The adoption of CCS by the cement industry: A game theoretic analysis

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The slow roll-out of CCS in hard to abate industries

- **Hard to abate sectors**: cement, steel, glass & chemicals sectors **are not on track in terms of decarbonization**
  - https://www.iea.org/articles/the-challenge-of-reaching-zero-emissions-in-heavy-industry
  - https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members/executive-summary
- **CCS** would be a key technology but it **is not deployed**: it is not a mature technology, capital intensive, disruptive, historically low ETS prices, free allocations…
- The paper focuses on the **role of imperfect competition** within the sector to explain this delay **and suggest relevant public policies**
- Why taking **cement** is a perfect case study

The standard cost benefit analysis for a decarbonization project

the abatement cost (€/ton CO_2) for CCS
illustrative data for cement (source Gardarsdottir, S.O., et al., 2018.)

$AC = [c + iF/Q - d] / A$ (€/ton CO_2)

$AC = [112{,}81 + 4\%*250 - 38{,}18]/0{,}626$

$AC = 135{,}1$ €/ton CO_2

Quinet SCC(2030) = 250 €/ton CO_2

production 1 Mt/year Q	unit	dirty plant	CCS plant
Opex **d** c	€/ton cem	38,18	112,81
plant	€/ton cem	38,18	52,81
emission rate A	tCO2/tcem	0,626	
transport and sequestration	€/ton cem		60,00
Capex of CCS F	M €		250
discount rate i			4%

Agenda for analyzing the role of imperfect competition

Formalize a continuous time **model for the adoption of a clean technology under imperfect competition** when firms initially operate with a dirty technology with increasing carbon tax

Characterize **the Nash equilibria of the game**

Design the relevant public policies in terms of subsidies assuming market concentration exogeneously regulated

Three relevant sources of literature

CCS rate of adoption with several sectors/countries

- Optimal control models (Ayong Le Kama et al , 2013; Amigues et al, 2016; Moreaux et al, 2024...)

Imperfect competition in the cement sector

- Repeated two stage model featuring short term (quantities) and long term (capacity through entry and exit) with horizontal differentiation (Ryan, 2012; Fowlie et al, 2016)

Imperfect competition and the timing of innovation

- Reinganum, 1981; Fudenberg and Tirole, 1985

Our model: an adoption game in continuous time

Main assumptions

- A given market structure
- Two infinite lifetime technologies
- Dirty with variable cost increasing with social cost of carbon
- Clean with constant variable cost and fixed investment
- Short term competition is Cournot

The adoption game has 6 parameters

Continuous time model **with n firms each of which operating either with a dirty or a clean technology**

Dirty technology with a variable cost increasing over time

$\delta(t) = \mu_0 + \mu_1 SCC(t)$

μ_1 emission rate ; t = 2024 is time zero, $SCC(t) = SCC(2024)e^{it}$ *that is* Hotelling rule with i social discount rate

Clean technology with variable cost normalized at zero and a fixed sunk cost for adoption F *(yearly annualized $f = iF$)*

Demand function normalized as $p = 1 - Q$

Short term Cournot competition to select quantities

Long term competition through adoption time of the clean technology *t is as $\delta(t)$*

The short term Cournot equilibrium at time t

$$q_c(k;t) = \frac{1}{n+1}\big(1 + (n-k)\delta(t)\big)$$
$$q_d(k;t) = \frac{1}{n+1}\big(1 - (k+1)\delta(t)\big)$$
$$p(k;t) = \frac{1}{n+1}\big(1 + (n-k)\delta(t)\big)$$
$$\pi_c(k;t) = \frac{1}{(n+1)^2}\big(1 + (n-k)\delta(t)\big)^2$$
$$\pi_d(k;t) = \frac{1}{(n+1)^2}\big(1 - (k+1)\delta(t)\big)^2$$
$$cs(k;t) = \frac{1}{2}(1-p)^2 = \frac{1}{2(n+1)^2}\big(n - (n-k)\delta(t)\big)^2$$
$$w(k;t) = cs(k;t) + k\pi_c(k;t) - kf + (n-k)\pi_d(k;t)$$

At time *t* denote *k* = clean firms, *n - k* = dirty firms

Two cases are considered :

