Cost-Benefit Analysis for Green Demonstrators: Application to the Container Glass Industry in France

February 2024

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Abstract

Adopting disruptive technologies for decarbonizing hard-to-abate industrial sectors requires experimentation through demonstration (pilot) projects. However, from an economic perspective, the potential long-term benefits and the difficulties in designing relevant public policies are not addressed in the standard valuations of those projects. This paper shows that cost-benefit analysis (CBA) at the sector level provides clues to solve these issues, integrating knowledge spillovers from the pilot throughout the industry and the technical change from value-added cost components in adjacent activities. Such analysis gives the optimal trajectory for decarbonizing the sector. Our suggested CBA also delivers the relevant abatement cost for the pilot, a key indicator of public policy. Applied to France's large-scale, high-quality container glass sector, CBA obtains an abatement cost of around 200€/tCO_2 for the pilot deploying a decarbonized hybrid technology, which is 50% lower than previous standard approaches. Additionally, we show that subsidizing the pilot associated with a commitment to transfer knowledge to follower plants is sufficient to decentralize the social optimum if governments implement an emissions tax internalizing the environmental cost. This approach could be applied in other hard-to-abate sectors to trigger the early deployment of disruptive innovations and facilitate the designing of relevant public policies.

Key words: Disruptive Technologies, Pilot Projects, Cost-Benefit Analysis, Carbon Neutrality, Knowledge Spillover

JEL Classification: Q550, Q520, Q420, O330, O380

Word Count: 10163 words

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1. Introduction

The European Union's Green Deal aims to achieve Net Zero Emissions (NZE) by 2050 (European Commission, 2020). Despite this, the industrial sector has experienced faster growth in emissions than any other sector over the past two decades (R. Shukla et al., 2022). In France, the industrial sector contributed to 24% of national emissions in 2019 (IEA, 2021). To reach NZE by 2050, emissions from energy consumption in the sector should reach complete carbon neutrality (Ministère de la transition écologique, 2022). According to (IEA, 2022a), the decarbonization of the so-called "hard-to-abate" industries is currently "not on track" to reach NZE by 2050. A review of seven energy-intensive industrial sectors—iron & steel, (petro-) chemistry, cement, pulp & paper, ceramics, glass, and food—has found that relying solely on efficiency improvements and increased electrification is not enough to achieve full industrial decarbonization suggesting that breakthrough technologies are necessary for substantial progress in reducing emissions in these industries (Gerres et al., 2019).

The adoption of breakthrough technologies necessitates the implementation of demonstration or pilot projects. (Hellsmark et al., 2016) define demonstration projects as a tool to progress knowledge and lower risk to optimize designs for future large-scale deployment at a lower cost across the whole industrial sector, a process commonly known as "knowledge spillover". (Hellsmark et al., 2016) analyzed demonstration projects in Sweden focused on biomass and black liquor conversion, while (Stolper et al., 2022) studied Dutch shipping pilot projects. Both identified the learning processes as the primary outcomes of those projects. Empirical studies have further emphasized the importance of learning and knowledge spillover, particularly in adopting emerging renewable energy technologies. (Newbery, 2018) estimated a cumulative spillover value of about $110 billion for solar photovoltaic (PV) costs from 2010 to 2015 at a global level. (Nemet et al., 2020) analyzed the US PV systems from 2008-2014, discovering that the overall learning effects could contribute to a 21% reduction in the panel cost (13% from learning-by-doing, 6% from intra-firm spillovers, and 2% from inter-firm spillovers).

Although a necessary step in the energy transition path, investment in first-of-a-kind pilot projects faces many challenges. As (Nemet et al., 2018) discussed, on the one hand, private firms are reluctant to finance their demonstration initiatives due to high capital requirements, technology risk, uncertain demand, and low appropriability of spillovers. On the other hand, even if the spillover impacts justify governmental intervention, public authorities face difficulties in identifying and evaluating the importance of such impacts. This challenge can arise from their limited visibility into the broader innovation landscape or the potential influence of political motives and favors, which can overshadow the projects' social value.

The economic valuation of demonstration projects is essential to overcoming these challenges. Standard Cost-Benefit Analysis (CBA) focuses on the demonstrator projects within their finite lifetime. However, CBA must be reformulated to compare trajectories that include the benefits accruing to the whole sector from demonstrators. Moreover, these sector trajectories must be aligned with the NZE constraint as conceptualized in (Meunier and Ponssard, 2023). Previously, only a limited number of studies have reformulated CBA considering trajectories. (Vogt-Schilb et al., 2018) introduced a convex investment cost of capital in their energy transition across various sectors, demonstrating its potential to advance the launch date of the transition. (Creti et al., 2018) introduced learning-by-doing in the valuation of the transition of a fleet of vehicles based on hydrogen fuel cells. (Kasser et al., 2024) extended this methodology by explicitly defining relative learning rates to identify niches for fuel cell electric buses in markets dominated by battery electric buses. Our contribution adds one more study to this limited number of papers while emphasizing benefits from the demonstration phase into the entire sector and inferring the relevant public policy.

Our empirical investigation concerns the high-quality container glass industry segment. We use data from a study by the French Agency for Ecological Transition (ADEME) within the framework of the "VERCANE-Carbon Neutral Glass Melting" program (ADEME, 2022), the objective being to decarbonize the container (or hollow) glass sector. The initial research program found that the costs and risks associated with most of available decarbonization solutions at the pilot level outweighed the benefits of reducing emissions. As a result, concerns were raised on the possible paths to overcome these barriers. This initial valuation for a potential pilot plant indicated an abatement cost exceeding 400 €/tCO_2, compared to a social cost of carbon of 250 €/tCO_2 in 2030 for France (Quinet, 2019). In parallel, the Furnace for Future (F4F) initiative was launched in 2020, endorsed by 19 glass manufacturers at the European level. The proposal for a First-of-a-Kind Low Emissions Furnace did not receive European support despite receiving high evaluation scores in terms of innovation, sectoral approach, and scalability.

These unfavorable attempts to secure public support based on standard evaluation metrics motivated this paper. We identify the optimal sequencing of the transition across the sector to maximize the spillover benefits and explicitly highlight the potential loss that would occur if the transition were executed based on the technical lifespan of the plants. We demonstrate that the launch of the demonstration plant should occur much earlier than suggested by traditional CBA. This early deployment leads to a lower corresponding abatement cost, around 200 €/tCO_2, primarily because it considers the long-term benefits of the sector. The magnitude of these benefits depends on the spillover rate and the number of plants in the sector. In the container glass industry segment under study in France, which encompasses 27 plants, the achievement of this abatement cost is contingent on only 13 follower plants benefiting from the spillover generated by the pilot project.

