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Market design for emission trading schemes

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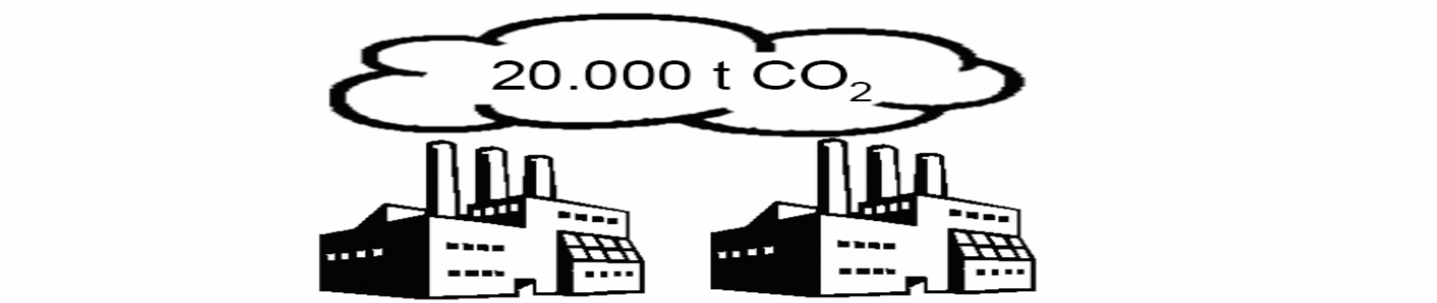
Joint work with Juri Hinz

EU ETS: Emission trading on company level

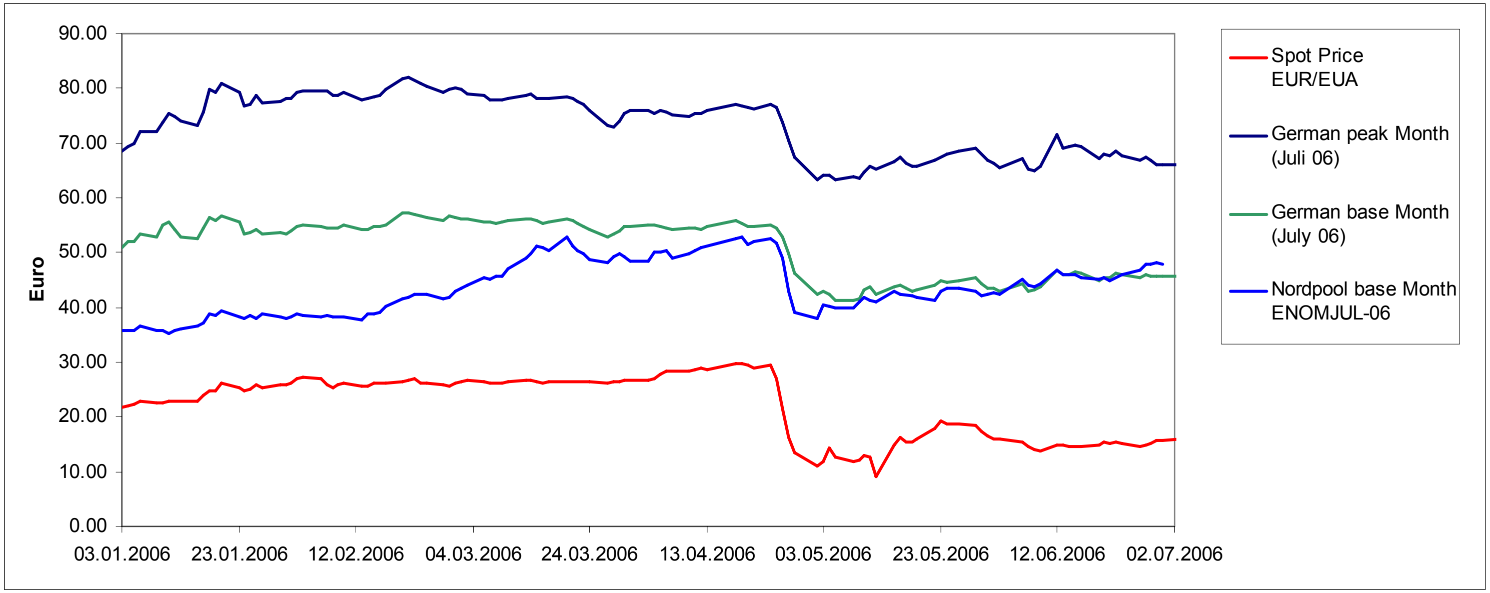
- Objective: Cost effective accomplishment of EU-member states Kyoto targets.
- Cost savings through Emission Trading



	Company A	Company B	
CO2-Emissions	11’000 t	11’000 t	Before Regulation
CO2-Emissions Costs	10’000 t 5’000 €	10’000 t 9’000 €	Without Emission-Trading
CO2-Emissions Costs	9’000 t 3’000 €	11’000 t 7’000 €	With Emission-Trading

Disposition of 1’000 t Emission Allowances at 7 € / t CO2

EUA price formation



- Electricity producers received allowances for free, now they charge us.

Question: Is this due to market malfunction?

Answer: No! Market works. In this talk we will show that this is the equilibrium outcome. Emissions are reduced at lowest social costs. However a particularity of this scheme is a capital transfer from consumer to producer. (But easy to correct)

EUA price formation

Insight:

- EUA enters electricity by factor 0.5. Why?
- Since in average 0.5 t CO2 are emitted when 1 MWh electricity is produced.
- ➢ Emission coefficients are important
- In this talk we address a new trading scheme with the same reduction performance but cheaper electricity.

Idea:

- Change emission coefficients by regulation!

In this talk

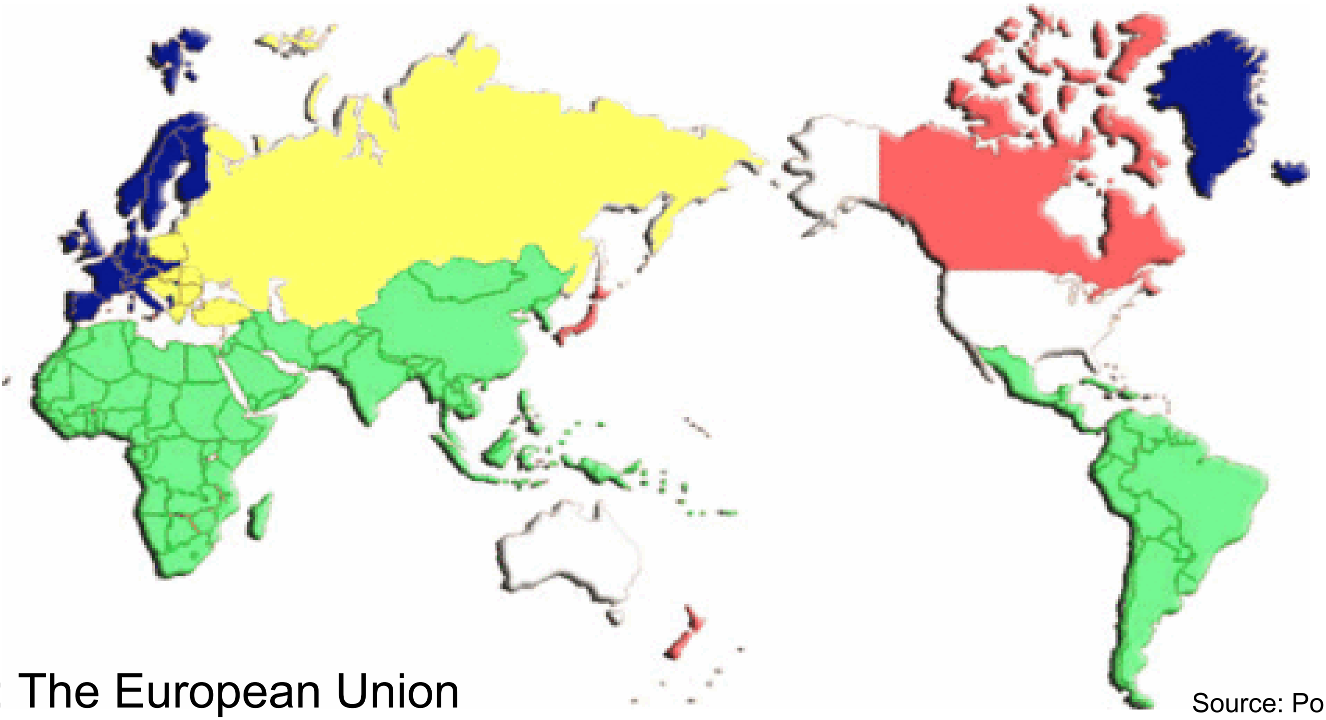
- **Kyoto protocol: Emission trading on country level**
- European emission trading scheme: Emission trading on company level
- Stochastic multi period model for allowance and electricity price formation
- Electricity price
- Windfall profits
- Adjusted trading schemes
- Allowance price