***Base case**: $1/(n+1)^2 > f$*

CCS does not affect market concentration

***Extension:** $1/(n+1)^2 < f$*

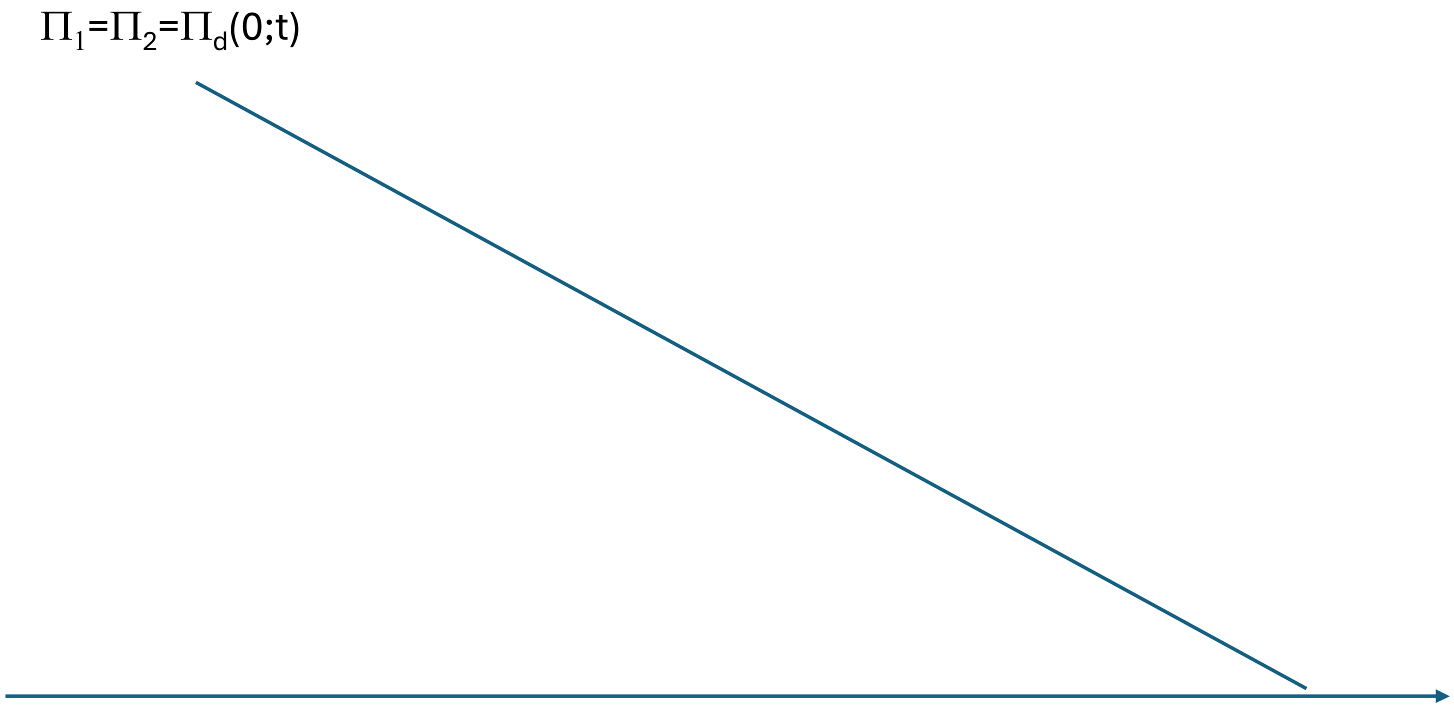
CCS affects market concentration :

Similarities and differences with the innovation game of Reinganum, 1981

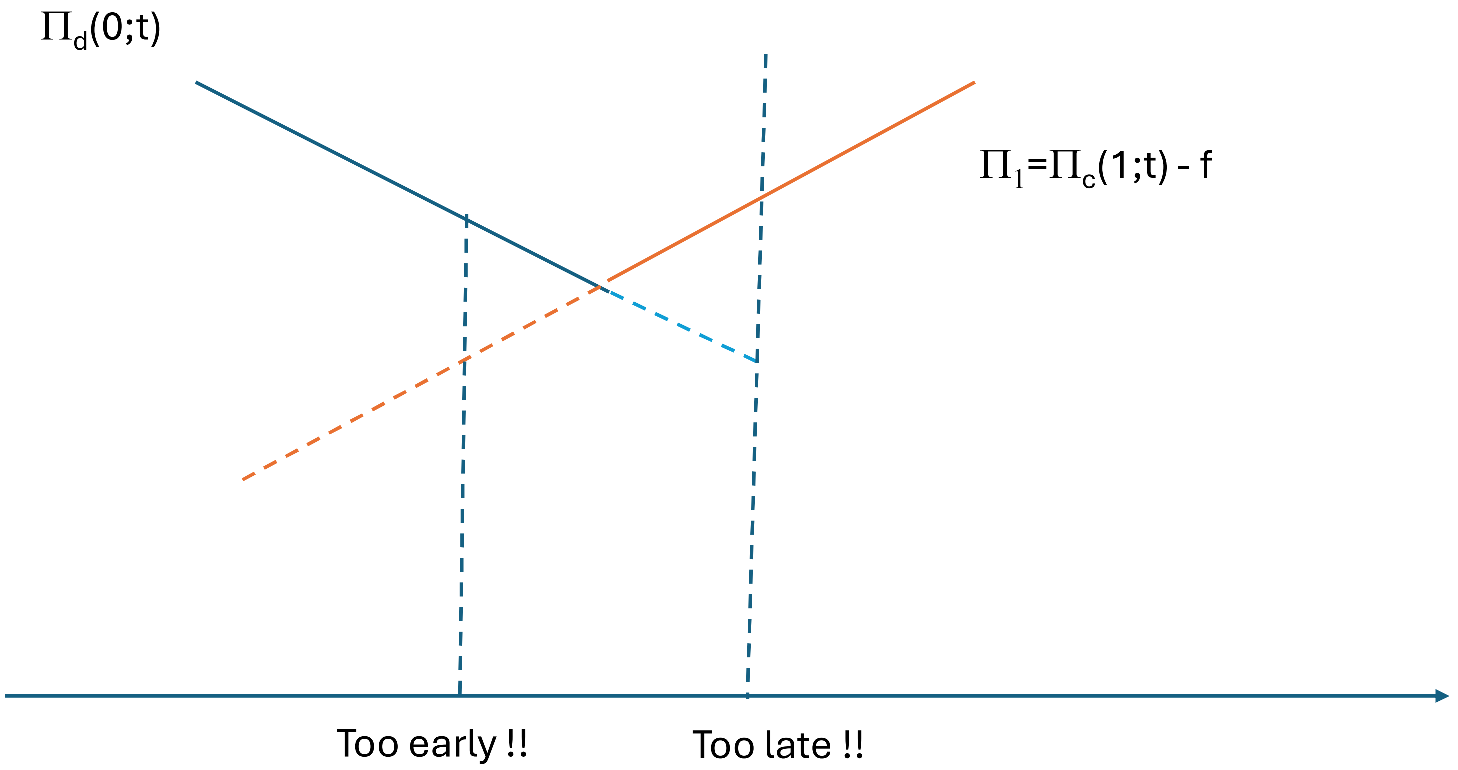
	Innovation game	Adoption game
Number of firms fixed (symmetric)	Imperfect competition	Cournot competition
Fixed cost	Decreasing over time	Constant
Variable costs	Constant	Increasing for dirty firms
Public policy analysis	None	Main focus