Altogether, this paper makes three main contributions. Firstly, it suggests ways to design a sector-level CBA, differentiating the roles of pilot and follower plants. The analysis incorporates two main aspects: endogenous and exogenous technical progress and stranded assets avoidance. For technical progress, we distinguish between endogenous and exogenous learning effects. Within an industrial context, endogenous learning is achieved through the accumulation of knowledge and experience acquired from industrial operations as the deployment levels of emerging technologies increase. Industrial units operating within the same sector can learn from one another and share best practices, leading to the spillover of endogenous learning. On the other hand, exogenous learning involves drawing insights and innovations from other relevant sectors at the global level. We differentiate between these two channels. For the issue of stranded assets, the question of implementing a decarbonized technology is typically addressed at the renewal time of plants, independent of the potential appropriability of the benefits coming from the demonstration plant. Instead, the optimal sequence of decarbonization through the sector should integrate this point, including additional maintenance expenses for extended lifetimes or costs associated with stranded assets for shortened lifetimes. Considering these points, contrarily to a standard CBA that focuses solely on the pilot-level analysis, our framework allows for modeling the benefits of spillovers to follower plants. These benefits, in turn, influence the abatement cost of the pilot plants, resulting in a lower abatement cost than the one derived from a standard analysis.

The second contribution concerns the public policy to trigger early deployment of pilot plants. Existing discussions on the need for governmental intervention to craft supportive policies for innovation have explored the justification for such intervention based on spillover effects (Hellsmark and Jacobsson, 2012; Hendry et al., 2010; Sagar and van der Zwaan, 2006; Strandholm et al., 2018). In recent years, research and innovation funders, including Horizon Europe and the EU Innovation Fund, increasingly emphasized on the significance of Research and Development (R&D) projects, indicating a sustained commitment to this trend (European Commission, 2023). (Hellsmark et al., 2016) and (Nemet et al., 2018) provided implications for policymakers in making support decisions regarding demonstration projects, such as prioritizing learning as the objective of these projects, encouraging private sector engagement, and making demand pull policy robust in parallel with R&D subsidies. Our investigation differs from each of these other studies. Herein, a subsidy to the pilot associated with a commitment to transfer knowledge to follower plants would be sufficient to decentralize the social optimum when implemented alongside a carbon tax that internalizes the social cost of carbon. While most empirical papers on this subject emphasize pitfalls through the capture of public agencies by private firms, our contribution facilitates the design of an efficient public policy.

As the third contribution, we demonstrate the applicability of the proposed CBA framework by applying it to the high-quality container glass industry in France. The container glass industry is a critical component of the global supply chains for various major industries such as food and beverage, pharmaceutical, and cosmetic applications. France, the second-largest container glass producer in Europe, relies heavily on fossil fuel energy in glass melting furnaces (European Commission, 2021). Developing a carbon-neutral trajectory for decarbonized furnaces is a requirement for the NZE commitments (ADEME, 2021a). This more comprehensive approach could be applied in other hard-to-abate sectors to trigger an early deployment of disruptive innovations. The previously applied CBA studies within the energy transition field typically overlooked optimizing sector-level trajectories by considering the dynamic impacts of demonstration projects. These works include the CBA by (Hong et al., 2018) for the building sector, (Gigli et al., 2019) for the recycling system, (Oliveira Neto et al., 2019) for cleaner production in the textile industry, (Liu et al., 2019) for emission reduction measures in the transportation sector, (Yang et al., 2021) for electric vehicle charging, (Lal et al., 2022) for biofuels in the energy sector, (Hekrle et al., 2023) for green rooftops in the building sector, (Ding et al., 2023) for decarbonization pathways in ceramic industry, (Fang et al., 2023) for concentrated solar thermal gasification of biomass for continuous electricity generation, and (Tao et al., 2023) for recycling of glass fiber. To the best of our knowledge, our study represents the first instance of applying the methodology that accounts for the dynamic impacts of a demonstrator within an industrial context.

The paper is structured as follows: Section 2 provides an overview of the glass industry in general, delves into a specific segment under examination, and introduces the VERCANE pilot project. Section 3 outlines the proposed dynamic model for the CBA. Section 4 describes the model calibration process based on data from container glass furnaces in France. Section 5 presents the results obtained from the calibration process. In Section 6, a sensitivity analysis is conducted to evaluate the robustness of the results. Section 7 discusses the study's implications in modeling the dissemination of knowledge, highlighting sources of uncertainties and limitations and offering suggestions for future research. Section 8 articulates the policy recommendations that emerged from the analysis. Finally, Section 9 summarizes the study's conclusions.

2. Overview of the Container Glass Sector

The European Union (EU) is the world's largest glass producer, accounting for about one-third of the global production, with approximately 31 million tons of glass produced in 2019 (European Commission, 2021). The EU's strong demand from various industries such as construction, automotive, and packaging, as well as its strict environmental regulations promoting the use of recyclable materials like glass, make it the largest market for its production, with about 80% of the glass produced being consumed within the EU. In Appendix A.1, we detail the emitting profile of this sector.

France, the geographical scope of this study, is the second European glass producer behind Germany, with an annual production capacity of more than 5 million tons (GAE, 2021). The requirements and fields of activity of glassmakers vary greatly depending on the final product. Glass products are generally classified into five major sub-sectors: hollow/container glass, flat glass, fiberglass, specialty, and domestic glass. The container glass sub-sector on which this study will focus plays a crucial role in industries such as food and beverage, medical, pharmaceuticals, and perfume supply chains. This segment accounts for about 75% of volume production in France (ADEME, 2021), which is expected to be maintained in the future, as we detail in Appendix A.2.

The container glass industry is classified into different segments based on the end-use product's coloring depending on the glass's residual impurities. The so-called flint (or clear) and super-flint (or ultra-clear) are high-quality container glass categories whose production requires special sand with low iron oxide levels and are characterized by their transparency and brilliance. These types of hollow glass have limitations in using recycled glass (called "cullet"), resulting in more energy required to melt the batch materials. In France, more than 80% of the hollow glass production capacity (about 3.5 million tons of Glass) is dedicated to high-quality glass. In 2020, 49 furnaces were in operation (GlassGlobal, 2020). They have been (re)constructed since 2010 (GlassGlobal, 2020) and are operated by eight manufacturing firms. In Appendix A.2, we detail the firms' market share based on their total production capacity.

In the container glass sector, GHG emissions of scope 1 (directly arising from fossil fuel combustion) and scope 2 (indirectly from electricity use) are primarily related to the energy input into the melting furnaces operating at temperatures between 1200-1500°C. As shown in Fig. 1, in France, fossil fuel combustion in melting furnaces has accounted for approximately 75% of the total CO2 emissions in the container glass industry (ADEME, 2021b). Furnaces also generate process GHG emissions through decarbonizing lime and sodium carbonate in the batch composition, accounting for about 20% of the total emissions. However, due to the low-carbon electricity mix in France, the indirect emissions from power consumption constitute a small share (5%) of the total emissions. Overall, the sector consumed over 11 TWh of energy, representing approximately 3% of thermal and 2% of electrical energy consumed by French industries. This level of energy consumption resulted in the emission of 2.7 MtCO2, which accounts for roughly 4% of the total national greenhouse gas emissions (ADEME, 2021b).

