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Imperfect Competition and the Adoption of Clean Technology: The Case of CCS in Cement

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Abstract

This paper studies the adoption of clean technology in an oligopolistic setting, focusing on carbon capture and storage (CCS) in the cement sector. Firms can choose between two technologies: a carbon-intensive ("dirty") technology and a low-carbon ("clean") one. Initially, all firms operate with the dirty technology, whose variable cost increases over time with the social cost of carbon, following Hotelling's rule. Clean technology has a constant marginal cost but requires a sunk investment cost. Firms engage in short-term Cournot competition, and the adoption decision is modeled as a dynamic game in continuous time. We show that imperfect competition leads to inefficiently delayed adoption due to preemption incentives, with firms eventually coordinating on a late joint adoption equilibrium. We propose two corrective public policies: a fixed-cost subsidy and a time-dependent subsidy on profit flows. Calibrating our model to the cement industry, assuming five competitors, we find that without policy intervention, CCS adoption would occur in 2042 rather than the socially optimal date of 2030. Obtaining optimal timing requires either a 70% fixed-cost subsidy or a time-dependent subsidy equivalent to 20% of that amount, although it requires more information for implementation.

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1 Introduction

Cement is widely recognized as a hard-to-abate sector. According to the Net Industry Tracker (World Economic Forum, 2023), global cement production generated 2.6 gigatonnes (Gt) of CO_2 emissions, accounting for 6% of total greenhouse gas emissions. Of this, 1.3 Gt came from process emissions and 0.75 Gt from fuel combustion. Cement demand is projected to increase by 50% by 2050. To fully decarbonize the sector, carbon capture and storage (CCS) is considered the only viable option.

The abatement cost of CCS is estimated to be around 60 to 200 euros per ton, depending on the technology, future energy prices, and the local conditions for CO_2 transport and storage (Voldsund et al., 2018; Criqui, 2023). These costs seem reasonable compared to the current price of the ETS.[1] However, actual CCS deployment in the European cement sector remains limited (Levina et al., 2023). Various barriers have contributed to this gap, including historically generous free allowance allocations, the disruptive nature of CCS, and environmental constraints on storage capacity. This paper argues that an additional factor may explain this limited uptake: the imperfect competition that characterizes the cement industry. This aspect has received little attention so far. We discuss public policies designed to counteract this source of inefficiency.

The oligopolistic nature of the cement industry comes from its structural characteristics: high capital intensity, high transport costs, maturity of its technology, and costly capacity adjustments. Markets are often regional, with only a handful of competitors operating in each one (for a discussion of these characteristics and their implications, see, for instance (Boyer and Ponssard, 2013)). Competition in the cement industry can thus be modeled through two interconnected submodels: (i) short-run Cournot competition of a given set of firms operating existing plant capacities; (ii) long-run competition that includes entry and exit to accommodate demand and technological changes (*e.g.* replacing wet kilns with more efficient dry kilns). The most elaborated formalization along these lines is due to (Ryan, 2012). This model has been

[1] The ETS price was around 80 euros per ton in September 2024

used to assess the static and dynamic implications of alternative market-based regulations that limit greenhouse emissions in the US cement industry (Fowlie et al., 2016). Grandfathering and output-based allocations have also been discussed in a static Cournot model in (Ponssard and Walker, 2018).

Motivated by these ideas, we develop a stylized model for the adoption of clean technology in imperfect competition, a model simple enough for analytical treatment while capturing the key strategic issues of the adoption of CSS by the cement sector. We assume two available technologies: one carbon-intensive ("dirty") and one zero-carbon ("clean"). Initially, all competitors use the dirty technology, whose variable cost depends on the social cost of carbon. At any time, any competitor may adopt the clean technology, whose variable cost is constant but requires a fixed upfront investment. Technologies are assumed to have an infinite lifespan. We assume a linear demand function cleared at each point in time through Cournot competition. No capacity constraints are introduced. Assuming that the social cost of carbon increases over time, a firm will either adopt the clean technology at some time or exit the market. We analyze how the diffusion of clean technology is affected by imperfect competition and design relevant public policies. We assume that carbon pricing is set at the Pigovian level and that firms are compensated for uncertainties so that the private interest rate is equal to the social discount rate. This allows us to focus on the negative externality due to imperfect competition.

We show that a Pareto-dominant Nash equilibrium exists in which all firms adopt clean technology simultaneously. However, this equilibrium occurs significantly later than the socially optimal adoption time. Our model thereby offers a novel explanation for the delayed deployment of CCS in the cement sector and motivates policy intervention.

Based on our calibration to the cement industry, the Pareto dominant Nash equilibrium would lead to an adoption date for CCS around 2042, while the socially optimal date would be 2030. Two policy instruments would advance adoption to the socially optimal date, either a subsidy of 70% of the fixed cost or a time-dependent subsidy on the profit stream, which costs around five times less in total but requires more information to be implemented. A sensitivity analysis is performed around 20% of the calibrated values of the CAPEX of CCS or the transport and sequestration cost, as well as regarding an increase of 20% of the social cost of carbon (from 110 euro per ton of CO_2 in 2024 to 133 euro per ton of CO_2). The benefit of a public policy remains significant over this range of parameters.

Our work contributes to the extensive literature on the timing of innovation.[2] Among them, three articles are directly related to our approach.[3]

Our adoption game has strong similarities with the innovation game introduced in Reinganum (1981). The general setting is very close: the diffusion under imperfect competition of either an innovation or a clean technology. There are three differences: (i) profit flows are often implicit, while our model relies on explicit Cournot profits; (ii) variable costs are time-independent , whereas in ours, the variable cost of the dirty technology rises over time with the carbon price; (iii) the cost of adoption typically decreases over time; in our case, it is fixed. Moreover, while prior work has largely focused on characterizing equilibria, our paper emphasizes public policy design as a tool to correct inefficiencies. Despite these differences, the path to obtaining a Nash equilibrium is similar. There are two solution concepts proposed in the literature: either with precommitment (Reinganum, 1981) or with preemption (Fudenberg and Tirole, 1985). The first corresponds to long information lags between the firms, and the second to short information lags. The first solution concept would be more appropriate when there exist structural asymmetries between the competitors, while the second would correspond to symmetric contexts. Both will be explored: the first is also instrumental in constructing the second. We introduce two concepts of social optima (Proposition 4): (i) a first-best derived as a perfect-competition benchmark and (ii) a second-best optimum derived in which the regulator leaves the market structure unchanged. The second-best provides a more relevant benchmark for the cement industry, where environmental and antitrust policies are typically addressed separately. Finally, in Milliou and Petrakis (2011), two modes of imperfect competition are introduced to determine profit flows: Cournot or Bertrand. The analysis is limited to two competitors that produce a homogeneous good, and both the precommitment and the preemption solution concepts are discussed. It is shown that with Bertrand competition, innovation occurs later than with Cournot. We expect that a similar result would be valid in our adoption game since the benefit of adoption is smaller due to more intense competition.

We also contribute to the literature on the economic analysis of CCS, and in particular its diffusion in the cement sector. A large number of studies

[2]For surveys, see, for instance, (Reinganum, 1989) and (Hoppe, 2002)

[3]There is also a large literature on the interplay between imperfect competition and green innovation. See for instance (Montero, 2002) or more recently (Martín-Herrán and Rubio, 2025).

analyze the potential global contribution of CCS. Some of them are analytic theoretical stylized models, while others rely on large complex multi-sector optimization models (known as integrated assessment models). Within the first category, several papers examine the optimal timing of CCS adoption using optimal control models. This literature includes features such as continuous capture rate (Ayong Le Kama et al., 2013), learning-by-doing (Amigues et al., 2016), several sectors or countries (Amigues et al., 2014; Chen et al., 2024), or carbon utilization (Moreaux et al., 2024). In comparison to this body of work, our model assumes that greenhouse gas emissions are correctly priced and focuses on the timing of adoption in an imperfect competition setting. Our modeling of the CCS technology is also simpler as we assume that the implementation of CCS induces a fixed sunk CAPEX, constant OPEX, and full capture of emissions. Another important simplification concerns the fact that there are no capacity constraints.

The second category of articles seeks to quantify the cost and benefit of CCS for achieving decarbonization. Paltsev et al. (2021) compares global industrial output in hard-to-abate sectors (cement, chemicals, iron, and steel) with and without CCS under a 2 degree climate constraint. Their scenarios are developed using the multi-sector and multi-region MIT Economic Projection and Policy Analysis (EPPA). They show that without CCS industrial production in 2100 would increase to 1.6 times its value in 2010 while it would increase to 3.5 to 7 times, depending on the CCS technology. Holz et al. (2021) addresses the same question (the goal is to achieve 85 % reduction in CO_2 emissions by 2050), now including in the picture both the electricity and infrastructure sectors. The paper shows that there is not much to be gained by CCS (2 % cost reduction). However, there is only a 50 % reduction in CO_2 emissions in cement. A recent technology roadmap published by the International Energy Agency (2018) points out several levers to curb emissions in the cement sector: energy efficiency, fuel mix, new low carbon cements, demand management. These levers have no impact on the emissions that come from the chemical transformation of calcium to clinker at high temperature. Only CCS can fully eliminate the latter. In Mari and Sourisseau (2021), three scenarios are elaborated with experts of the French cement industry. The scenario of BAU under current policies leads to a 54 % reduction in CO_2 emissions in 2050 relative to 2015, while the objective proposed for the industrial sectors in France is 81 %. Two alternative scenarios are explored to achieve the objective. The first scenario requires drastic demand management that leads to a decrease of 60 % in cement production.

The second scenario is techno-push that includes the deployment of CCS initiated in 2035, which leads to a very limited decrease of 6 % in cement production. Obrist et al. (2021) discusses various levers to decarbonize the Swiss cement industry. Using a techno-economic bottom-up optimization model based on TIMES (The Integrated Markal-Efom System) under different policies (EU 2050 target for energy efficiency, CO_2 reduction, EU-ETS price...), they show that only CCS allows for achieving the target. Similar studies have been done for Japan (Otsuki et al., 2024) and Canada (Zhang et al., 2023).

The potential benefit of CCS in these prospective studies contrasts with the limited number of projects in the cement industry. Rossi (2023) identifies only 7 large-scale lime and cement projects announced throughout Europe, totaling a potential emissions reduction of 6.3 Mt CO_2 per year compared to more than 120 Gt CO_2 for the whole sector.[4] For Carlsen (2024), the slow deployment of CCS in the US is reflected in the fact that there is currently only one project that involves CCS: Heidelberg Materials cement plant in Mitchell, Indiana. This plant has the benefit of being located above geologic formations that are ideal for carbon sequestration. When its CCS system is fully operational, 95 % of the CO_2 generated at the facility, up to 2 million tons, will be captured and injected far below the earth's surface each year. Several other cement companies are seeking to retrofit their facilities with carbon capture systems, taking advantage of dedicated grants for carbon capture from the US Department of Energy.