Kyoto Protocol

In 1997, concrete targets for curbing GHG emissions were established in The Kyoto protocol.

- Emission obligations: Each Annex B country that has ratified the Kyoto Protocol is obliged to reach a domestic target for carbon dioxide (CO2) equivalent emissions, by an average of 5,2 % below 1990 level, by the first commitment period of 2008 to 2012.
- Defines flexible mechanisms: JI, CDM and International Emission Trading (not EU ETS).
- It entered into force on 16 February 2005 after Russia ratiefied it in november 2004.

Kyoto country status



Source: Pointcarbon

- Blue: The European Union
- Yellow: Annex I countries with economies in transition. Potential JI host countries
- White: Annex I countries that have not ratified the Kyoto Protocol
- Red: Annex II countries outside of the European Union
- Green: Non-Annex I countries. Potential CDM host countries

Flexible (Kyoto-) mechanisms

- **International emission trading**
    - Annex B party can sell AAU (Assigned amount unit’s) conceded by the Kyoto protol, to an other Annex B party. (Annex B are obliged to emission reductions)
    - Full Banking, no Borrowing
- **Joint Implementation**
    - An Annex B country or a company from one Annex B country participates in financing an emission reduction project in another Annex B country. (From 2008)
    - AAU are withdrawn from the registry of the host country, while ERU is sold.
    - Restricted Banking
- **CDM**
    - An Annex B country or a company from one Annex B country participates in financing an emission reduction project in a Non Annex B country. (from 2000)
    - Restricted Banking

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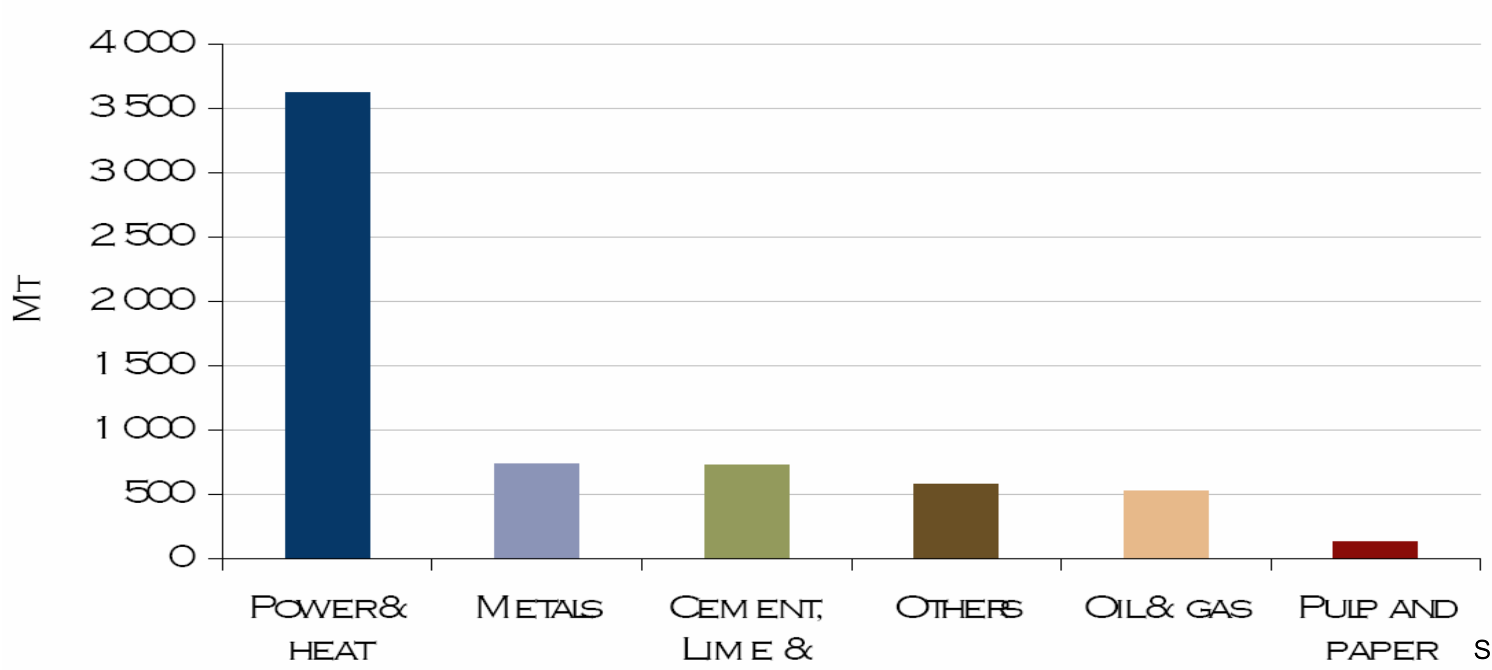
European emission trading scheme (EU ETS)

