Stochastic Finance 2010
Summer School Ulm
Lecture 3: Emission Trading

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Agenda

Carbon Target

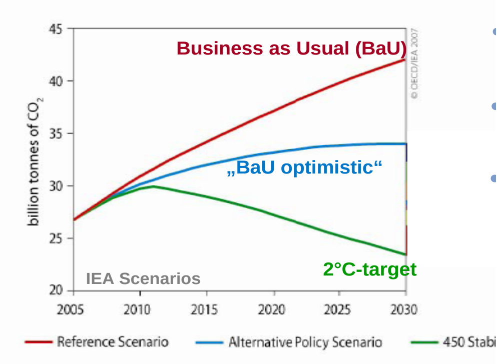

Figure: Global CO2 Emmissions.

Policy Options

Cap-and-trade systems	strong carbon price signal
Green taxes/ subsidies	
Tradeable green quota/feed-in tariffs	$\Updownarrow$
Standards and regulation	
R & D support	weak carbon price signal

Cap-and-trade systems

- European Emissions Trading Scheme (EU ETS) launched 2005. It is the world's largest carbon market to date, covering more than 40% of the carbon dioxide emitted in Europe. European member states agreed in December 2008 to extend this scheme until 2020 and open it up to new sectors, most notably aviation.

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- Proposal to introduce a US-wide cap-and-trade scheme by the new U.S. administration; Canada interested in linking up.
- Australia's Carbon Pollution Reduction Scheme (CPRS) and New Zealand's Emissions Trading Scheme (NZ ETS) are in different stages of development.

Basic idea of cap-and-trade systems

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- **During** the compliance period, the companies can **trade** permits among each other
- **At the end** of the compliance period, a regulated company has to **hand in** one permit or **pay a penalty fee** per unit of emission

Permit price in the EU ETS during the first phase

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

Permit price in the EU ETS during the first phase

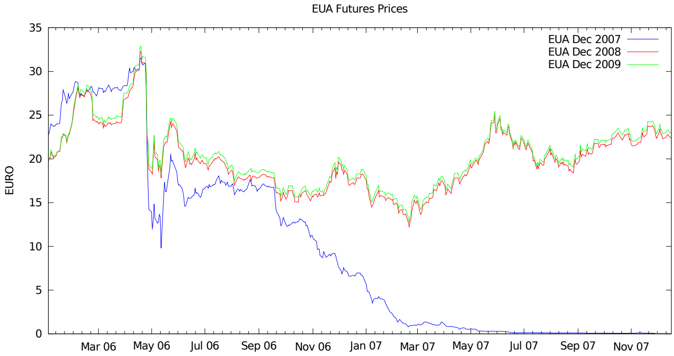

Figure: EUA-Dec07/08/09 futures price (22 April 2005 - 17 December 2007).

Analyze permit price jumps using an equilibrium model

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- Cap-and-trade system is a market-based policy instrument for reducing emissions
- Equilibrium models have been widely used in literature with the aim of showing theoretical properties of emission trading systems, especially, its cost-effectiveness.
- EU ETS is by far the largest cap-and-trade system. Prices during the first phase exhibited jumpy behaviour and an extreme price drop in April/May 2006. Price dynamics have been analyzed using jump-diffusion models, GARCH-models and regime-switching models.

Motivation of the talk

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- Explain the permit price slump in 2006 with an equilibrium model
- Analyse cap-and-trade systems with additional features (hybrid models)

Agenda

Overview on selected stochastic equilibrium models

Carmona et al. (2009) consider 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.

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

where

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

Overview on selected stochastic equilibrium models

A market equilibrium in emission permits consists of

- A^* (one-dim. stoch. process for forward price on permits)
- S^* (multi-dim. stoch. process for the prices of the products)
- θ^* (multi-dim. stochastic process of optimal trading strategies)
- ξ^* (multi-dim. stoch. process of opt. production strategies)

such that for given A^* and S^*

θ^* and ξ^* leads to a situation where all the firms are satisfied by their strategy in the sense that the terminal wealth

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

and the Market clearing condition on permits

$\sum_i \theta_t^{*i} = 0$ is satisfied and the supply meets demand for each good $\sum_{i,j} \xi_t^{*i,j,k} = D_t^k$.

