# Modeling Emission Trading Schemes

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Joint work with H.J. Lüthi, R. Carmona, J. Hinz, A. Porchet,

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# EU ETS: Emission trading on company level

- Cost effective accomplishment of Emission Targets.

Cap: 20‘000t $CO_2$

| | Company A Coal | Company B Gas | |
|---|---|---|---|
| $CO_2$-Emissions | 11’000 t | 11’000 t | Before Regulation |
| $CO_2$-Emissions | 10’000 t | 10’000 t | Without Emission- |
| Costs | 5’000 € | 11’000 € | Trading |
| Allocation | 10’000 t | 10’000 t | With |
| $CO_2$-Emissions | 9’000 t | 11’000 t | Emission- |
| Costs | 2’000 € | 8’000 € | Trading |

1’000 t Emission Allowances at 8 € / t $CO_2$

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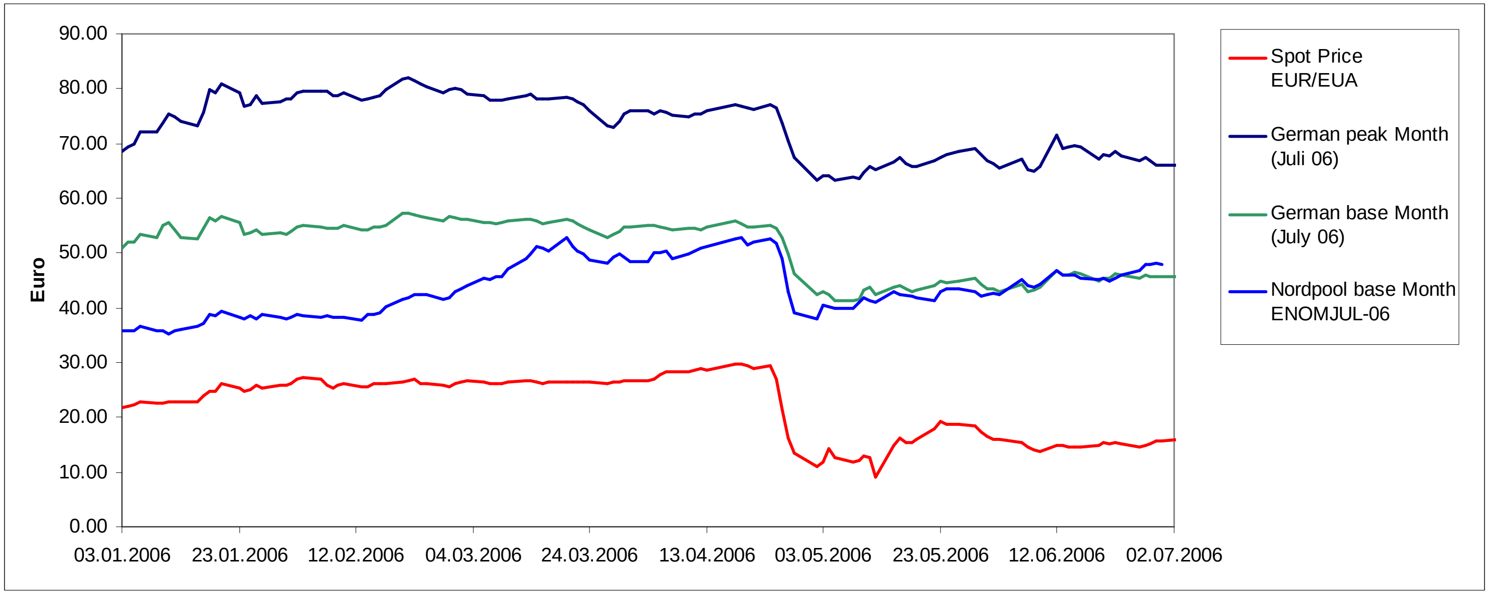
# Windfall profits




- Allowances enter electricity price as an extra commodity that is used for production
- Several Approaches are considered to reduce Windfall profits:
  Emission Tax, Auctioning of the Initial Allocation, Relative Scheme (uGPS)

# Reduction of windfall profits

**Tax**

- Even a tax can fail to reduce windfall profits to a reasonable level.
- We show that a Tax is not suited to reach an absolute reduction target (such as specified in the Kyoto Protocol) in the case of stochastic reduction costs.

**Auctioning**

- Even for a 100% Auction zero Windfall profits can not be reached in markets with a lot of clean production capacity.

# In this talk

- **Stochastic model for inter temporal allowance and electricity price formation**
- Comparison of climate policies applied to the Japanese electricity sector
  - Standard Emission Trading Scheme
  - Emission Trading Scheme with auction of all allowances
  - Emission Tax
  - Relative Emission Trading Scheme
- EU ETS with CERs and banking
- Social optimality

# Literature

- “Market Design for Emission Trading Schemes”

  (to appear in Siam Review , R. Carmona, M.Fehr, J.Hinz, A. Porchet)

- “Optimal Stochastic Control and Carbon Price Formation”

  (Siam Journal on Control and Optimization, R. Carmona, J. Hinz, M. Fehr)

- “The Clean Development Mechanism and Joint Price Formation for Allowances and CERs”

  (accepted, R. Carmona, M. Fehr)

- “Properly designed emission trading schemes do work”

  (submitted, R. Carmona, M. Fehr, J. Hinz)

- “Option Pricing in EU ETS”

  (preprint, P. Barrieu, U. Cetin, M.Fehr)

- “An auction based generation performance standard”

  (preprint, R. Carmona, M. Fehr)