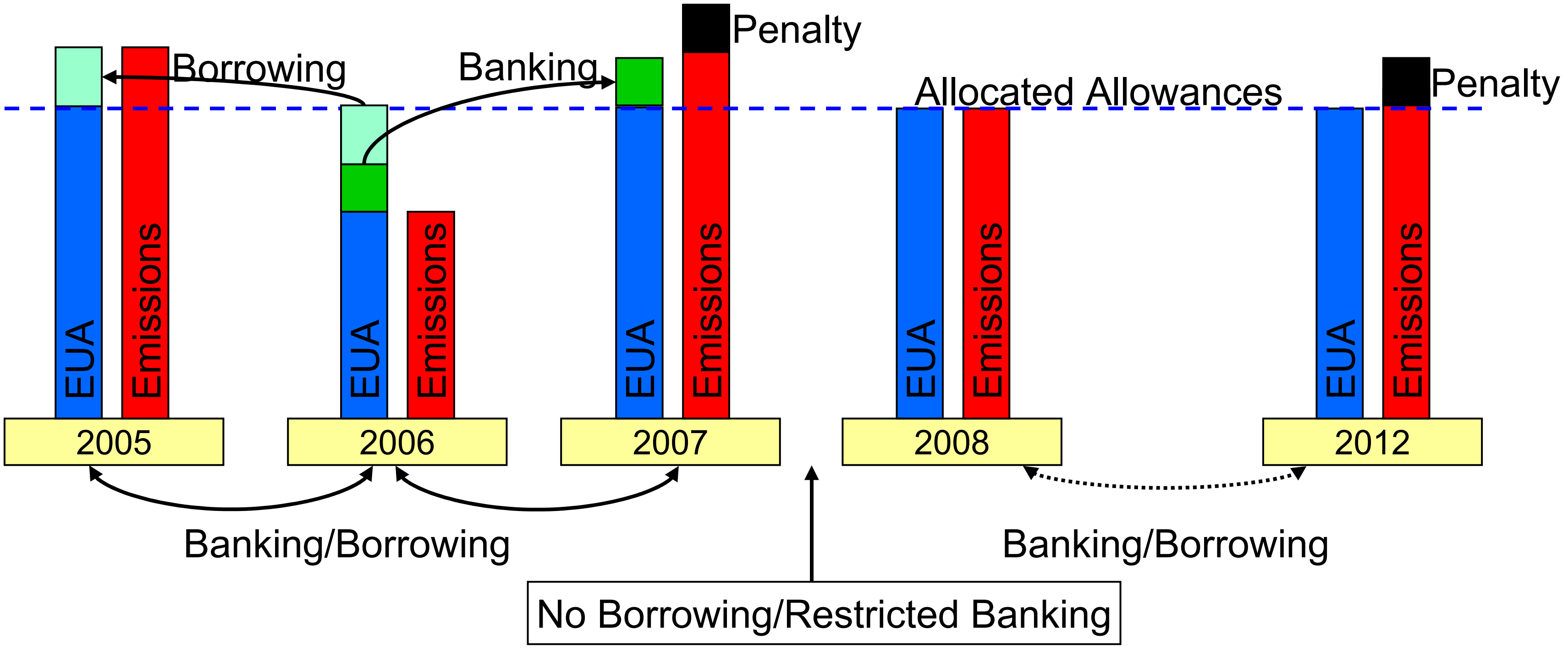
- Support the reduction target due to the Kyoto Protocol
- Mandatory emission trading scheme on company level
- Includes 12’000 installations (45% of the entire EU carbon emission)

Allocation per sector 2005-2007



Source: Pointcarbon

EU ETS regulations



Agents reduce their penalty by

- costly abatement strategies
- allowance trading

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How to link EUA to fuel and climate

Objective

for given game rules, exploit the mechanism of price formation, while electricity demand and fuel prices are uncertain

Approach

Fundamental model where agents

- face caps on their carbon emission by allocated initial credits
- are averse of potential penalty payments
- apply best production strategies to prevent penalty
- trade allowances

Model ingredients

Determine $(A_t)_{t=0}^{T}$ EUAs spot price, $(S_t)_{t=0}^{T-1}$ electricity price

given

- $(\Omega, \mathcal{F}, P, (\mathcal{F}_t)_{t=0}^{T})$ filtered space
- $\pi_T \in [0, \infty[$ penalty for each ton not covered by EUA
- $i = 1, \dots, N$ agents (electricity producers) with
  - $\tilde{\theta}_0^i \in [0, \infty[$ initial credit of emission allowances
  - $(P_t^{i,j})_{t=0}^{T-1}$ costs for electricity production with technology $j = 1, \dots, M_i$
  - $c^{i,j}$ emissions per MWh of technology $j = 1, \dots, M_i$
  - Γ_T^i ($\mathcal{F}_T$ -measurable) uncontrolled carbon emission
  - $(D_t)_{t=0}^{T-1}$ markets electricity demand (inelastic)

Model ingredients

Strategies of agents $i = 1, \ldots, N$

- $\theta^i = (\theta^i_t)_{t=0}^T, \; \theta^i_0 = \tilde{\theta}^i_0$ allowance trading policy, giving at T

  $$\sum_{t=0}^{T-1} \theta^i_t (A_{t+1} - A_t) - \theta^i_T A_T$$

- $\xi^i = ((\xi^{i,j}_t)_{j=1}^{M_i})_{t=0}^{T-1}$ production policy, $[0, \lambda^{i,j}]$ -valued, gives at T

  total pollution $\sum_{t=0}^{T-1} \sum_{j=1}^{M_i} c^{i,j} \xi^{i,j}_t$ and revenue $\sum_{t=0}^{T-1} \sum_{j=1}^{M_i} (S_t - P^{i,j}_t) \xi^{i,j}_t$

Model ingredients

Agents optimize their own revenue

- Each agent manages the own revenue

$$\underbrace{\sum_{t=0}^{T-1} \theta_t^i (A_{t+1} - A_t) - \theta_T^i A_T + \sum_{t=0}^{T-1} \sum_{j=1}^{M_i} (S_t - P_t^{i,j}) \xi_t^{i,j} - \pi_T(\Gamma_T^i + \sum_{t=0}^{T-1} \sum_{j=1}^{M_i} c^{i,j} \xi_t^{i,j} - \theta_T^i)^+}_{=L_T^{\theta^i,\xi^i,i}(A,S)}$$

- Given $A = (A_t)_{t=0}^{T}$ and $S = (S_t)_{t=0}^{T-1}$ agents $i = 1, \ldots, N$ select

$$(\theta^i(A,S), \xi^i(A,S)) = \text{argmax}\Big((\theta^i, \xi^i) \mapsto E(L_T^{\theta^i,\xi^i,i}(A,S))\Big)$$

Equilibrium condition

- Market equilibrium, is characterized by allowance and electricity price processes $A^* = (A_t^*)_{t=0}^{T}$, $S^* = (S_t^*)_{t=0}^{T-1}$

  such that individual optimal production strategies satisfy the markets electricity demand

  $$\sum_{i=1}^{N} \sum_{j=1}^{M_i} \xi_t^{i,j}(A^*, S^*) = D_t$$

  at each time point $t = 0, \ldots, T-1$ and all individual optimal EUA positions sum up to the initially allocated credit

  $$\sum_{i=1}^{N} \theta_t^i(A^*, S^*) = \sum_{i=1}^{N} \tilde{\theta}_0^i \qquad t = 0, \ldots, T$$

Structure of the equilibrium

- The production policy $\xi^* \in \mathcal{K}$ satisfying the markets demand

  at lowest costs

$$E(G_T(\xi^*)) = \sup_{\xi \in \mathcal{K}} E(G_T(\xi))$$

$$G_T(\xi) = -\sum_{t=0}^{T-1}\sum_{i=1}^{N}\sum_{j=1}^{M_i} P_t^{i,j}\xi_t^{i,j} - \pi_T(\underbrace{\sum_{i=1}^{N}\Gamma_T^i - \sum_{i=1}^{N}\tilde{\theta}_0^i}_{=\Gamma_T} + \underbrace{\sum_{t=0}^{T-1}\sum_{i=1}^{N}\sum_{j=1}^{M_i} c^{i,j}\xi_t^{i,j}}_{=\Pi_T(\xi)})^+$$

$$\mathcal{K} = \{\xi = (((\xi_t^{i,j})_{j=1}^{M_i})_{i=1}^{N})_{t=0}^{T-1} | \sum_{i=1}^{N}\sum_{j=1}^{M_i}\xi_t^{i,j} = D_t\}$$

is the equilibrium production policy

Equilibrium electricity and allowance prices

Under natural assumptions, carbon market equilibrium is determined by

- Solving the global optimal control problem

$$E(G_T(\xi^*)) = \sup_{\xi \in \mathcal{K}} E(G_T(\xi))$$

- Determining the EUA price as marginal contribution of an extra allowance to lower the expected penalty payment

$$A_t^* = \pi_T E(1_{\{\Gamma_T + \Pi_T(\xi^*) \geq 0\}} \mid \mathcal{F}_t) \qquad t = 0, \dots, T$$