Overview on selected stochastic equilibrium models

Permit price in the model of Carmona et al. (2009)

$$
\begin{aligned}
S_t &= Pe^{-r(T-t)} \cdot \mathbb{P}\left(q_{[0,T]} > N | \mathcal{F}_t\right) \\
&= \begin{cases} Pe^{-r(T-t)} & \text{if } q_{[0,t]} \geq N \\ Pe^{-r(T-t)} \cdot \mathbb{P}\left(q_{[t,T]} > N - q_{[0,t]} | \mathcal{F}_t\right) & \text{if } q_{[0,t]} < N \end{cases}
\end{aligned}
$$

- P is the penalty fee to be paid for each emission unit not covered by an emission allowance at the compliance time T.
- N is the amount of emission allowances handed out by the regulator
- $q_{[0,t]}$ is a stochastic process that models the cumulative emissions in the compliance period

Overview on selected stochastic equilibrium models

Permit price in the model of Chesney and Taschini (2008)

specifies 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.

Linear approximation approach of Chesney and Taschini (2008)

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

Overview on selected stochastic equilibrium models

Moment matching approaches of Grüll and Kiesel (2009)

- Log-normal (moment matching)

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

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- Reciprocal gamma (moment matching)

$$q_{[t_1,t_2]} \approx \tilde{q}^{IG}_{[t_1,t_2]} = IG(\alpha_{IG}, \beta_{IG})$$

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$$q_{[t_1,t_2]} \approx \tilde{q}^{IG}_{[t_1,t_2]} = IG(\alpha_{IG}, \beta_{IG})$$

- where the parameters $\mu_L(t_1,t_2)$, $\sigma_L(t_1,t_2)$ and α_{IG} and β_{IG} 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 and a reciprocal gamma 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

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

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- 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.

Auxiliary functions for moments of integral over GBM

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

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

Agenda

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.

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

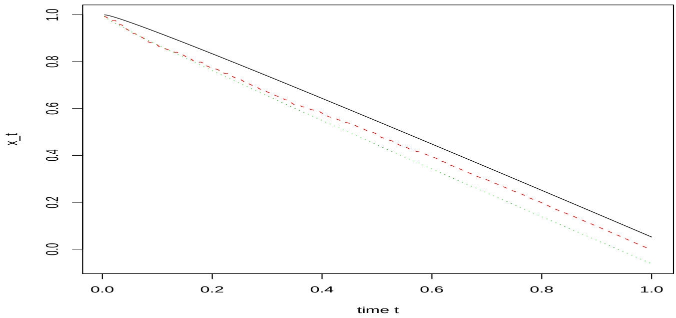

Figure: Trajectory of x_t for $t \in [0, 1]$, $N = Q_0 = 100$, $\mu = 0.02$ and $\sigma = 0.05$.

Numerical illustrations

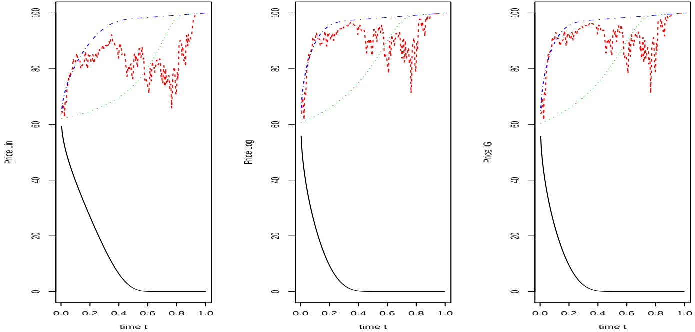

Figure: Trajectory of $S_t^{Lin}(x_t)$ (left), $S_t^{Log}(x_t)$ (middle) and $S_t^{IG}(x_t)$ (right) for $t \in [0, 1]$, $N = Q_0 = 100$, $\mu = 0.02$ and $\sigma = 0.05$.