This paper contributes to this empirical literature by providing new explanations to understand why the sector seems to be late to adopt CCS, while the need to adopt CCS appears indispensable to eliminate CO_2 emissions.

The paper proceeds as follows. Section 2 introduces the theoretical model. Section 3 characterizes the equilibria. Section 4 examines welfare implications and policy instruments. Section 5 discusses several extensions. Section 6 calibrates the model to the cement industry and presents simulation results. Section 7 concludes.

[4] A significant CCS deployment in Europe takes place in Norway, where it benefits from low-cost access to CO_2 sequestration facilities. https://www.brevikccs.com/en

2 Model description

In the spirit of (Reinganum, 1981) and (Fudenberg and Tirole, 1985), we consider a market with n identical firms producing a homogeneous good in continuous time. Firms can adopt one of two production technologies: a carbon-intensive ("dirty") technology or a zero-carbon ("clean") technology. We assume that carbon pricing fully internalizes the social cost of carbon (SCC), leading to a variable cost for the dirty technology that increases over time. In contrast, the clean technology (*e.g.* CCS) has a constant marginal cost but is initially more expensive and requires a fixed-cost initial investment.

Firms compete in two dimensions: (i) short-run quantity competition in the market and (ii) long-run competition in technology adoption. At each point in time, firms generate cash flows that depend on the technology they use. Initially, the dirty technology yields higher cash flows, but this advantage diminishes and eventually reverses as carbon pricing increases. As a result, adopting the clean technology becomes profitable in the long run. Our focus is on how the timing of technology adoption is shaped by competitive interactions among firms.

2.1 Short-run Cournot competition

At each time t, firms, indexed by j, compete in the market à la Cournot and produce a quantity $q_j(t)$. We assume a linear demand function is $p(t) = 1-q(t)$, with $p(t)$ the price and $q(t) = \sum_{j=1}^{N} q_j(t)$. There are two technologies: a clean technology with constant marginal cost c normalized at 0, and a dirty technology with constant marginal cost $\delta(t)$ increasing with t. We take

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

with $\mu_0 \leq 0$, the cost advantage of the dirty technology over the clean technology without carbon pricing, $\mu_1 \geq 0$ the intensity of the emission, and $SCC(t)$ the social cost of carbon at time t. We assume that Hotelling's rule applies and that the growth rate of $SCC(t)$ is equal to the social discount rate denoted i.

Assumption 1 *The value of the parameters $\mu_0; \mu_1; SCC(0)$ is such that:*

$$\mu_0 + \mu_1 SCC(0) < 0$$

This assumption ensures that dirty technology is initially more profitable. The firms may adopt the clean technology at any time $t > 0$, incurring a fixed cost F. The private interest rate for firms is assumed to be equal to the social discount rate i. We note $f = iF$ the annual equivalent of the fixed cost. Since $\delta(t)$ increases with time, depending on its strategy, a firm k will either adopt the clean technology at some time or exit the market.

The question is to derive the adoption times of the firms from a Nash equilibrium of the continuous-time game. Since $\delta(t)$ is a strictly increasing function of t, it is equivalent to determine an adoption time or a dirty cost at which adoption takes place.

Consider first the solution of the quantity game at time t for k clean firms and $n - k$ dirty firms. We use standard notations in function of k and t: $cs(k;t)$ for consumer surplus, $\pi_c(k;t)$ (resp. $\pi_d(k;t)$) for the profit function of a firm using the clean (resp. dirty) technology; $w(k;t)$ for the welfare function. The Cournot equilibrium gives:

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

The existence of a fixed cost for the clean technology may affect the market structure: the initial one may not be the long term one. There is a maximum number of firms, $\bar{n}$, that can profitably adopt the clean technology. It is the largest integer such that $\pi_c(n;t) \leq f$. That is,

$$\bar{n} = \lfloor \frac{1}{\sqrt{f}} - 1 \rfloor \tag{2}$$

In the main part of the model, we assume that the clean technology does not affect the market structure of the industry.

Assumption 2 *We assume that the number of firms n is lower than $\bar{n}$.*

Assumption 2 ensures all firms eventually adopt the clean technology and remain active in the market. The case $\bar{n} < n$ will be discussed as an extension.

We now give some preliminary results for the continuous time game. Consider a set of adoption times t_k for $k = 1$ to n. The discounted profit of firm k from 0 to ∞ is denoted $\Pi_k(t_k)$. It depends on the adoption times of all firms. Let us explicitly highlight the dependence of Π_k on t_k. We define $t_0 = 0$ and $t_{n+1} = \infty$. Π_k writes:

$$\Pi_k(t_k) = \sum_{j=0}^{k} \int_{t_j}^{t_{j+1}} \pi_d(j-1;\nu)e^{-i\nu}d\nu - Fe^{-it_k} + \sum_{j=k}^{n} \int_{t_j}^{t_{j+1}} \pi_c(j;\nu)e^{-i\nu}d\nu \tag{3}$$

The derivative of $\Pi_k(t_k)$ with respect to t_k is: $e^{-it_k}(iF + \pi_d(k-1;t) - \pi_c(k;t))$. It is easy to see that $\Pi_k(t_k)$ is concave. To maximize its discounted profit given the other adoption times, firm k should be indifferent between producing with dirty or clean technology:

$$\pi_c(k;t_k) - f = \pi_d(k-1;t_k) \tag{4}$$

Denote t_k^* the solution of this equation for $k = 1, ..., n$ and Π_*^C the associated discounted profits. Importantly, adoption dates t_k^* depend only on k and not on the adoption times of other firms $t_{k'}^*$ with k' different from k.

Lemma 1 *Adoption dates t_k^* increase with k, while discounted profits Π_k^* decrease with k.*

This lemma implies that there are decreasing returns in the rank of adoption: the higher the number of earlier adopters, the lower the discounted profit of the current adopter. This property, along with Assumptions 1 and 2, makes the adoption game similar to the innovation game introduced in Reinganum (1981) and further discussed in (Fudenberg and Tirole, 1985); the path to solve it can follow the same routes.

3 Nash equilibria in the continuous time game

3.1 The precommitment equilibria

We first consider the solution concept proposed by Reinganum (1981), which we refer to as the precommitment equilibria. Firms are ranked from 1 to n, leading to $n!$ symmetric equilibria with equilibrium discounted profits depending only on the rank. Consider one such equilibrium: firm k, where $k = 1, \dots, n$, determines its adoption time t_k based solely on its rank in the adoption process. This is precisely the assumption used in Lemma 1. Denote t_k^C the Nash equilibrium with precommitment for a given ranking of the firms: $t_k^C = t_k^*$.

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

$$\delta_k^C = \delta(t_k^C) = \begin{cases} \frac{1}{n-2k}\left(\sqrt{1+\alpha_k} - 1\right) & \text{if } 2k < n \\ \frac{f(n+1)^2}{2n} & \text{if } 2k = n \\ \frac{1}{2k-n}\left(1 - \sqrt{1-\alpha_k}\right) & \text{if } 2k > n \end{cases} \quad (5)$$

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.*

A few comments can be made about this proposition. First, note that Assumption 2 ensures that $f(n+1)^2 < 1$, hence $0 < \alpha_k < 1$, so δ_k^C is well-defined. Second, all firms remain active in the market and eventually adopt the clean technology.[5] Third, a higher number of firms delays adoption for all players. Intuitively, in a more competitive environment, the incremental gain from early adoption decreases, as firms anticipate a longer transition period with

[5] Indeed, as δ increases, firms using the dirty technology produce less, potentially leading to market exit before adopting the clean technology later. However, this proposition demonstrates that this scenario does not occur within the model.

lower rents from being an early mover. Fourth, a higher fixed cost f discourages early adoption, as firms require a longer period of profitability to recover the initial investment. In addition, the transition itself becomes more spread out as f increases: not only do firms adopt later on average, but the overall duration of the transition (the time between the first and the last adopter) also increases with the fixed cost. This reflects the fact that higher adoption costs exacerbate the heterogeneity in incentives across firms.

3.2 The preemption equilibria

Since the discounted profits in a precommitment equilibrium are decreasing according to the adoption dates, there could be a race to be the first adopter. This makes the solution concept questionable for both the innovation game and the adoption game. Fudenberg and Tirole (1985) propose another solution concept, assuming that firms may preempt each other. An adoption at time t of a firm may be preempted by an adoption of a competitor at time $t-\epsilon$. This approach is certainly more appropriate for the cement industry: a regional oligopoly with mature technologies and low information delay about competitors' moves.

3.2.1 The adoption game with $n = 2$

The formal resolution of such a game is complex. Solving continuous-time games requires going through a discrete-time version with small intervals and letting the lengths of them go to zero. Fudenberg and Tirole directly construct the solution to the innovation game with two firms using intuitive ideas. More precisely, they show that two cases may occur: on top of a unique diffusion equilibrium, there may or may not exist a class of joint adoption equilibria, and they provide the condition for the existence of the latter.[6] These constructions also apply to the adoption game. The key idea is that to avoid preemption, the discounted equilibrium payoffs of the two firms must be equal.

Indeed, if the discounted equilibrium payoffs of two firms are equal, preemption of the first adopter by the second is unprofitable: interchanging the two firms is also a Nash equilibrium and it leaves the discounted equilibrium payoffs unchanged. There are two alternatives to obtain this equality in pure

[6] See Proposition 2 in Fudenberg and Tirole (1985).

