Impact of Emission Trading on the Energy-mix

ETS and energy-mix problem

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Introduction

- **What we have done**: a model to analyse the **impact of an emission trading system** on the technology-mix decision in the electricity sector;
- **Objective of this research**: asses the **effectiveness** of emission trading systems to address environmental policies;

Introduction

- Major focus of the literature on ETS have focused on a rather short term impact, that is the **fuel-switching** on the merit order of the electricity supply;
- This work focuses instead on the **long term impact of ETS**, that is the **energy-mix**, i.e. the mix of technologies that the electricity generation sector is going to adopt in the long run.

Model settings

- Three technologies: renewable sources (r), coal (c) and gas (g).
- Renewable (green) sources tend to have very **high investment costs**, but generate electricity power at almost zero operating costs;
- Coal has operating costs significantly lower than gas (mainly driven by the different costs of the fuels). However coal plants have a higher **emission rate** (CO2) than gas for every unit (MWh) of energy.

Model settings

- Producers take competitive decisions with respect **generation**, but have incentives to take cooperative decisions with respect to **energy-mix** (long run)
- High market **concentration** and a strong incentive to find **cooperative solutions** make the monopolist model suitable for the energy-mix problem in the electricity sector
- Decision maker is a monopolist with the objective to **maximize the expected profit of the sector**

Model settings

- Two periods model $[0, 0^+)$ and $[0^+, T]$
  - **Expansion decision** is taken in $t = 0$, new capacities $(Q_r^*, Q_c^*$ and $Q_g^*)$ are immediately added to the initial endowment $(Q_r, Q_c$ and $Q_g)$ and operative;
  - Building period of new plants is not interesting. $[0^+, T]$ is sufficiently long to represent the **useful life** of a plant and the **redemption time** of emission certificates (no banking, no borrowing);
- In $t = 0$ electricity demand D for the period $[0^+, T]$ is unknown. It is distributed as $N(\mu, \sigma)$ and is the only source of risk.

Emission market, certificates and relevant events

- In $t = 0$ the authority issues the number of certificates (C) at (risk neutral) price c_a.
- We can assume that the authority fixes C such that:

$$C < m_c Q_c + m_g Q_g$$

  i.e. full emissions from current polluting plants cannot be covered.
- Relevant ETS cash flows for the sector are the initial payment, the "opportunity cost" charged on the electricity price, the (eventual) payment of the penalty. Trading of certificates in $[0^+, T]$ between producers are not relevant.

Model settings

- Demand is revealed at $t = 0^+$; individual producers solve **generation decision**: **no-switch** (r, c, g) or **fuel switch** (r, g, c) ,
- At the same time equilibrium price for electricity p and emission certificates are also solved (i.e. $c_a = 0$ or f) ;
- Generation is distributed during delivery period $[0^+, T]$ at a constant equilibrium price.

Model settings - variable costs

- Renewable plants have zero emission. On the contrary, to generate $1MWh$ of electricity, gas and coal plants emit respectively m_g and m_c tons of CO2,
- operating costs for the three technologies are respectively:

technology	Unit operating costs
Renewable source	0
Coal	$c_{v,c} + m_c c_a = c_{v,c} + p_{a,c}$
Gas	$c_{v,g} + m_g c_a = c_{v,g} + p_{a,g}$

Model settings - Fixed costs

- **Fixed costs** for **coal** and **gas** plants are defined as:

$$FC_c = c_{f,c} Q_c^T, \qquad (1)$$
$$FC_g = c_{f,g} Q_g^T.$$

where $Q_{\cdot}^T$ is a compact notation for the summation of current plus new capacity $(Q_{\cdot} + Q_{\cdot}^*)$ .and $c_{f,c}, c_{f,g}$ can be interpreted as the costs required to operate, maintain and repay a unit of production capacity for the two conventional technologies.