The path to derive a Nash equilibrium is similar

The Reinganum approach is based on an exogenous ordering of the firms

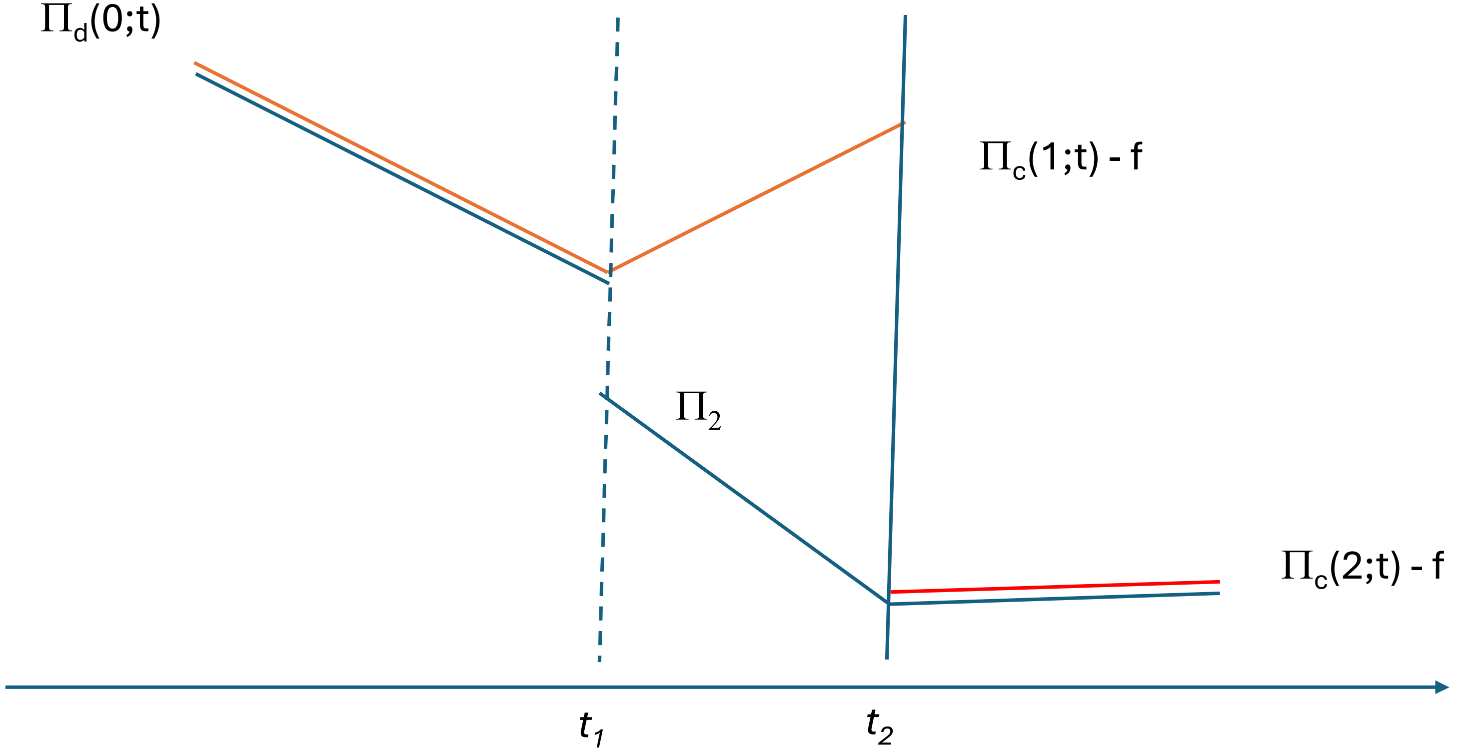


Firm 1 adopts at time *t*



The optimal adoption time for firm 1

$\Pi_c(1; t_1) - f = \Pi_d(0; t_1)$



The precommitment equilibrium (Reinganum)

Proposition 1 *Adoption times of adoption in a precommitment equilibrium are given by:*

$$\delta_k^C = \delta(t_k^C) = \begin{cases} \frac{1}{n-2k}\left(\sqrt{1+\alpha_k}-1\right) & \text{if } 2k < n \\ \frac{f(n+1)^2}{2n} & \text{if } 2k = n \\ \frac{1}{2k-n}\left(1-\sqrt{1-\alpha_k}\right) & \text{if } 2k > n \end{cases} \tag{6}$$

with $\alpha_k = \frac{f(n+1)^2|n-2k|}{n}$.

The timing of adoption has the following properties:

1. *all firms adopt the clean technology and remain active on the market;*
2. *adoption dates increase with the number n of firms;*
3. *adoption dates and the duration of the transition increase with the fixed cost f.*

The equilibrium discounted cash flows are decreasing from firm *1* to firm *n* which suggests preemption !!