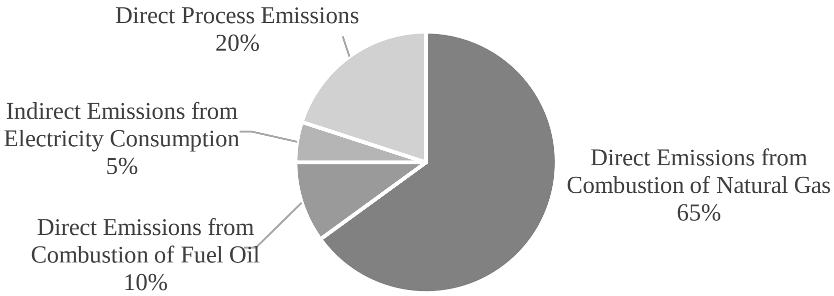

Fig. 1. Sources of Emission in French Container Glass Sector (ADEME, 2021)

Considering the high volumes of energy consumption, switching the fuel for the melting process is the most critical lever in the sector's decarbonization. Moreover, the furnaces constructed from refractory materials are designed to operate continuously for their entire technical lifetime. Any disruption to this thermal process could result in explosions, the solidification of the liquid glass, and the impossibility of restarting the furnace.

As the choice of decarbonization technology will depend on the size of the furnace, this study proposes a classification into small-scale furnaces, denoting capacities of less than 150 tons of daily glass production, and large-scale furnaces for higher capacities. In France, over 80% of high-quality container glass, equivalent to approximately 2.9 million tons of glass, is produced within large-scale furnaces with capacities ranging from 150 to 450 tons of glass per day. The remaining 20%, accounting for around 0.6 million tons of glass, is produced in smaller-scale furnaces (GlassGlobal, 2020).

Low or zero-carbon alternative fuels for melting glass include electricity, hydrogen (H2), and biofuels. Given that the availability of biomass is a concern as a sought-after alternative in other sectors, it is not considered a promising alternative in the container glass sector (Parsons Brinckerhoff and DNV GL, 2015). Electric heating is advantageous in terms of efficiency; however, they are currently used for smaller furnaces, and no established electric furnace produces the entire production volume of large-size furnaces (Meuleman and Holman, 2019). Decarbonized hydrogen is viewed as a supplement to carbon neutrality, compatible with the current large-scale gas furnaces. Furthermore, the on-site production of H2 through electrolysis provides the supplementary values of ancillary services and the co-production of heat and oxygen to be valorized directly at furnaces to improve combustion efficiency. However, hydrogen faces challenges, such as the current cost of production, which is not competitive with the wholesale market price of electricity, and energy losses during the conversion of electricity to hydrogen. Altogether, the most promising decarbonized technology for the carbon neutrality of the large-scale, high-quality container glass segment would be a hybrid technology that uses electricity and decarbonized gas, such as hydrogen (FEVE, 2021).

Several attempts have been made to scale up hybrid furnace technology in the EU, notably through the Furnaces for Future (F4F) project initiated by the European Container Glass Federation (FEVE) in 2020, involving 19 leading container glass companies, constituting over 90% of European production (FEVE, 2021). Despite progressing to the second stage of the EU Innovation Fund call, the F4F project failed to secure funding, leading to independent national pursuits (see Appendix A.3 for more details). In France, the two glass producers of the F4F project, SAVERGLASS and VERESCENCE, established a separate French consortium for the "VERCANE-Carbon Neutral Glass Melting" project. This project was supported by ADEME in 2021 for the preliminary study of the transition solutions for the high-quality container glass sector involving various stakeholders, including glass manufacturers, furnace developers, industrial energy suppliers, and academics (ADEME, 2022). The preliminary study identified hybrid technology as suitable for large furnaces, with detailed technical implementation and cost estimation. The study proposed moving to a pilot phase to experiment and refine the technology, intending to transfer benefits to the entire sector. The pilot project selected five existing furnaces (three small-scale and two large-scale) for high-quality hollow glass production in France.

This overview reveals the difficulty of designing a relevant institutional framework to address the decarbonization of a sector in which the technology requires pilot studies with potential benefits to be spread within the whole sector. On the one hand, proposing a pilot with a limited number of firms results in a narrow perimeter for CBA, leading to high abatement costs and a lack of available public funds for project initiation. Additionally, the dissemination of knowledge throughout the sector remains uncertain. On the other hand, in the case of a large consortium, two key issues arise: (i) determining how to conduct a sector-level CBA rather than a pilot-level analysis and (ii) regulating the expected cooperation during the pilot phase to ensure compatibility with long-term sectoral competition. This paper addresses these research questions, drawing insights from information and feedback from previous studies.

3. Model

We introduce the general framework of CBA in Section 3.1. For further clarity and understanding of relevant aspects of the analysis, we present some theoretical results in a simplified case in Section 3.2.

3.1. The General Framework of CBA

In the general framework of CBA, we consider the decarbonization of a sector. The sector involves N plants currently operating with an emitting technology to be replaced by a clean technology consistent with the NZE constraint to be decarbonized by the year 2050. Define j as one of the plants, with j going from 1 to N. Time is denoted t as a continuous variable going from 0 to infinity. The social discount rate is denoted i. The social cost of carbon (SCC) is assumed to follow Hotelling's rule (Hotelling, 1931), that is $P_0\, e^{it}$ at time t where P_0 is the SCC at time $t=0$.

For each plant j, denote s_j as the time when the substitution of emitting technology by clean technology takes place. The sequence (s_j) defines the trajectory for decarbonizing the sector. More specifically, we are interested in a trajectory in which a pilot ($j=1$) is launched at date s, and the other plants (with $j = 2$ to N) follow at successive time $s+D_j$ so that D_j is the delay between the launches of each follower plant j and the pilot plant. Without loss of generality, assume $D_j \leq D_{j+1}$, let D stands for the sequence $(D_2,\dots,D_N)$, and denote (s,D) a trajectory. By construction, $s+D_N \leq 2050$ reflects the NZE constraint.

For a given trajectory, we compute the total discounted social cost of the trajectory at time $t = 0$ as the sum of:

1) The discounted cost of using the emitting technology in the plants up to the implementation of the clean technology at (s_j), to be denoted $\Gamma_d(s,D)$;

2) The discounted environmental cost of the emissions until complete decarbonization, which occurs at the date $Max(s_j)$, to be denoted $\Gamma_e(s,D)$;
3) The discounted cost of using the clean technology from the launch dates (s_j) to infinity, to be denoted $\Gamma_c(s,D)$.

