-and-trade scheme with price p
- Firm must pay tax and procure certificates for emissions

e_0	baseline emission
e	emissions after abatement
a	$= e_0 - e$;
$c(a)$	abatement costs, $c' > 0$, $c'' > 0$

- Optimization problem

$$\min_e \{c(e_0 - e) + te + pe\} = \min_e \{f(e)\} \tag{1}$$

- First-order-condition (*)

$$c'(e_0 - e^*) = t + p$$

Tax and Trade: optimization problem

- Since $c' > 0$ we can invert $e^* = e_0 - c'^{-1}(t+p) = e^*(t,p)$
- Since $f''(e) = c''(e_0 - e) > 0$ it is a minimum
- Differentiation of (*) w.r.t. the variable t:

$$\frac{\partial}{\partial t} c'(e_0 - e^*(t,p)) = \frac{\partial}{\partial t}(t+p)$$

$$-c''(e - e^*(t,p)) \frac{\partial}{\partial t}(e^*(t,p)) = 1$$

$$e_t^* = -\frac{1}{c''} < 0$$

- Thus increases in tax reduce emissions; By symmetry $e_p^* = -\frac{1}{c''} < 0$ increases in price reduce emissions and $e_t^* = e_p^*$

Tax and Trade: optimization problem

Assume a cap E, n identical firms, such that the aggregate emissions are $E = ne^*$.
For constant tax t formally

$$dE = ne_p^* dp, \text{ so } \frac{dp}{dE} = (ne_p^*)^{-1} < 0$$

that is an increase in the cap reduces the price.
For fixed cap we have

$$ne_t^* dt + ne_p^* dp = 0$$

$$\frac{dp}{dt} = -\frac{e_t^*}{e_p^*} = -1.$$

That is ”a small increase in tax results one-for-one in an equivalent reduction of the permit price".

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Tax and Trade: optimization problem

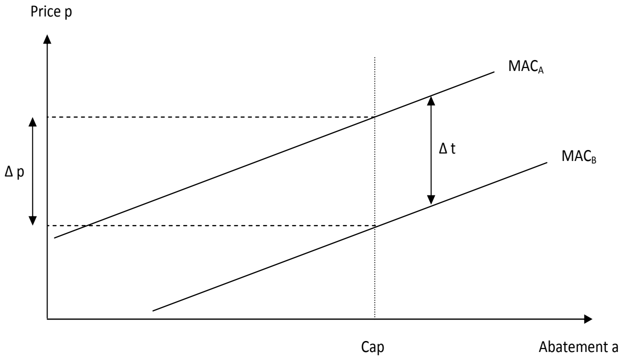

Figure : Relation of tax and permit price.

Tax and Trade

- MAC to use (for example) wind generation is how much it costs to generate electricity by wind compared with the cheapest alternative.
- So tax increase reduces MAC, because it reduces the opportunity cost of wind generation. Thus opportunity cost of abatement have decreased since the firm will pay a higher penalty not to abate.

Tax and Trade

- Model shows that an increase in tax reduces the permit price
- No additional abatement will be achieved
- The average carbon price will be reduced and the risk that the price system will collapse is increased

Subsidies and Trade

- Model shows that an increase in subsidies reduces the permit price
- A higher level of subsidy for an abatement technology reduce the abatement cost at any given level of production
- For a given emission cap, demand for permits will be lower and so will be the price.

Subsidies and Trade: optimization problem

Subsidy s applies equally to all firms and technologies provided accordingly to the level of abatement $a = e_0 - e$

- Optimization problem

$$\min_e \{c(e_0 - e) - s(e_0 - e) + pe\} = \min_e \{f(e)\} \qquad (2)$$

- First-order-condition

$$f'(e) = -c'(e_0 - e) + s + p = 0$$

so

$$c'(e_0 - e) = s + p$$

and

$$e^* = e_0 - c'^{-1}(s + p) = e^*(s, p)$$

Subsidies and Trade: optimization problem

The same calculation as above shows

$$\frac{dp}{ds} = -\frac{e_s^*}{e_p^*} = -1.$$

The higher the subsidy, the lower the permit price.

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Trade and Trade

- Two separate trading programs apply upstream to firms that produce electricity and downstream to firms that consume it.
- Example: UK with EU ETS for electricity producers and Carbon Reduction Commitment for firms and organizations that are primarily electricity consumers.

Trade and Trade

Compliance upstream

- higher electricity price
- equivalent to tax on energy consumption (linked to carbon price)
- downstream implicit price of carbon

Increase in upstream permit prices

- increase tax downstream
- decrease downstream carbon price (see part 1)

Uniliteral Tax and Trade

- Firms are identical
- Tax only affects a fraction f of firms
- Uniliteral tax leads to diverging marginal costs and so increased mitigation costs.

Unilateral tax and trade

- Firms are identical with optimal emissions $e^*(t,p)$; $e_p^* = e_t^* = -\frac{1}{c''}$
- Tax affects only a fraction of firms f (a fraction of the system-wide emissions) $0 < f < 1$
  So

$$E = fne^*(t,p) + (1-f)ne^*(p) \tag{3}$$

Assuming

$$e_p^{*f} = e_p^{*(1-f)}$$

We find

$$dE = fne_t^* dt + ne_p^* dp$$

Unilateral tax and trade

Fix E, then the impact of the tax on the permit price is

$$0 = fe_t^* dt + e_p^* dp \Rightarrow \frac{dp}{dt} = -f\frac{e_t^*}{e_p^*} = -f$$

The impact of the tax change on permit prices is diluted and different for the two categories

$$\frac{de^{*f}}{dt} = e_t^{*f} + e_p^{*f}\frac{dp}{dt} = -\frac{1}{c''} + (-\frac{1}{c''})(-f) = -(1-f)\frac{1}{c''} < 0$$

$$\frac{de^{*1-f}}{dt} = e_p^{*(1-f)}\frac{dp}{dt} = \frac{f}{c''} > 0$$

So the emissions for firms subject to tax fall, but the emissions for firms with no tax increase.

Unilateral tax and trade

The impact on marginal costs for taxed firms is (use $c'(e_0 - e^*) = t + p$))

$$\frac{d(c^f)'}{dt} = \frac{dt}{dt} + \frac{dp}{dt} = 1 - f > 0$$

and for untaxed firms

$$\frac{d(c^{1-f})'}{dt} = \frac{dp}{dt} = -f < 0$$

Diverging marginal costs mean that the gains from trade are, at least in part, reversed. (Remember firms where identical, now mitigation costs increase.)

Unilateral tax and trade

Tables based on quadratic cost functions
Mitigation costs rise because more expensive technologies in countries with tax would substitute out more cost-effective emissions reduction technologies in countries without tax.

Impact of Overlapping Tax

Table 1 The Impact of an overlapping tax by France, Ireland, the UK, or all three on the EU Allowance price in 2010

	Tax Level			
	5€ per tCO_2	10€ per tCO_2	15€ per tCO_2	20€ per tCO_2
France	-0.18 €	-0.37 €	-0.55 €	-0.73 €
Ireland	-€ 0.03	-€ 0.06	-€ 0.09	-€ 0.12
UK	-€ 0.34	-€ 0.67	-€ 1.01	-€ 1.34
France+Ireland+UK	-€ 0.55	-€ 1.10	-€ 1.65	-€ 2.19

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Impact of Overlapping Tax by 2020

Table 2 The Impact of an overlapping tax by France, Ireland, the UK, or all three on EU-wide mitigation costs by 2020 (per cent increase)

	Tax Level			
	5€ per tCO_2	10€ per tCO_2	15€ per tCO_2	20€ per tCO_2
France	0.3%	1.1%	2.4%	4.2%
Ireland	0.0%	0.2%	0.3%	0.6%
UK	0.6%	2.3%	5.1%	9.0%
France+Ireland+UK	1.2%	4.6%	10.4%	18.5%

Technology Policies and Trade

- A technology-specific measure affects only part of the MAC curve and will lead to a compositional reorientation of the curve
- In EU ETS fuel switching from coal to gas is targeted
- Trading price may fall, but mitigation cost will rise in general.