- Fixed costs for **renewable sources** on the contrary tend to be developed progressively in less efficient places. This amounts to increasing investment and maintenance costs:

$$FC_r = c_{f,r} Q_r^T + \alpha \left(Q_r^T \right)^2. \qquad (2)$$

Emission market, certificates and relevant events

Thresholds for maximum generation such that the overall emissions are not greater than C. Two thresholds appear H_{cg} and H_{gc}.

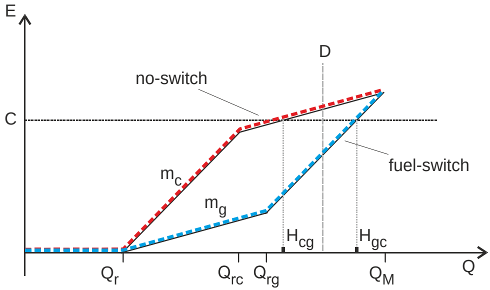


Figure: Emissions (E) as function of the total quantity of energy generated (Q).

The two thresholds correspond to two alternative merit orders of energy supply, that we call '*no switch*' (r, c, g) and '*fuel switching*' (r, g, c) . D is a possible level of the demand.

The equations defining H_{cg} and H_{gc} change depending of two conditions:

$$H_{cg} = \begin{cases} Q_r^T + C/m_c, \text{if } C \leq m_c Q_c^T \\ Q_r^T + Q_c^T + \frac{C - Q_c^T m_c}{m_g}, \text{ if } C > m_c Q_c^T \end{cases}$$

and

$$H_{gc} = \begin{cases} Q_r^T + C/m_g, \text{if } C \leq m_g Q_g^T \\ Q_r^T + Q_g^T + \frac{C - Q_g^T m_g}{m_c}, \text{ if } C > m_g Q_g^T \end{cases} .$$

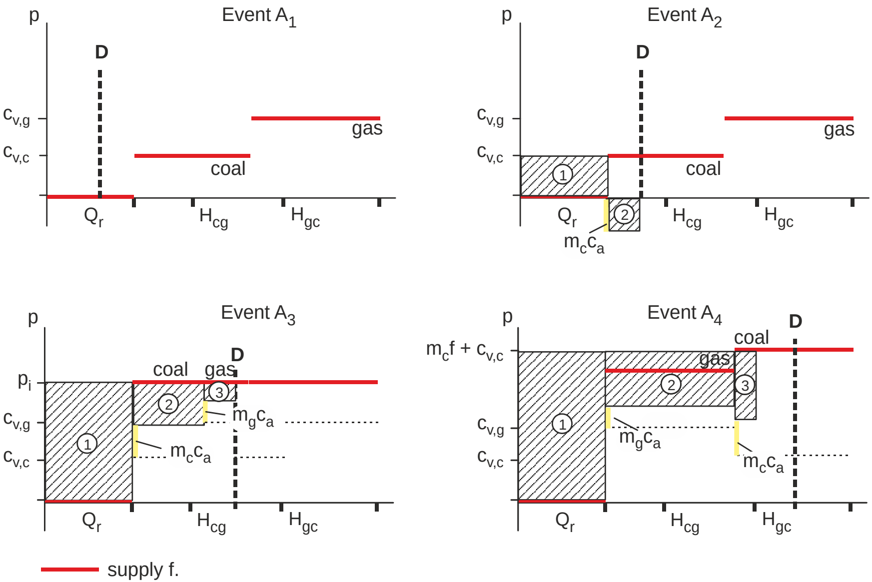
Emission market, certificates and relevant events

However, whatever the setting, the level of the demand will determine **four relevant events**, conditioning the level of profits:

Event	Label	Certificate price	Electricity price
$D \in [0, Q_r + Q_r^*]$	A_1	0	0
$D \in (Q_r + Q_r^*, H_{cg}]$	A_2	0	$c_{c,v}$
$D \in (H_{cg}, H_{gc})$	A_3	$c_a \in [0, f]$	$p_i = c_{2,v} + c_a$
$D \in [H_{gc}, +\infty)]$	A_4	f	$m_c f + c_{c,v}$

- Event A_3 is substantially different form the others, since the equilibrium outcome depends on a new source of uncertainty, affecting the generation decision of each producer: **what other producers will decide**.