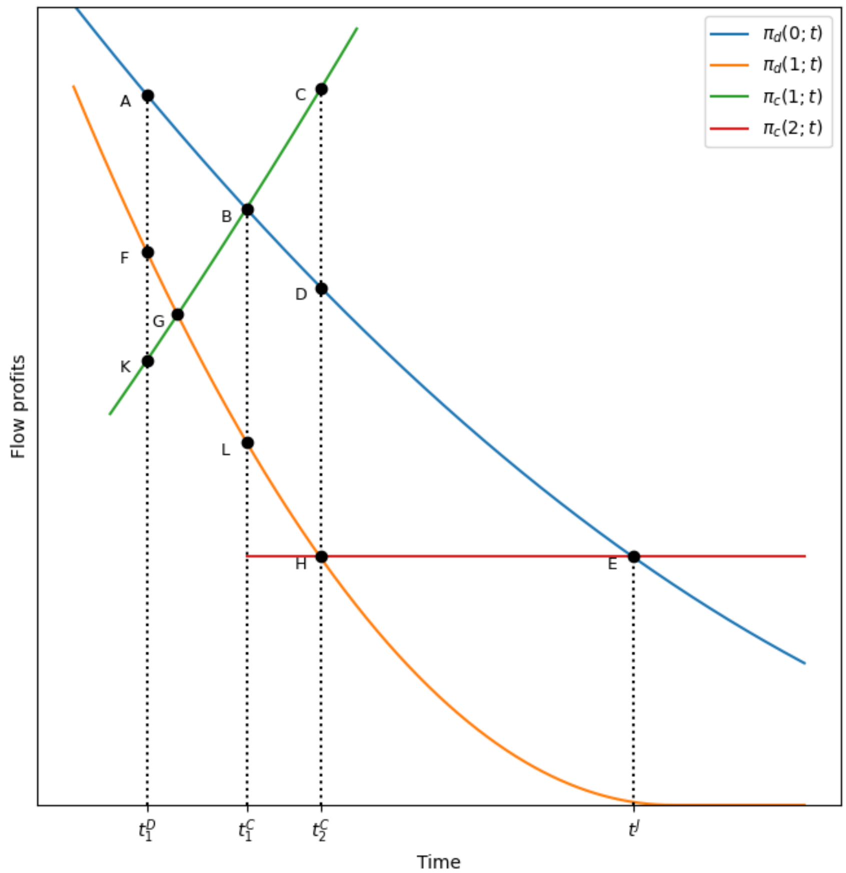

Figure 1: The adoption game with $n = 2$.

strategies. A first and simple way is that the two firms adopt at the same time. Denote t^J this adoption time. This alternative is called the joint adoption equilibrium. A second alternative is to have two adoption times, to be denoted t_1^D and t_2^D. Given Proposition 1 we certainly have $t_1^D < t_1^C$, and since firm 2 adopts later than firm 1, we also have $t_2^D = t_2^C$. This alternative is called the diffusion equilibrium.[7]

Let us draw a stylized graph (see Figure 1) and first check that we have drawn the lines representing the stage payoffs properly. We have $\pi_d(0;t) > \pi_d(1;t)$ and the difference increases with t; $\pi_c(1;t)$ increases with t because of the competitive advantage associated with adoption and $\pi_c(1;t_1^C) - f = \pi_d(0;t_1^C)$ (label B); $\pi_c(2;t) - f$ is constant and $\pi_c(2;t_2^C) - f = \pi_d(1;t_2^C)$ (label H).

The equilibria can be derived from the graph. First of all, observe that as soon as one firm has adopted at time t, the best response of the other firm is to adopt at t_2^C if $t \leq t_2^C$ or at t if $t > t_2^C$. Consider now the diffusion equilibrium $(t_1^D; t_2^D = t_2^C)$. To ensure that the discounted equilibrium payoffs of the two firms are equal, it must be that:

$$\int_{t_1^D}^{t_2^C} (\pi_c(1;t) - f)e^{-it}dt = \int_{t_1^D}^{t_2^C} \pi_d(1;t)e^{-it}dt$$

which means that the discounted value of the area of the triangle FGK is equal to the discounted value of the area of the triangle GCH. If the first mover were to adopt at any time between t_1^D and t_2^C, the other firm could profitably preempt it. Clearly, adopting before t_1^D for the first mover or after t_2^C for the second mover cannot be an equilibrium. Interestingly, the threat of preemption destroys the competitive advantage of adoption.

Consider now a situation in which both firms adopt simultaneously. The adoption time which maximizes the discounted profit of the firms t^J is such that $\pi_c(2;t^J) - f = \pi_d(0;t^J)$. The condition for this adoption time to be a Nash equilibrium is that this discounted payoff be larger than the discounted payoff of the firm that moves first in the equilibrium with precommitment; otherwise, one firm would preempt at t_1^C and the other firm's best response would be to adopt at t_2^C. This condition is satisfied if the following assumption is satisfied:

[7]There are two such pure strategy equilibria depending on the ranking of the firms; Fudenberg and Tirole propose a randomization process to eliminate this indeterminacy; this requires to construct a discrete time model; we leave this construction for future research.

Assumption 3

$$\int_{t_1^C}^{t_2^C} (\pi_c(1;t) - f)e^{-it}dt + \int_{t_2^C}^{t^J} (\pi_c(2;t) - f)e^{-it}dt < \int_{t_1^C}^{t^J} \pi_d(0;t)e^{-it}dt$$

Assumption 3 can be interpreted as the discounted value of the discounted area of the triangle BCD being less than that of the triangle DHE. That this is the case in the graph **??** comes from the proximity of t_1^C and t_2^C relative to that of t_2^C and t^J. Under Cournot instantaneous competition, assumption 3 is satisfied if f is not too close to the long-term profit $1/(n+1)^2$, *i.e.* adopting the clean technology in the long run is significantly profitable.

If both firms select the adoption time t^J, the threat of adopting as soon as the other firm adopts is credible and prevents preemption at $t^J - \epsilon$. Clearly, no firm has an incentive to delay adoption later than t^J. If assumption 3 holds, adopting simultaneously at t^J is a Nash equilibrium.

Observe that we may select earlier adoption times for the joint adoption equilibrium, as long as assumption 3 remains valid with $t \leq t^J$. If there are multiple joint adoption equilibria, it is easily seen that the one at which the firms adopt the latest (at t^J) Pareto dominates all other joint adoption equilibria, dominates the outcomes of the equilibrium with precommitment, and dominates the outcomes of any of the diffusion equilibria. In fact, this will be the case in our application to the cement industry (Section 7).

We generalize these ideas to derive preemption equilibria with n firms, keeping in mind the equality of the equilibrium discounted profits for all firms.

3.2.2 Equilibria with diffusion

To construct a sequence of adoption times t_k^D with $k = 1, ..., n$ we start with the adoption times of the equilibrium with precommitment and derive recursively the adoption times t_k^D with $k = n, ..., 1$ to equalize the equilibrium discounted profits. We certainly have $t_n^D = t_n^C$ and $t_{n-1}^D \leq t_{n-1}^C$ as shown for the case $n = 2$. Whatever the adoption time $t_{n-2}^D \leq t_{n-1}^D$ the discounted profits for the firms $n-1$ and n remain equal. If t_{n-1}^D is sufficiently early it may be that it is good enough for firm $n-2$ to avoid preemption and clearly the discounted profit of firm $n-2$ equals that of the two other firms; otherwise $t_{n-2}^D < t_{n-1}^D$. This leads to the following algorithm.

Algorithm 1 *Initiate the algorithm with* $m = \bar{m} = 1$ *and* $t_n^D = t_n^C$

1. *Step m*

   Define t^D_{n-m} *such that*

$$\int_{t^D_{n-m}}^{t^D_{n-m+1}} \big[\pi_c(n-m;t) - f - \pi_d(n-m;t)\big] e^{-i\nu} d\nu = 0 \qquad (6)$$

   If $m = n-1$ *the algorithm ends otherwise go to step* $\bar{m}$

2. *Step* $\bar{m}$

   If

$$\pi_c(n-m-1; t^D_{n-m}) - f \leq \pi_d(n-m-1; t^D_{n-m}) \qquad (7)$$

   Define t^D_{n-m-1} *such that:*

$$t^D_{n-m-1} = t^D_{n-m}$$

   If $\bar{m}+1 = n$ *the algorithm ends otherwise go to step* $\bar{m}$ *updated to* $\bar{m}+1$

   If:

$$\pi_c(n-m-1; t^D_{n-m}) - f > \pi_d(n-m-1; t^D_{n-m}) \qquad (8)$$

   Go to Step m updated to $\bar{m}+1$*.*

Step m ensures that the discounted profits of firms $n-m+1$ and $n-m$ are equal. Step $\bar{m}$ ensures that t^D_{n-m-1} is good enough for not being preempted by firm $n-m-2$. By construction, the discounted profits of the n firms adopting along the sequence t^D_k with $k = n, ..., 1$ are equal.

There are other diffusion equilibria: take for instance $t^D_k = t^C_k$ for $k = 2, ..., n$ and define t^D_1 such that:

$$\int_{t^D_1}^{t^D_n} \big[\pi_c(1;t) - f - \pi_d(1;t)\big] e^{-i\nu} d\nu = 0 \qquad (9)$$

One may combine these two recursive processes and generate other equilibria which satisfy the equal profit condition. This is so because, as already mentioned, when comparing the discounted profits of two firms k and $k+1$, the adoption dates of the other firms affect these two profits similarly so that equality remains valid.

Observe that the diffusion equilibrium in which $n-1$ firms adopt simultaneously at t^C_n Pareto dominates all other diffusion equilibria.

3.2.3 Equilibria with joint adoption and the Pareto optimality

Let t^J solves:

$$\pi_c(n;t) - f = \pi_d(0;t)$$

In this section, we explicitly assume that the discounted profit at t^J is higher than the one associated with the first adopter in the equilibrium with precommitment. In other words, we assume that the extension of assumption 3 to n firms holds. Define $t_0^J \leq t^J$ such that it remains valid. We show that simultaneous adoption at t_n^J with $t_0^J \leq t_n^J \leq t^J$ is a Nash equilibrium.

Indeed, there is no incentive for a firm to delay adoption since its discounted profit can only decrease; if it advances adoption by ϵ the other firms would immediately adopt at $t-\epsilon$ which by construction is also an equilibrium. And there is no incentive for any firm to preempt to t_1^C which would generate a sequence of best responses corresponding to the inferior equilibrium with precommitment.

Proposition 2 *The optimal adoption time with joint adoption t^J is:*

$$\delta^J = \delta(t^J) = 1 - \sqrt{1-(n+1)^2 f)} \tag{10}$$

and the following properties for the optimal joint adoption hold:

1. *all firms adopt the clean technology and remain active on the market;*
2. *it takes places after the latest adoption time in both precommitment or with diffusion equilibria ;*
3. *it increases with the number n of firms;*
4. *it increases with the fixed cost f.*

Under instantaneous Cournot competition the optimal joint equilibrium Pareto dominates the diffusion equilibria as well as any of the joint equilibria t_n^J with $t_0^J < t_n^J \leq t^J$. The underlying idea is straightforward. Consider an equilibrium with diffusion in which adoption times are t_k^D with $k = 1, ..., n$. Denote Π_n^D the corresponding discounted profit. Delay the adoption times of all the firms $k < n$ to t_n^D and denote $\bar{\Pi}_n^D$ the new discounted profit. Denote Π^J the discounted profit of the optimal joint equilibrium. By construction delaying an earlier adoption increases the discounted profit of the firm adopting later so that we have:

$$\Pi_n^D \le \bar{\Pi}_n^D \le \Pi^J \tag{11}$$

These inequalities give the following proposition.