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Possible Impact of Subsidies I

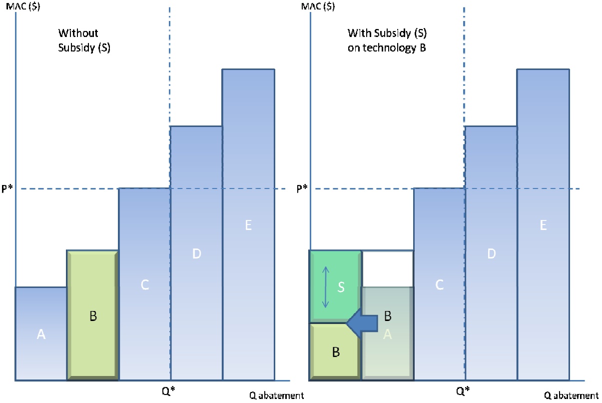

Figure 2 Subsidizing abatement technology B (by amount S per unit), changes its position along the MAC curve, but does not affect the permit price (p*) because the cost of technology B stays below the margin both before and after the subsidy. The total amount of abatement (Q*) remains the same.

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Possible Impact of Subsidies II

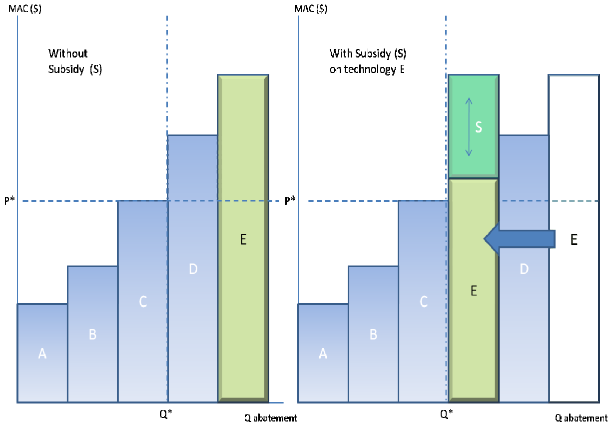

Figure 3 Subsidizing abatement technology E (by amount S per unit) changes its position along the MAC curve, but does not affect the permit price (p*), because the cost of technology E with subsidy remains above the margin. The total amount of abatement (Q*) remains the same.

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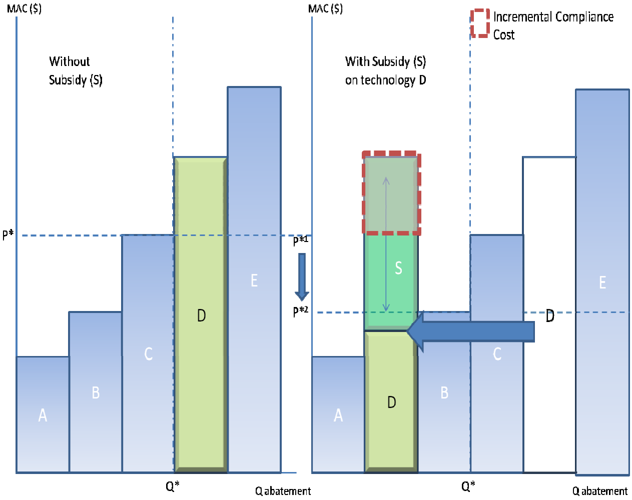
Possible Impact of Subsidies III



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Agenda

Economics of Climate Change

Emission Trading Schemes

Equilibrium Models
- Deterministic Equilibrium Model
- Stochastic Equilibrium Model
- Dynamics of CO2 permit prices

Reduced Form Models

Flexible Mechanisms under the Kyoto Protocol

Capital Market and Renewable Energy Projects

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Rubin 1996: Firm i's optimization problem

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

$$\min_{\theta_i, e_i} \left\{ \int_0^T e^{-rt} [C_i(e_i(t)) + P(t)\theta_i(t)] dt \right\} \tag{4}$$

$$\text{subject to } \dot{B}_i = S_i(t) - e_i(t) + \theta_i(t) \tag{5}$$

$$B_i(0) = 0 \text{ and } B_i(t) \geq 0 \tag{6}$$

$$e_i(t) \geq 0 \tag{7}$$

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)

$\theta^*(t) = (\theta_1^*(t), \ldots, \theta_N^*(t))$ (vector of optimal trading volumes)

$E^*(t) = (e_1^*(t), \ldots, e_N^*(t))$ (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.

$$\min_{e_1,\ldots,e_N} \left\{ \int_0^T e^{-rt} \sum_{i=1}^{N} C_i(e_i(t))dt \right\} \tag{8}$$

$$\text{subject to } \dot{B}(t) = \sum_{i=1}^{N} (S_i(t) - e_i(t)) \tag{9}$$

$$B(0) = 0 \text{ and } B(t) \geq 0 \tag{10}$$

$$e_i(t) \geq 0 \quad \text{for all } i = 1, \ldots, N \tag{11}$$

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

- follows Hotelling's rule 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

Proof:
Follows from evaluating the necessary conditions (hereby use the Hamiltonian)

Rubin 1996: Necessary (and sufficient) conditions for firm i's minimization problem

The **Hamiltonian** is given by

$$H_i = e^{-rt}[C_i(e_i(t)) + P(t)\theta_i(t)] + \lambda_i[S_i - e_i + \theta_i]$$

and the **generalized Hamiltonian** is given by $L_i = H_i - \Phi_i B_i - \tau_i e_i$
Hence

$$\dot{B}_i = \frac{\partial L_i}{\partial \lambda_i} = S_i - e_i + \theta_i \tag{12}$$

$$\dot{\lambda}_i = -\frac{\partial L_i}{\partial B_i} = \Phi_i \tag{13}$$

$$B_i \geq 0, \quad \Phi_i \geq 0, \quad \Phi_i B_i = 0 \tag{14}$$

$$\frac{\partial L_i}{\partial e_i} = e^{-rt} C_i'(e_i) - \lambda_i \geq 0 \tag{15}$$

$$e_i \geq 0, \quad \tau_i \geq 0, \quad e_i \frac{\partial H_i}{\partial e_i} = 0 \tag{16}$$

$$B_i(T) \geq 0, \quad \lambda_i(T) \leq 0, \quad B_i(T)\lambda_i(T) = 0 \tag{17}$$

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.

$$\sup_{\theta^i,\xi^i} \mathbb{E}\left[\underbrace{S^i(\xi^i) - C^i(\xi^i)}_{production} + \underbrace{T^i(\theta^i)}_{trading} - \underbrace{\Pi\left(\varepsilon^i + e^i(\xi^i) - \Delta^i - \theta^i_T\right)^+}_{penalty}\right] \tag{18}$$

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^* lead to a situation where all the firms are satisfied by their strategy.

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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

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

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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

$$\inf_{\xi} \mathbb{E}\left[\underbrace{C(\xi)}_{production} - \underbrace{\Pi\left(\varepsilon + e(\xi) - \Delta\right)^+}_{penalty}\right] \tag{19}$$

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 regu
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

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

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 price is the marginal cost of production of the most expensive production means used to meet demand D_t^k

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

Basic Model

- Risk-neutral companies with total initial endowment e_0
- Total emissions dynamics are

$$dy_t = \mu(t, y_t)dt + \sigma(t, y_t)dW_t \tag{20}$$

  with deterministic drift and volatility.
- Central planner who minimizes total expected cost over a trading period $[0, T]$ by deciding at any time instant whether to costly abate some of the CO2 emissions or not.
- At the end of the period actual accumulated emissions and penalty costs are determined.

Basic Model II

- x_t are the total expected emissions over the trading period
- Then

$$x_t = -\int_0^t u_s ds + \mathbb{E}_t\left[\int_0^T y_s ds\right] \tag{21}$$

- u_t is the optimal rate of abatement which is actively chosen by the central planner.
- So x_t is a controlled stochastic process.

Total Emissions

- x_T are the realized emissions that relate to a potential penalty function
- Without abatement total expected emissions are

$$x_0 = \mathbb{E}\left[\int_0^T y_s ds\right]$$

- The dynamics of the total expected emissions are

$$dx_t = -u_t dt + G(t) dW_t \tag{22}$$

- $G(t)$ is the volatility of the uncontrolled part of x_t and depends both on the drift $\mu(t, y_t)$ and the volatility $\sigma(t, y_t)$ of the emission rate.