Emission market, certificates and relevant events



Certificate price

By arbitrage arguments it can be shown that c_a is equal to risk-neutral expectation of the indifference price in the case of event A_3 and the penalty due in case of the event A_4.It is worth noticing that events A_3 and A_4 depends from the technology-mix decision of the representative agent:

$$
\begin{aligned}
c_a &= c_a^b P\left(A_3\right) + fP\left(A_4\right) \qquad (3) \\
&= f\left(1 - \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{H_{gc}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx\right) + \\
&+ c_a^b \left(\frac{1}{\sigma\sqrt{2\pi}} \int_{H_{cg}}^{H_{gc}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx\right).
\end{aligned}
$$

Producers must not have homogeneous beliefs

Theorem

Suppose that for some states of nature ω, $H_{cg} < D(\omega) < H_{gc}$, agents have homogeneous beliefs, market adopts uniform auction. Then market fails: that is neither the 'no-switch' nor the 'fuel-switch' solutions provide a Pareto optimal decision to market participants.

This result implies that some additional hypothesis must be adopted to let an 'intermediate' solution develop in the market. For intermediate solution we mean an ordering of the individual supply function where the cheapest (conventional) technology cannot be offered at full, that is $Q_1^{off} < Q_1$.

Producers must not have homogeneous beliefs

- An example of intermediate solutions (red dotted lines).
- Market forces bring individuals to converge to meet demand D and exhaust perfectly emissions C.

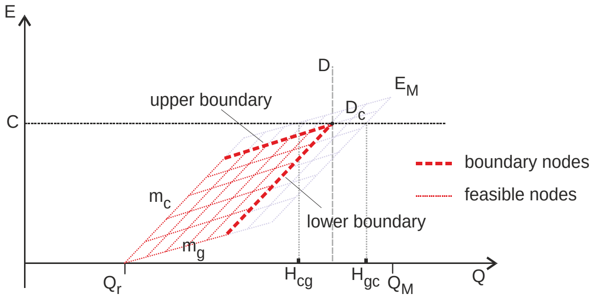


Figure: Any sequence of nodes in binomial tree starting from $(Q_r, 0)$ and finishing in point D_c is an example of intermediate solution, where the satisfaction of demand (D) obtains operating both technologies, before any of the two is completely saturated.

Producers are uncertainty and use price signal

Theorem

Under the settings introduced so far and the conditions of event A_3, the emission market will find a unique equilibrium price c_a and a demand of certificates equal to C, that is equal to the number of certificates issued by the authority. This amounts to say the the system will emit as much pollutant as planned by the authority. Moreover such emissions will originate an electricity generation plan for coal and gas with quantities:

$$Q_c^{off} = \frac{m_g D - C - m_g Q_r}{m_g - m_c}$$

for coal and

$$Q_g^{off} = \frac{C + m_c Q_r - m_c D}{m_g - m_c}$$

for gas, so that $Q_c^{off} + Q_g^{off} = D$.

Profit function

Net profit is a step function depending on D (which determines the event)

$$G|A_1 = -FC - c_a C$$

$$G|A_2 = -FC - c_a C + c_{v,c}\left(Q_r + Q_r^*\right).$$

$$\begin{aligned} G|A_3 = & -FC - c_a C \\ & + p_i\left(Q_r + Q_r^*\right) + c_a^b C. \end{aligned}$$

$$\begin{aligned} G|A_4 = & -FC - c_a C \\ & + \left(m_c f + c_{v,c}\right)\left(Q_r + Q_r^*\right) \\ & + \left(m_c f + c_{v,c} - c_{v,g}\right)\left(Q_g + Q_g^*\right) \\ & + \left(m_c f\right)\left(H_{gc} - Q_r - Q_r^* - Q_g - Q_g^*\right) \end{aligned}$$