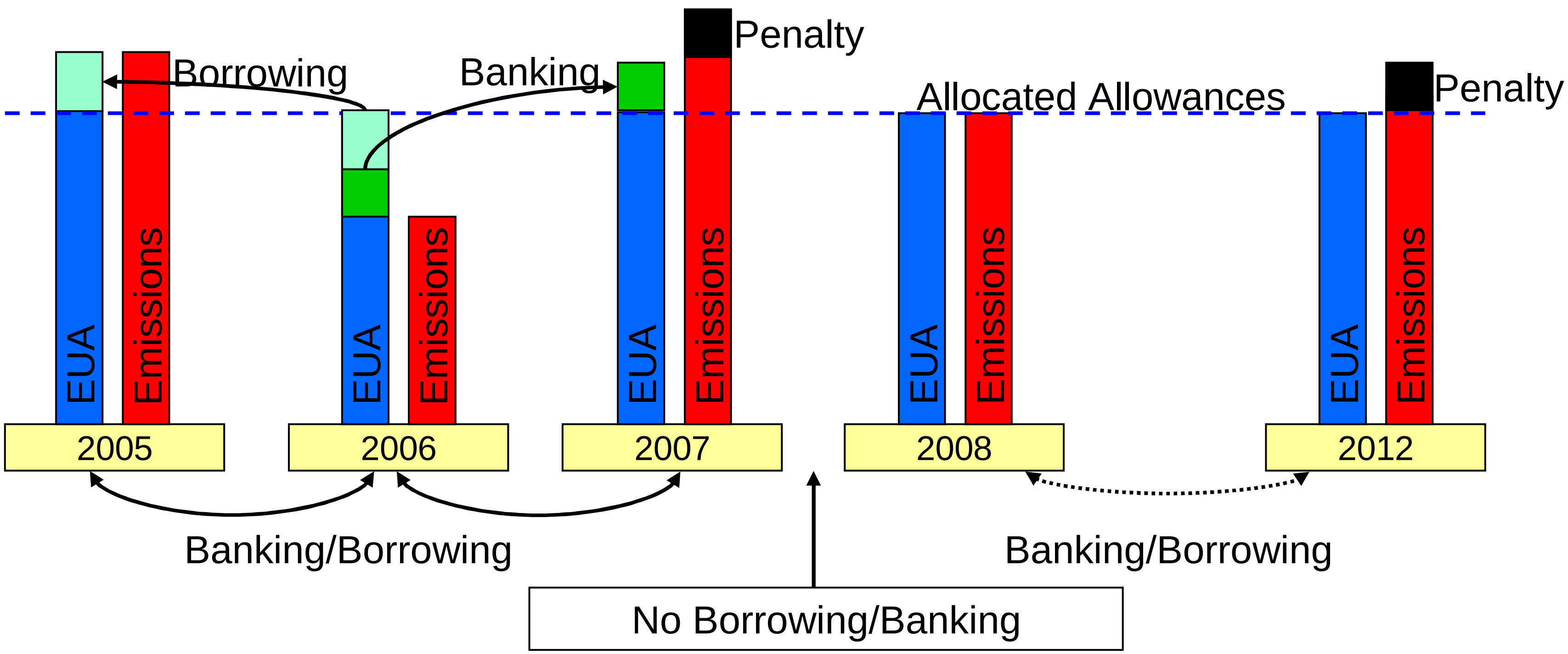
- “Storage costs in commodity option pricing”

  (submitted, M. Fehr, J. Hinz)

# Other Directly Related Literature

- *«Pricing and hedging in carbon emissions markets.»* International Journal of Theoretical and Applied Finance (to appear, U. Cetin, M. Verschuere)
- *«Dynamic behavior of carbon spot prices. Theory and empirical evidence.»* (J. Seifert, M. Uhrig-Homburg and M. Wagner)
- *«The Endogenous Price Dynamics of the Emission Allowances: An Application to CO2 Option Pricing»* (M. Chesney, L. Taschini)
- *«Environmental Economics and Modeling Marketable Permits: A Survey»* (L. Taschini)

# EU ETS regulations




**Agents reduce their penalty by**

- costly abatement strategies
- allowance trading

# 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 $j = 1, \dots, M_i$
  - $e^{i,j}$ emissions per MWh of technology $j = 1, \dots, M_i$
  - $\Gamma_T^i$ ( $\mathcal{F}_T$ -measurable) uncontrolled carbon emission
  - $(D_t)_{t=0}^{T-1}$ markets electricity demand (inelastic)

# Model ingredients

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

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

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

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

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

- 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 definition

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

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

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

# Representative planer problem

To characterize the equilibrium we define following representative planer problem which is to satisfy markets electricity demand at lowest overall costs (including fuel costs and penalty payments due to the trading scheme)

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

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

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

# Main Theorem

**Under natural assumptions, it holds that**

- There exists a solution $\xi^* \in \mathcal{U}$ to the global optimal control problem

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

- If $\xi^* \in \mathcal{U}$ is a solution of the global optimization problem, then

  the processes $(A^*, S^*)$ defined by

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

  $$S^*_t = \max_{i=1,\ldots,N} \max_{j=1,\ldots,M_i} (P^{i,j}_t + e^{i,j} A^*_t) 1_{\{\xi^{*i,j}_t > 0\}} \qquad t = 0, \ldots, T-1$$

  form a market equilibrium.

- The equilibrium allowance price process is almost surely unique.
- The price $S^*$ is the smallest equilibrium price in the sense that for any other equilibrium price process $\bar{S}$ , we have $S^* \leq \bar{S}$ almost surely.