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Optimisation problem of the central planner I

$$\max_{u_t} \mathbb{E}_0 \left[\int_0^T e^{-rt} C(t, u_t) dt + e^{-rT} P(x_T) \right] \tag{23}$$

with

$$\begin{aligned} C(t, u_t) &= -\tfrac{1}{2} c u_t^2 \\ P(x_T) &= \min[0, p(e_0 - x_T)] \end{aligned}$$

Optimisation problem of the central planner II

- $C(t, u_t)$ are the abatement costs per unit of time. c constant implies no change in technology occurs. The quadratic form implies linearly increasing marginal abatement costs.
- $P(x_T)$ is the penalty function, with p the penalty including all costs.
- r is the constant interest rate.

Solution of the control problem

Let $V(t, x_t)$ be the expected value of the optimal policy given x_t. By a standard Hamilton-Jacobi-Bellman argument we arrive at

$$V_t = -\frac{1}{2}(G(t))^2 V_{xx} - \frac{1}{2c} e^{rt} (V_x)^2 \tag{24}$$

with boundary condition

$$V(T, x_T) = e^{-rT} P(x_T)$$

and optimal control

$$u_t = -\frac{1}{c} e^{rt} V_x$$

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Permit Prices

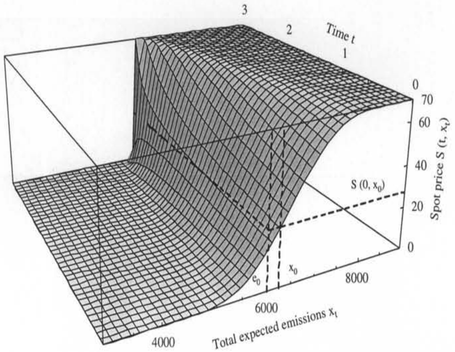

Fig. 1. Equilibrium spot price $S(t, x_t)$—risk neutral special case. The figure shows the equilibrium spot price of emission certificates dependent on time t and total expected emissions x_t within a trading period, where the emission rate y_t follows a white noise process and interest $r = 0$. Initial endowment $e_0 = 6000$, initial total expected emissions $x_0 = 6240$, and expected spot price level $S(0, x_0) = 27.46$ are indicated by dashed lines. Upper price bound is $p = 70$.

Permit Price Dynamics

- Recall that the permit price must equal the marginal abatement costs, so

$$S(t, x_t) = cu_t = -e^{rt} V_x(t, x_t) \tag{25}$$

- Using Itô's formula and the HJB-PDE we find that the discounted permit price is a martingale.
- Its dynamics are

$$dS(t, x_t) = G(t) S_x(t, x_t) dW_t \tag{26}$$

Implied Permit Price Volatility

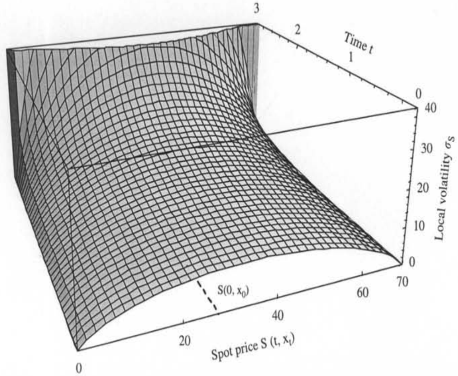

Fig. 2. Local volatility σ_S—risk neutral special case. This plot presents the local volatility σ_S for the resulting spot price process $S(t, x_t)$ dependent on time and spot price level, where the emission rate y_t follows a white noise process. The expected spot price level $S(0, x_0) = 27.46$ for $x_0 = 6240$ is indicated by the dashed line. The upper price bound is $p = 70$. The plot is cut at $\sigma_S = 40$ because σ_S reaches infinity at $t = T$.

Individual Company Models

- Each individual company has an endowment e_{i0}
- Individual emissions dynamics are

$$dy_{it} = \mu(t, y_{it})dt + \sigma(t, y_{it})dW_{it} \tag{27}$$

with deterministic drift and volatility.

Individual Emissions

- x_{it} are the total expected emissions of company i over the trading period
- Then

$$x_{it} = -\int_0^t u_{is} ds - \int_0^t z_{is} ds + \mathbb{E}_t \left[\int_0^T y_{is} ds \right] \tag{28}$$

- u_{it} is the individual rate of abatement
- and z_{it} is the instantaneous amount of permits bought or sold.

Individual Emissions Dynamics

- The dynamics of the total expected emissions are

$$dx_{it} = -[u_{it} + z_{it}]dt + G_i(t)dW_{it} \tag{29}$$

- $G_i(t)$ is the volatility of the uncontrolled part of x_{it} and depends both on the drift $\mu_i(t, y_{it})$ and the volatility $\sigma_i(t, y_{it})$ of the emission rate.

Optimisation Problem for the individual Company

$$\max_{u_{it}, z_{it}} \mathbb{E}\left[\int_0^T e^{-rt} C_i(t, u_{it}) dt - \int_0^T e^{-rt} S(t) z_{it} dt + e^{-rT} P_i(x_{iT})\right] \tag{30}$$

with $S(t)$ the permit price and

$$\begin{aligned} C_i(t, u_{it}) &= -\tfrac{1}{2} c_i u_{it}^2 \\ P_i(x_{iT}) &= \min[0, p(e_{i0} - x_{iT})] \end{aligned}$$

Solution of the control problem

Let $V^i(t, x_{it})$ be the expected value of the optimal policy for company i. By a standard Hamilton-Jacobi-Bellman argument we arrive at

$$\begin{aligned} 0 &= \max_{u_{it}, z_{it}} \Big[e^{-rt}(C_i(t, u_{it}) - S(t) z_{it}) \\ &\qquad + V_t^i - V_x^i(u_{it} + z_{it}) + \tfrac{1}{2}(G_i(t))^2 V_{xx}^i \Big] \end{aligned}$$

with boundary condition

$$V^i(T, x_{iT}) = e^{-rT} P_i(x_{iT}).$$

Equilibrium Solution

- We solve the HJB for N companies and use the market clearing condition

$$\sum_{i=1}^{N} z_{it}^{*} = 0$$

- The first-order conditions give

$$\begin{aligned} u_{it}^{*} &= -\frac{1}{c_i} e^{rt} V_x^i \quad i = 1, \dots N \\ S(t) &= -e^{rt} V_x^i \quad i = 1, \dots N \end{aligned}$$

- So again

$$S(t) = c_i u_{it}^{*}, \; i = 1, \dots N.$$

Joint Cost Problem I

Again we image a central planner who has to solve

$$\max_{u_{it}} \mathbb{E}\left[\int_0^T e^{-rt}\sum_{i=1}^N C_i(t,u_{it})dt + e^{-rT}\sum_{i=1}^N P_i(x_{iT})\right] \tag{31}$$

with C_i and P_i as before.
We assume only one source of randomness, i.e. $W_{it} = W_t$, then we have the joint value function as

$$V(t, x_{1t}, \ldots, x_{Nt}) = \sum_{i=1}^N V_i(t, x_{it}).$$

Joint Cost Problem II

The joint cost problem now is

$$0 = \max_{\{u_{it}, i=1,\dots,N\}} \left[e^{-rt} \sum_{i=1}^{N} C_i(t, u_{it}) + \sum_{i=1}^{N} (V_t^i - V_x^i u_{it}) + \frac{1}{2} \sum_{i=1}^{N} (G_i(t))^2 V_{xx}^i \right]$$

with boundary condition

$$\sum_{i=1}^{N} V^i(T, x_{iT}) = e^{-rT} \sum_{i=1}^{N} P_i(x_{iT}).$$

Joint Problem Solution

- The first-order conditions give

$$u_{it}^{**} = -\frac{1}{c_i} e^{rt} V_x^i, \; i = 1, \ldots N$$

- Due to linearity we also have

$$u_{it}^{**} = \operatorname{argmax} \left\{ \max_{u_{it}} \left[e^{-rt} C_i(t, u_{it}) + V_t^i - V_x^i u_{it} + \frac{1}{2} (G_i(t))^2 V_{xx}^i \right] \right\}$$

- Again

$$S(t) = c_i u_{it}^{**} = -e^{rt} V_x^i, \; i = 1, \ldots N.$$

Equivalence to Equilibrium Solution

$$
\begin{aligned}
& u_{it}^{**} \\
= \quad & \operatorname{argmax}\left\{\max_{u_{it}, z_{it}} \quad \left[e^{-rt} C_i(t, u_{it}) - e^{-rt} S(t) z_{it} + e^{-rt} S(t) z_{it}\right.\right. \\
& \qquad \left.\left. + V_t^i - V_x^i u_{it} + \tfrac{1}{2}(G_i(t))^2 V_{xx}^i\right]\right\} \\
= \quad & \operatorname{argmax}\left\{\max_{u_{it}, z_{it}} \quad \left[e^{-rt}(C_i(t, u_{it}) - S(t) z_{it})\right.\right. \\
& \qquad \left.\left. + V_t^i + V_x^i(-u_{it} - z_{it}) + \tfrac{1}{2}(G_i(t))^2 V_{xx}^i\right]\right\} \\
= \quad & u_{it}^{*}
\end{aligned}
$$