Proposition 3 *If there exists a joint adoption equilibrium that maximizes the discounted profit of the firms, it Pareto dominates all other equilibria with preemption (and by construction the outcomes of the equilibrium with precommitment).*

4 Social optima and public policies

4.1 First-best and second-best adoption timing

In our adoption game, there are two possible ways to define a social optimum. We refer to the first-best as the socially optimal timing of adoption t^{FB} by a representative price-taking firm. In contrast, the second-best is defined as the optimal simultaneous adoption t^{SB} of the clean technology by all firms in the imperfect competition setting. In this section, we will focus on the second-best as we leave the efficiency issue of short-term competition to antitrust policy (collusion, mergers, tit-for-tat...) so that we assume that Cournot competition, as such, cannot be affected by regulation. Hence, in this setting, restoring the first-best is not feasible.

The second-best is obtained by maximizing the discounted flow of the consumer surplus plus the industry profit, which gives the following Proposition in which t^{SB} denotes the corresponding time of adoption, in which $\delta^{SB} = \delta(t^{SB})$. For reference, we also give the first-best adoption time t^{FB}, in which case the regulator should subsidize the whole fixed cost of the firm, and the consumer price be equal to the marginal cost.

Proposition 4 *The first-best adoption time t^{SB} is such that:*

$$\delta^{FB} = \delta(t^{FB}) = 1 - \sqrt{1 - 2f} \tag{12}$$

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. *Second-best date happens after at least half of precommitment dates:* $\delta^{SB} > \delta_k^C$ *for* $2k \leq n$

4. *First-best and second-best dates increases with the fixed cost* f*.*

5. *Second-best dates increases with the number* n *of firms;*

Expressions of δ^{FB} and δ^{SB} are well-defined since $f \leq 1/(n+1)^2$.

We now turn to the question of defining a policy instrument which would reduce the inefficiency generated by imperfect competition, *i.e.* increase the discounted welfare by advancing adoption. As discussed earlier, several market equilibria types may be considered. We focus in what follows on the precommitment equilibrium and on the preemption equilibrium with joint adoption.

4.2 Policy in the precommitment equilibrium

Under some circumstances, firms may adopt the precommitment as the market equilibrium. This might be so if they behave myopically, in particular in their asymmetries such as different environments to adopt the clean technology. We show that in this case there is no interest in a policy instrument that would advance adoption if the number of firms is not too low.

The flow of welfare, $w(t)$, at time t is: $w(k;t) = cs(k;t) + k\pi_c(k;t) + (n-k)\pi_d(k;t) - kf$. We can use this decomposition to analyze the total impact of the adoption of clean technology by the firm k on the three components of the welfare. It turns out that it is positive for the consumer surplus (the average cost decreases), but it is negative for the profits of all firms, *i.e.* the other firms are worse off and null by construction for firm k. For $n = 1$, the total impact is clearly positive, as there are no other firms. As n increases, it becomes negative. More precisely, we get the following lemma.

Lemma 2 *The total impact of the adoption of clean technology by the firm* k *on welfare is always negative if the number of firms is greater than or equal to 4. It is positive for* $n = 1$ *and* $n = 2$*. For* $n = 3$*, it is negative if* $f \leq 6/49$*.*

The preceding lemma gives the following proposition.

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.*

In essence, when firms act in a precommitting or myopic way, and the market involves four or more participants, policies that push for earlier adoption by individual firms can decrease overall societal welfare. This is because the negative externality on the profits of non-adopting firms outweighs the benefits of consumer surplus. Thus, in such market structures under precommitment, interventions to accelerate adoption may be counterproductive from a welfare perspective.

4.3 Policy in the joint adoption preemption equilibrium

Anticipating that the preemption equilibrium with the optimal joint adoption is selected by the firms, we concentrate on this case: without any policy instrument, the market equilibrium corresponds to a joint adoption at time t^J. Building on observed practices, we consider two instruments: subsidizing the fixed cost of the clean technology or directly subsidizing the profit flows.

Proposition 6 *Two instruments may decentralize the second-best in the preemption 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.

The Proposition is easily proved. Regarding the subsidy on fixed costs, let λ be the fraction of f to be subsidized. The date of the optimal joint adoption would occur at $t(\lambda)$. The regulator should select λ to maximize the increase in discounted welfare from $t(\lambda)$ to t^J. Since the total subsidy appears as positive in the industry profit, it disappears in the welfare. It is a transfer from consumers to industry. Altogether, the increase in discounted welfare is exactly the one corresponding to the one of the second-best given that what happens past t^J is eliminated. Hence the optimal subsidy is such that: $t(\lambda) = t^{SB}$. Comparing equation (10) with equation (13) gives the result.

The subsidy on profit flows is based on the fact that, given this subsidy, the firm k is indifferent to adopting clean technology at any time t_n^s between t^{SB} and t^J. We assume that the state agency can contract on the adoption at t^{SB} so that it can determine t_n^s to maximize the corresponding social welfare. Again we are back to the expression corresponding to the second-best; the optimal flow the subsidy starts at t_n^s such that:

$$t_n^s = t^{SB}$$

Technically the flow subsidy is the limit subsidy to achieve this goal.

The two instruments induce the same adoption date but differ with respect to the corresponding discounted transfers. Since by construction of $\delta^{J\lambda}$ we also have

$$\pi_d(0; t^{SB}) = \pi_c(n; t^{J\lambda}) - (1 - \lambda^{J\lambda})f$$

it follows that:

$$\theta(t^{SB}) = \pi_d(0; t^{SB}) - (\pi_c(n; t^{SB}) - f) = \pi_d(0; t^{SB}) - (\pi_c(n; t^{J\lambda}) - f) = \lambda^{J\lambda} f$$

The flow of subsidies is identical at $t = t^{SB}$, for $t > t^{SB}$ it remains constant for the subsidy of the fixed cost and it decreases for the subsidy of the profit flow. The flow of subsidies advantages the consumers, the fixed cost subsidy advantages the firms. A combination of both types of subsidies is feasible.

Contrary to the precommitment equilibrium, Proposition 6 states that there is always room for a public policy that advances clean technology adoption.

5 Extensions

5.1 Heterogeneous fixed costs

It may be realistic to assume that firms are not perfectly symmetric. In particular, the transport and sequestration costs may differ from one firm to another. In that case, it is natural to consider that there is only one relevant equilibrium with precommitment, the one in which the ordering of adoption corresponds to the ordering of these costs: the firm with the lowest transport and sequestration cost adopting first. The heterogeneity generates a longer diffusion process compared with the one in which all the firms have a cost identical to the lowest one. This longer process decreases the social welfare. We know from Proposition 5 that advancing adoption of a firm is not welfare-increasing if $n > 3$.

The risk of preemption of the equilibrium with precommitment with heterogeneous costs is much weaker since preempting a firm with a lower cost is certainly costly. If we delete the possibility of preemption, it seems that there is no public policy to increase the social welfare.

We propose the following far-fetched idea. Allocate subsidies to the less competitive firms so that all the costs are identical to the lowest one. Symmetry is back and the firms are expected to select the Pareto optimal joint adoption equilibrium. An equal subsidy to all firms will then advance adoption and increase social welfare.

5.2 The case of almost competitive market: $n > \bar{n}$

Suppose that the initial market is almost perfectly competitive (n going to ∞), the adoption of the clean technology induces market concentration. We will show that imperfect competition generates a delay in the adoption relative to the first-best and investigate the relevant public policies.

Consider first how the different approaches are affected when n is large. Since the adoption of the clean technology induces a fixed cost f, $n - \bar{n}$ firms will exit the market. Exit time occurs when the flow profit of the dirty firms equals zero. This time depends on the number of clean firms. Denote k this number then the exit time t_k^e is such that:

$$\delta(t_k^e) = \frac{1}{k+1} \tag{16}$$

Observe that $\delta(t_k^e)$ is decreasing with k. Consider the equilibrium with precommitment identified in Proposition 1 with $\bar{n}$ firms in the market. The relative positions of $\delta(t_k^e)$ and $\delta(t_k^C)$ may complicate the analysis except in the case $\delta(t_{\bar{n}}^e) \geq \delta(t_{\bar{n}}^C)$. We prove that this is indeed the case if n is large so that the following proposition holds:

Proposition 7 *As n goes to ∞, δ_k^C, for $k = 1, ..., \bar{n}$, converges to $\delta_\infty^C = \sqrt{f}$.*

Consider now the preemption equilibrium with joint adoption in which $\bar{n}$ firms adopt at t and $n - \bar{n}$ firms exit at $t^e_{\bar{n}}$. As n goes to ∞ the dirty firms make zero discounted profit, the $\bar{n}$ firms make a profit flow equal to $\pi_c(\bar{n}; t) - f$ from t to $t^e_{\bar{n}}$, that is $\delta^2(t) - f$, and $\frac{1}{(\bar{n}+1)^2} - f$ thereafter. To eliminate any preemption threat it should be that the discounted profit of a firm adopting at t be null. If an adopting firm were to adopt at $t-\epsilon$ the other adopting firms would immediately follow and their discounted profit would decrease; if it were to adopt at $t+\epsilon$ an exiting firm would adopt at t and the best response would be to exit at $t^e_{\bar{n}}$. This gives the following proposition.[8]

Proposition 8 *As n goes to infinity, an equilibrium path in which $\bar{n}$ firms adopt at t_∞^P and $n - \bar{n}$ firms exit at $t^e_{\bar{n}}$ is a preemption equilibrium with joint adoption iff t_∞^P solves:*

$$\int_{t_\infty^P}^{t^e_{\bar{n}}} \left[\delta^2(t) - f\right] e^{-i\nu} d\nu + \frac{e^{-it^e_{\bar{n}}}}{i}\left[\frac{1}{(\bar{n}+1)^2} - f\right] = 0 \tag{17}$$

Denote $\delta_\infty^P = \delta(t_\infty^P)$. Table 1 gives the limit values for quantities, price, profits, consumer surplus as n goes to infinity. Observe that the flow of consumer surplus does not depend on δ_∞^P since clean firms use limit pricing with respect to dirty firms. Maximizing the welfare amounts to maximizing this profit so that $\delta_\infty^{SB} = \delta(t_\infty^C)$.