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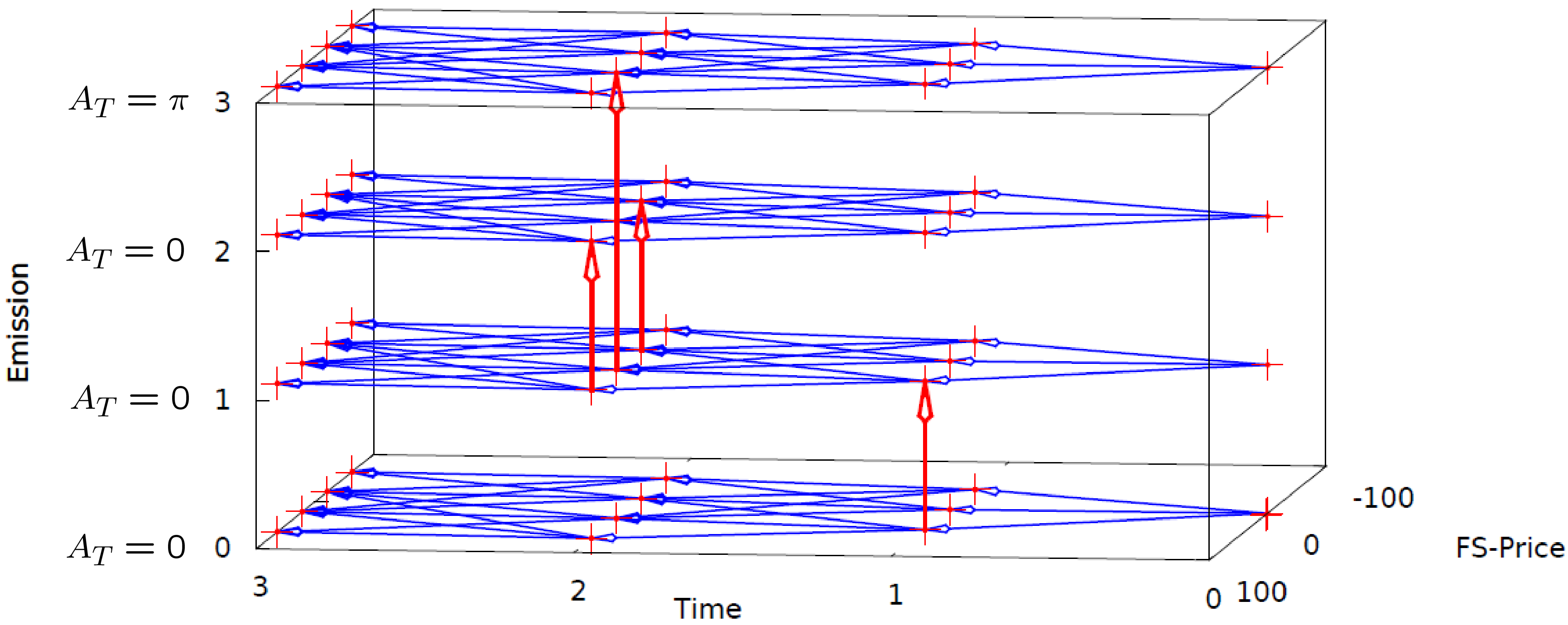
# Dynamic Programming

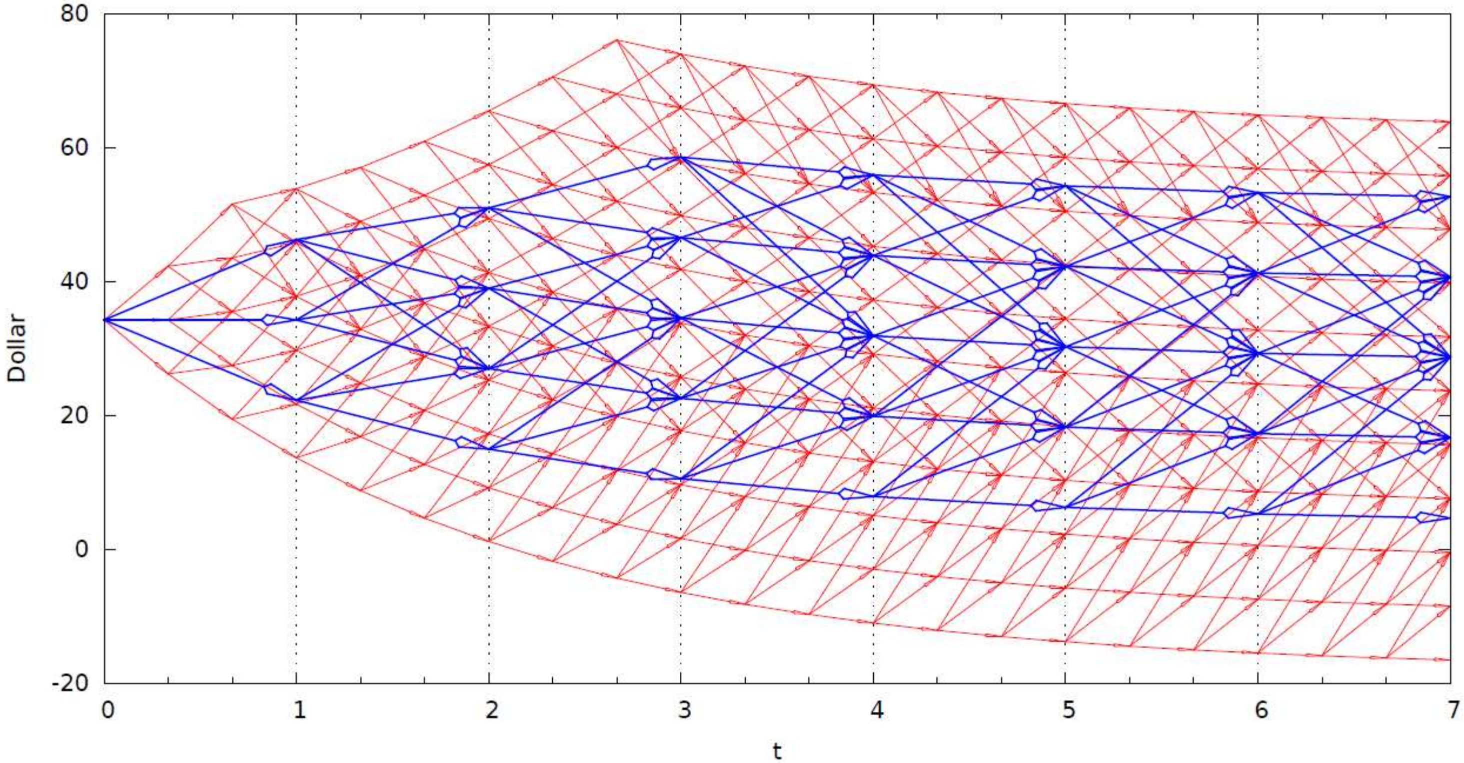
- The global optimal control problem $\sup_{\xi \in U} E(G_T(\xi))$ can not be solved exactly.
- We solve a discrete version by backward induction using a trinomial forest.




- At the end of a period the penalty is paid in case that emissions exceed the cap.
- At each node a fuel switch is performed iff fuel switch price < allowance price
- Store the allowance price at each node.