The optimal trajectory minimizes the total discounted social cost, which is:

$$\Gamma(s,D)=\Gamma_d(s,D)+\Gamma_e(s,D)+\Gamma_c(s,D) \tag{Eq.1}$$

The term $\Gamma_d(s,D)$ is obtained through operating the emitting plants as Business As Usual. We suppose that the emitting technologies have finite lifetimes. If the clean technology is not launched at the end of the lifetime of an emitting plant, there will be some adjustment costs (either extra maintenance costs or some assets will be lost). These will be introduced in $\Gamma_d(s,D)$.

For i=1 to N, let E_j denote the emissions of plant j. Thanks to Hotelling's rule, $\Gamma_e(s,D)$ can be written as:

$$\Gamma_e(s,D)= s\, P_0\, (E_1 + \ldots + E_N) + D_2\, P_0\, (E_2 + \ldots + E_N)+ \ldots + (D_N - D_{N-1}) P_0\, (E_N) \tag{Eq.2}$$

The term $\Gamma_c(s,D)$ deserves more attention. Denote $\gamma_j(s_j)$, the discounted cash cost of the clean plant j as seen from time $t = s_j$, it would be expressed as $\gamma_j(s_j)\, e^{-is_j}$ when viewed from time $t = 0$. We shall introduce exogenous technical change, learning-by-doing, and eventually spillover impacting the discounted cash cost of each plant. To do so, it will be convenient to assume that the clean technology has a finite lifetime denoted T that could be renewed within subsequent investments.

We leave aside the index j for simplicity of notations. At the initial launch of the clean technology and each further renewal there is a set-up cost (possibly integrating the discounted operational costs over the technology's lifetime) consisting of three components: f_1, f_2 and f_3. The first component is time-independent, the second one depends on calendar time through exogenous technical change, and the third one is reduced at each renewal of the plant through learning-by-doing. While the value of f_1 remains unchanged, we assume short-term and long-term values for f_2 and f_3, respectively f_2^H and f_2^L, and f_3^H and f_3^L. The exogenous technical change is a decreasing function $\mu(t)\epsilon[0, 1]$. We define the learning-by-doing by a scalar parameter λ with values in [0, 1]. The function $\mu(t)$ and the parameter λ are assumed independent of the plant under consideration. We define by F_1, F_2, and F_3 the discounted cost components of a clean plant in which the clean technology is launched at s and infinitely renewed every T period. We have:

$$F_1=f_1(1+e^{-iT}+ e^{-i2T}\ldots)= f_1/(1- e^{-iT}) \tag{Eq.3}$$

$$F_2 = f_2^L/(1- e^{-iT}) + (f_2^H - f_2^L)\,[\mu(s)+ \mu(s+T)\, e^{-iT}+ \mu(s+2T)\, e^{-i2T}+\ldots] \tag{Eq.4}$$

$$F_3 = f_3^L/(1- e^{-iT}) + (f_3^H - f_3^L)\,(1+ (1-\lambda)e^{-iT}+ (1-\lambda)^2 e^{-i2T}+\ldots)= f_3^L/(1- e^{-iT})+ (f_3^H - f_3^L)\,(1- (1-\lambda)e^{-iT}) \tag{Eq.5}$$

The cost components F_1, F_2, and F_3 may depend on j, while only F_2 depends on s through the function $\mu(t)$. The discounted cost of a clean plant when the launch of the clean technology takes place at time s is obtained by the summation of the three components:

$$\Gamma_c(s,D)= F_1+F_2+F_3 \tag{Eq.6}$$

Let us now introduce spillover from a clean pilot technology launched at s to a follower plant j, which is launched with a delay D_j at time $s+D_j$. It is assumed that only the cost component F_3 is reduced by a factor that depends on D_j. We denote ν as a scalar with values in [0, 1], independent of the plant under consideration, and assume that the reduction is given by $e^{-\nu Dj}$. The spillover rate ν can be seen as a cost reduction factor per unit of time associated with the dissemination of accumulated knowledge. The expression of $\gamma_j(s_j)$ is defined accordingly.

In Section 4, we calibrate the general framework for the case of the container glass industry in France. Ordinarily, only a numerical analysis can obtain the trajectory (s,D) that minimizes $\Gamma(s,D)$. Thanks to some simplifying assumptions, the optimization problem can be solved analytically. This simplified case will highlight the difference between a standard CBA, in which plants are analyzed independently of each other, and a CBA over the whole sector with spillover.

3.2. Some theoretical results in a simplified case ($T = +\infty$, $\mu(t) \equiv 0$, $\lambda = 0$, $\nu \geq 0$)

The simplified assumptions are as follows: all plants are identical regarding production capacity and age, spillover exists, but there is no exogenous technical change or learning-by-doing. Additionally, an infinite lifetime is assumed for the plants. The N ongoing identical plants operate with an emitting technology (each emitting E tCO_2 per unit of time) to be replaced by a clean one. We take $\Gamma_d(s,D)=0$ and $\gamma_c(s) = F$ for the pilot plant. Assuming that the clean technology is launched in all other plants at time $s+D$, the total discounted cash cost for these plants are $\gamma_c(s+D)= e^{-\nu D}F$. Altogether, the total social discounted cost of the trajectory writes:

$$\Gamma(s,D)=\Gamma_e(s,D)+\Gamma_c(s,D)$$

Where $\Gamma_e(s,D)=P_0E(Ns+(N-1)D)$ stands for the discounted environmental cost of emissions and $\Gamma_C(s,D) = F\,e^{-is}\,(1+(N-1)e^{-(\nu+i)D})$ stands for the total discounted cash cost for the sector.

As $\Gamma(s,D)$ is a convex function, the optimal trajectory can be obtained from the first-order conditions: making the partial derivatives with respect to s and D equal to zero. Let s_0 stand for the optimal launch time of the clean technology with a standard CBA (the plants are taken independently without spillover). The standard abatement cost is computed as the annualized incremental cost of substituting the emitting technology by the clean one (iF) divided by the total abatement (E). It is such that the value of the social cost of carbon at time s_0 equals the abatement cost ($P_0e^{is_0} = iF/E$). The following proposition gives the dependence of s and D on the spillover rate ν and the number of plants N.