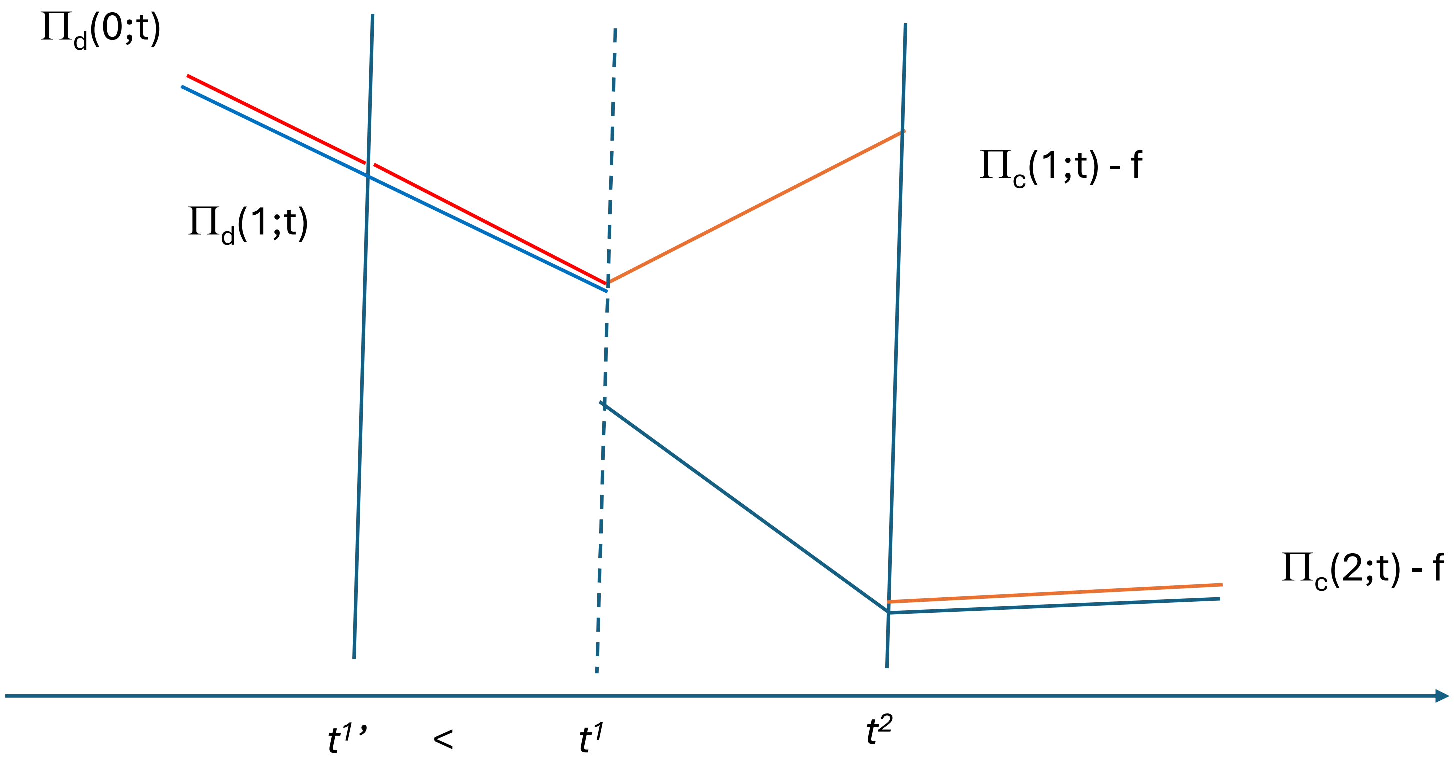
The preemption equilibrium
(Fudenberg Tirole 1985)

Take the case of **two competitors** adopting at t_1 and t_2

For competitor 2 not to preempt competitor 1 it must be that :