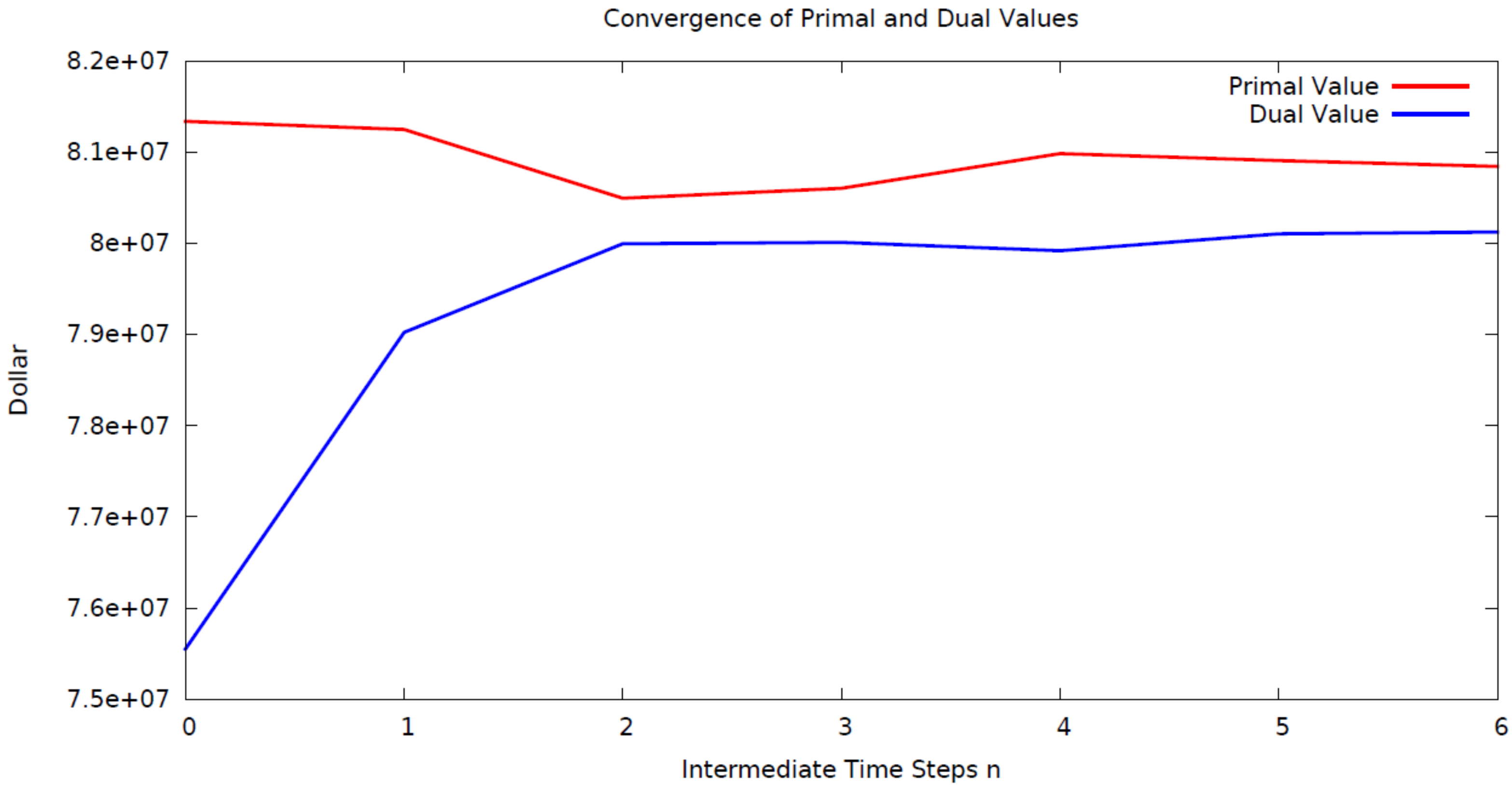
# Trinomial Tree

- Does the error decrease when we refine the discretization for the backward induction?




- Trinomial Trees are refined by introduction of intermediate time steps at which the process is sampled.

# Behavior of Error Bounds for Reduction Costs




- For a discretization with daily time sampling and no intermediate time points the error of reduction costs is +/- 1%.

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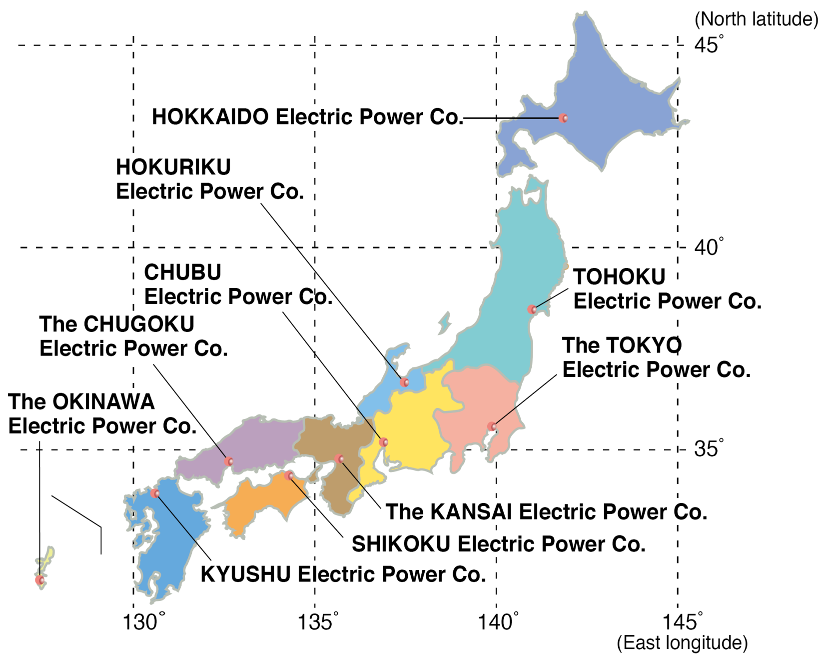
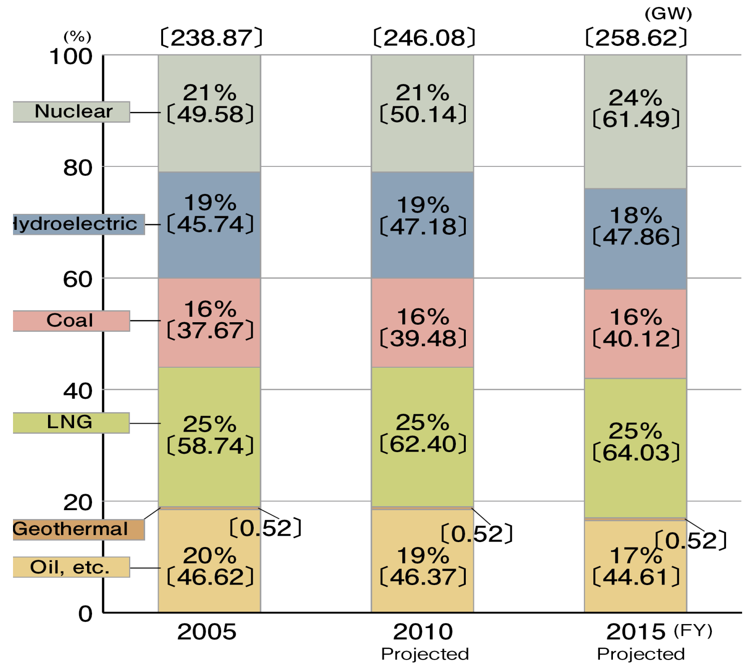
# Case Study: Japan