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

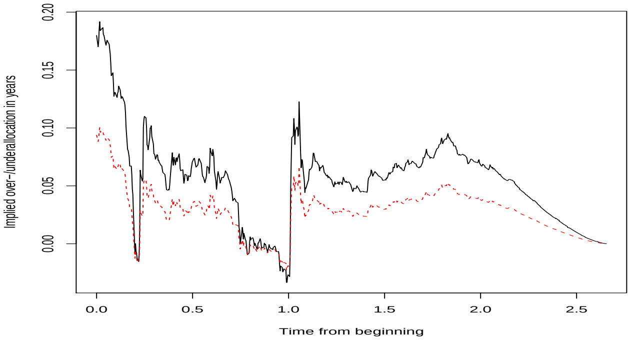

Figure: Implied $x_t - (T - t)$ for first phase for fixed $\mu = 0.02$ and $\sigma = 0.05$. Linear approximation approach (straight line), log-normal moment matching (dashed line). Positive values correspond to overallocation.

Agenda

Permit price Delta

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

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

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

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

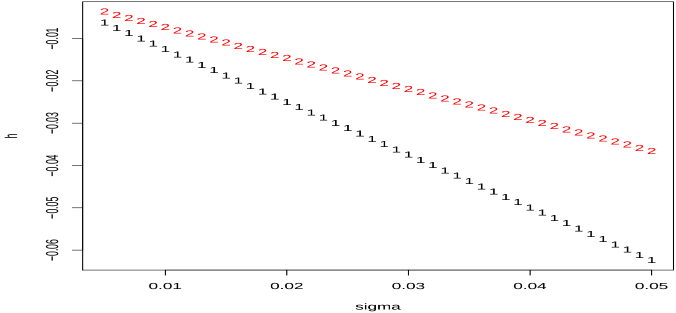

Figure: Linear approximation ("1"), log-normal moment matching ("2").

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Price Floor Using a Subsidy

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- 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.

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- A company with a permit shortage at compliance date faces a penalty P.
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- 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:

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

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.

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

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- 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.

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

Comparison of schemes

Mechanism	Advantages	Disadvantages
Offset safety valve	(a) Relatively simple to implement (b) Lower expected enforcement costs for regulated companies than in an ordinary cap-and-trade system (c) Regulator faces no financial burden	(a) Price ceiling is not guaranteed under all circumstances (b) Creates uncertainty on the projects for active emission reduction (c) Weakens the pressure for actions within the system, i.e. environmental targets are not ensured
Subsidy	(a) Relatively simple to implement (b) Reduces investment uncertainty under all circumstance (c) Stimulates reduction efforts in the system	(a) Regulator might face a significant financial burden whose size is hardly quantifiable a priori
Price collar	(a) Price collar is guaranteed under all circumstances (b) Lower expected enforcement costs for regulated companies than in an ordinary cap-and-trade system	(a) Permit prices do not reflect real expectations on the level of cumulative emissions after market intervention. The permit price volatility is not necessarily reduced (b) Regulator might face a significant financial burden when the price floor is reached (c) Regulator cannot plan the size of the financial burden and when the cash outflows will occur (d) Environmental targets are loosened when the price ceiling is reached.
Allowance reserve	(a) Compared to price collar, environmental target is only weakened up to a certain level	(a) Price bounds cannot be guaranteed under all circumstances (b) Drawbacks of price collar (see above)
Regulator offers options	(a) Regulator faces no financial burden (b) Price bounds are guaranteed for those companies willing to pay for these options (c) Environmental targets are not affected	(a) Policy regulator bears the price risk of the options written

Table 2: Advantages and disadvantages of the different schemes under investigation.

Hybrid sytem= Ordinary system + options

Mechanism		Corresponds to a combination of an ordinary cap-and-trade system and
Subsidy	-	Free of charge European-style put option with strike price equal to the price floor offered for free
Price collar	-	Free of charge American-style call option with strike price equal to the price ceiling (unlimited amount) Free of charge American-style put option with strike price equal to the price floor (unlimited amount)
Allowance reserve	-	Free of charge American-style call option with strike price equal to the price ceiling (limited amount) Free of charge American-style put option with strike price equal to the price floor (limited amount)
Options	-	European-style or American-style put and call options offered at a certain price

Agenda

Conclusion

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- Permit prices are inherently prone to jumps
- Price jumps of the magnitude of 2006 are unlikely to occur again as the measurement of the emission data has been improved significantly
- Hybrid schemes can be seen as ordinary schemes plus options

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