Profit function

The probabilities of the four events

$$P\left(A_1\right) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{Q_r+Q_r^*} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

$$P\left(A_2\right) = \frac{1}{\sigma\sqrt{2\pi}} \int_{Q_r+Q_r^*}^{Q_r+Q_r^*+H_{cg}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

$$P\left(A_3\right) = \frac{1}{\sigma\sqrt{2\pi}} \int_{Q_r+Q_r^*+H_{cg}}^{Q_r+Q_r^*+H_{gc}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

$$P\left(A_4\right) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{Q_r+Q_r^*+H_{gc}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

Energy-mix problem

Maximize

$$E\left[G\right] = -FC - c_a C +$$
$$+ c_{v,c}\left(Q_r + Q_r^*\right)\frac{1}{\sigma\sqrt{2\pi}}\int_{Q_r+Q_r^*}^{H_{cg}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$
$$+ \left[p_i\left(Q_r + Q_r^*\right) + c_a^b C\right]\frac{1}{\sigma\sqrt{2\pi}}\int_{H_{cg}}^{H_{gc}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$
$$+ \left[\left(m_c f + c_{v,c}\right)\left(Q_r + Q_r^*\right) + \left(m_c f + c_{v,c} - c_{v,g}\right)\left(Q_g + Q_g^*\right) +\right.$$
$$\left. + m_c f\left(H_{gc} - Q_r - Q_r^* - Q_g - Q_g^*\right)\right]\frac{1}{\sigma\sqrt{2\pi}}\int_{H_{gc}}^{+\infty} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

s.t.

$$FC + c_a C \leq M,\ Q_r^* \geq -Q_r,\ Q_c^* \geq 0,\ Q_g^* \geq 0.$$

Analysis

- We approach the problem studying the **partial derivatives** of $E[G]$ with respect to the three decision variables. We report their analytical expression.
- Let's recall that due to the presence of H_{gc} and H_{cg} in the constraints and the equation of $E[G]$, the **domain of the problem can be divided into four sub-domains** ($D1$, $D2$, $D3$ and $D4$) on the plain $\left(Q_c + Q_c^*, Q_g + Q_g^*\right)$ is shown in the following picture

Analysis

Projection of the four sub-domains

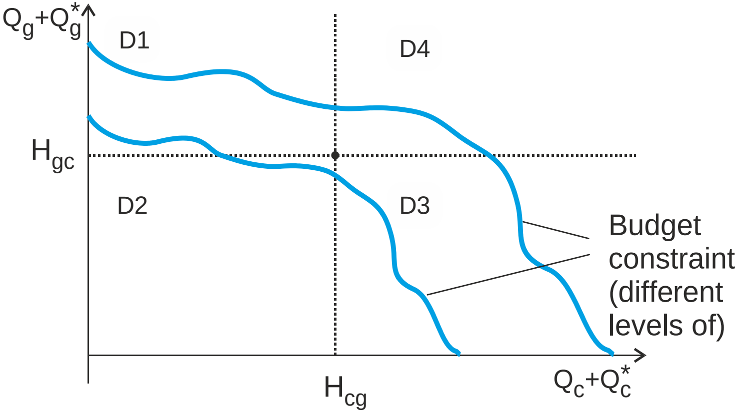


Figure: $D1$, $D2$, $D3$ and $D4$ sub-domains on the plain $\left(Q_c + Q_c^*, Q_g + Q_g^*\right)$

Analysis

The derivative $\partial E\left[G\right]/\partial Q_r^*$ can be treated only numerically:

$$\frac{\partial E}{\partial Q_r^*} = -c_{f,r} - 2\alpha Q_r^T + \frac{c_{v,c}}{\sigma\sqrt{2\pi}} \int_{Q_r+Q_r^*}^{H_{cg}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

$$+ c_{v,c} Q_r^T \frac{1}{\sigma\sqrt{2\pi}} \left\{ \left[e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \right]_{H_{cg}} - \left[e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \right]_{Q_r+Q_r^*} \right\}$$