Proposition 1 *The optimal trajectory (s,D) is the solution of two equations:*

$$P_0e^{is} = P_0e^{is_0}(i+\nu)/(i+N\nu) \tag{Eq.7}$$

$$e^{(\nu+i)D} = e^{i(s_0-s)}(i+\nu)/i \tag{Eq.8}$$

Proof:

$$\delta\Gamma(s,D)/\delta s=0 \Leftrightarrow P_0e^{is}=iF[1+(N-1)e^{-(\nu+i)D}]/E\,N \tag{Eq.9}$$

$$\delta\Gamma(s,D)/\delta D=0 \Leftrightarrow P_0e^{is}=F[(i+\nu)\,e^{-(\nu+i)D}]/E \tag{Eq.10}$$

Noting that $P_0e^{is_0} = iF/E$, *Eq.10 gives Eq.8; replacing* $e^{(\nu+i)D}$ *by its value in Eq.9 gives Eq.7.*

Proposition 1 can be interpreted as follows. At the launch time s, the social cost of carbon is P_0e^{is} so that Eq.7 gives the abatement cost for the pilot plant as the abatement cost of the plant taken independently, $P_0e^{is_0}$, multiplied by a decreasing function of the spillover rate and the number of followers. The higher the spillover rate and the number of followers, the earlier the launch of the pilot. To interpret Eq.8, let us make a marginal CBA discounted at time 0 in which we postpone the delay D by Δt. The set-up cost of the follower plant decreases by two terms: the first is the decrease at time $s+D$ in the annual cost for the period Δt: $ie^{-i(s+D)}e^{-\nu D}F\Delta t$. The second one is the decrease coming from a more significant spillover for the discounted flow of cost from $s+D$ to infinity: $e^{-i(s+D)}e^{-\nu D}F(1-e^{-\nu\Delta t})= \nu\, e^{-i(s+D)}e^{-\nu D}F\Delta t$. Altogether, the decrease in the discounted cash cost is $(i+\nu)\,e^{-i(s+D)}e^{-\nu D}F\,\Delta t$ while the social cost of the emissions increases by $P_0E\,\Delta t$. At the optimal D we should have $P_0E=(i+\nu)e^{-i(s+D)}e^{-\nu D}F$ which is equivalent to Eq.8. The marginal CBA for the follower plant takes into account the impact of the spillover and is independent of the number of follower plants. To put it differently, the relative launch dates of the follower plants do not change as the number of plants in the sector increases.

Proposition 1 also provides a relevant way to decentralize the CBA at the plant level, either for the pilot or any of the follower plants. We may interpret this decentralization as the dynamic abatement costs induced by the optimal trajectory. With some manipulations, we get the following corollary.

Corollary *The dynamic abatement costs for the pilot and the follower plants induced by the optimal trajectory are respectively:*

$$P_0 e^{is} = (i+\nu)iF/E(i+N\nu) \qquad \text{(Eq.11)}$$

$$P_0 e^{i(s+D)} = (i+\nu)F[i/(i+N\nu)]^{\nu/(i+\nu)}/E \qquad \text{(Eq.12)}$$

Let *(s*, D*)* stand for the optimal trajectory, we have the following result.

Proposition 2 *The total discounted social cost for the optimal trajectory* $\Gamma(s^*,D^*)$ *is a decreasing function of the spillover rate* ν *while the discounted cash cost* $\Gamma_c(s^*,D^*)$ *is independent of* ν*, it writes:*

$$\Gamma_c(s^*,D^*) = NFe^{-is_0} \qquad \text{(Eq.13)}$$

Proof:

Let us take the derivative of $\Gamma(s^*,D^*)$ *with respect to* ν *and using the envelope theorem, we get:*

$$d\Gamma(s^*,D^*)/d = \delta\Gamma(s^*,D^*)/\delta\nu = -D^*Fe^{-is^*}(N-1)e^{-(\nu+i)D^*}$$

which is negative.

Using (5) gives the expression of $\Gamma_c(s^*,D^*)$*.*

As the spillover rate increases, $\Gamma_c(s^*,D^*)$ remains constant, it is the discounted incremental cash cost of the transition for a plant in the standard CBA multiplied by the number of plants. Since $\Gamma(s^*,D^*)$ decreases, $\Gamma_c(s^*,D^*)$ must decrease as well i.e., the total emissions decrease which is not apparent: the launch time for the pilot decreases, but, as will be seen in the numerical example below, nothing can be said about the optimal delay.

We consider a situation in which firms, each operating one plant in an independent inelastic market, should make the decisions. Suppose that there is perfect appropriability of the spillover; the question is how to decentralize the social optimum as a market solution in which firms follow a private independent cost-benefit analysis. If the emission externality is internalized through a carbon tax (Pigou taxation), it remains to correct for the impact of the spillover for the choice of implementing the clean technology by the pilot plant.

Proposition 3 *Assuming an independent inelastic market, perfect appropriation of the spillover by the following plants, and Pigou taxation of the carbon externality, the optimal trajectory can be decentralized by a private CBA through a subsidy* ΔF *for the pilot plant such as:*

$$\Delta F/F = (N-1)\nu/(i+N\nu) \qquad \text{(Eq.14)}$$

And no subsidy is required for the follower plants.

Proof: This is a direct consequence of Proposition 1.

Fig. 2 shows a numerical illustration of the results. In this illustration, the following assumptions are taken; i=3%, $P_0 = 1$, E=1, and F=100, which gives s_0=37. In Fig.2 (left), we depict the abatement costs of the pilot and followers divided by the standard abatement cost, that is, when $\nu = 0$. We see that (i) for small values of the spillover rate, the follower plant is launched later compared to the launch date without spillover but earlier for more significant spillover rates; (ii) the dynamic abatement cost of the pilot decreases as a function of ν. Fig.2 (right) depicts the impact of the number of follower plants on the optimal launch date of the pilot as a function of ν. We see that (i) the launch date of the pilot decreases as a function of ν; (ii) as the number of follower plants in the sector increases, the optimal pilot launch date occurs earlier.

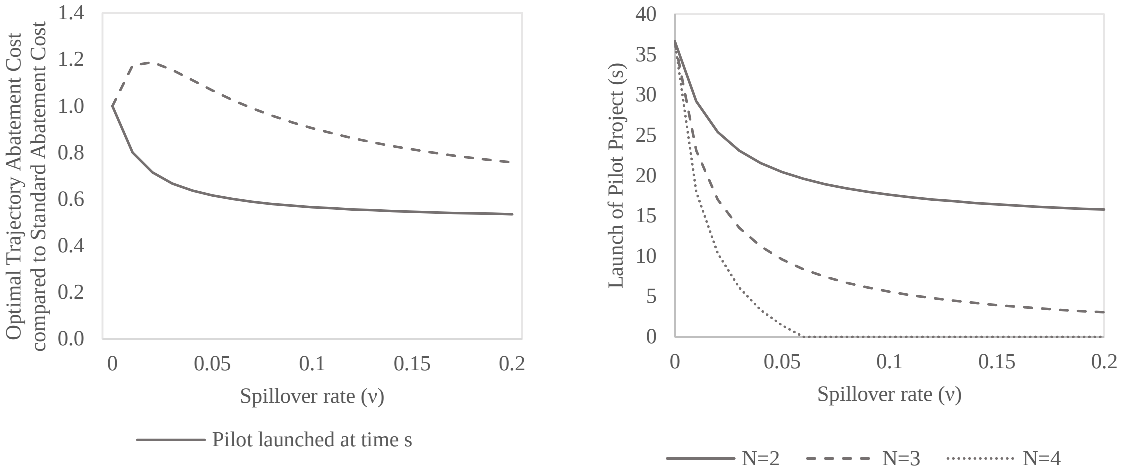

Fig. 2. Numerical Illustration. (Left): The abatement costs induced from the optimal trajectory as a function of the spillover rate; (Right): The optimal launch date for the pilot plant as a function of the number of plants and the spillover rate