- Identifying electricity price as the markets marginal production costs

$$S_t^* = \max_{i=1,\dots,N} \max_{j=1,\dots,M_i} (P_t^{i,j} + c^{i,j} A_t^*) 1_{\{\xi_t^{*i,j} > 0\}} \qquad t = 0, \dots, T-1$$

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Electricity price

$$S_t^* = \max_{i=1,\ldots,N} \max_{j=1,\ldots,M_i} (P_t^{i,j} + c^{i,j} A_t^*) 1_{\{\xi_t^{*i,j}>0\}} \qquad t = 0,\ldots,T-1$$

- If $\pi_T = 0$ it follows that $(A_t^*)_{t=0}^{T-1} = 0$ and the BAU electricity price mechanism is recovered. Calculate for each t a solution $\tilde{\xi}_t$ to

$$\begin{aligned}
\sup_{((\xi_t^{i,j})_{j=1}^{M_i})_{i=1}^{N}} \quad & \sum_{i=1}^{N} \sum_{j=1}^{M_i} -P_t^{i,j} \xi_t^{i,j} \\
\text{s.t.} \quad & \sum_{i=1}^{N} \sum_{j=1}^{M_i} \xi_t^{i,j} = D_t \\
& \xi_t^{i,j} \leq \lambda^{i,j} \qquad i = 1,\ldots,N, j = 1,\ldots,M_i \\
& \xi_t^{i,j} \geq 0 \qquad i = 1,\ldots,N,\ j = 1,\ldots,M_i
\end{aligned}$$

$$\tilde{S}_t = \max_{i=1,\ldots,N} \max_{j=1,\ldots,M_i} P_t^{i,j} 1_{\{\tilde{\xi}_t^{i,j}>0\}} \qquad t = 0,\ldots,T-1$$

Electricity price

$$S_t^* = \max_{i=1,\dots,N} \max_{j=1,\dots,M_i} (P_t^{i,j} + c^{i,j} A_t^*) 1_{\{\xi_t^{*i,j} > 0\}} \qquad t = 0, \dots, T-1$$

- If $\pi_T > 0$ it follows that allowance enters electricity price as an extra commodity

Reason: due to the individual optimization problem:

$$\sum_{t=0}^{T-1} \theta_t^i (A_{t+1} - A_t) - \theta_T^i A_T + \sum_{t=0}^{T-1} \sum_{j=1}^{M_i} (S_t - P_t^{i,j}) \xi_t^{i,j} - \pi_T \Big(\Gamma_T^i + \sum_{t=0}^{T-1} \sum_{j=1}^{M_i} c^{i,j} \xi_t^{i,j} - \theta_T^i\Big)^+$$

electricity production causes not only production costs but also costs due to the increased potential penalty payments. In equilibrium this is marginally given by $A_t^* = \pi_T E(1_{\{\Gamma_T + \Pi_T(\xi^*) \geq 0\}} \mid \mathcal{F}_t)$ per t of extra emitted CO2.

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Connection to optimal rescheduling policies

- Given BAU production policies $\tilde{\xi} \in \mathcal{K}$ define the space of rescheduling policies

$$\begin{aligned}\mathcal{S} := \quad & \{((((\zeta_t^{i,j})_{j=1}^{M_i})_{i=1}^{N})_{t=0}^{T-1} \,|\, \zeta_t^{i,j} \in [-\tilde{\xi}_t^{i,j}, \lambda^{i,j} - \tilde{\xi}_t^{i,j}] \\ & \textstyle\sum_{i=1}^{N} \sum_{j=1}^{M_i} \zeta_t^{i,j} = 0 \text{ for all } t = 0, \ldots, T-1\}.\end{aligned}$$

- With $\xi = \tilde{\xi} + \zeta$ global optimal control problem $\xi \mapsto E(G_T(\xi))$ corresponds to the problem of finding optimal rescheduling strategies based on BAU scenario

$$\sup_{\zeta \in \mathcal{S}} E\Big(\sum_{i=1}^{N} \sum_{j=1}^{M_i} \sum_{t=0}^{T-1} -P_t^{i,j} \zeta_t^{i,j} - \pi\big(\Lambda_T + \sum_{i=1}^{N} \sum_{j=1}^{M_i} \sum_{t=0}^{T-1} c_t^{i,j} \zeta_t^{i,j}\big)^{+}\Big)$$

where $\Lambda_T = \displaystyle\sum_{i=1}^{N} \sum_{j=1}^{M_i} \sum_{t=0}^{T-1} c_t^{i,j} \tilde{\xi}_t^{i,j} + \sum_{i=1}^{N} (\Gamma_T^i - \tilde{\theta}^i)$ are BAU emissions

Social costs and windfall profits

- Expected social costs caused by trading scheme are given by possible penalty payments and abatement costs

$$V = \sup_{\zeta\in\mathcal{S}} E\Big(\sum_{i=1}^{N}\sum_{j=1}^{M_i}\sum_{t=0}^{T-1} -P_t^{i,j}\zeta_t^{i,j} - \pi\big(\Lambda_T + \sum_{i=1}^{N}\sum_{j=1}^{M_i}\sum_{t=0}^{T-1} c_t^{i,j}\zeta_t^{i,j}\big)^{+}\Big)$$

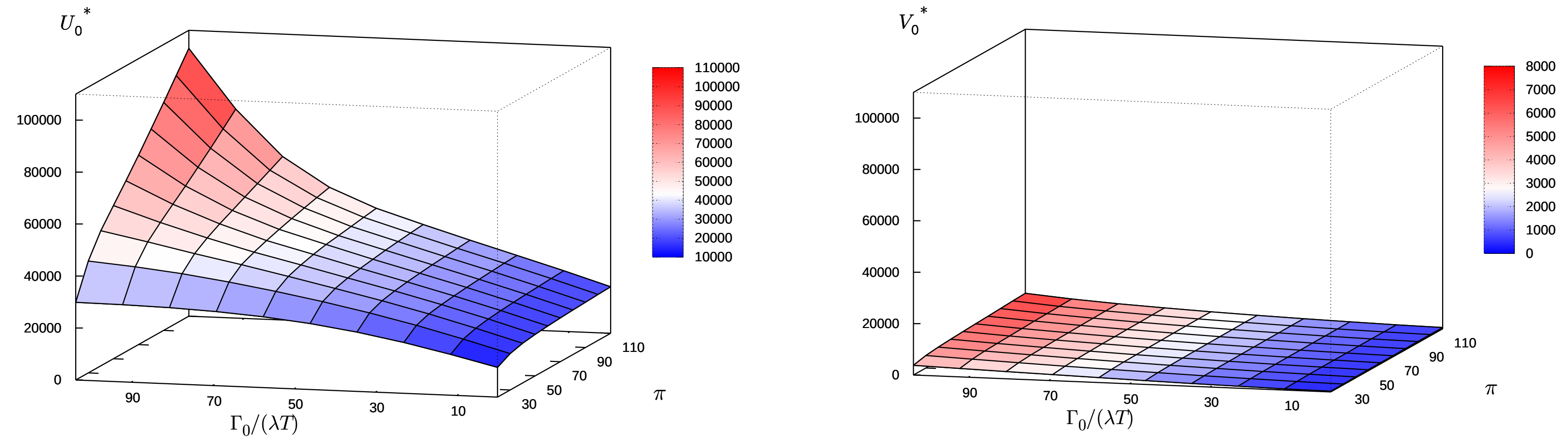
- Expected burden carried by the end consumer is

$$U = E\Big(\sum_{t=0}^{T-1}(S_t^{*} - \tilde{S}_t)D_t\Big)$$

- Windfall profits are given by

$$U - V$$

Windfall profits



Plotted in million Euro, 7% cap, electricity production of 3000 TWh, average marginal emission 0.5 t/MWh