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Basic Model

- Total emissions dynamics are

$$dy_t = \mu(y_t)dt + \sigma(y_t)dW_t \tag{32}$$

  with deterministic drift and volatility.
- buy or sell z_t permits in the market
- abate u_t with cost function $C(u_t)$
- pay penalty costs

Basic Model II

- x_{t,T_k} are the total expected emissions in $[0, T_k]$
- Then

$$x_{t,T_k} = -\int_0^t u_s ds - \int_0^t z_u du + \mathbb{E}_t\left[\int_0^{T_k} y_s ds\right] \tag{33}$$

Multi-period Framework

- Consider n consecutive trading periods $[0, T_1], [T_1, T_2], \ldots [T_{n-1}, T_n]$ with inter-period banking (no borrowing).
- Initial endowment of $e_{T_{k-1}}$ at the beginning of each period $[T_{k-1}, T_k]$.
- Have to pay penalty if emissions x_{T_k} from 0 to T_k exceed the total allocated permits

$$e_{T_k} = \sum_{T_j < T_k} e_{T_j}.$$

- With $R(x_{T_k}) = e_{T_k} - x_{T_k}$ penalty cost are

$$P(x_{T_k}) = P \min\{0, R(x_{T_k})\}$$

Multi-period Optimisation problem

$$\max_{u_t, z_t} \quad \mathbb{E}_0 \quad \left[\int_0^{T_n} e^{-rt} C(u_t) dt - \int_0^{T_n} e^{-rt} S(t) z_t dt \right.$$
$$\left. + \sum_{j=1}^{n} e^{-rT_j} P(x_{T_j}) + R(X_{T_n}) S_{end} \right]$$

Equilibrium Solution

N companies with

- u_{it} is the individual rate of abatement
- and z_{it} is the instantaneous amount of permits bought or sold
- solve their individual cost problem
- with market clearing condition

$$\sum_{i=1}^{N} z_{it}^{*} = 0 \ \ \forall t \in [0, T_n]$$

Permit Price Process

- The general structure is still

$$S(t) = \sum_{T_j > t} e^{-r(T_t - t)} P \mathbb{E}_t \left[\mathbf{1}_{\{R(x_{T_j}) < 0\}} \right] + e^{rt} S_{end}$$

- The first-order conditions give

$$S(t) = c_i u_{it}^*, \; i = 1, \ldots N.$$

Solution Strategy

- Start with the last period
  - find the characteristic PDE with boundary conditions from optimality principle of stochastic control
  - solve for strategy value function V_n
- step back one period
  - find the characteristic PDE
  - solve for strategy value with boundary condition from next periods value
- derive abatement strategy from HJB

Agenda

Permit price in the EU ETS during the first phase

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

Cumulative Emissions

To calculate permit prices, we specify the process for the cumulative emissions in the framework of Carmona et al. by

$$q_{[0,t]} = \int_0^t Q_s ds$$

where the emission rate Q_t follows a Geometric Brownian motion.
There is no closed-form density for $q_{[0,t]}$ available.

Approximation Approaches

- Linear approximation approach of Chesney and Taschini (2008)

$$q_{[t_1,t_2]} \approx \tilde{q}^{Lin}_{[t_1,t_2]} = Q_{t_2}(t_2 - t_1)$$

- Moment matching of Grüll and Kiesel (2009): Log-normal (moment matching)

$$q_{[t_1,t_2]} \approx \tilde{q}^{Log}_{[t_1,t_2]} = logN\left(\mu_L(t_1,t_2), \sigma^2_L(t_1,t_2)\right)$$

where the parameters $\mu_L(t_1,t_2)$, $\sigma_L(t_1,t_2)$ are chosen such that the first two moments of $\tilde{q}^{Log}_{[t_1,t_2]}$ and $\tilde{q}^{IG}_{[t_1,t_2]}$, respectively, match those of $q_{[t_1,t_2]}$.

Moment matching requires two steps

- Compute the first two moments m_k of a log-normal random variable and solve for the parameters.

  In the log-normal case we have that $m_k = e^{k\mu + k^2 \frac{\sigma^2}{2}}$ and

$$\sigma^2 = \ln\left(\frac{m_2}{m_1^2}\right) \qquad \mu = \ln(m_1) - \frac{1}{2}\sigma^2$$

- Compute the first two moments of the integral over a geometric Brownian motion

$$\begin{aligned} \mathbb{E}\left[q_{[t_1,t_2]}\right] &= Q_{t_1}\alpha_{t_2-t_1} \\ \mathbb{E}\left[\left(q_{[t_1,t_2]}\right)^2\right] &= 2Q_{t_1}^2\beta_{t_2-t_1} \end{aligned}$$

and plug those into the above equation.

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Auxiliary functions for moments of integral over GBM

$$\alpha_{t_2-t_1} = \begin{cases} \frac{1}{\mu}\left(e^{\mu(t_2-t_1)} - 1\right) & \text{if } \mu \neq 0 \\ t_2 - t_1 & \text{if } \mu = 0 \end{cases} \tag{34}$$

$$\beta_{t_2-t_1} = \begin{cases} \frac{\mu e^{(2\mu+\sigma^2)(t_2-t_1)} + \mu + \sigma^2 - \left(2\mu+\sigma^2\right) e^{\mu(t_2-t_1)}}{\mu(\mu+\sigma^2)(2\mu+\sigma^2)} & \text{if } \mu \neq 0 \\ \frac{1}{\sigma^4}\left(e^{\sigma^2(t_2-t_1)} - 1\right) & \text{if } \mu = 0 \end{cases} \tag{35}$$

Permit price - linear approximation

The permit price at time t is given by

$$S_t^{Lin} = \begin{cases} Pe^{-r\tau} & \text{if } q_{[0,t]} \geq N \\ Pe^{-r\tau} \cdot \Phi\left(\dfrac{-\ln\left(\frac{1}{\tau}\left[\frac{N-q_{[0,t]}}{Q_t}\right]\right) + \left(\mu - \frac{\sigma^2}{2}\right)\tau}{\sigma\sqrt{\tau}} \right) & \text{if } q_{[0,t]} < N \end{cases}$$

where

$\tau = T - t$ is the time to compliance.

$\Phi(\cdot)$ denotes the c.d.f. of a standard normal random variable.

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Permit price - log-normal moment matching

The permit price at time t is given by

$$S_t^{Log} = \begin{cases} Pe^{-r\tau} & \text{if } q_{[0,t]} \geq N \\ Pe^{-r\tau} \cdot \Phi\left(\frac{-\ln\left(\frac{N-q_{[0,t]}}{Q_t}\right) + 2\ln(\alpha_\tau) - \frac{1}{2}\ln(2\beta_\tau)}{\sqrt{\ln(2\beta_\tau) - 2\ln(\alpha_\tau)}} \right) & \text{if } q_{[0,t]} < N \end{cases}$$

where
$\tau = T - t$ is the time to compliance and
α_τ, β_τ are obtained by calculating the first and the second moment of the integral over a geometric Brownian motion.
$\Phi(\cdot)$ denotes the c.d.f. of a standard normal random variable.

Permit price - reciprocal gamma moment matching

The permit price at time t is given by

$$S_t^{IG} = \begin{cases} Pe^{-r\tau} & \text{if } q_{[0,t]} \geq N \\ Pe^{-r\tau} \cdot G\left(\frac{Q_t}{N - q_{[0,t]}} \middle| \frac{4\beta_\tau - \alpha_\tau^2}{2\beta_\tau - \alpha_\tau^2}, \frac{2\beta_\tau - \alpha_\tau^2}{2\alpha_\tau \beta_\tau}\right) & \text{if } q_{[0,t]} < N \end{cases}$$

where
$\tau = T - t$ is the time to compliance and
α_τ, β_τ are obtained by calculating the first and the second moment of the integral over a geometric Brownian motion.
$G(x|a, b)$ denotes the c.d.f. of a gamma random variable with shape parameter a and scale parameter b.