Since $t_\infty^P \leq t_\infty^C$ the preemption equilibrium with joint adoption is Pareto dominated by the precommitment equilibrium, a situation which is in sharp contrast with the case $n \leq \bar{n}$. And the threat of preemption leads to a too early adoption. The best public policy would be to enforce the precommitment equilibrium.

6 Application to the cement industry

6.1 The calibration

We use an extended model for calibration that involves eight parameters:

$$i, SCC(2024), a, b, c, d_0, d_1, FC$$

[8] We could not identify any preemption equilibrium with diffusion.

δ	$\delta(t=0) \leq \delta \leq \delta_\infty^P$	$\delta_\infty^P \leq \delta \leq \delta^e$	$\delta^e \leq \delta$
k	0	$\bar{n}$	$\bar{n}$
$n-k$	n	$n-\bar{n}$	0
q_c	0	$\lim \frac{[1+(n-\bar{n})\delta]}{(n+1)} = \delta$	$\frac{1}{(\bar{n}+1)}$
q_d	$\lim \frac{(1-\delta)}{(n+1)} = 0$	$\lim \frac{(1-(\bar{n}+1)\delta)}{(n+1)} = 0$	0
p	$\lim \frac{(1+n\delta)}{(n+1)} = \delta$	$\lim \frac{(1+(n-\bar{n})\delta)}{(n+1)} = \delta$	$\frac{1}{(\bar{n}+1)}$
π_c	0	$\lim \frac{(1+(n-\bar{n})\delta)^2}{(n+1)^2} - f = \delta^2 - f$	$\frac{1}{(\bar{n}+1)^2} - f$
π_d	$\lim \frac{(1-\delta)^2}{(n+1)^2} = 0$	$\lim \frac{(1-(\bar{n}+1)\delta)^2}{(n+1)^2} = 0$	0
cs	$\lim \frac{n^2(1-\delta)^2}{2(n+1)^2} = \frac{(1-\delta)^2}{2}$	$\lim \frac{(n-(n-\bar{n})\delta)^2}{2(n+1)^2} = \frac{(1-\delta)^2}{2}$	$\frac{\bar{n}^2}{2(\bar{n}+1)^2}$

Table 1: Limit values when n goes to infinity

The demand function is $p = a - bQ$, the constant marginal cost of the clean technology is c, the constant marginal cost of the dirty technology at time t is $d(t) = d_0 + d_1 e^{it}$. The fixed cost is FC. Time $t = 0$ is taken as 2024. The social cost of carbon writes $SCC(t) = SCC(2024)e^{i(t-2024)}$.

Parameter	unit	original value	normalized as	normalized value
i	% per year	4	i	4
$SCC(2024)$	€/t	110.64	$SCC(2024)$	110.64
a	€/t	200	(a-c)/(a-c)	1
b	€/t^2	2 10^{-5}	b/b	1
d_0	€/t	38.2	$\mu_0 = (d_0 - c)/(a-c)$	-0.856
d_1	CO_2/t cem	0.626	$\mu_1 = d_1/(a-c)$	0.007
c	€/t	112.81	$(c-c)/(a-c)$	0
FC	€ for 1 Mt	250 10^6	$f = biFC/(a-c)^2$	0.0258

Table 2: Original and reduced data

These parameters $i, SCC(2024)$ are calibrated as follows. Based on long-term economic growth and pure time preference rates, the EU Commission proposes a range of 3.5 to 5.5 % for the social discount rate [9]; we shall use 4 %. According to a recent survey of expert carbon analysts, the average forecast for a carbon quota price for 2030 is 140 euros, which gives $SCC(2024) = 140e^{-6i} = 110.64$.[10]

[9] see https://www.csilmilano.com/docs/WP2013_03.pdf.

[10] see https://www.homaio.com/post/2030-eua-price-predictions.

The calibration of the variable costs d_0 and c comes from Voldsund et al. (2018).[11] For the reference plant, the total OPEX is 42.0 euro per ton of clinker (Table 3.5 page 20). We take the oxyfuel CCS process as the most mature CCS under development; the total OPEX is 58.1 euro per ton of clinker (Table 6.5 page 40). The clinker/cement ratio is equal to 0.737 (Table 2.2, page 8). We inflate these costs from 2014 to 2024 by a factor equal to 1.23 % based on standard inflation rates in Europe. Altogether, we obtain 38.18 and 52.81 euro per ton for the two total OPEX respectively. We introduce an estimate of 60 euro per ton for transport and sequestration costs based on the ADEME sectoral study Mari and Sourisseau (2021) not included in Voldsund et al. (2018). This gives: $d_0 = 38.18, c = 112.81$. The CO_2 emission rate for a ton of clinker is 0.85, so that, for a ton of cement, $d_1 = 0.85 \times 0.737 = 0.626$.

We assume a sunk investment cost of 250 M€ for a cement plant with 1 Mt cement capacity per year, according to recent press releases.[12]

For the linear demand function, we take $a = 200e/t$ and $b = 2 \times 10^{-5} e/t^2$. We have $\Delta p/\Delta Q = -b$ so that the price elasticity would be $\epsilon = [\Delta Q/Q]/[\Delta p/p] = -0.48$, somewhat higher than the value of $-.2$ that appears in some specialized literature (see, for example, (Sijm et al., 2008) and (Cook, 2009)).

To obtain the calibrated values of μ_0, μ_1, and f, we normalize the original data as follows: $\mu_0 = (d_0 - c)/(a - c)$, $\mu_1 = d_1/(a - c)$, and $f = biFC/(a - c)^2$ (see Table 2). A date t associated with $\delta(t)$ corresponds to a calendar time t such that:

$$t = 2024 + \frac{1}{i} \ln \left[\frac{\delta(t) - \mu_0}{SCC(2024)\mu_1} \right]$$

We assume that there are 5 firms in the market ($n = 5$). Note that the maximum number of firms that could adopt clean technology in this market is $\bar{n} = 1/\sqrt{f} - 1 = 5.226$.

6.2 Simulation results

The equilibria of the calibrated game are depicted in Table 3. Only two preemption with diffusion equilibria are displayed. The first corresponds to the 5 firms adopting sequentially, and the second to 1 firm adopting first

[11] These assumptions should be updated on a case by case basis depending on the regional market under study.

[12] see https://www.holcim.com/what-we-do/green-operations/ccus/go4zero.

and the other 4 adopting later simultaneously. These two equilibria are respectively denoted (4,1) and (1,4). Note that in equilibrium (4,1) the first 4 firms adopt at the same time: there is no need to advance adoption to deter preemption (see algorithm 1). The other preemption equilibria with diffusion (3,2) and (2,3) are not displayed. Table 3 also displays the corresponding discounted profits.

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 $(1,4)$	2025.9	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 $(1,4)$	58.6	58.6	58.6	58.6	58.6
Joint adoption	88.7	88.7	88.7	88.7	88.7

Observe that the adoption dates for the precommitment equilibrium are close to each other, from 2028.2 to 2029.9. Adoption generates a non-sustainable competitive advantage. The equilibria with diffusion extend the adoption process, which would start at 2025.9 or 2027.4 depending on the equilibrium that is considered. The joint equilibrium delays the adoption date to 2041.7, which benefits the firms: they get a discounted profit much higher than the ones associated with the other equilibria: adopting in sequence decreases the profit flow in the short term compared to no adoption. The extension of assumption 3 holds which ensures the existence of the joint adoption equilibrium.

Table 4 gives the impacts of the two policy instruments on the Joint adoption. Second-best is also displayed. Welfare is significantly improved (from 3079 to 3567.5 million euros). The consumer surplus and the total emissions depend only on the adoption date. The former is remaining at 3256.5 million euros and the latter at 13 millions tons of CO_2. Subsidizing the fixed cost implies a much larger transfer than subsidizing the profit flow;

this explains the difference in industry profits (1019 and 444 million euros). Consumer surplus and industry profits increase relative to Joint adoption.

A natural benchmark for the transfer is to compare its level with the discounted value of the carbon tax collected along the decarbonization trajectory. Its value is 880 million euros; both policy instruments are self-sustainable from a financial point of view.

It is interesting to compare these results with either the Precommitment or the Preemption equilibria. They are displayed in the Table. Since the adoption dates would be earlier, the consumer surplus increases, to the detriment of the industry profit. However, the welfare decreases, but only slightly. This suggests that it would be worthwhile to look for some instrument that may favor these equilibria.

Table 4: Simulations results for public policies

	Adoption date	Welfare	Consumer surplus	Transfer	Industry profit	Total Emissions
Second-best	2029.8	3567.5	3256.5	0	311	13
Subsidy on flow profits	2029.8	3567.5	3256.5	133	444	13
Subsidy on fixed costs	2029.8	3567.5	3256.5	708	1019	13
Joint adoption	2041.7	3079	2636	0	444	28
Precommitment	2028.2*	3567.1	3278	0	289	10
Diffusion (1,4)	2025.9*	3557	3265	0	292	11
Diffusion (4,1)	2027.4*	3549	3294	0	254	8

Notes: Monetary measures are given in million euros, total emissions in million tons of CO_2. Adoption dates for Diffusion equilibria and Precommitment, only the first dates are presented.

For completeness, Table 5 gives the limit adoption values in the case of an almost competitive market at time t^0, that is n going to ∞. Observe that: $t^P_\infty = 2027.1 < t^{SB} = t^C_\infty = 2030.3$. Preemption leads to inefficient early adoption. Precommitment, if enforced, would leads to efficient adoption.

Table 5: Exit and limit adoption dates when n goes to ∞

Exit date t^e	2030.4
Precommitment t^C_∞	2030.3
Joint adoption t^P_∞	2027.1

Table 6: Sensitivity analysis

n	Parameters	Adoption dates			Welfare gain (%)
		First-Best	Second-best	Joint adoption	
5	Base	2026.7	2029.8	2041.7	33.32
5	-20% transport cost	2022.3	2025.5	2035.7	28.76
5	-20% fixed cost	2026.5	2029.0	2037.5	26.04
5	+20% initial SCC	2022.0	2025.2	2037.0	34.31
4	Base	2026.7	2029.1	2035.7	18.38
4	+20% transport cost	2030.4	2032.9	2040.9	22.15
4	+20% fixed cost	2026.8	2029.7	2038.1	22.12

Note: welfare gains are defined as $(W^{SB} - W^J)/(W^{FB} - W^J)$

6.3 Sensitivity analysis

We perform a sensitivity analysis decreasing or increasing the cost of CCS either through transport or fixed costs. The range goes from -20% to $+20\%$ for the transport cost and from -20% to $+20\%$ for the fixed cost. We also consider a higher social cost of carbon in 2024 (+20%). Table 6 gives the adoption dates for the first-best, the second-best, and the joint adoption equilibrium.