4. Calibration of the Model

We calibrate our model for decarbonizing large-scale, high-quality container glass production, targeting plants with a daily capacity exceeding 150 tons of glass. This sector encompasses 27 plants in France, contributing to an annual glass production of approximately 2.9 million tons. Currently, these plants deploy natural gas combustion in their furnaces. Within the VERCANE project, two plants have been strategically chosen as demonstrators for deploying the decarbonized hybrid furnace technology (one reconstructed in 2016 with a capacity of 155 tons of Glass per day, another one reconstructed in 2021 with a capacity of 307 tons of Glass per day). Furnaces' operational data from Glass Global 2020 (depicted in Fig. 3) includes production capacity and the latest reconstruction date of each melting furnace. We assume that the demand for container glass is inelastic, remaining stable over the years. Furthermore, we consider energy consumption, emissions, and costs directly proportional to each plant's production capacity (detailed in sections 4.1 and 4.2).

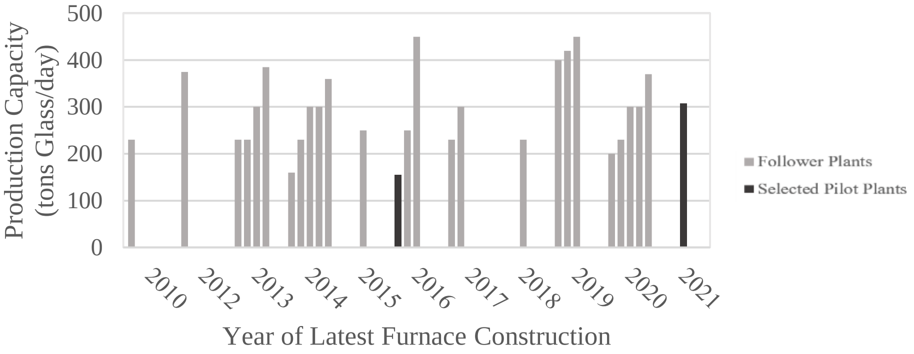

Fig. 3. Production capacity of latest reconstructed plants and the selected pilot plants in the sector (GlassGlobal, 2020)

Fig. 4 shows the schematic of the reference emitting furnace (left) to be replaced by a hybrid furnace (right) considered in this study. In the reference fossil fuel-based technology, the natural gas and oxygen are externally supplied to the oxy-fuel furnace for the combustion process, emitting CO_2, Sulfur Dioxide (SOx), Nitrogen Dioxide (NOx), and Carbon Monoxide (CO). Concerning the hybrid technology, we do not consider the on-site dedicated renewable electricity production due to the high energy consumption associated with the glass melting process and limitations in available surface area. However, the hybrid furnace necessitates a connection to high-voltage electricity from the grid, with Guarantees of Origin (GO) to ensure a renewable source of electricity. In the most developed hybrid furnace technology, 80% of supplied electricity will be consumed directly for electrical heating, while the remaining 20% will be used to operate an on-site electrolyzer to produce low-carbon hydrogen and oxygen co-products. This furnace can only perform switches between those ratios very rarely. In order to minimize the footprint, a high-pressure storage solution will be used to store the large quantities of hydrogen required to compensate for the electrolyzer's stop.

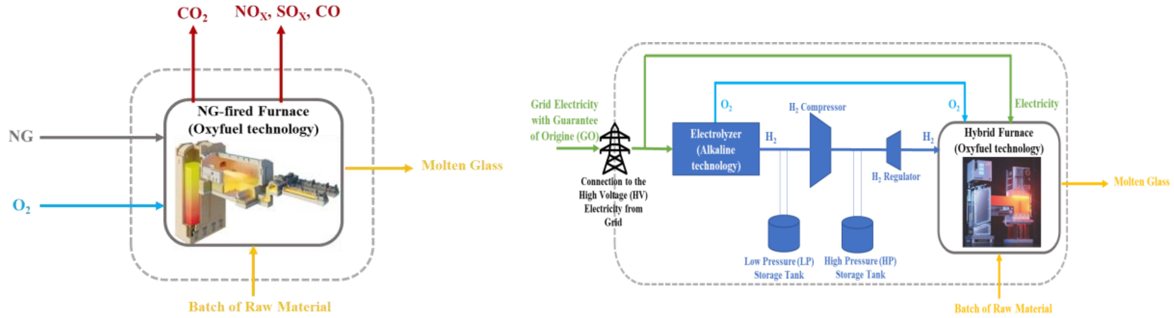

Fig. 4. The schematic of the reference fossil-based furnace (left) to be replaced by the decarbonized hybrid furnace (right)

4.1. Business-As-Usual (BAU) Pathway: NG-fired Furnaces

Table 1 outlines the technical assumptions regarding the current NG-fired furnaces, encompassing their technical lifetime, energy consumption, and emission intensity. The total discounted cost of NG-fired furnaces over their lifetime, presented in Table 2, is denoted in 2023 monetary values. The cost components include furnace equipment, installation, Operational and Maintenance (O&M) expenses, NG consumption, and emission and pollution costs. Notably, no inflation rate is taken into account. The social discount rate (SDR) adopted for this analysis aligns with the prevailing rate in France set at 3.2% instead of a previously used rate of 4.5% recently recommended by France Stratégie, the government policy analysis body in France (Ni and Maurice, 2021).

To monetize the social value of the abatement of air pollution (NOx, SOx, and CO) from the combustion of natural gas, we use the central values suggested by the Environmental Prices Handbook (Bruyn et al., 2018). As per the handbook's suggestion, we have considered a constant value for air pollutants over the years.