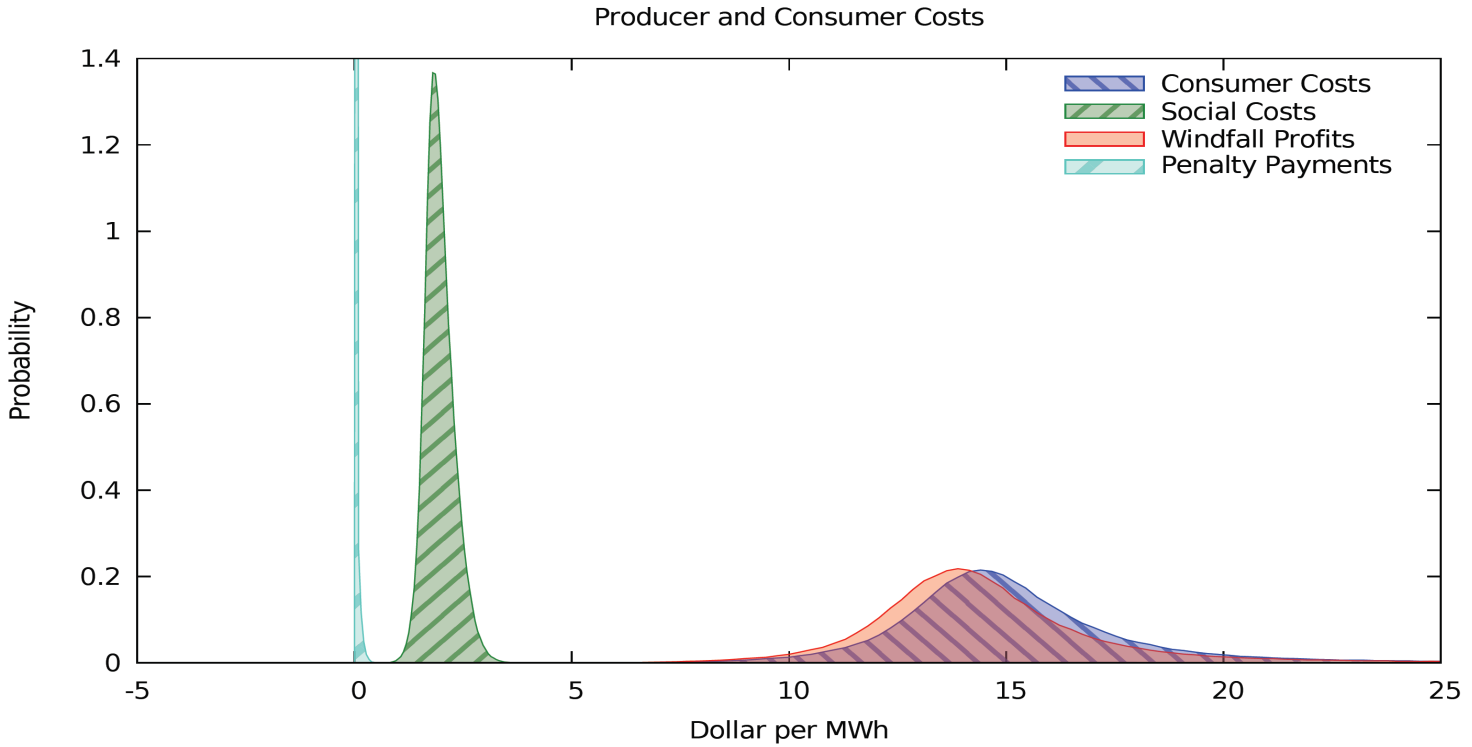



- Penalty: 100$
- Reduction Target: 300Mt i.e. 20% of average BAU Emission
- Assume: Emission Reductions come from Coal-Gas Switch

# Cost of a standard ETS (Japan)

Fictitious trading scheme covering the Japanese electricity sector, with 20% reduction target and 100$ penalty.




- Low Reduction Cost (2-3$/MWh)
- High Consumer Cost (~15$/MWh)
- This gives rise for huge extra profits for electricity producers (Windfall Profits)