Relating theoretical permit prices to allocation

We introduce the following two random variables that are very easy to interpret

Time needed to exhaust the remaining permits

$$x_t := \frac{N - q_{[0,t]}}{Q_t}$$

and

Over-/Underallocation in years

$$x_t - (T - t)$$

Numerical illustrations

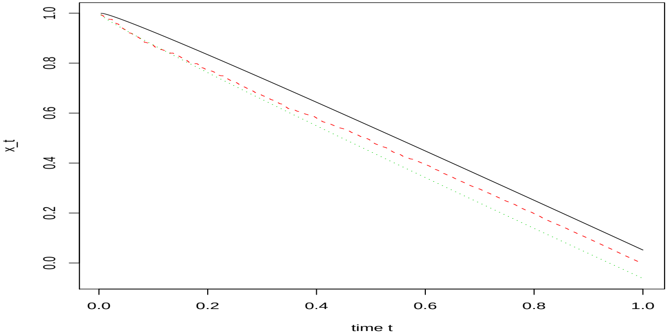

Figure : Trajectory of x_t for $t \in [0, 1]$, $N = Q_0 = 100$, $\mu = 0.02$ and $\sigma = 0.05$.

Numerical illustrations

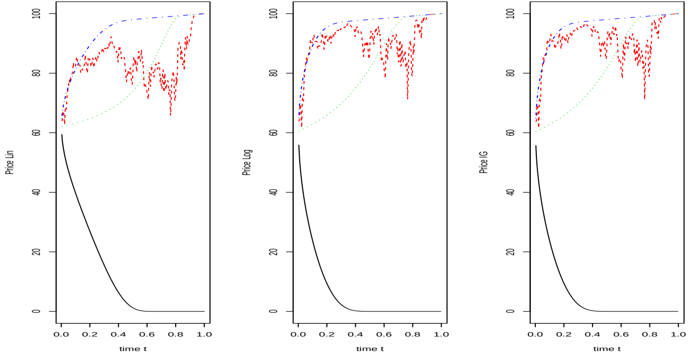

Figure : Trajectory of $S_t^{Lin}(x_t)$ (left), $S_t^{Log}(x_t)$ (middle) and $S_t^{IG}(x_t)$ (right) for $t \in [0, 1]$, $N = Q_0 = 100$, $\mu = 0.02$ and $\sigma = 0.05$.

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Implied over-/underallocation during the first phase of the EU ETS

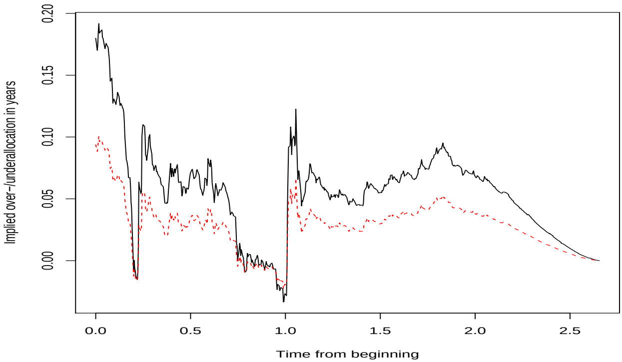

Figure : Implied $x_t - (T - t)$ for first phase for fixed $\mu = 0.02$ and $\sigma = 0.05$. Linear approximation approach (straight line), log-normal moment matching (dashed line). Positive values correspond to overallocation.

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Permit price Delta

For $t \in [0, T)$ and $q_{[0,t]} < N$

- $$\frac{dS_t^{Lin}}{dx_t}(x_t) := -\frac{Pe^{-r\tau}}{\sigma\sqrt{\tau}} \cdot \frac{1}{x_t}\phi\left(\frac{-\ln\left(\frac{1}{\tau}x_t\right) + \left(\mu - \frac{\sigma^2}{2}\right)\tau}{\sigma\sqrt{\tau}}\right) < 0$$

- $$\frac{S_t^{Lin}((1+h)x_t) - S_t^{Lin}(x_t)}{S_t^{Lin}(x_t)} = -\frac{\phi\left(\frac{-\ln\left(\frac{1}{\tau}x_t\right)+\left(\mu-\frac{\sigma^2}{2}\right)\tau}{\sigma\sqrt{\tau}}\right)}{\Phi\left(\frac{-\ln\left(\frac{1}{\tau}x_t\right)+\left(\mu-\frac{\sigma^2}{2}\right)\tau}{\sigma\sqrt{\tau}}\right)} \cdot \frac{h}{\sigma\sqrt{\tau}}$$

Price slumps and allocation

We show that a price slump of more than 50% can be related to an implicit change in x_t of less than 5%.
We introduce the following notation

- $t - \Delta$ is the date before the publication of verified emissions that affected the permit price (28 April 2006)
- t is the date of the announcement of cumulative emissions (15 May 2006)

Price slumps and allocation

Using

- the cumulative emissions until t denoted by $q_{[0,t]}$
- the futures permit price at and before publication of emission data denoted by $F(t,T)$ and $F(t-\Delta,T)$, respectively

the implicit time needed to exhaust the remaining permits before the announcement was $h(\sigma)$ per cent larger than the previous estimate $\bar{x}_t$ where

$$h(\sigma) = \frac{F(t,T) - F(t-\Delta,T)}{P\phi\left(\Phi^{-1}\left(\frac{F(t,T)}{P}\right)\right)} \cdot f^{approx}(\sigma, t, \bar{x}_t)$$

Price slumps and allocation

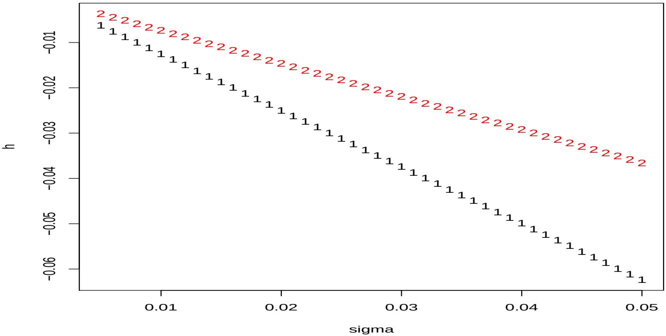

Figure : Linear approximation ("1"), log-normal moment matching ("2").

Price Floor Using a Subsidy

- The severe permit price drop, followed by a price hovering above zero for more than five months during the first phase of the EU ETS, persuaded several policy makers that new cap-and-trade schemes would need additional safety-valve features.
- In particular, policy makers have been concerned about permit prices that are either too low or too high.
- Thus setting a price floor and/or ceiling has been proposed.

Price Floor Using a Subsidy – Regulation

- A company with a permit shortage at compliance date faces a penalty P.
- If a company ends up with an excess of permits, it receives a subsidy S per unit of permit.
- Let $0 < S \leq P$ and let N be the initial amount of permits allocated to relevant companies.

Permit Price in hybrid system

Denote the futures permit price by $\tilde{F}(t,T)$:

$$
\begin{aligned}
\tilde{F}(t,T) &= P \cdot \mathbb{P}\left(q_{[0,T]} > N \mid \mathcal{F}_t\right) + S \cdot \mathbb{P}\left(q_{[0,T]} \leq N \mid \mathcal{F}_t\right) \\
&= P \cdot \mathbb{P}\left(q_{[0,T]} > N \mid \mathcal{F}_t\right) + S \cdot \left(1 - \mathbb{P}\left(q_{[0,T]} > N \mid \mathcal{F}_t\right)\right) \\
&= S + \frac{P-S}{P} \cdot P \cdot \mathbb{P}\left(q_{[0,T]} > N \mid \mathcal{F}_t\right) \\
&= S + \frac{P-S}{P} \cdot F(t,T) = \; F(t,T) + S\left(1 - \frac{F(t,T)}{P}\right),
\end{aligned}
$$

where $F(t,T) = P \cdot \mathbb{P}\left(q_{[0,T]} > N \mid \mathcal{F}_t\right)$ is the futures permit price in an ordinary system.