- Huge windfall profits

Solution

- Auctioning of allowances
- Other offset regulations

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Adjusted trading scheme

A cheaper scheme with the same production strategies is reached by following adjustments:

- Reduce all emission factors by l

$$\bar{c}^{i,j} = c^{i,j} - l, \qquad l \in]-\infty, \infty[$$

- Instead reduce the allocation to

$$\tilde{\theta}_0^i - \frac{\tilde{\theta}_0^i}{\sum_{i=1}^{N} \tilde{\theta}_0^i} \sum_{t=0}^{T-1} l D_t$$

(and allocate it at T)

Adjusted trading scheme

The overall short position in emission allowances is maintained

$$\bar{\Pi}_T(\xi) + \bar{\Gamma}_T = \Pi_T(\xi) - \sum_{t=0}^{T-1} lD_t + \Gamma_T + \sum_{t=0}^{T-1} lD_t = \Pi_T(\xi) + \Gamma_T$$

- Global optimization problem and strategies are preserved

$$\bar{G}_T(\xi) = -F_T(\xi) - \pi_T(\bar{\Pi}_T(\xi) + \bar{\Gamma})^+ = G_T(\xi)$$

$$\bar{\xi}^* = \xi^*$$

$$\begin{array}{rcl} (\bar{A}_t^*)_{t=0}^T & = & \pi_T E(1_{\{\bar{\Pi}_T(\bar{\xi}^*) + \bar{\Gamma}_T \geq 0\}} | \mathcal{F}_t)_{t=0}^T \\ & = & \pi_T E(1_{\{\Pi_T(\bar{\xi}^*) + \Gamma_T \geq 0\}} | \mathcal{F}_t)_{t=0}^T = (A_t^*)_{t=0}^T \end{array}$$

- But electricity price decreases

$$\begin{array}{rcl} \bar{S}_t^* & = & \max_{i=1,\ldots,N} \max_{j=1,\ldots,M_i} (P_t^{i,j} + (c^{i,j} - l)\bar{A}_t^*) 1_{\{\bar{\xi}_t^{*i,j} > 0\}} \\ & = & S_t^* - lA_t^* \quad \text{for } t = 0, \ldots, T-1. \end{array}$$

Adjusted trading scheme

Following adjustments are simpler to realize:

- As before assign

$$\overline{c}^{i,j} = c^{i,j} - l, \qquad l \in]-\infty, \infty[$$

- Reduce the initial allocation by a fixed amount (and allocate it at $t = 0$)

$$\overline{\theta}_0^i = \tilde{\theta}_0^i - \frac{\tilde{\theta}_0^i}{\sum_{i=1}^N \tilde{\theta}_0^i} E(\textstyle\sum_{t=0}^{T-1} l D_t)$$

  - $l = 0$ corresponds to a trading scheme with **fixed cap**
  - $l = \frac{\sum_{i=1}^N \tilde{\theta}_0^i}{E(\sum_{t=0}^{T-1} D_t)}$ gives $\overline{\theta}_0^i = 0$ which corresponds to a trading scheme with **relative cap**

Relative vs fixed cap

- **How does this change the optimal abatement problem?**

$$\sup_{\zeta\in\mathcal{S}} E\Big(\sum_{i=1}^{N}\sum_{j=1}^{M_i}\sum_{t=0}^{T-1} -P_t^{i,j}\zeta_t^{i,j} - \pi\big(\Lambda_T + \underbrace{\sum_{i=1}^{N}\sum_{j=1}^{M_i}\sum_{t=0}^{T-1} c_t^{i,j}\zeta_t^{i,j}}_{\Xi_T}\big)^{+}\Big)$$

- As seen before in EU ETS we have

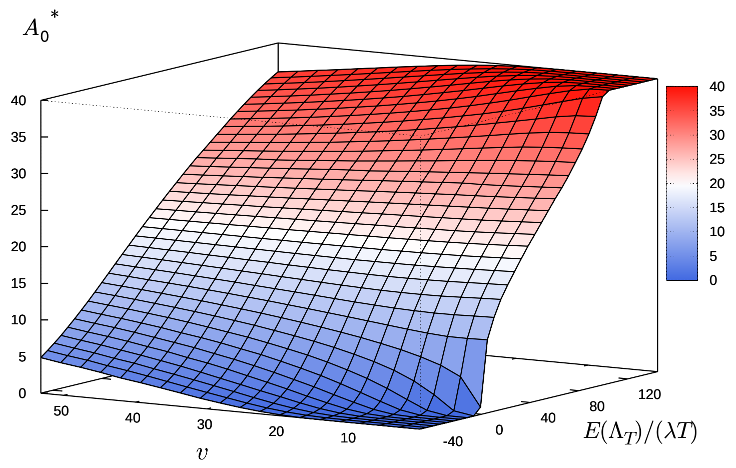
$$\Lambda_T = \sum_{i=1}^{N}\sum_{j=1}^{M_i}\sum_{t=0}^{T-1} c_t^{i,j}\xi_t^{i,j} + \sum_{i=1}^{N}\Gamma_T^i - \tilde{\theta}_0^i$$

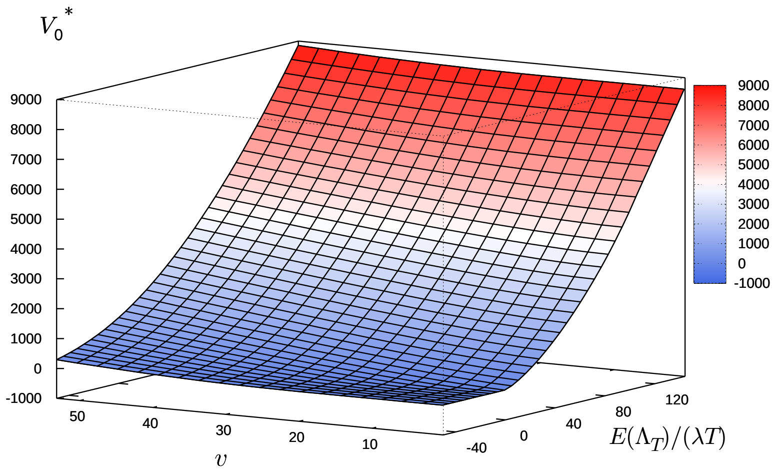
- In the adjusted scheme we find

$$\bar{\Lambda}_T = \sum_{i=1}^{N}\sum_{j=1}^{M_i}\sum_{t=0}^{T-1}(c^{i,j}-l)\xi_t^{i,j} + \sum_{i=1}^{N}\Gamma_T^i - \tilde{\theta}_0^i + E\Big(\sum_{t=0}^{T-1} lD_t\Big)$$

hence it follows that $E(\Lambda_T) = E(\bar{\Lambda}_T)$!