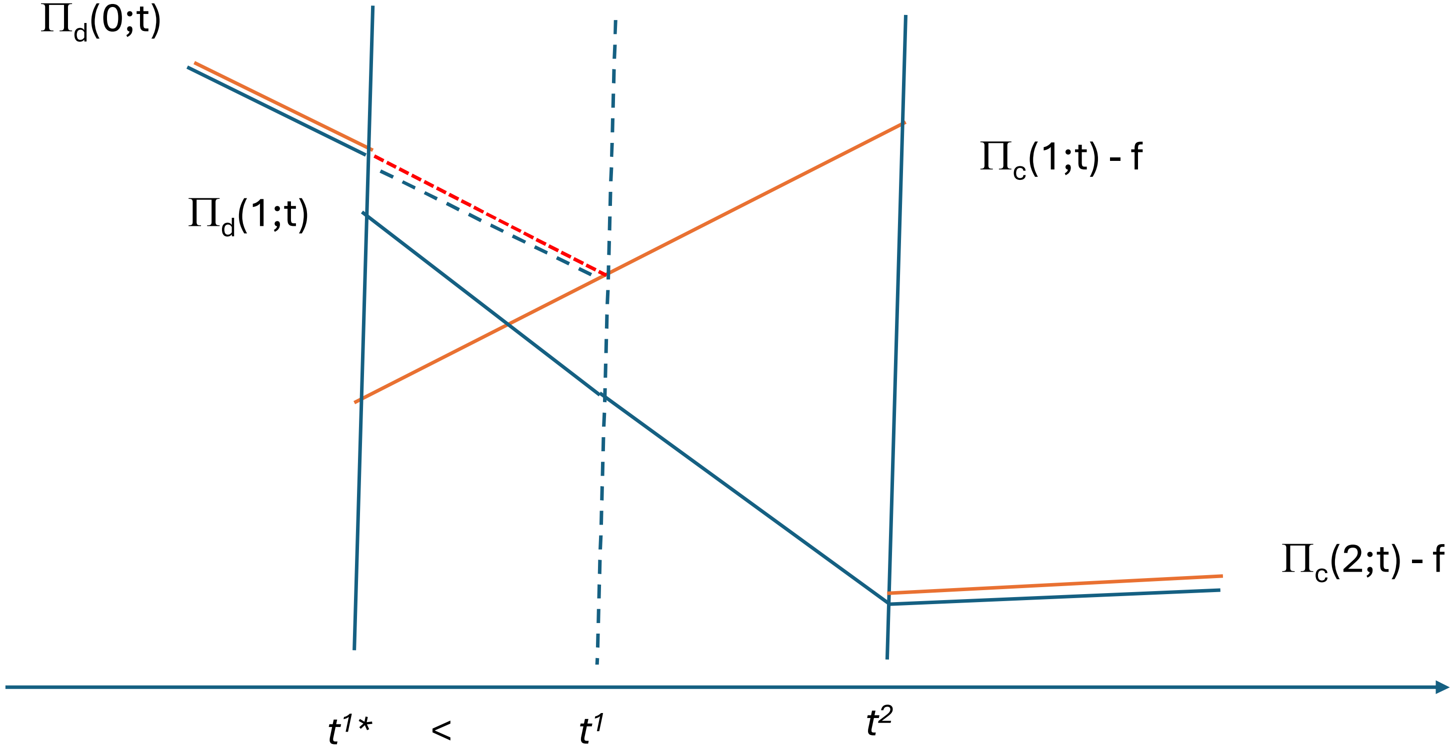
- Either: **diffusion equilibrium**
  - No incentive to inverse positions which implies that these discounted profits are equal
- Or: **joint adoption equilibrium**
  - They adopt at the same date which implies that $t_1 = t_2$

The diffusion equilibrium with n=2



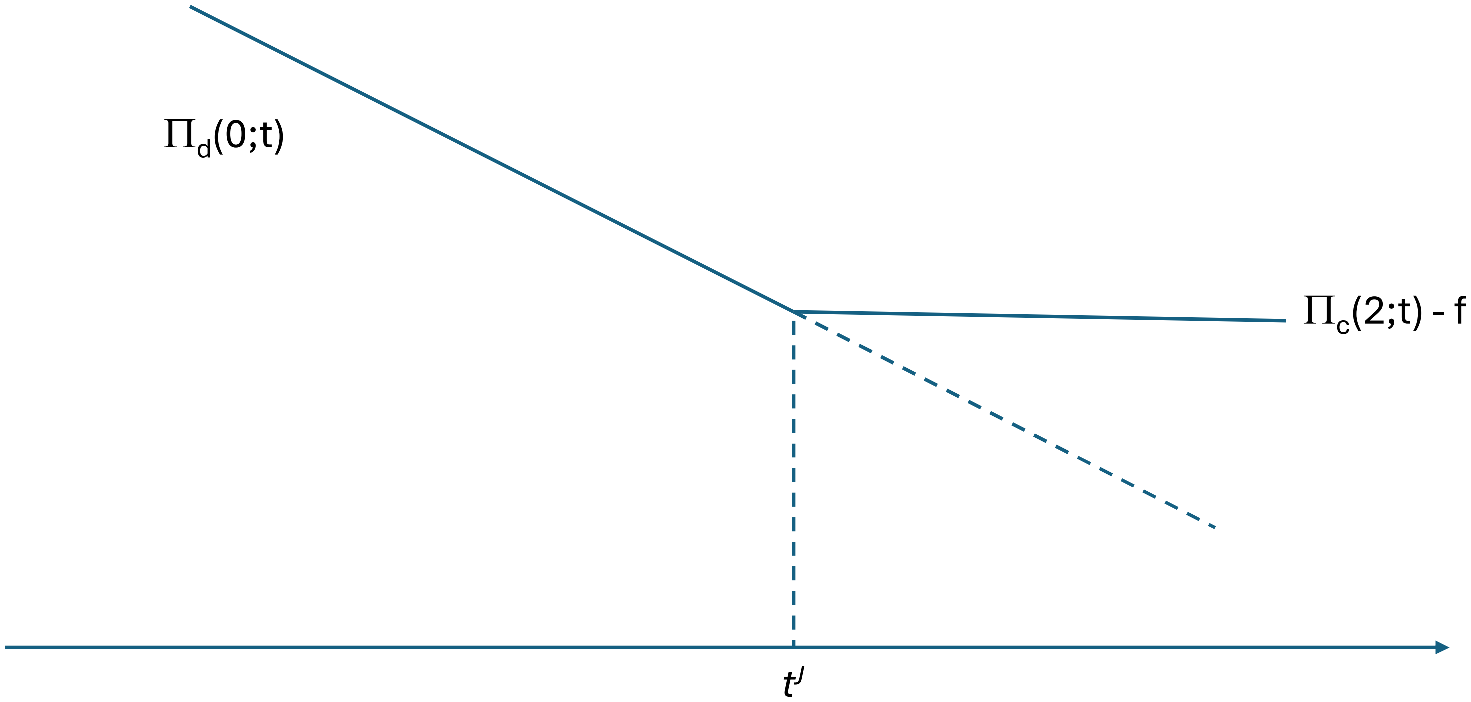
The diffusion equilibrium with n=2

$$\int_{t_1^P}^{t_n^P} \left[\pi_c(1;t) - f - \pi_d(1;t)\right] e^{-i\nu} d\nu = 0$$