Decomposition of permit price in hybrid system

Computing the value of a put with strike S shows that the price in the hybrid scheme is the price in the ordinary scheme plus the value of a put option on the price in the ordinary scheme with strike S and maturity T:

$$
\begin{aligned}
& \mathbb{E}\left[(S - F(T,T))^+ \mid \mathcal{F}_t\right] \\
= \quad & \mathbb{E}\left[\left(S - P\mathbf{1}_{\{q_{[0,T]} > N\}}\right)^+ \mid \mathcal{F}_t\right] \\
= \quad & (S-P)^+ \,\mathbb{P}\left(q_{[0,T]} > N \mid \mathcal{F}_t\right) + (S-0)^+ \,\mathbb{P}\left(q_{[0,T]} \leq N \mid \mathcal{F}_t\right) \\
\overset{S \leq P}{=} \quad & S \cdot \mathbb{P}\left(q_{[0,T]} \leq N \mid \mathcal{F}_t\right).
\end{aligned}
$$

Expected enforcement costs for regulated companies

Let f_q be the probability density function of the cumulative emissions $q_{[0,T]}$ in the entire regulated period. The expected enforcement costs for relevant companies in an ordinary system are

$$EEC = P\int_N^{\infty}(x-N)f_q(x)dx \geq 0.$$

Similarly, the expected enforcement costs for regulated companies in this hybrid system are

$$EEC^{PF} = P\int_N^{\infty}(x-N)f_q(x)dx - S\int_0^N(N-x)f_q(x)dx.$$

So, the total expected enforcement costs for regulated companies under this hybrid system are lower than under an ordinary system.

$$EEC - EEC^{PF} = S\int_0^N(N-x)f_q(x)dx \geq 0.$$

Enforcement costs for regulator

- A price floor ensured by the presence of a subsidy is relatively easy to implement and has the further advantage of lowering the expected enforcement costs for regulated companies.
- The presence of the subsidy could induce a higher stimulus in technology and abatement investments, favoring the achievement of emission reduction targets.
- However, the implementation of such a hybrid system might result in a significant financial burden for the environmental policy regulator. The current magnitude of this burden can be obtained by calculating the price of the put option.

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Hybrid systems

Scheme	Price bound	Prices can exceed bounds	Link with offsets market	Description of the mechanism
Existing cap-and-trade scheme				
Offset safety-valve	Upper	Yes	Yes	Flexible limit on the use of offsets
Proposed safety-valve mechanisms for cap-and-trade schemes				
Subsidy price floor	Lower	No	No	Subsidy
Price collar	Upper & Lower	No	No	Regulator sells unlimited amount of permits at the price ceiling and buys unlimited amount of permits at the price floor
Allowance reserve	Upper & Lower	Yes	No	Regulator sells limited amount of permits at the price ceiling and buys limited amount permits at price floor
Regulator offers options	Upper & Lower	No (for owner of options)	No	Regulator sells options at a market price

Permit Prices

- Recall the emission rate

$$dQ_t = Q_t(\mu dt + \sigma dW_t)$$

- The cumulative emissions are

$$q_{[0,t]} = \int_0^t Q_s ds$$

- The futures permit price is given as

$$F(t, T) = P\mathbb{P}\left[q_{[0,T]} > N | \mathcal{F}_t\right]$$

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Approximative Pricing

- Linear approximation approach

$$
\begin{aligned}
q_{[t_1,t_2]} &\approx \tilde{q}^{Lin}_{[t_1,t_2]} = Q_{t_2}(t_2 - t_1) \\
&= Q_{t_1} e^{\left\{\log(t_2-t_1)+\left(\mu-\frac{\sigma^2}{2}\right)(t_2-t_1)+\int_{t_1}^{t_2}\sigma dW_t\right\}}
\end{aligned}
$$

- Moment matching

$$
\begin{aligned}
q_{[t_1,t_2]} &\approx \tilde{q}^{Log}_{[t_1,t_2]} \\
&= Q_{t_1} \exp\left\{\int_{t_1}^{t_2}\mu_t dt + \int_{t_1}^{t_2}\sigma_t dW_t\right\}
\end{aligned}
$$

where the functions μ_t and σ_t are defined by the functions α_t, β_t from the moment matching.

Carmona-Hinz Approach

- Use a lognormal process

$$\Gamma_T = \Gamma_0 \exp\left\{ \int_0^T \sigma_t dW_t - \frac{1}{2}\int_0^T \sigma_t^2 dt \right\}$$

with $\Gamma_0 > 0$ and $\sigma(.)$ a deterministic square-integrable function.

- Define the futures price under a risk-neutral measure $\mathbb{Q}$ as

$$F(t, T) = P\mathbb{Q}\left[\Gamma_T > 1 | \mathcal{F}_t\right]$$

Reduced-Form Dynamics

The martingale

$$a_t = \mathbb{E}^{\mathbb{Q}}\left[\mathbf{1}_{\{\Gamma_T > 1\}} | \mathcal{F}_t\right]$$

is given by

$$a_t = \Phi\left[\frac{\Phi^{-1}(a_0)\sqrt{\int_0^T \sigma_s^2 ds} + \int_0^t \sigma_s dW_s}{\sqrt{\int_t^T \sigma_s^2 ds}}\right]$$

and solves the stochastic differential equation

$$da_t = \Phi'\left(\Phi^{-1}(a_t)\right)\sqrt{z_t}dW_t$$

with

$$z_t = \frac{\sigma_t^2}{\int_t^T \sigma_u^2 du}$$

Reduced-Form Dynamics – Proof

- a_t formula is straightforward calculation
- For dynamics use that

$$a_t = \Phi(\xi_t)$$

with

$$\xi_t = \frac{\xi_{0,T} + \int_0^t \sigma_s dW_s}{\sqrt{\int_t^T \sigma_s^2 ds}} \text{ and } \xi_{0,T} = \log \Gamma_0 - \frac{1}{2}\int_0^T \sigma_s^2 ds.$$

Starting with the dynamics of ξ_t an application of Itô's formula gives the result.

Model Parametrization

- For constant σ we find $z_t = (T-t)^{-1}$, so a richer specification is needed.
- A standard model is

$$da_t = \Phi'\left(\Phi^{-1}(a_t)\right)\sqrt{\beta(T-t)^{-\alpha}}dW_t$$

  which specifies a family $\sigma_s(\alpha,\beta)$.
- So $z_t(\alpha,\beta) = \beta(T-t)^{-\alpha}$ and

$$\begin{aligned}\sigma_t^2(\alpha,\beta) &= z_t(\alpha,\beta)\exp\left\{-\int_0^t z_s(\alpha,\beta)ds\right\} \\ &= \begin{cases}\beta(T-t)^{-\alpha}e^{-\frac{\beta}{1-\alpha}\left[T^{1-\alpha}-(T-1)^{1-\alpha}\right]} & \alpha \neq 1 \\ \beta(T-t)^{\beta-1}T^{-\beta} & \alpha = 1.\end{cases}\end{aligned}$$

Objective Measure

- We do a historical calibration and change measure to the objective measure.
- The standard change of measure gives

$$\frac{d\mathbb{P}}{d\mathbb{Q}} = \exp\left\{\int_0^T H_s dW_s - \frac{1}{2}\int_0^T H_s^2 ds\right\}).$$

- Under constant market price of risk $H_t \equiv h$ and by Girsanov's theorem

$$\tilde{W}_t = W_t - ht$$

is a $\mathbb{P}$ Brownian motion.

Objective Measure

- Under $\mathbb{P}$

$$d\xi_t = \left(\frac{1}{2} z_t \xi_t + h\sqrt{z_t}\right) dt + \sqrt{z_t} d\tilde{W}_t,$$

  so ξ_τ given ξ_t is Gaussian.
- So we can invert permit prices to obtain ξ values and calculate the log-likelihood to obtain estimates for α and β.

Pricing Formula

For a European call with strike K and maturity τ the option price is

$$C_t = e^{-\int_t^\tau r_s ds} \int_{-\infty}^{\infty} (P\Phi(x) - K)^+ \Phi_{\mu_{t,\tau},\sigma_{t,\tau}}(dx)$$

with

$$\mu_{t,\tau} = \begin{cases} \xi_t \left(\frac{T-t}{T-\tau}\right)^{\frac{\beta}{2}} & \alpha = 1 \\ \xi_t \exp\left\{\frac{\beta}{2(1-\alpha)}[(T-t)^{1-\alpha} - (T-\tau)^{1-\alpha}]\right\} & \alpha \neq 1. \end{cases}$$

and

$$\sigma^2_{t,\tau} = \begin{cases} \left(\frac{T-t}{T-\tau}\right)^{\beta} - 1 & \alpha = 1 \\ \exp\left\{\frac{\beta}{1-\alpha}[(T-t)^{1-\alpha} - (T-\tau)^{1-\alpha}]\right\} - 1 & \alpha \neq 1. \end{cases}$$

Two-period Model

- We consider a two-period model, $[0, T]$ and $[T, T']$, with banking and withdrawal
- Let $\mathbb{Q}$ be a martingale measure and $(A_t)_{t\in[0,T]}$ and $(A'_t)_{t\in[0,T']}$ be the futures contracts which are $\mathbb{Q}$ martingales.
- Let $N \in \mathcal{F}_T$ resp. $N' \in \mathcal{F}_{T'}$ be non-compliance in the first resp. second period.