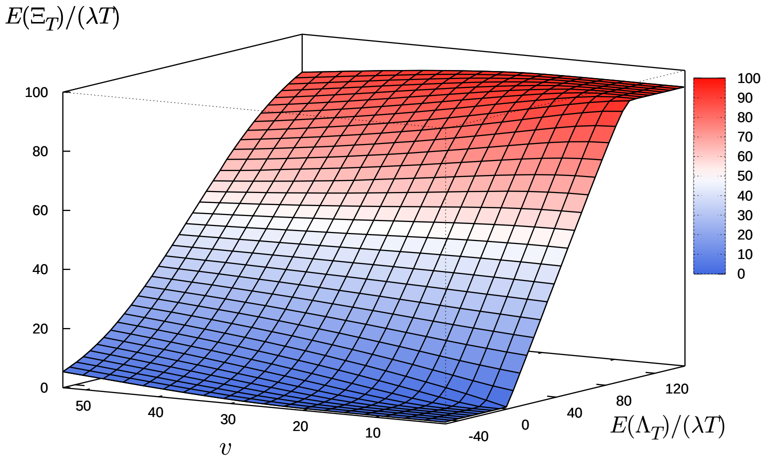
Relative vs fixed cap





- Simulation indicates that with less uncertainty:
  - Allowance price nearly unchanged
  - Social costs nearly unchanged
  - Expected saved carbon nearly unchanged
- **Electricity price decreases**

Relative vs fixed cap



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Equilibrium electricity and allowance prices

Under natural assumptions, carbon market equilibrium is determined by

- Solving the global optimal control problem

$$E(G_T(\xi^*)) = \sup_{\xi \in \mathcal{K}} E(G_T(\xi))$$

- Determining the EUA price as marginal contribution of an extra allowance to lower the expected penalty payment

$$A_t^* = \pi_T E(1_{\{\Gamma_T + \Pi_T(\xi^*) \geq 0\}} \,|\, \mathcal{F}_t) \qquad t = 0, \ldots, T$$

- Identifying electricity price as the markets marginal production costs

$$S_t^* = \max_{i=1,\ldots,N} \max_{j=1,\ldots,M_i} (P_t^{i,j} + c^{i,j} A_t^*) 1_{\{\xi_t^{*i,j} > 0\}} \qquad t = 0, \ldots, T-1$$

Fuel switching

- Switch electricity production from coal to gas
- Emits less carbon per MWh electricity
- Causes costs per ton of saved carbon

$$\mathcal{E}_t = \frac{h_G G_t - h_C C_t}{c_G - c_C}$$

G_t = gas price

C_t = coal price

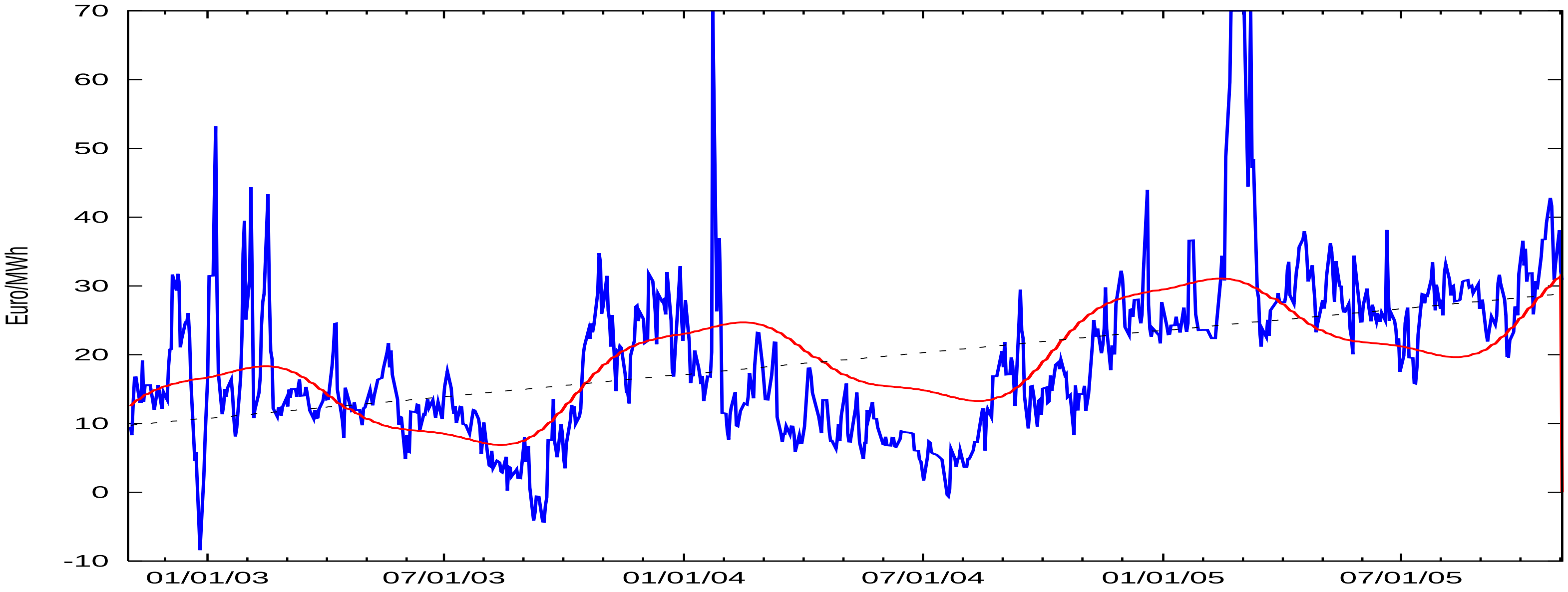
h_G, h_C = specific heating rate of gas, coal

c_G, c_C = specific emission rate gas, coal

The abatement problem reduces to

$$\sup_{\zeta \in \mathcal{S}} E\left(\sum_{t=0}^{T-1} -(c_C - c_G)\mathcal{E}_t \zeta_t - \pi\left(\Lambda_T - \sum_{t=0}^{T-1} (c_C - c_G)\zeta_t\right)^+\right)$$

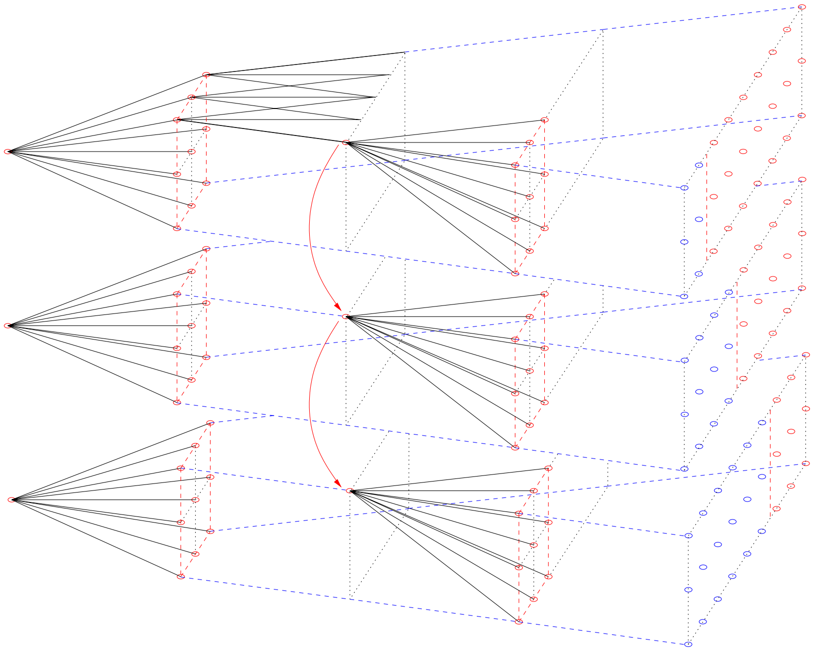
Fuel switch price process



- Fuel switch process is modeled by discrete version of ornstein uhlenbeck process
- $E(\Lambda_T|\mathcal{F}_t)$ is modeled by a discrete version of brownian motion