The results are not much affected by a change of the fixed cost of CCS. An increase may reduce the number of firms that may adopt CCS; in our calibrated model, that number would decrease from 5 to 4. Decreasing market competition makes adoption more profitable, which advances adoption. This explains why the adoption dates for a +20% increase are lower than for the base case with $n = 5$. Changing the transport cost or, which is qualitatively equivalent, changing the total OPEX of the dirty technology has a significant impact on the results.

As expected, an increase in the social cost of carbon advances the adoption dates. In the calibrated model, firms make their decisions based on a deterministic projection of the carbon price, the EU-ETS for Europe. Observe that our estimate of the market price in 2030 (140 euro per ton of CO_2) is lower than most national valuations of a social cost.[13] Increasing the SCC by +20% advances all adoption dates by approximately 5 years.

The sensitivity analysis also shows that adopting an instrument to achieve

[13] A recent valuation for France is 300 euro per ton of CO_2 in 2030, see https://www.strategie.gouv.fr/publications/la-valeur-de-laction-pour-le-climat-une-reference-pour-evaluer-et-agir)

the second-best significantly improves welfare relative to the joint equilibrium.

7 Discussion and conclusion

7.1 Policy recommendations

The standard cost-benefit analysis used by environmental agencies to evaluate projects consists of the comparison of the abatement cost with the social cost of carbon.[14] If the former is lower than the latter, the project is socially beneficial and may be eligible for support.

For the calibrated model, the standard abatement cost in euro/tCO_2 is:

$$AC = [c + iF/Q - d_0]/d_1 = [112.81 - 38.18 + 4\% * \frac{250000000}{1000000}]/0.626 = 135.1$$

According to our assumption for the SCC, the corresponding adoption date is 2029.1. In our stylized framework, the SCC is perfectly internalized and there is no need to subsidize the project: CCS should be adopted by the industry at that date.

The argument of the paper is that this is not what will happen. Firms make their decisions conditional on a profit analysis, and not on that cost-benefit analysis. The profit analysis of a given firm will maximize the discounted sum of three components: the profit prior to the adoption of the clean technology, the interim profit associated with the competitive advantage as long as competitors have not adopted, and the long-term profit post-adoption once CCS is adopted by all competitors. The optimal date of adoption for the firm is the one that maximizes that discounted sum, but to perform the analysis one requires making an assumption on the underlying competition process.

We have extensively explored several assumptions and concluded that the most credible one consists in all the competitors adopting at the same date, *i.e.* to select the best joint equilibrium with preemption as the dominant Pareto equilibrium. This is so because the gain in interim profit generates a preemption race to be the first firm to adopt. This race decreases the discounted profit so much that it is in the best interest of all the firms to

[14] see, for instance, evaluation guides for the European Innovation Fund: https://www.euinnovationfund.eu/)

adopt simultaneously. This theoretical result is interpreted as one of the factors that explain the observed late adoption of CCS in the cement industry. Imperfect Cournot competition does create an externality which has a strong influence on the outcome. Thus the need for public intervention.

The public policy which maximizes the social welfare takes the form of subsidizing either the fixed cost or the profit stream. The two instruments induce the same adoption date but differ in two respects: Firstly, subsidizing the fixed cost is simple and its optimal level is easy to calculate while subsidizing the profit flow requires much more information to be implemented; Secondly, the discounted values of the two transfers are different, subsidizing the fixed cost is about 5 times costlier than subsidizing the profit flow. In the calibrated model of the cement industry we have taken $n = 5$, the joint adoption date is 2041.7 and the public policy advances adoption to 2029.8. The welfare increases by about 16 %.

A sensitivity analysis relative to the cost assumptions shows that the results are robust with respect to the fixed cost of CCS but may significantly depend on the transport and sequestration cost, or on the total OPEX of the dirty plant. There are some reasons to think that the transport and sequestration costs are similar across firms in a regional market but not from one regional market to another one. Coordinating on the transport and sequestration CO_2 infrastructure may decrease these costs. This provides another motivation for the firms to select the joint adoption equilibrium.[15] Decreasing the transport cost is qualitatively equivalent to increasing the total OPEX of the dirty technology: the less competitive the dirty technology, the earlier the adoption date of CCS. In that respect, there may be strong asymmetries across firms in the same region; if there are, this may trigger selecting the precommitment equilibria in which the less competitive dirty firm is the first to adopt.

The main body of our analysis for the cement sector is done assuming symmetric firms and an initial market structure which will not be affected by CCS adoption (all the firms remain profitable in the long run). We have discussed extensions of our model as regards these two assumptions. A large asymmetry would certainly undermine the role of preemption. A competitive initial symmetric market structure would put a lot of pressure for preemption and firms would adopt too early.

[15] For an illustrating example see the Peak Cluster project in the UK `https://peakcluster.co.uk/`

While we believe that our analysis provides interesting and new insights, there are many caveats that limit its direct implementation. An operational discussion of CCS adoption in the cement sector and the role of public policy should integrate factors such as the discrepancy between the private cost of carbon and the SCC, as well as between the private cost of capital and the social interest rate; it should also integrate cost uncertainties as regards the implementation of CCS, the environmental accessibility of sequestration zones, and the associated cost of storage and transportation of CO_2. Another limitation of our analysis comes from the assumption that the market is homogeneous. As it is the case for green electricity, some consumers may be prepared to pay a premium for green cement. In France, the RE2020 regulation has strengthened the requirements for new construction, and the standard EN-197-5 has authorized the marketing of a new generation of carbon-light cements, known as ternary cements. It would be interesting to formalize the corresponding situation building on Galasso and Tombak (2014) and explore its consequences on the adoption process.

Implementing our analysis would thus require a substantial effort that could only be carried out with close interactions with professionals. Our theoretic analysis is a starting block that provides guidelines in this process.[16] These guidelines could be useful to study the adoption process in other hard-to-abate industries, the lime sector being a primary example given the fatal CO_2 emissions and the imperfect competition prevailing in the sector.

7.2 Further research

Our main theoretical insight is that firms are induced to adopt clean technology simultaneously through an informal focal point argument. The result would be worth exploring formally. Three directions could be pursued. The first concerns the concept of preemptive solution in symmetric games, which would require building on the results in Laraki et al. (2005). Extending precommitment and preemption to asymmetric firms would also be interesting, either in terms of the variable costs of the clean and dirty technologies. We suspect that this asymmetry would introduce a natural ordering of firms for the precommitment equilibrium and give some credibility to this solution concept. The joint adoption equilibrium with preemption would also be affected; the discounted equilibrium profits would no longer be equal. We

[16] For an article illustrating such an implementation process see (Sadighi et al., 2024).

suspect that the adoption date would be selected according to the most efficient firm. Whether the best joint equilibrium for the most efficient firm Pareto dominates the precommitment equilibrium with the natural ordering of firms should be revisited. A third extension could concern the Cournot assumption for short-term competition. The result that subsidizing the fixed cost does not improve the discounted welfare is based on this assumption (Proposition 5). That the intensity of short-term competition matters is clear since that proposition is not valid in the pure monopoly case. More fundamentally, going from Cournot to Bertrand competition changes the nature of the adoption game and a complete reassessment of the solution concepts is required. Finally, introducing capacity constraints would make the model more realistic but much more complex to handle analytically.

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A Proofs

A.1 Proof of Lemma 1

Proof. For a given t and a given n and all $(k, n-k)$ with $k \leq \bar{n}$, define the function $\phi(k;t)$ as follows:

$$\phi(k;t) = \pi_c(k;t) - \pi_d(k-1;t) = \frac{n\delta(t)}{(n+1)^2}\big(2 + ((n-2k)\delta(t)\big)$$

Note that:

$$\phi(k-1;t) - \phi(k;t) = 2\delta^2(t)\frac{n}{(n+1)^2}$$

with $\delta(t) > 0$ since it cannot be profitable to adopt the clean technology at a time t for which the cost differential is negative or null. It follows:

$$\phi(k-1;t) > \phi(k;t)$$

but $\phi(k;t)$ increases with t since $\delta(t)$ is such that $t_k \geq t_{k-1}$.

The discounted profit of the two firms that adopt in t_{k-1} and t_k differ only within this time interval. In that interval, the firm that adopts at t_{k-1} makes a higher flow profit minus the annualized fixed cost than its flow profit without adopting. The flow profit of the firm that adopts at t_k is lower than the latter since it competes with one more clean firm. ■

A.2 Proof of Proposition 1

Proof. Assumption 1 ensures that δ_k^C is well defined. Note that, thanks to Assumption 1, $\forall k$, δ_k^C can be framed by the following inequality:

$$\frac{1}{2n}(n+1)^2 f \leq \delta_k^C \leq \frac{1}{n}(n+1)^2 f \leq \frac{1}{n} \tag{18}$$

It follows that:

1. Inequality 18 ensures that $\forall k$, $\delta_k^C \leq \frac{1}{k}$ which is the date at which firm $k+1$ to firm n would face a negative cash flow.