(Non-) Compliance at T

- In case of compliance, i.e. event $\Omega - N$, since A_T is the spot price at T and the permit can be banked, we have

$$A_T \mathbf{1}_{\{\Omega - N\}} = \kappa A'_T \mathbf{1}_{\{\Omega - N\}}$$

with $\kappa = \exp\{-\int_T^{T'} r_s ds\}$ a discount factor.

- In case of non-compliance

$$A_T \mathbf{1}_N = \kappa A'_T \mathbf{1}_N + P \mathbf{1}_N$$

- Thus

$$A_t - \kappa A'_t = \mathbb{E}_t^{\mathbb{Q}}[A_T - \kappa A'_T] = \mathbb{E}_t^{\mathbb{Q}}[P \mathbf{1}_N]$$

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Reduced-Form Model

- As in the one period case, we set

$$A_t - \kappa A'_t = P\Phi(\xi_t^1)$$

  with ξ_t^1 a Gaussian process driven by a Brownian motion W_t^1.
- Assume that the ETS ends after the second period, then

$$A'_t = P\Phi(\xi_t^2)$$

  with ξ_t^2 a Gaussian process driven by a Brownian motion W_t^2.

Pricing Formula

For a European call written on a futures in the first period with strike K and maturity τ we decompose the payoff

$$(A_\tau - K)^+ = (A_\tau - \kappa A'_\tau + \kappa A'_\tau - K)^+ = (P\Phi(\xi_t^1) + \kappa P\Phi(\xi_t^2) - K)^+$$

We obtain for the option price

$$C_t = e^{-\int_t^\tau r_s ds} \int_{\mathbb{R}^2} (P\Phi(x_1) + \kappa P\Phi(x_2) - K)^+ \Phi_{\mu_\tau, \sigma_\tau}(dx_1 dx_2)$$

where the parameters of the two-dimensional Gaussian distribution depend on the individual drift and volatility terms and the correlation of ξ^1 and ξ^2.

Parameters of the Pricing Formula

The means are

$$\mu^1_{t,\tau} = \Phi^{-1}\left(\frac{A_t - \kappa A'_t}{P}\right)\sqrt{\left(\frac{T-t}{T-\tau}\right)\beta_1}$$

$$\mu^2_{t,\tau} = \Phi^{-1}\left(\frac{\kappa A'_t}{P}\right)\sqrt{\left(\frac{T'-t}{T'-\tau}\right)\beta_2}$$

and the covariance matrix is

$$\nu^{1,1}_{t,\tau} = \mathbb{V}\mathrm{ar}(\xi^1_\tau) = \left(\frac{T-t}{T-\tau}\right)^{\beta_1} - 1$$

$$\nu^{2,2}_{t,\tau} = \mathbb{V}\mathrm{ar}(\xi^2_\tau) = \left(\frac{T'-t}{T'-\tau}\right)^{\beta_2} - 1$$

$$\nu^{1,2}_{t,\tau} = \nu^{2,1}_{t,\tau} = \beta_1^{\frac{1}{2}}\beta_2^{\frac{1}{2}}\frac{\int_t^\tau (T-u)^{\frac{\beta_1-1}{2}}(T'-u)^{\frac{\beta_2-1}{2}}\rho du}{(T-\tau)^{\frac{\beta_1}{2}}(T'-\tau)^{\frac{\beta_2}{2}}}$$

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Agenda

Project-based Mechanisms

- 2005: Emissions Trading (EU ETS) was launched in the European Union as a measure to meet the Kyoto commitment
- Flexible Mechanisms as Clean Development Mechanism (CDM) and Joint Implementation (JI) can be used by countries to meet their Kyoto commitment and also by companies within the framework of EU emissions trading

Objectives of CDM/JI

- To save the same or a higher amount of CO2 for the same financial effort and by using fewer financial resources (abatement costs are lower)
- Sustainability, emissions reduction, technology transfer, contribution towards economic development

Cost Advantage

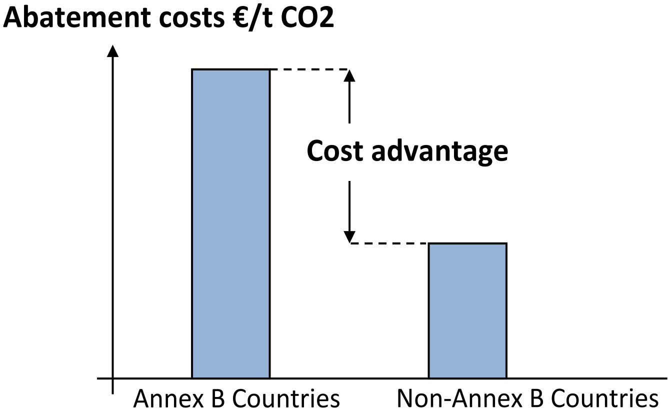


Figure : Cost advantage due to CDM/JI

Clean Development Mechanism (CDM)

- Emission reduction projects in a developing or an emerging country (e.g. China, India, Brazil, Malaysia)
- Accepted technologies (photovoltaic, wind power, biomass, energy efficiency; no nuclear projects!)
- Projects generate Certified Emission Reductions (CER) in the amount of tonnes of emissions that have been avoided (compared to the 'business-as-usual'-scenario, that means claim for additionality)

Secondary CERs: issued, tradable credits with guaranteed delivery
Primary CERs: purchased forward directly from project (or fonds), subject to individual project and delivery risks

Joint Implementation (JI)

- Emission reduction projects in an industrialized or a transition country (e.g. Russia, Ukraine), which has committed to a cap, solely in sectors not covered in the ETS
- Analogous to CDM, but reduces the emission budget of the country where the project takes place
- Projects generate ERU (Emissions Reduction Unit) in the amount of the avoided emissions (compared to the 'business-as-usual'-scenario)
- from 2008 onwards accepted in the EU ETS

CERs and ERUs can be used by
1) Countries, for compliance under the Kyoto Protocol
2) Companies within the EU ETS (up to 22%), for compliance

Example of the Project-based Mechanisms

Construction of a wind farm abroad:

- annual electricity production: 300 GWh
- no emissions occur during production

Electricity production at a coal power plant:

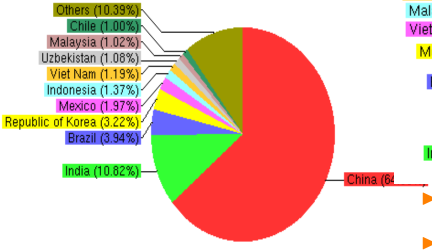
- 300,000 tonnes of CO2 emissions annually

Example of the Project-based Mechanisms

- By the construction of the wind farm, emissions amounting to 300,000 tonnes per year have been avoided
- Therefore, emission certificates amounting to 300,000 tonnes per year will be generated

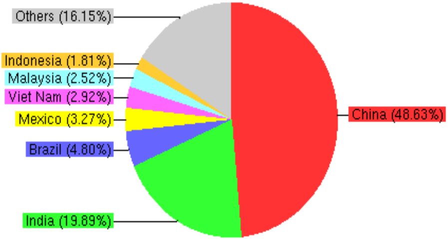
Distribution of CDM Projects and generated CERs by host country

Expected average annual CERs from registered projects (total: 605,014,135):



- 68% renewables projects

Registered project activities (total: 4,248):



- 5600 projects worldwide
- 2,7 bn CERs expected until end of 2012

Types of Risk Involved

- Market risk
- Volume Risk
- Credit Risk
- Delivery Risk

CDM/JI Risk Management Example

- We combine a CDM project with an ERPA
- Recall an Emission Reduction Purchase Argreement (ERPA) is a transaction that transfers carbon credits between two parties under the Kyoto Protocol. The buyer pays the seller cash in exchange for carbon credits, thereby allowing the purchaser to emit more carbon dioxide into the atmosphere.
- Assume an ERPA with 10 €/ t CO2