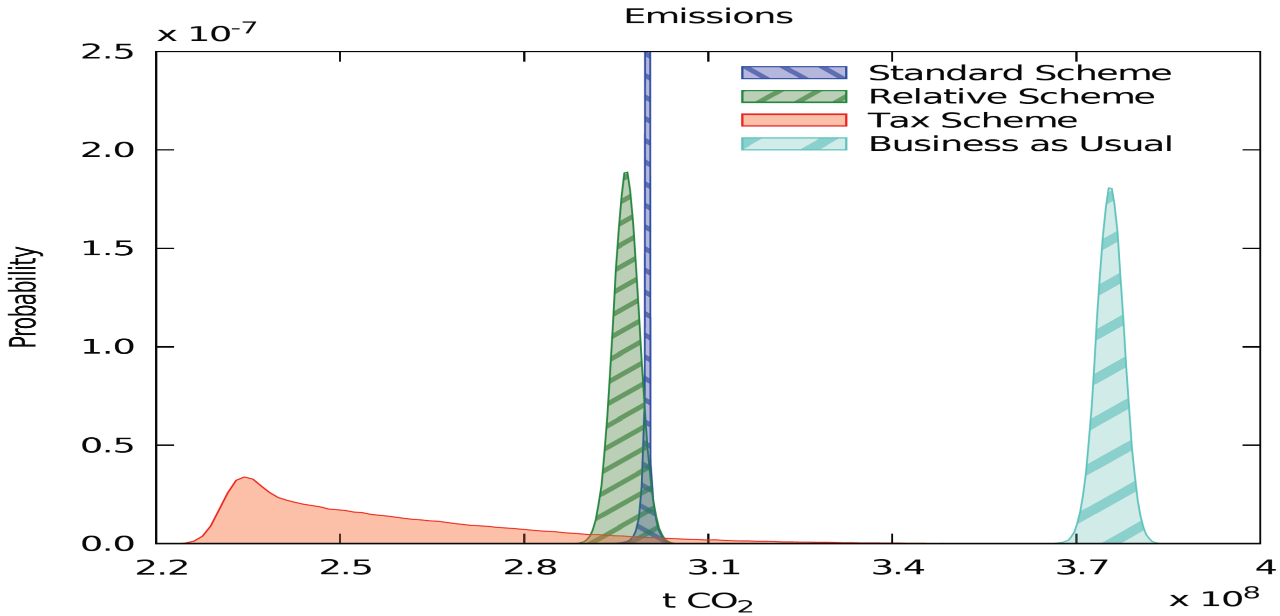
# Alternative Designs of ETS

Add Emission Tax and allocation of allowances that is relative to the produced amount of electricity

$$L^{A,S,i}(\theta^i,\xi^i) := \sum_{t=0}^{T-1}\sum_{j\in J^i}(S_t - P_t^{i,j} - ze^{i,j})\xi_t^{i,j} + \sum_{t=0}^{T-1}\theta_t^i(A_{t+1}-A_t) - \theta_T^i A_T - \pi\left(\Gamma_T^i - \tilde{\theta}_0^i + \Pi^i(\xi^i) - \sum_{t=0}^{T-1}\sum_{j\in J^i} y\xi_t^{i,j} - \theta_T^i\right)^+$$

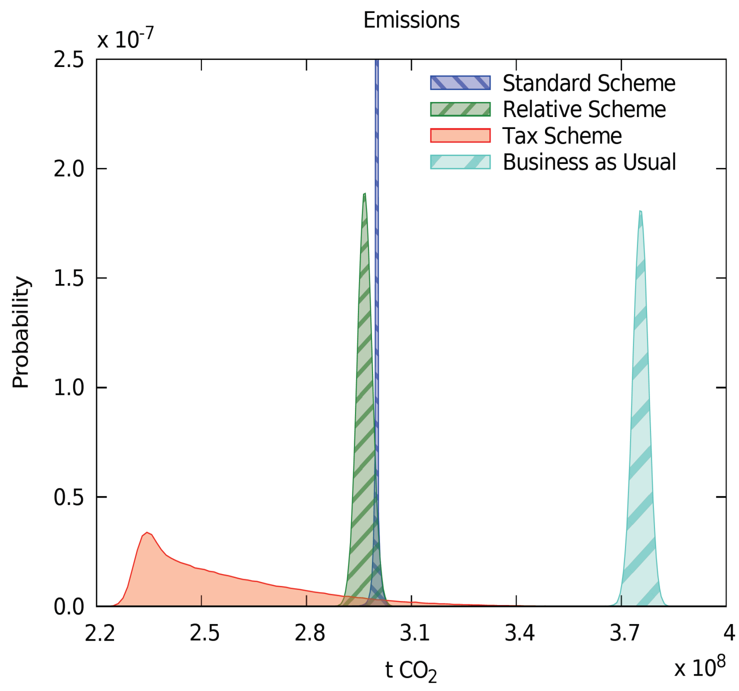
- $z$ Tax (e.g. Dollar) per ton CO2
- $y$ Number of allowances allocated per MWh of produced electricity
- **Tax scheme:** $z>0, y=0, \pi=0, \tilde{\theta}_0^i=0$
- **Relative scheme (uGPS):** $z=0, y>0, \pi>0, \tilde{\theta}_0^i \geq 0$

# Reduction Target




- To compare schemes under fair conditions we choose parameters such that a reduction target of 20% is reached with 95% probability. I.e. the emission distributions have the same 5% quantile.
- For the relative scheme this is reached for $y = 0.4$ and an initial allocation corresponding to 1/3 of the cap. Its financial value is ~ 2-3 Billion $ / year. This should be enough for the regulator to be able to set sound incentives.