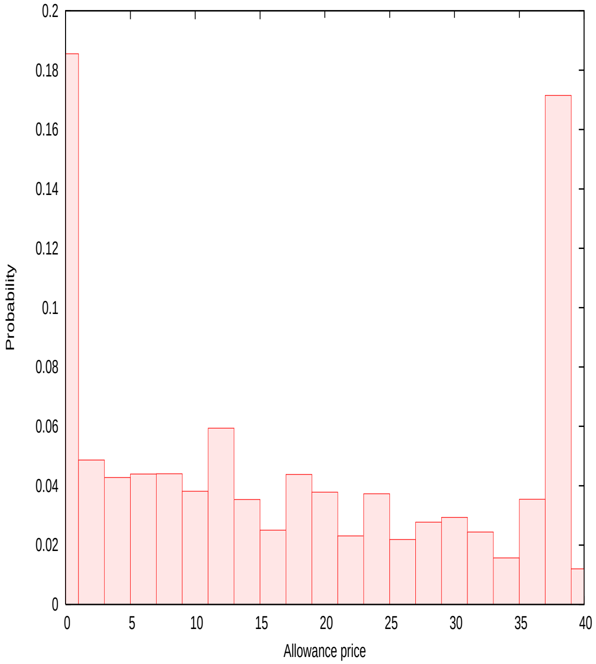
Solve optimal control problem

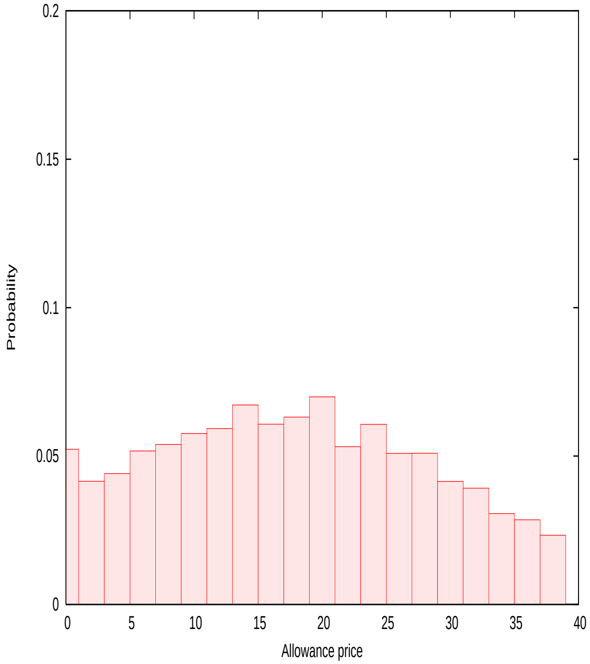
- The global optimal control problem $G_T(\xi^*) = \sup_{\xi \in U} E(G_T(\xi))$ is solved by backward induction using trinomial forest, with two stochastic dimensions: allowance demand and fuel switch price

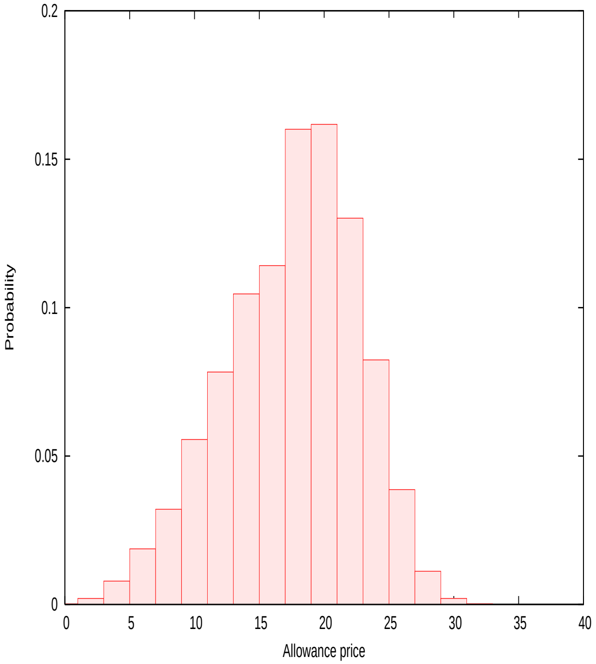


- At the end of a period the penalty for non compliance is paid
- At each node a fuel switch is performed if and only if fuel switching price is lower than marginal expected penalty
- Allowance price is marginal cost of one extra allowance, i.e. marginal expected penalty