Table 1. Technical assumptions for the NG-fired furnaces

Parameter	Value	Unit	Source
Lifetime of Furnace	15	Years	Experts Interview
NG Consumption of the Furnace	1.15	MWh/tGlass	(Scalet et al., 2013)
CO_2 Emission Factor	0.181	tCO_2/MWh of NG	(Simmons, 2020)
NOx Emission Factor	0.003	kg/tGlass	(Scalet et al., 2013)
SOx Emission Factor	1	kg/tGlass	
CO Emission Factor	0.5	kg/tGlass	

Table 2. Breakdown of the discounted cost component over the finite lifetime of the NG-fired Furnaces

Cost Component	Discounted Cost Over the Lifetime	Unit	Assumption	Source
Furnace Equipment	210	€/tGlass	14 €/tGlass of Equipment Cost for the Large-Scale NG-fired Furnace	Authors’ Estimation
Furnace Installation	90	€/tGlass	40% of Equipment Cost	Experts Interview
Furnace O&M	105	€/tGlass	4% of Equipment Cost Per Year	
NG Consumption	810	€/tGlass	Average NG Price in France in 2022: 60 €/MWh	(Eurostat, 2022a)
NOx Emission	180	€/tGlass	14800 €/tNOx	Central Values from (Bruyn et al., 2018)
SOx Emission	75	€/tGlass	11500 €/tSOx	
CO Emission	0.015	€/tGlass	52.6 €/tCO	
Total	**1470**	**€/tGlass**	-	-

As indicated in Table 2, we assume that the maintenance costs remain constant over the initial 15 years of the furnaces' useful lifetime, as the asset operates under normal conditions, requiring routine maintenance and occasional repairs. In this period, a common rule of thumb for estimating maintenance costs based on the equipment cost is to allocate approximately 4% of the initial equipment cost for annual maintenance expenses. However, at the end of its useful lifetime, the furnace transitions into the wear-out phase with a significant increase in maintenance costs as the asset ages, leading to higher failure rates, frequent breakdowns, and the need for extensive repairs or component replacements. We assume that as the furnaces' lifetime is extended more than 15 years, the maintenance costs will increase linearly as a percentage of the equipment cost. This implies that the longer the asset remains in service beyond its initial lifespan, the higher the proportion of the equipment cost that needs to be allocated to maintenance expenses. We assume this value will gradually increase to 25% of the equipment cost until the maximum extended lifespan of 30 years. This assumption introduces a criterion for the industrial decision-maker, offering the choice between extending the operational life of their assets or reinvesting in emitting assets when the optimal decarbonization date has not yet been achieved.

Regarding the cost of the CO_2 emissions, adhering to the Hotelling assumption, we apply a Social Cost of CO_2 Emission (SCC) value of €195/tCO_2 in 2023. This aligns with the projected value of €250/tCO_2 in 2030, as established in economic models referenced in the study of (Quinet, 2019), with growth accounted for at the Social Discount Rate (SDR) of 3.2%. Notably, in Quinet's study, the SCC is derived considering political constraints, commencing at a low level.

4.2. Decarbonization Pathway: Hybrid Technology (80%Electricity+20%Hydrogen)

Table 3 details the technical assumptions related to decarbonized hybrid furnaces. Drawing insights from interviews with VERCANE project experts, we assume a similar lifetime for hybrid furnaces as NG-fired furnaces (15 years). Notably, the energy efficiency of hybrid furnaces for heating is higher than NG-fired furnaces. Alkaline is the chosen electrolyzer type for stable hydrogen production, complemented by high-pressure hydrogen storage for 12 hours per day.

We categorize the cost components for the hybrid technology based on their learning impact. In Table 4, no learning impact is considered for cost components with already developed technological bricks, including the cost of connecting to the High Voltage (HV) grid and the electricity consumption. Long-term total discounted costs remain consistent with short-term discounted costs. Table 5 shows the technological bricks spanning various industrial markets, including the equipment costs of the electrolyzer, high-pressure storage tanks, and hydrogen compressors, which are considered to be influenced by exogenous technological change. Long-term values are forecasted by extensive models referenced in the table. Table 6 reflects the cost components associated with disruptive technologies exclusively deployed within the sector: the cost of the hybrid furnace and its installation and O&M costs.

In this category, learning-by-doing is expected to decrease costs as deployment levels increase in the sector. Long-term values are derived from interviews with experts and the Authors' estimations. We assume that in the long-term, the cost of hybrid furnace technology will decrease to achieve the cost of the current NG-fired furnace.

Table 3. Technical assumptions for hybrid furnaces

Parameter	Value	Unit	Source
Lifetime of Furnace	15	Years	Experts Interview
Energy Efficiency of Hybrid Compared to NG-fired Furnace	1.3	-	
Electrolyzer Type	Alkaline	-	
Electrolyzer Efficiency	63%	-	
Electrolyzer Lifetime	15	Years	
Electrolyzer Stack Lifetime	8	Years	
Hydrogen Storage Pressure	350	bar	
Hydrogen Storage Time	12	Hours/day	
Electricity Consumption to Compress Hydrogen	3	KWh/kg H_2	(U.S. Department of Energy, 2020)

Table 4. Breakdown of the discounted cost component of hybrid furnace not exposed to learning impact

Cost Component	Discounted Cost	Unit	Assumption	Source
HV Equipment	45	€/tGlass	35€/MWh of Furnace Consumption	Experts Interview + Authors' Estimation
HV Installation	15	€/tGlass	40% of Equipment Cost	
HV O&M	15	€/tGlass	4% of Equipment Cost Per Year	
Electricity	1560	€/tGlass	Average Electricity Price in France 2022: 120 €/MWh	(Eurostat, 2022b)
Total	**1635**	**€/tGlass**	-	-

Table 5. Breakdown of the discounted cost component of hybrid furnace exposed to exogenous technical change

Cost Component	Short-term Total Discounted Cost	Long-term Total Discounted Cost	Unit	Short-term Assumption	Long-term Assumption	Source
Electrolyzer Equipment	81	12	€/tGlass	1505€/KW of Electrolyzer in 2021	230€/KW of Electrolyzer in 2050	IEA NZE (IEA, 2022b)
Electrolyzer Stack Replacement	40.5	6	€/tGlass	50% of Electrolyzer Equipment Cost	Follow the cost reduction ratio of electrolyzer	Experts Interview+ Authors' Estimation
H2 Storage Tank Equipment	4.5	3	€/tGlass	500 €/kg H2 in 2023	500 €/kg H2 in 2050	(U.S. Department of Energy, 2020)
H2 Compressor Equipment	18	9	€/tGlass	7000 €/KW in 2023	3500 €/KW in 2050	
Total	**150**	**30**	**€/tGlass**	-	-	-

Table 6. Breakdown of the discounted cost component of hybrid furnace exposed to endogenous learning