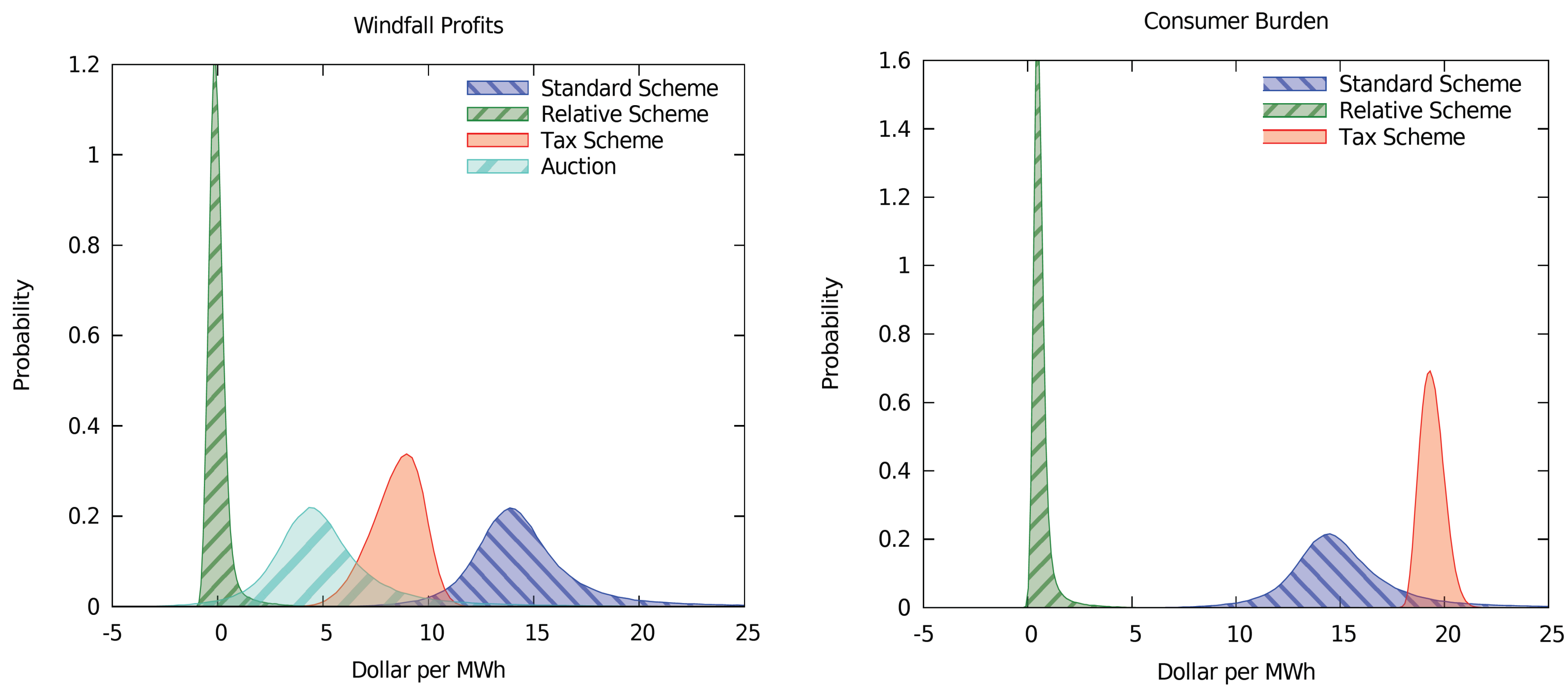
# Emissions and Reduction Costs (Japan)





- Tax scheme is not suited to control emissions, when abatement costs are stochastic.
- For the same emission quantile to be reached, the reduction costs of the tax scheme are huge.

# Windfall Profits and Consumer Costs (Japan)




- Only Relative Scheme is suited to control Windfall Profits
- Only Relative Scheme gives low Consumer Costs

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- **EU ETS with CERs and banking**
- Social optimality

# EU ETS with banking and CERs

*"The Clean Development Mechanism and Joint Price Formation for Allowances and CERs"* , R. Carmona and M.Fehr

**Dynamic stochastic equilibrium model:**

- Consider several emission markets, e.g. EU ETS, US ETS, Japan ETS indirectly linked by CDM and with compliance regulation similar to EU ETS:
  - In case of non compliance excess emissions have to be covered in the next period and a financial penalty $\pi$ is due for each ton of excess emissions.
  - Banking of EUAs/CERs is allowed without restrictions on the banked amount
  - The amount of CERs that is allowed to be used in each compliance period is restricted by a constant $\kappa$
- Risk neutral agents apply reduction and trading strategies:
  - Trade in allowances (e.g. EUAs) and CERs for several compliance periods
  - Apply short term reduction measures (Fuel switching)
  - Apply long term reduction measures (Refurbishing of power plant, CDM)

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# Equilibrium prices of indirectly linked ETSs

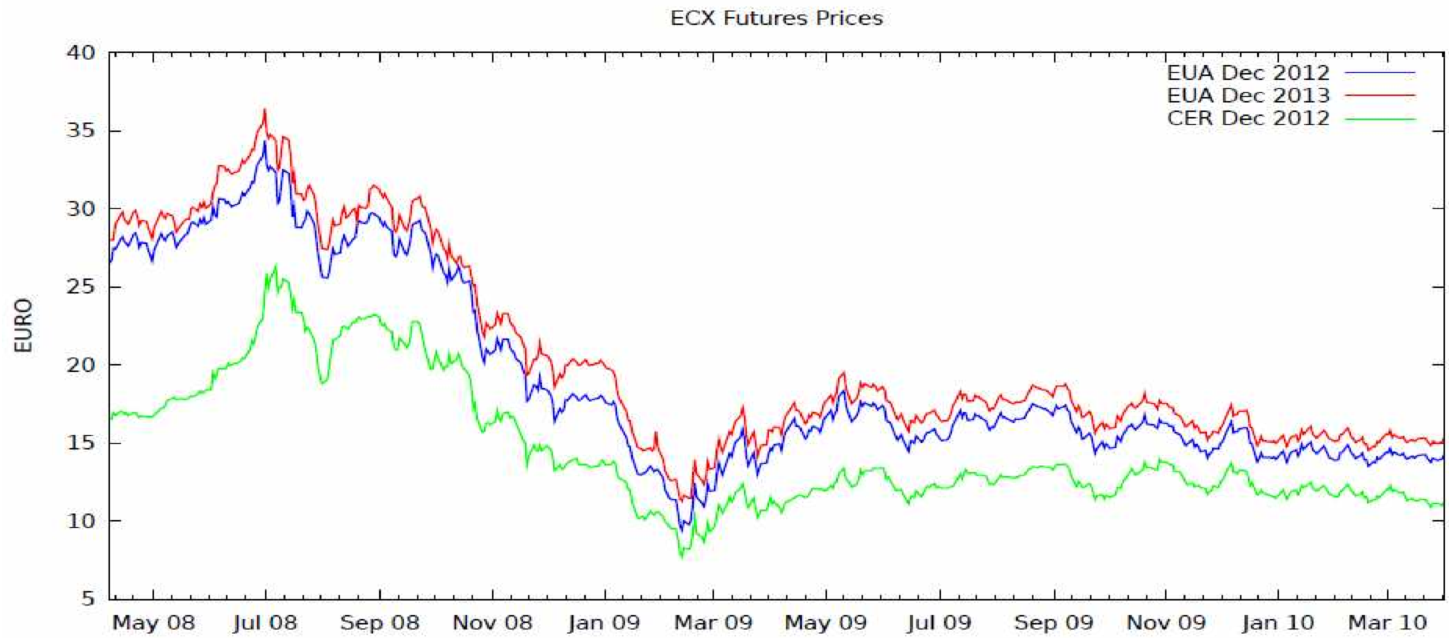
Assume that Emissions exceed the amount $\kappa$ , then the equilibrium EUA/CER prices at the end $T$ of the 2008-2012 phase of EU ETS are related by