$$+ \frac{p_i}{\sigma\sqrt{2\pi}} \int_{H_{cg}}^{H_{gc}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx + \left[p_i Q_r^T + c_a^b C \right] \frac{1}{\sigma\sqrt{2\pi}} \left| e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \right|_{H_{cg}}^{H_{gc}}$$

$$+ \frac{m_c f + c_{v,c}}{\sigma\sqrt{2\pi}} \int_{H_{gc}}^{+\infty} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx - \frac{m_c f}{\sigma\sqrt{2\pi}} \left(H_{gc} - Q_r^T - Q_g^T \right) \left[e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \right]_{H_{gc}}$$

Analysis

The other two partial derivative can be studied, from a theoretical point of view, in the $D1$, $D3$ and $D4$ sub-domains.

$$\frac{\partial E(G)}{\partial Q_g^*} = -c_{f,g} + \Big[\left(p_i - c_{v,c}\right)\left(Q_r + Q_r^*\right) + f\left(C - m_c H_{gc}\right)$$

$$+(c_{v,g} - c_{v,c})(Q_g + Q_g^*)\Big] \frac{1}{\sigma\sqrt{2\pi}} \left[e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}\right]_{H_{gc}} \cdot \frac{\partial H_{gc}}{\partial Q_g^*}$$

$$+ \left[m_c f \frac{\partial H_{gc}}{\partial Q_g^*} + c_{v,c} - c_{v,g}\right] \frac{1}{\sigma\sqrt{2\pi}} \int_{H_{gc}}^{+\infty} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx$$

Analysis

As for the derivative $\frac{\partial E(G)}{\partial Q_c^*}$:

$$\frac{\partial E(G)}{\partial Q_c^*} = -c_{f,c} + c_{v,c}\left(Q_r + Q_r^*\right)\frac{1}{\sigma\sqrt{2\pi}}\left[e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}\right]_{H_{cg}}\frac{\partial H_{cg}}{\partial Q_c^*}$$

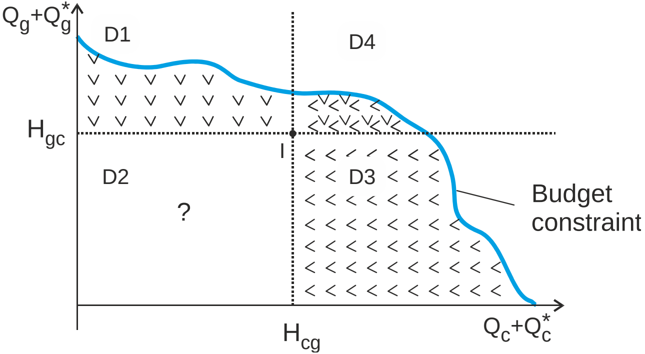
$$+p_i\left(Q_r + Q_r^*\right)\frac{1}{\sigma\sqrt{2\pi}}\left\{\left[e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}\right]_{H_{gc}}\cdot\underbrace{\frac{\partial H_{gc}}{\partial Q_c^*}}_{=0} - \left[e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}\right]_{H_{cg}}\frac{\partial H_{cg}}{\partial Q_c^*}\right\}$$

$$+m_c f\frac{\partial H_{cg}}{\partial Q_c^*}\frac{1}{\sigma\sqrt{2\pi}}\int_{H_{gc}}^{+\infty} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}dx$$

$$-\left[f\left(m_c H_{gc} - C\right) + c_{v,c}r + (c_{v,c} - c_{v,g})g\right]\frac{1}{\sigma\sqrt{2\pi}}\left[e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}\right]_{H_{gc}}\underbrace{\frac{\partial H_{gc}}{\partial Q_c^*}}_{=0}$$

Analysis - Sign of the partial derivatives

The study of the derivatives $\frac{\partial E(G)}{\partial Q_g^*}$ and $\frac{\partial E(G)}{\partial Q_c^*}$ in the $D1, D3$ and $D4$ domains implies that $E\left[G\right]$ can reach the maximum in D_2 or along the boundaries.