CDM/JI Risk Management Example II

- Sell the expected volume V_{exp} of 50 000 t CO2 forward at 15 €/t CO2
- Now the volume delivered is a random variable V and the certificate spot price S is random.
- So the portfolio value P at delivery is

$$P = 15 \times V_{exp} - 10 \times V + (S - 15) \times (V_{exp} - V)^{+} + S \times (V - V_{exp})^{+}$$

- So we face two risky scenarios
  - Higher volume with low spot
  - lower volume with higher spot

Allowance Price Versus CERs

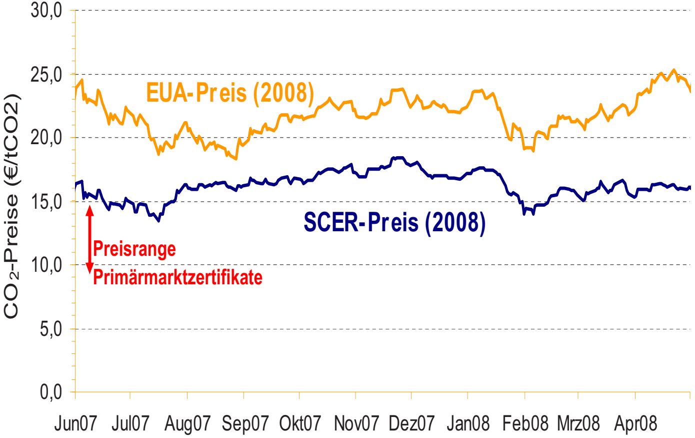


Figure : Price Difference EUA vs SCER

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Allowance Price Versus CERs

- Reason for price difference: Limited number of SCER for use in EU
- Intensive discussion of that in Barrieu and Fehr (2010).

Challenges in CDM Projects

- Regulatory Risk
  - Possible changes of CDM frame after 2012 with an impact on private investments
  - Acceptance of project-types and countries (China, Brazil)
- CDM Acceptance
  - Long and bureaucratic
  - not transparent, concrete methodic unknown
- Country Risk
  - local (CDM-) infrastructure: people, infrastructure
  - local energy infrastructure
  - local political risk

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Agenda

Economics of Climate Change

Emission Trading Schemes

Equilibrium Models

Reduced Form Models

Flexible Mechanisms under the Kyoto Protocol

Capital Market and Renewable Energy Projects
- Carbon Bonds
- Impact of Carbon Markets on Investment Markets

Carbon Revenue Bonds

- To finance high initial cost for Renewable Energy (RE) projects future returns of the project are securitized
-
  - Sell future electricity from RE project
  - Sell environmental credits from RE project
- Only revenue from environmental credits is used for bond
- Rigorous forecast analysis of revenues, sensitivity tests and risk analysis is required.

Structure of Bond

- pass-through: all revenues are directly passed trough to the owner of the bond
-
  - maturity: T
  - revenues in year 1: c_i
  - rate of return: r
  - initial price: x
- Fair price

$$x = \sum_{i=1}^{T} \frac{c_i}{(1+r)^i}$$

EUA Time Series

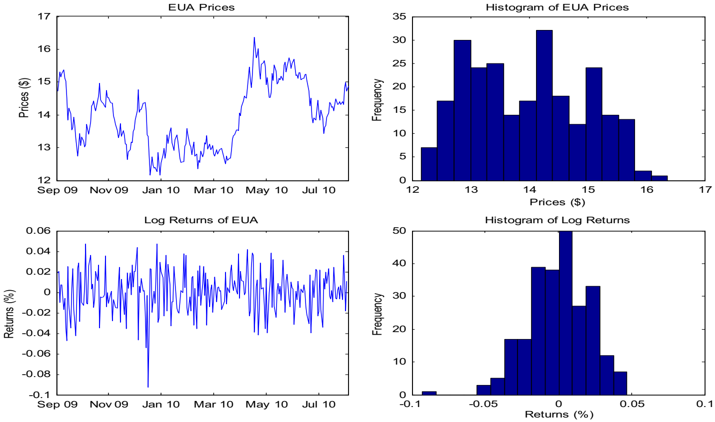

Fig. 3. Time series and histograms of EUA prices and log returns.

QQ-Plots for EUA fits

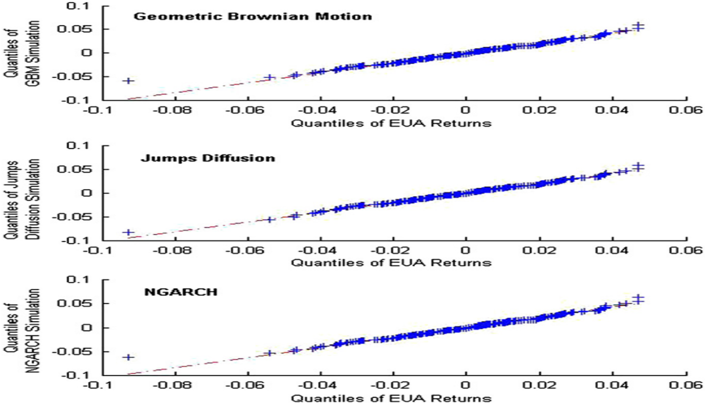

Fig. 4. QQ plots of EUA returns versus simulated returns.

Carbon Bond Histogram

A. Tang et al. / Energy Policy 45 (2012) 691–703

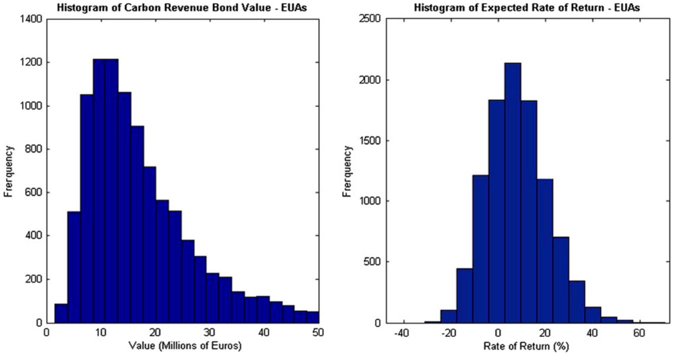

Fig. 5. Histogram of bond value and histogram of expected Return for EUAs.

Financial Implications of Carbon Policies

- Modern risk management has to include the consequences of climate change.
- Regulatory risk (reduction targets for carbon emissions) transforms into financial risk for several asset classes.
- Carbon inefficient firms tend to have a higher credit spread and higher refinancing costs.

Factors Affecting Carbon Risk

- Energy intensity and fuel mix – firms that are dependent on fossil fuels face higher costs.
- Direct, indirect and embedded emissions of a firm's product affect market position.
- Marginal abatement costs.
- Technology trajectory – progress in adapting low-carbon emission technologies.

Motivation for Investors to Invest in Carbon-related Assets

- Financial Motivation
  - Portfolio diversification
  - Potential fundamental price appreciation of carbon
  - Hedging financial risk due to carbon price increases
- Green Motivation
  - Compliance with UN principles of responsible investment (UN PRI)
  - Public opinion, behaviour as corporate citizen
  - Incentivizing the corporate sector by taking carbon credits from the market

Risk In Renewable Energy Companies

- Costs: as the costs of producing RE come down while the costs of producing fossil fuels rise, a substitution will occur.
- Capital: Government and private capita
- Competition: between governments as they try to build greener economies
- China: huges efforts to establish a green economy
- Consumers: demand products with less impact on the economy
- Climate Change: will be tackled by investment in greener technologies.

CAPM Analysis of RE Companies

- Empirical evidence shows that RE companies have a β close to two.
- Model: *i* firm, *t* time

$$R_{it} = \alpha_i + \beta_{it} R_{mt} + \epsilon_{it}$$

  R returns, α component that is independent of the market.
- Higher beta values indicate a higher equity cost of capital.Investors must then be compensated through higher expected returns in order to take on the higher risk. A higher equity cost of capital can affect borrowing costs and it can also affect the discount rate used in net present value calculations.

CAPM Analysis of RE Companies II

- Which factors affect systematic risk (the β)?
- Empirical analysis shows:
  - Increases in sales growth reduce market risk
  - Increases in oil price returns increases systematic risk
- In order to foster RE companies governments can implement policies to increase sales of such companies (e.g. PV-industry and feed-in tariffs).