The joint adoption equilibrium with n = 2

$\Pi_c(2; t^J) - f = \Pi_d(0; t^J)$



Proposition

For our adoption game
the optimal joint adoption equilibrium
Pareto dominates all diffusion equilibria

Defining the relevant social optimum

(max the discounted social welfare)

First best

or

Second best for a given market structure

The second-best adoption time t^{SB} is such that:

$$\delta^{SB} = \delta(t^{SB}) = 1 - \sqrt{1 - \frac{2f(n+1)^2}{(n+2)}} \tag{13}$$

and these timings have the following properties:

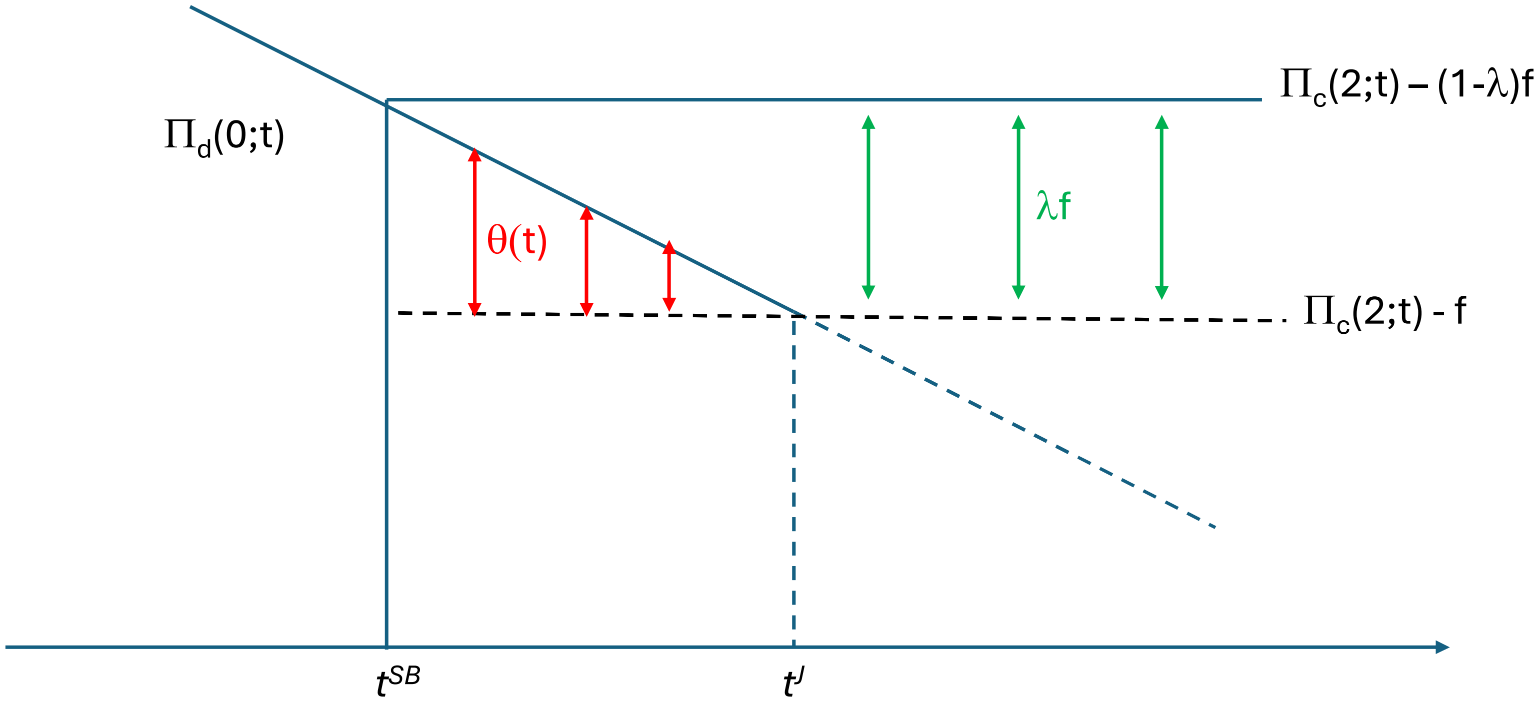
1. *First-best date happens before second-best date, which happens before the joint adoption date:* $\delta^{FB} < \delta^{SB} < \delta^J$
2. *First-best date happens before the first precommitment date:* $\delta^{FB} < \delta_1^C$
3. *First-best and second-best dates increases with the fixed cost* f.
4. *Second-best dates increases with the number* n *of firms;*

Second best social optimum

No public policy for the precommitment equilibrium!

Proposition 5 *A policy that advances adoption for a firm does not improve the discounted welfare of a precommitment equilibrium as soon as the number of firms is larger than or equal to 4.*

Two policy instruments to achieve the second best with the joint adoption equilibrium



Public policies for the joint adoption equilibrium

Proposition 6 *Two instruments may decentralize the second-best in the pre-emption joint adoption equilibrium:*