A particular scenario

Numerical studies can bring to the solution in special cases, but we are interested in theoretical results which can be valid for every economically significant choice of parameters. In this study we have chosen the following values:

Param.	Value	Units	notes
$c_{v,r}$	0	€$/MWh$	
$c_{v,c}$	2.5	€$/MWh$	
$c_{v,g}$	4	€$/MWh$	
m_c	.89	t CO2 / MWh	
m_g	.36	t CO2 / MWh	
α	0		
$c_{f,r}$	7.04	€$/MWh$	wind on-shore
$c_{f,c}$	8	€$/MWh$	
$c_{f,g}$	4	€$/MWh$	

A particular scenario

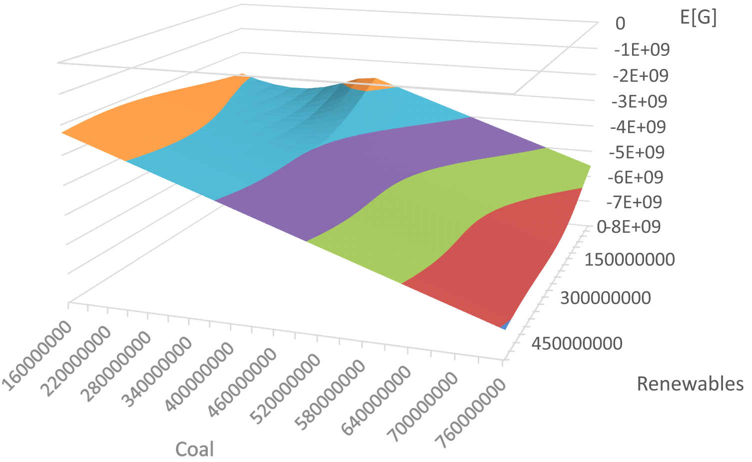
Param.	Value	Units	notes
M	$\{1,2\} \times 10^{10}$	e	
C	$\{100, 200, 400, 4000\} \times 10^{6}$	t	
f	100	e/tCO2	
Q_r	$250'000$	GWh	
Q_c	$250'000$	GWh	
Q_g	$250'000$	GWh	
μ	$500'000$	GWh	
σ	$250'000$	GWh	

Comparing optimal solutions given different Number of Certificates

Numb. Certificates	E[G]	Qr	Qc	Qg	Elec. Price	Certif. Pr.	Init. Investm.
50'000'000	20'543'562'405	278'838'382	250'000'000	250'000'000	**72**	**66**	5'947'118'041
100'000'000	16'683'965'547	181'169'740	250'000'000	250'000'054	**67**	**62**	8'470'778'667
200'000'000	9'068'188'614	149'026'887	250'000'000	250'000'144	**47**	**44**	10'000'194'209
400'000'000	-495'568'544	51'473'470	348'314'758	250'000'000	**18**	**18**	9'361'389'195
4'000'000'000	-2'267'124'876	**409'122'483**	250'000'000	250'000'000	**0**	**3**	3'000'000'000

Numb. Certificates	p(A1)	p(A2)	p(A3)	p(A4)	G(A2)	G(A3)	G(A4)
50'000'000	10%	5%	13%	**72%**	697'095'956	978'384'787	37'749'823'104
100'000'000	5%	6%	23%	66%	452'924'349	699'378'187	39'702'034'033
200'000'000	4%	17%	32%	47%	372'567'217	686'372'811	46'760'967'717
400'000'000	2%	80%	0%	18%	128'683'675	549'260'457	57'834'822'521
4'000'000'000	26%	72%	0%	**1%**	1'022'806'208	0	0

Two optima can be distinguished



Conclusions

- The effectiveness of ETS for climate and environmental policy is **poor if not even contrary**.
- Expansion of renewables **is highest when ETS has no influence** at all (price of certificates equal to zero).
- Under some conditions, **ETS even introduces incentives to expand coal plants**.
- **Fuel switching** (gas instead of coal) is marginal.