- EUAs
$$A_T = \mathbb{E}\Big[A'_T + \pi \mathbf{1}_{\{N\}} + [C'_T - A'_T]^+ \mathbf{1}_{\{N^c\}} \mathbf{1}_{\{M\}} \Big| \mathcal{F}_t\Big]$$
- CERs
$$C_T = \mathbb{E}\Big[C'_T + [\pi + A'_T - C'_T]^+ \mathbf{1}_{\{N\}} \mathbf{1}_{\{L\}} + [A'_T - C'_T]^+ \mathbf{1}_{\{N^c\}} \mathbf{1}_{\{L\}} \Big| \mathcal{F}_t\Big]$$
- $A_T$ EUA 2012, $A'_T$ EUA 2013
- $C_T$ CER 2012, $C'_T$ CER 2013
- $N$ Event that the overall market does not comply
- $M$ Event that compliance can only be met with the use of CERs
- $L$ Event that the total amount of CERs in the market is smaller than the maximum amount of CERs that can be used in EU ETS

# Modeling EUAs and CERs consistently

"Option Pricing in EU ETS" preprint, P. Barrieu, U. Cetin, M. Fehr

- Arbitrage free model for EUAs/CERs
- Closed form




- Correlation of EUAs and CERs is due to compliance regulations (EUAs and CERs can be exchanged up to some extent)

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# Social Optimality of Standard ETS vs Penalty

- Montgomery proved in a deterministic setting that emission trading schemes are socially optimal in the sense that a given emission target is reached at lowest possible costs.
- Because he is working in a deterministic setting, the emission target is a hard constraint, i.e. emissions in equilibrium have to stay below the cap.
- However, emissions are stochastic in real life, and a stringent emission target can rapidly become prohibitive. Hence emission trading schemes, as e.g. EU ETS, allow for excess emissions modulo a penalty $\pi$ which at the same time serves as a safety valve for the allowance price.
- Economists argue that safety valves reduce the efficiency of the scheme.
- However if we adapt the definition of social optimality to a stochastic setting, the scheme with safety valve is socially optimal!
- The penalty / buy out price $\pi$ is closely related to the emission target.

# Reduction Target

- A natural choice is to control the emission distribution by a risk measure, as was done before.
- Like Value At Risk, this measure does a poor job at controlling the tail of the distribution since it controls only the frequencies of exceedances and not their actual sizes.
- In complete analogy with the expected shortfall, we propose here to control the emissions by setting an upper bound $\eta$ on the expected excess emission

$$E^{\lambda}(\xi) = \mathbb{E}\left[\sum_{i\in I}\left(\Delta^{i} + \sum_{i,j,k,t} e^{i,j,k}\xi_t^{i,j,k} - \lambda\right)^{+}\right]$$

  above some threshold $\lambda$ under a production strategy $\xi = \{\xi_t^{i,j,k}\}$ .
- Choose cap $\Lambda := \sum_{i\in I} \Lambda_0^i$ and penalty $\pi$ such that in equilibrium the reduction target is satisfied, i.e. $E^{\lambda}(\xi) \leq \eta$ .

# Definition of Social Optimality

An emission regulation is said to be socially optimal if for every choice of the threshold $\lambda \geq 0$ and upper bound $\eta > \tilde{a}(\lambda) := \inf_{\xi \in \mathcal{U}} E^{\lambda}(\xi)$ there exist regulatory parameters such that (at least) one corresponding equilibrium production schedule $\xi^*$ is a solution of the social optimization problem:

$$\begin{aligned} \inf \quad & \mathbb{E}[C(\xi)] \\ \text{s.t.} \quad & E^{\lambda}(\xi) \leq \eta \\ & \xi \in \mathcal{U}. \end{aligned}$$

# Social Optimality Result

- The corresponding cap is given by $\overline{\Lambda} = \sum_{i \in I} \overline{\Lambda}_0^i = \lambda$ and the penalty $\overline{\pi}$ is found as the Lagrange multiplier of the condition $E^\lambda(\xi) \leq \eta$ i.e. we compute $\overline{\pi}$ as the solution of

$$\sup \left\{ \inf_{\xi \in \mathcal{U}} \mathbb{E}[C(\xi)] + \pi(E^\lambda(\xi) - \eta) \middle| \pi \geq 0 \right\}$$

- The strategy $\overline{\xi}$ given by the solution of

$$\inf \left\{ \sup_{\pi \geq 0} \mathbb{E}[C(\xi)] + \pi(E^\lambda(\xi) - \eta) \middle| \xi \in \mathcal{U} \right\}$$

  is also a solution of the social optimization problem.
- Due to strong duality the pair $(\overline{\xi}, \overline{\pi})$ is a saddle point of $\mathbb{E}[C(\xi)] + \pi(E^\lambda(\xi) - \eta)$. Therefore $\overline{\xi}$ is also a solution of the global optimal control problem with penalty $\overline{\pi}$ and hence an equilibrium strategy.
- Consequently the Standard ETS is socially optimal.

# Conclusion

- This work gives the theoretical foundation and numerical foundation to analyze cap and trade schemes in a stochastic setting.
- As an application we highlighted assets and drawbacks of different policy designs and showed how to design schemes with low windfall profits.
- Extension to EU ETS with CERs and banking
- Social optimality

| | Std. ETS | Auction ETS | Emission tax | Relative ETS | Hybrid ETS |
|---|---|---|---|---|---|
| Target | ✓ | ✓ | ✓ | | ✓ |
| Cost eff. | ✓ | ✓ | ✗ | | ✓ |
| Incentives | ✓ | ✗ | ✗ | ✓ | ✓ |
| Windfall | ✗ | ✗ | ✗ | ✓ | ✓ |