2. easily: $\frac{\partial \delta_{n/2}^C}{\partial n} = f\frac{n^2-1}{n^2} > 0$ For the other, δ_k^C, it is useful to come back to the 2nd order polynomial:

$$(n-2k)(\delta_k^C)^2 + 2\delta_k^C - f\frac{(n+1)^2}{n} = 0$$

Differentiating gives:

$$\frac{\partial \delta_k^C}{\partial n} = \frac{1}{2((n-2k)\delta_k^C + 1)}\big(f\frac{n^2-1}{n^2} - (\delta_k^C)^2\big)$$

For $k = n - l$, this gives:

$$(2l-n)(\delta_{n-l}^C)^2 + 2\delta_{n-l}^C - f\frac{(n+1)^2}{n}$$

$$\frac{\partial \delta_{n-l}^C}{\partial n} = \frac{1}{2((2l-n)\delta_{n-l}^C + 1)}\big(f\frac{n^2-1}{n^2} + (\delta_{n-l}^C)^2\big)$$

as $(2l-n)\delta_{n-l}^C + 1 > 0$, this ensures $\frac{\partial \delta_{n-l}}{\partial n} > 0$

3. $\frac{\partial \delta_k^C}{\partial f} = \frac{(n+1)^2}{2n\sqrt{1+\alpha_k}} > 0$
   $\frac{\partial \delta_n^C - \delta_1^C}{\partial f} = \frac{(n+1)^2}{n}\big(\frac{1}{\sqrt{1-\alpha_n}} - \frac{1}{\sqrt{1+\alpha_1}}\big) > 0$

■

A.3 Proof of Proposition 2

Proof. Firms maximize the discounted flow of profit that is maximized:

$$\Pi_{NJ}(t) = \int_0^t \frac{1}{(n+1)^2}(1-\delta(\nu))^2 e^{-i\nu} d\nu - Fe^{-it} + \int_t^\infty \frac{1}{(n+1)^2} e^{-i\nu} d\nu$$

Taking the first derivative of this expression gives the result since it can be checked that $\Pi_n(t)$ is convex. Observe that $f \leq \pi_c(n,0) = 1/(n+1)^2$ so that this expression is well defined and clearly:

$$\delta^J = n\delta_n^C$$

The properties are simple to demonstrate:

1. When no firm has adopted, the n dirty firms would leave the market at $\delta = 1 > \delta^J$.

2. $\delta^J > \delta_n^C$ which ensures that joint adoption happens after the last adoption in both the precommitment and the diffusion equilibria.

3. $\frac{\partial \delta^J}{\partial n} = \frac{(n+1)f}{\sqrt{1-(n+1)^2 f}} > 0$ hence δ^J increases with n.

4. $\frac{\partial \delta^J}{\partial f} = \frac{(n+1)^2}{2\sqrt{1-(n+1)^2 f}} > 0$ hence δ^J increases with f.

■

A.4 Proof of Proposition 4

Proof.

Prior to adoption, the flow of industry profit is $\pi_d(0;t) = n(1-\delta)^2)/(n+1)^2$ while after adoption it is $\pi_c(n;t) = n/(n+1)^2 - f$. As for the consumer surplus, it is $cs(t) = (1-\delta(t))^2/2$ before adoption and $cs(t) = 1/2$ after adoption. The maximum is obtained for an adoption t such that the first derivative of the discounted welfare is null. Adding the two terms gives the optimal value for δ^{SB}. It solves:

$$\frac{1}{\frac{n}{2}+1}(2-\delta)\delta(\frac{1}{2}n+1)\frac{n}{(n+1)^2} = nf$$

that is:

$$(2-\delta)\delta = 2(n+1)^2 f \frac{1}{n+2}$$

and so

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

■

The proofs of properties are:

1. Using inequality 18 and the fact that $\delta^W < 2f$, we have $\delta_1^C - \delta^{FB} \geq \frac{1}{2n}f(n+1)^2 - 2f = \frac{1}{2n}f(n-1)^2 > 0$

2. When no firm has adopted, the n dirty firms would leave the market at $\delta = 1 > \delta^J$.

3. Using the fact that $\delta^{SB} \leq \frac{g(n+1)^2}{n+2}$, we have $\delta^{SB} \geq \delta_{n/2}^C = \frac{f(n+1)^2}{n} \geq \delta_k^C$ for $2k \leq n$

4. $\frac{\partial \delta^J}{\partial n} = \frac{(n+3)f}{(n+2)^2\sqrt{1-(n+1)^2 f}} > 0$ hence δ^J increases with n

5. $\frac{\partial \delta^J}{\partial f} = \frac{(n+1)^2}{2(n+2)\sqrt{1-(n+1)^2 f}} > 0$ hence δ^J increases with f

A.5 Proof of Lemma 2

Proof. Note $\Delta_k Z = Z(k; \delta_k^C) - Z(k-1; \delta_k^C)$, in which $\delta_k^C = \delta(t_k^C)$, with Z a function such as w, cs, π_c, π_d. With these notations we have:

$$\Delta w_k = \Delta cs(k; \delta_k^C) + (k-1)\Delta\pi_c(k; \delta_k^C) + (n-k)\Delta\pi_d(k; \delta_k^C) + \phi(k; \delta_k^C) - f$$

where by definition $\phi(k; \delta_k^C) = f$ with:

$$\Delta_k cs = \frac{\delta_k^C}{2(n+1)^2}\left(2n - (2n-2k+1)\delta_k^C\right) > 0 \tag{19a}$$

$$\Delta_k \pi_c = -\frac{\delta_k^C}{(n+1)^2}\left(2 + (2n-2k+1)\delta_k^C\right) < 0 \tag{19b}$$

$$\Delta_k \pi_d = -\frac{\delta_k^C}{(n+1)^2}\left(2 - (2k+1)\delta_k^C\right) < 0 \tag{19c}$$

$$\Delta_k w = \frac{\delta_k^C}{2(n+1)^2}\left(\delta_k^C(4n-6k+1) - 2n + 4\right) \tag{19d}$$

Using inequalities $\delta_k \leq \frac{1}{n}$ for all k we get:

$$\Delta_k w \leq \delta_k^C(1(4n-6k+1) - 2n + 4) = \delta_k^C(8 - 2n - (6k-1)/n)$$

Which is negative for $n \geq 4$.

For $n = 1$, $\Delta_1 w = 2(n+1)^2 \frac{\delta_1^C}{8}\left(2 - \delta_1^C\right) > 0$. For $n = 2$, $\Delta w_1 = \frac{3(\delta_1^C)^2}{18} > 0$ while $\Delta w_2 = -\frac{3(\delta_2^C)^2}{18} < 0$.

For $n = 3$ we have $\Delta_1 w = \delta_1^C(7\delta_1^C - 2)$ which is negative if $f \leq 6/49$ while $\Delta_2 w$ and $\Delta_3 w$ are negative.

■

A.6 Proof of Proposition 5

Proof.

A social planner seeking to maximize total discounted social welfare $\mathcal{W}$. Using the previous notations of instant social welfare $w(k; \delta)$, discounted welfare is:

$$\mathcal{W} = \int_0^{t_0} e^{-i\nu} w(0; \delta(\nu)) d\nu + \sum_{k=0}^{n} \int_{t_k}^{t_{k+1}} e^{-i\nu} w(k; \delta(\nu)) d\nu + \int_{t_n}^{+\infty} e^{-i\nu} w(n; \delta(\nu)) d\nu \tag{20}$$

Subsidizing the k^{th} adoption by a proportion λ_k of fixed costs has the effect of making adoption sooner. ($\frac{\partial \delta_k^C}{\partial \lambda_k} < 0$ The social planner who sets the optimal subsidy level solves the first-order condition: $\frac{\partial \mathcal{W}}{\partial \lambda_k} = 0 = \frac{\partial \delta_k^C}{\partial \lambda_k} e^{-it_k} \big(w(k-1; \delta_k^C) - w(k; \delta_k^C) \big) = -\frac{\partial \delta_k^C}{\partial \lambda_k} e^{-it_k} \Delta w^k$

Lemma 2 shows that welfare differences Δw^k are always negative as soon as the number of firms is larger than 4. Hence $\frac{\partial \mathcal{W}}{\partial \lambda_k} < 0$.

While this result applies to single subsidies, it also holds if a subsidy targets multiple firms. Indeed, lemma 2 ensures that welfare drops at each new clean technology adoption. Consequently, advancing the timing of adoption accelerates the welfare drop, which is costly in discounted terms.

■

A.7 Proof of Proposition 7

Proof. The explicit formulas for δ_k^C following lemma 1 remain valid when $n > \bar{n}$. Clearly $\delta_k^C(n)$ are increasing with n and converge to $\sqrt{f}$ when n go to ∞.

To get the results for $\delta_{\bar{n}}^J(n)$, one needs to revisit Proposition 5, introduce the flow profits that depend on the number of clean and dirty firms, and take the limit as n goes to infinity. From the flow profit of dirty firms, we see that a dirty firm exits ($i.e.$ $q_d(\bar{n}, n-\bar{n}) = 0$) the market at time t^e corresponding to $\delta^e = 1/(\bar{n}+1)$.

Assume for the time being that $\delta^e \geq \delta_{\bar{n}}^J(n)$, so that the discounted flow profit writes:

$$\Pi_{n>\bar{n}}^J(n;t) = \int_0^t [(1-\delta(\nu))^2/(n+1)^2] e^{-r\nu} d\nu - F e^{-rt}$$

$$+ \int_t^{t^e} [(1+(n-n>\bar{n})\delta(\nu))^2/(n+1)^2] e^{-r\nu} d\nu + \int_{t^e}^{\infty} [(1/(n>\bar{n}+1)^2] e^{-r\nu} d\nu$$

Taking the derivative and eliminating $e^{-rt_{\bar{n}}^J}$ gives:

$$(1-\delta_{\bar{n}}^J(n))^2/(n+1)^2 - (1+(n-\bar{n})\delta_{\bar{n}}^J(n))^2/(n+1)^2 + f = 0$$

and letting n go to infinity:

$$[\delta_{\bar{n}}^J(n)]^2 = f$$

Since $\sqrt{f} < 1/(\bar{n}+1)$, it follows that, as n goes to ∞, the $n-\bar{n}$ dirty firms indeed leave the market post adoption by the $\bar{n}$ clean firms so that our assumption is correct. If the level of subsidy is λ, similar calculations show that $\delta_{\bar{n}}^{J\lambda}(n)$ converges to $\sqrt{f(1-\lambda)}$.

For n is not large enough to have $\delta_{\bar{n}}^{J}(n) \leq \delta^e$, the $n-\bar{n}$ dirty firms will leave immediately at $\bar{\delta}_{\bar{n}}^{J}(n)$ in which $\bar{\delta}_{\bar{n}}^{J}(n)$ is now determined by maximizing:

$$\Pi_{\bar{n}}^{J}(n;t) = \int_0^t [(1-\delta(\nu))^2/(n+1)^2]e^{-r\nu}d\nu - Fe^{-rt} + \int_t^\infty [(1/(N+1)^2]e^{-r\nu}d\nu$$

which gives:

$$\bar{\delta}_{\bar{n}}^{J}(n) = 1-(n+1)\sqrt{1/(\bar{n}+1)^2 - f}$$

As long as $\delta^e < \bar{\delta}_N^J(n)$ it is indeed in the best interest of the $n-\bar{n}$ firms to remain in the market until $\delta(t) = \bar{\delta}_{\bar{n}}^{J}(n)$. Since $\bar{\delta}_{\bar{n}}^{J}(n)$ is decreasing with n to become negative, eventually it will be true that $\bar{\delta}_{\bar{n}}^{J}(n) \leq \delta^e$, which ends the proof.