1. *A subsidy on fixed costs, which subsidize the proportion of fixed costs:*

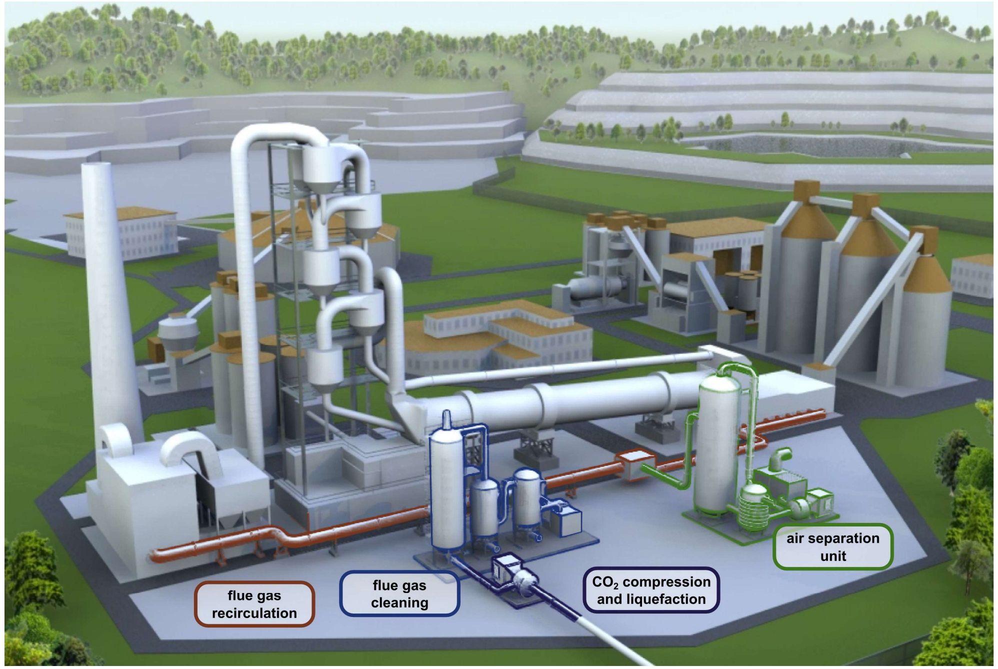
$$\lambda^{J\lambda} = \frac{n}{n+2} \tag{14}$$

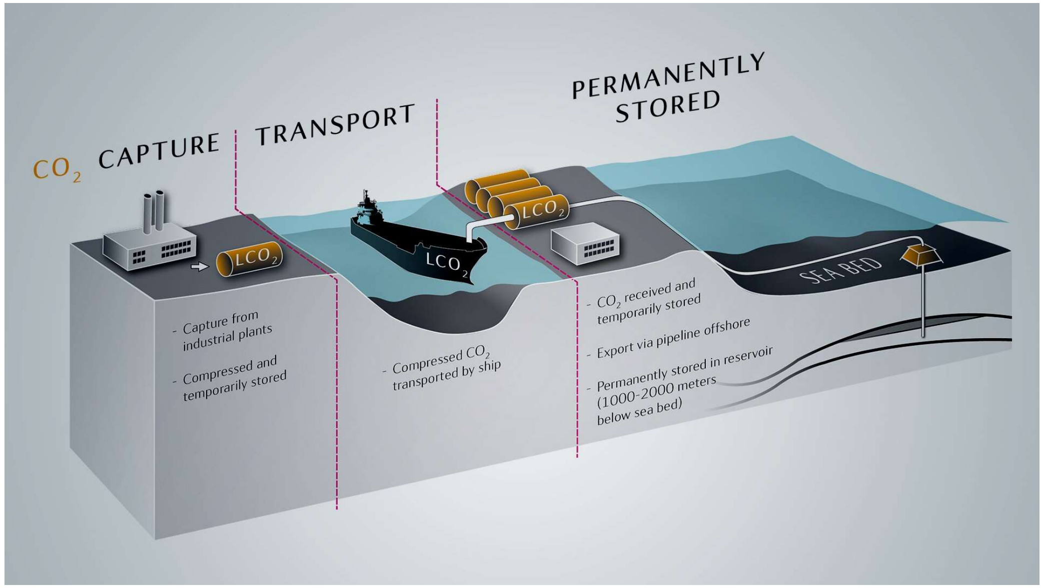
2. *A limited-time subsidy on profit $\theta(t)$ flow during the period $t^{SB} \leq t \leq t^{J}$*

$$\theta(t) = \pi_d(0;t) - (\pi_c(n;t) - f) \tag{15}$$

Both policy instruments induce the same adoption date but subsidizing the fixed cost is more costly than subsidizing the profit flow.

Case study: the cement industry
illustrative data
n=5, d=38,18 €/ton cement, c=112,81€/ton cement,
F=250 M€,
SCC(2030)=140 €/ton CO2, Hotelling
i= 4%
source Gardarsdottir, S.O., et al., 2018. authors estimates





The joint adoption equilibrium is the focal point

Table 3: Adoption dates and discounted profits in M euros for the calibrated game

Firm	1	2	3	4	5
Adoption dates					
Precommitment	2028.2	2028.4	2028.6	2029.0	2029.9
Diffusion (4, 1)	2027.4	2027.4	2027.4	2027.4	2029.9
Diffusion (1, 4)	2026.0	2029.9	2029.9	2029.9	2029.9
Joint adoption	2041.7	2041.7	2041.7	2041.7	2041.7
Profits					
Precommitment	58.8	58.5	58.1	57.5	55.5
Diffusion (4, 1)	50.9	50.9	50.9	50.9	50.9
Diffusion (1, 4)	58.8	58.8	58.8	58.8	58.8
Joint adoption	88.7	88.7	88.7	88.7	88.7

The two policy instruments deliver the second best with different distributional impacts

Table 4: Simulations results for public policies

	Adoption date	welfare	transfer	consumer surplus	industry profit
First-best	2026.7	4545	225	4320	0.0
Subsidy on fixed costs	2029.8	3567	708	2548	1019
Subsidy on flow profits	2029.8	3567	248	3008	560
Joint adoption	2041.7	3079	0	2636	444
BAU	2045.2	1438	0	1027	411