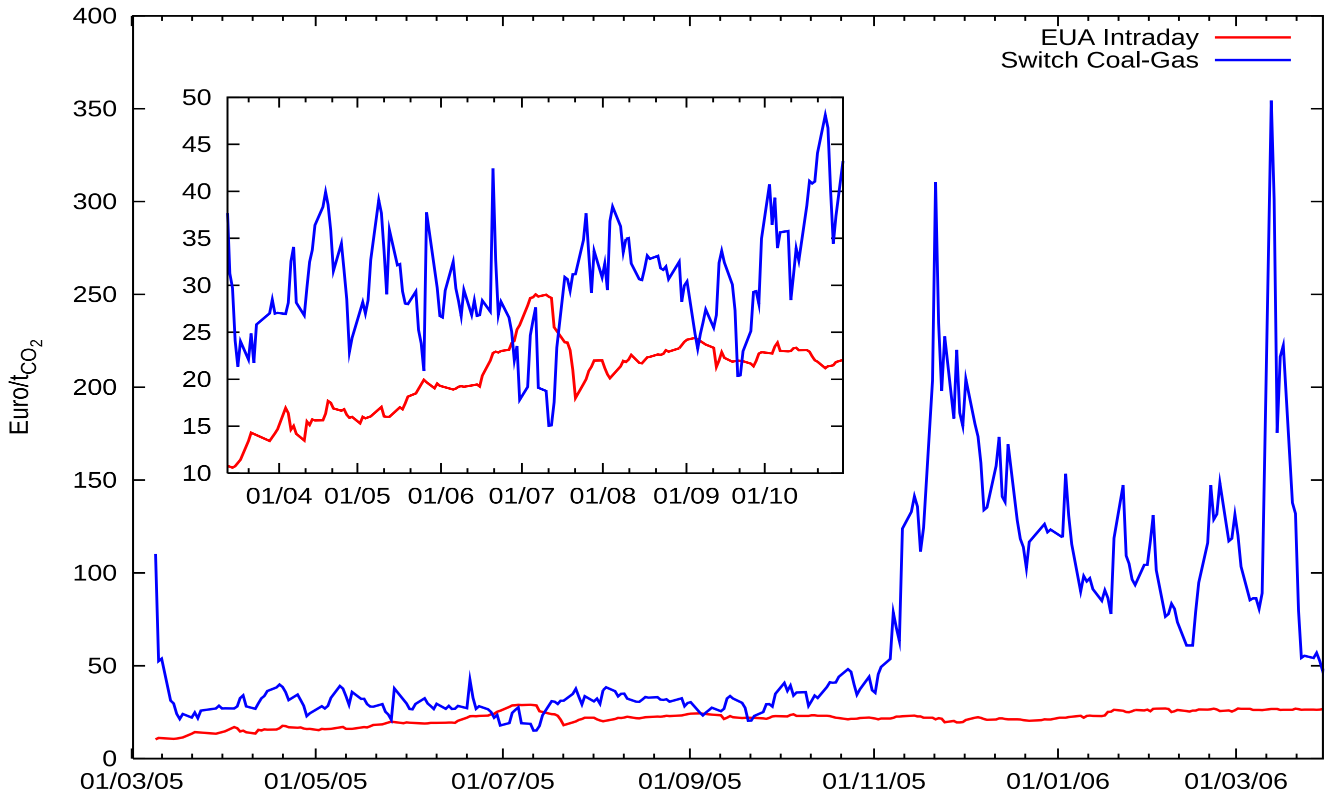
Allowance price distribution





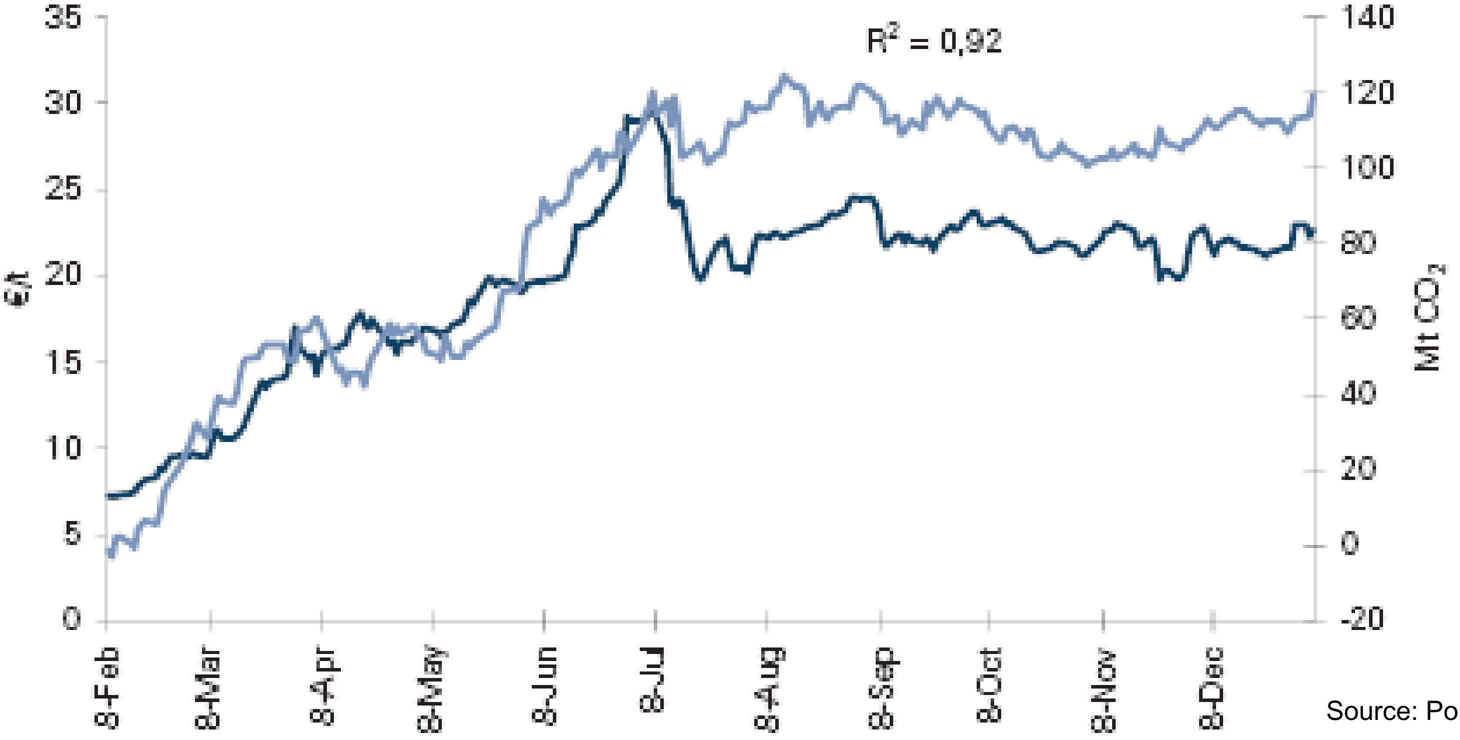


Fuel switch price vs EUA price



- Weak correlation

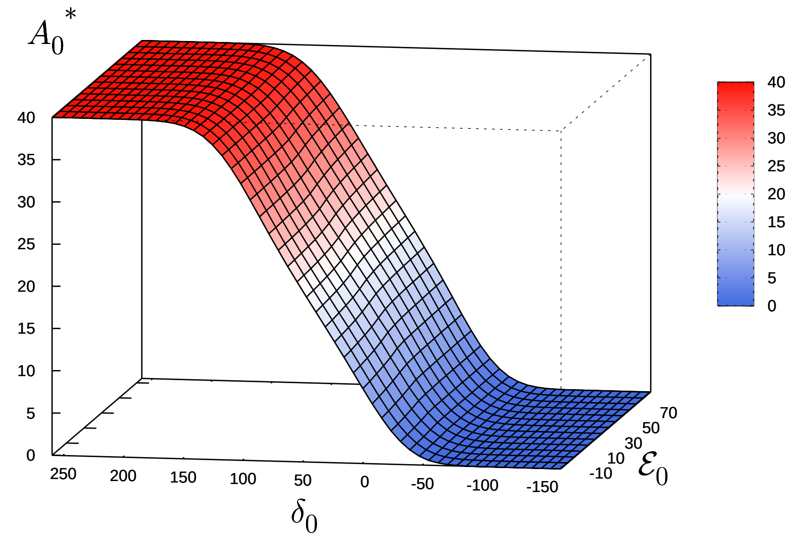
Emission to cap indicator vs EUA price



Source: Pointcarbon

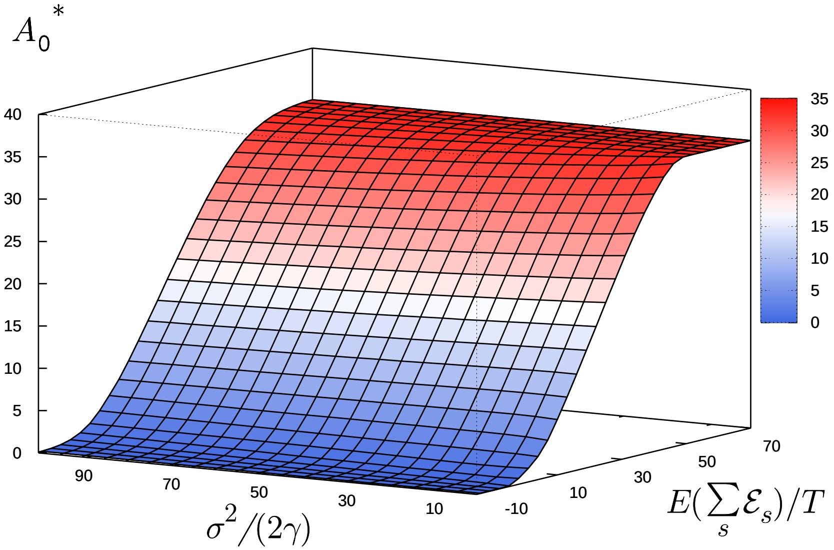
- 92% correlation

Allowance price vs model variables



- Strong correlation of EUA and reduction demand
- Weak correlation of EUA and fuel switch prices

Allowance price vs model parameters



- Long term fuel switch price is important

Price drivers

- Expected allowance demand
- Long term fuel prices
- Short term fuel prices

Conclusion

- Model predicts realistic allowance and electricity prices
- Windfall profits are due to the fixed cap
- Social costs and end consumer costs can be adjusted by charging factors