■

A.8 Proof of Proposition 8

Proof. We have for all $k \leq \bar{n}$

$$\pi_c(k;t) - f - \pi_d(k;t) = \frac{1}{n+1}\delta(2+\delta(n-1-2k) - f$$

which, as n goes to ∞, converges to

$$(\delta^2 - f)$$

Plugging this expression into the algorithm for the diffusion equilibria gives the result. Since

$$\int_{t_\infty^C}^{t^e} (\delta^2 - f)$$

is certainly non-negative, it follows that the precommitment equilibrium Pareto dominates the diffusion equilibrium, and from Corollary 1 we see that the social welfare is also higher.

■

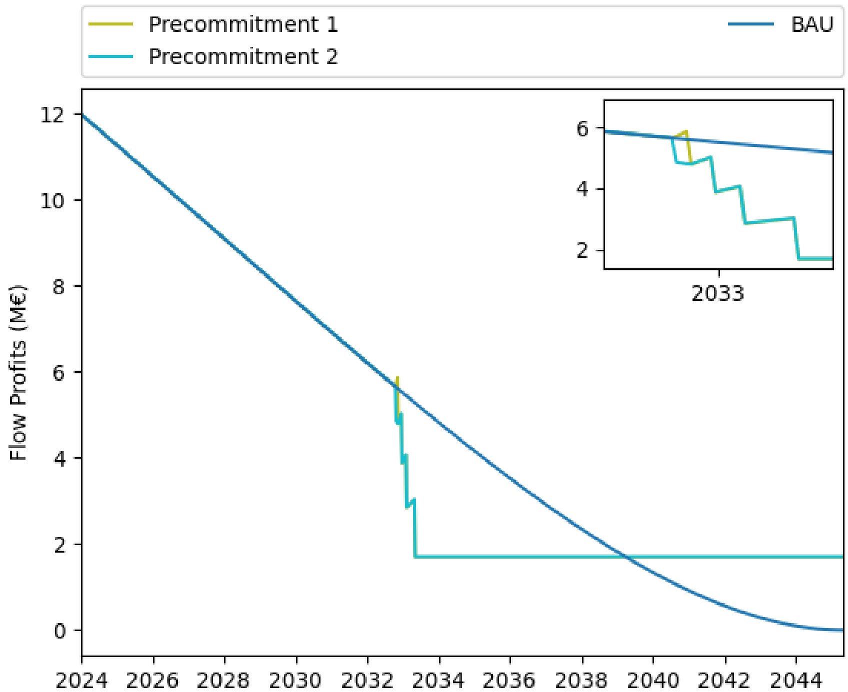

Figure 2: Evolution of profit flows.

B Details for the market equilibria of the calibrated adoption game

Figure 2 depicts the profit flows of the first and second firms compared to the BAU profit flow; the NE insert shows their detailed evolution. These two equilibrium flows differ only in the interval between the first and second adoptions. On this interval, the first adopter gets a flow higher than BAU while the second gets a flow below BAU, This illustrates the competitive advantage associated with adoption. As the other competitors adopt, the flows of both the first and second adopters remain below the BAU flow until the last adoption and then remain constant, crossing the BAU flow at the date 2039. The date 2041.0 is precisely the one that corresponds to the 5 firms adopting with the joint adoption equilibrium: the BAU profit flow equals the profit flow with 5 joint adoptions. From the graph, it is clear that the discounted profit for the joint adoption equilibrium is certainly higher than

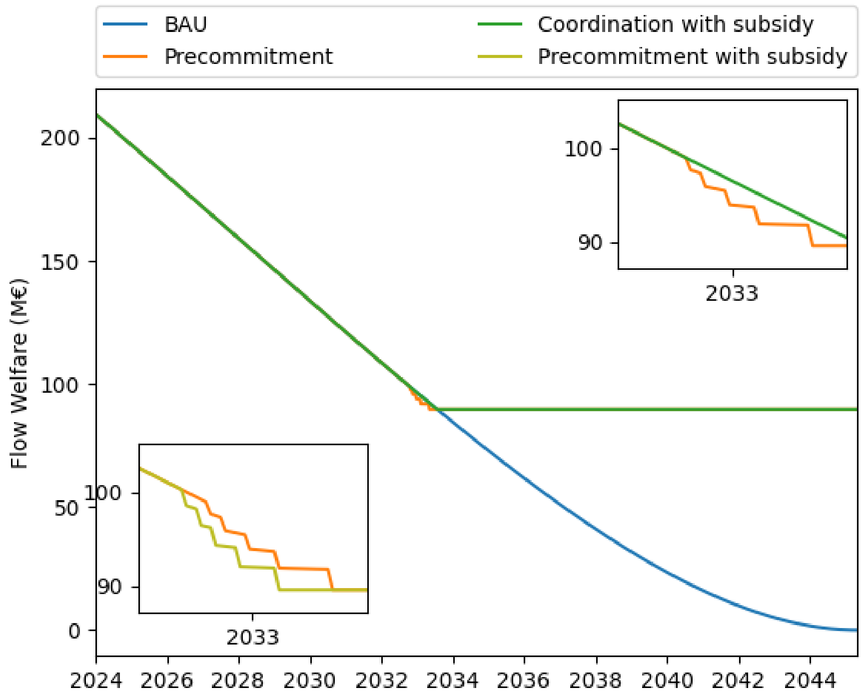

Figure 3: Evolution of welfare flows.

that of the first adopter with the precommitment equilibrium (calculation, respectively, gives 4046 M€and 3901 M€). Since the adoption dates for the diffusion equilibria with preemption are earlier than the first adoption date of the precommitment equilibrium, this ensures that the joint adoption preemption equilibrium dominates all the diffusion equilibria with preemption.

Consider now the graph of the welfare flows as shown in Figure 3. According to Proposition 6, the optimal subsidy for the cooperative equilibrium is $\lambda^{J\lambda} = N/(N+2) = 5/7$ and the corresponding adoption date is 2029.8. The NE insert compares the evolution of the welfare flows and shows that for the calibrated game the comparison is in favor of the joint adoption preemption equilibrium. The SW insert displays the welfare flows of two precommitment equilibria, one with a 4% and the other one without subsidy (calculation, respectively, gives 83,962 and 84,004 Me). It illustrates the fact that a subsidy deteriorates welfare (Lemma 2).

Figure 4 shows that emissions decrease earlier with precommitment than with joint adoption equilibrium with subsidy, to the detriment of industry profits, since we saw that the welfare comparison is not favorable. The corresponding abatement curves give the respective marginal abatement costs as outcomes of the model. For the calibrated game, the abatement cost corresponding to the first-best is 122.8 euro/ton CO_2. For that carbon price, the sector is fully decarbonized. With the joint adoption equilibrium, decarbonization is achieved at a carbon price of 139.0 euro / ton of CO_2. With the precommitment equilibrium, the decarbonization progressively occurs as the carbon price increases from 130.6 to 139.5 euro / ton CO_2. Without CCS, the decarbonization would be complete when the carbon price is such that the demand for cement is null, that is, $\delta(t) = 1$ or $SCC(t) = (1 - \mu_0)/\mu_1$, which gives $t = 2045.3$ and a carbon price at 258.3 euro / tons CO_2.

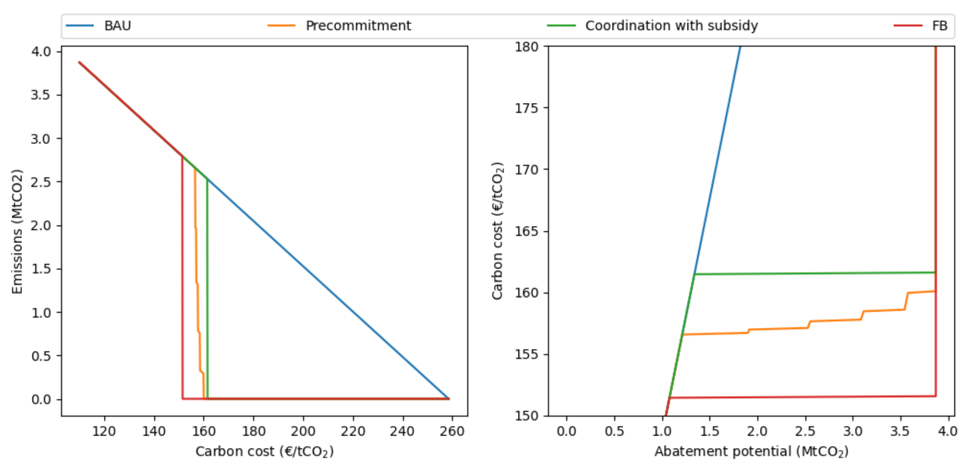

Figure 4: Evolution of emissions and abatement curve.

Figure 5 details the evolution of quantity and price along the precommitment and the cooperative equilibrium with subsidy. Compared to the 2024 levels, the long-term levels, respectively, correspond to a decrease in quantity of 6% and a price increase of 11%. In our calibrated game, the complete decarbonization of the cement sector is achieved by two levers: 20% due to a decline in demand and 80% due to radical CCS innovation.

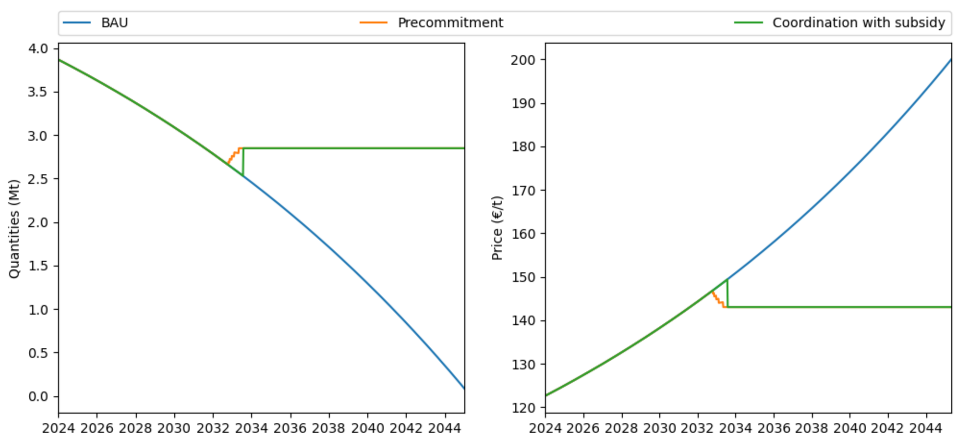

Figure 5: Evolution of quantity and price.