Key take away for the cement industry

- Preemption + Low short-term intensity of competition induce **a socially detrimental delay in CCS adoption** which is consistent with **the observed procastrination effect**
- With a public policy which **only correct imperfect internalisation of the cost of carbon (CCD)**
  - →**CCS is adopted in 2042** !!
- Public policies which either **subsidize the fixed cost of CCS or the profit flow** of adopting firms maximize the social welfare
  - →**CCS is adopted in 2030**

Main theoretic contribution of the paper

Formalize a continuous time model for the adoption of a clean technology under imperfect competition when firms initially operate with a dirty technology with increasing carbon tax

- Technologies have infinite lifetime, dirty with increasing variable cost, clean with constant variable cost
- Adoption induces a fixed sunk cost
- Short term Cournot competition

Characterize the **Nash equilibria of the game**

- There is a Pareto dominant NE in which all firms adopt simultaneously
- Adoption is late relative to the second best (keeping market structure unchanged)

Design the relevant public policies in terms of subsidies assuming market concentration exogeneously regulated

- Subsidizing the fixed cost of CCs or the profit flow are equivalent in terms of welfare maximization but have different distributional impacts

Extensions

Theory

Introduce asymmetry

Other forms of imperfect competition (Bertrand)

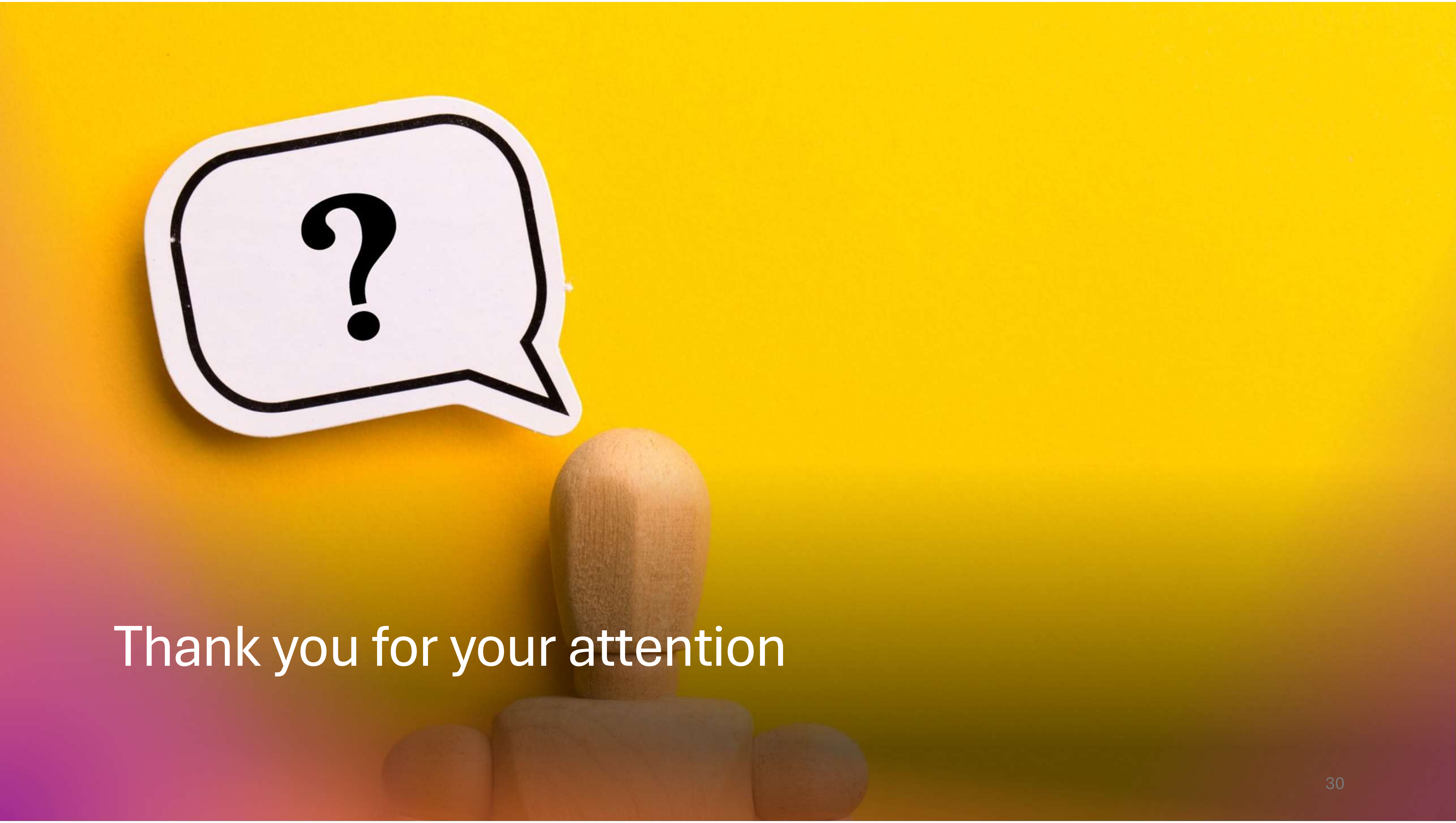
Vertical differentiation

Formalize the Nash equilibrium concept in continuous time games

Application

For an operational model other factors should be introduced: asymmetric firms, uncertainty on CCS cost, environmental acceptability, EU-ETS regulation...

From cement to other industry (i.e. the lime sector)


Thank you for your attention