Cost Component	Short-term Total Discounted Cost	Long-term Total Discounted Cost	Unit	Short-term Assumption	Long-term Assumption	Source
Furnace Equipment	270	210	€/tGlass	18 €/tGlass in 2023	Achieve the cost of BAU	Authors' Estimation
Furnace Installation	105	90	€/tGlass	40% of Equipment Cost		Experts Interview + Authors' Estimation
Furnace O&M	120	105	€/tGlass	4% of Equipment Cost		
Electrolyzer Installation	90	15	€/tGlass	110% of Equipment Cost		
Electrolyzer O&M	37.5	6	€/tGlass	4% of Equipment Cost		
H2 Storage Tank Installation	1.5	1.5	€/tGlass	40% of Equipment Cost		
H2 Storage Tank O&M	1.5	0.45	€/tGlass	2% of Equipment Cost		
H2 Compressor Installation	25.5	10.5	€/tGlass	140% of Equipment Cost		
H2 Compressor O&M	9	3	€/tGlass	4% of Equipment Cost		
Total	**675**	**420**	**€/tGlass**	-		-

4.3. Incremental Discounted Cash Cost of Deployment of Decarbonized Technology

In Table 7, the total incremental cash cost of the decarbonized trajectory at the launch date of each plant is expressed as the sum of the following components:

- f_1: the difference between the discounted cost of electricity consumption and connection to the grid electricity for the decarbonized technology (as per Table 4) and the discounted cost of using the emitting technology, including the emitting furnace cost, NG consumption cost, and local environmental costs (as per Table 2). Overall, f_1 is the incremental cost component which is not exposed to learning impacts.
- f_2: discounted cash cost of using the decarbonized technology exposed to exogenous technical change (as per Table 5)
- f_3: discounted cash cost of using the decarbonized technology exposed to endogenous learning (as per Table 6)

Table 7. Total incremental discounted cost components of decarbonized technology

Cost Component	Short-term	Long-term
f_1	150 €/tGlass (24%)	255 €/tGlass (36%)
f_2	150 €/tGlass (14%)	30 €/tGlass (4%)
f_3	675 €/tGlass (62%)	420 €/tGlass (60%)
Total	**975 €/tGlass (100%)**	**705 €/tGlass (100%)**

In the short term, the incremental cash cost of the decarbonized technology amounts to approximately 975 €/tGlass over the 15-year lifespan of the furnace. When applying a social discount rate of 3.2%, the annuity factor becomes 11.77 ($(1-(1+i)$^-$T)/i$). Referring to Table 1, the CO_2 emission intensity of glass production is determined to be 0.208 tCO_2/tGlass (calculated as 0.181 tCO_2/MWh of 1.15 MWh/tGlass). This leads to an abatement cost of approximately 400 €/tCO2 (975 / 11.77 / 0.208 = 398 tCO_2/tGlass). This value of abatement cost aligns with a projected launch year of 2045 based on the trajectory of the social cost of carbon. However, this standard analysis does not consider the impacts of technical progress or spillover effects.

The total discounted cash costs over the infinitive lifetime of the furnaces are calculated according to the general framework of the study outlined in equations 3 to 5 of Section 3.1. These calculations necessitate consideration for the rates of technical change, endogenous learning, and spillover, determining the pace at which each cost component converges to its long-term value. Regarding the rate of exogenous technical change, we assume that the short-term cost in 2023 would achieve its projected long-term cost in 2050 with a linear reduction rate. Thus, this reduction rate, denoted as $\mu(t)$, is dependent on the calendar time, calculated as $\mu(t) = (2050 - t)/27$. On the other hand, the endogenous learning rate (λ) depends on the number of renewals rather than the calendar time. To calibrate the spillover rate (v), we establish a connection between the spillover and learning rates, where $e^{-vT} = 1 - \lambda$. This assumption implies that when the delay between the pilot and follower is equivalent to one project lifetime, the rate of cost reduction from spillover aligns with the reduction attributed to learning-by-doing. For example, with λ set at 25%, the corresponding value of v would be 1.9% per year.

5. Results

Incorporating exogenous technical change, whose impact varies based on the launch time of each plant, and considering adjustment costs unique to each plant depending on their age, we determine the optimal trajectory through iterative numerical simulation. The process involves evaluating a given trajectory (s, Dj), representing the launch dates of the pilot and the delay for the launch of follower plants.

Minimizing the total discounted cost, including cash and emission costs (Eq.1) gives the optimal trajectory. We compare the optimal trajectory with the one where the plants are considered independently, and CBA is made over their finite lifetime. In the latter case, technical change, learning-by-doing, spillover effects, and adjustment costs are absent. The results for the launch dates, CO_2 emissions, and the total discounted costs are reported in Table 8 and Table 9 when we assume a learning rate of λ=25%.

Table 8. Results of sector-level and plant-level CBA

Parameter	Sector-level CBA	Plant-level Standard CBA Over the Lifetime of the Plant
Launch of pilot	s=0 (year 2023)	s_0=22 (year 2045)
Abatement Cost of Pilot (€/tCO_2)	200	400
Launch of Followers	$16 \leq s+Dj \leq 22$ (years 2039-2045)	$s_0+Dj = 0$ (year 2045)
Total CO_2 Emissions before Ramping of Energy Transition (MtCO_2)	10	14

Table 9. Breakdown of the total discounted cost components of sector-level and plant-level CBA

Cost Component	Sector-level CBA	Plant-level Standard CBA Over the Lifetime of the Plant
NG Consumption Cost (M€)	2590	3325
Local Environmental Cost (NOx,Sox, CO) (M€)	772	990
Adjustment Cost (M€)	504	0
CO_2 Emission Cost (M€)	2019	2798
Decarbonized Technology Cash (M€)	9553	10089
Total Discounted Cost (M€)	**15438**	**17203**

In the optimal trajectory, the pilot is launched at s=0 (in the year 2023, which is the base year of the study), whereas in the standard CBA, all plants would be launched at s_0=22 (in the year 2045), assuming no adjustment cost. Recall that the social discount rate is 3.2% and that the social cost of carbon follows Hotelling's rule with P_{2030} = 250 €/tCO_2. It follows that the dynamic abatement cost induced by the optimal strategy for the pilot plant is 200 €/tCO_2, whereas it would be 400 €/tCO_2 if it were carried out at the individual plant level. The comparison of the total discounted social costs shows that the optimal trajectory reduces the cost by 10 %. In absolute terms, the 1764 M€ reduction comes from 779 M€ in discounted CO_2 emission costs and 985 M€ in discounted cash costs.

In the optimal trajectory, the launch dates for implementing the decarbonized technology in the follower plants are spread over 2039-2045, and there are some adjustment costs. Table 10 details the launch dates of each follower plant, the number of renewals before the implementation of the decarbonized technology, and the number of years of extra maintenance.

Table 10. Impact of Optimal Trajectory (λ=25%) on the Age of the Follower Plants

Plant j	**Latest Reconstruction Year**	**Number of Renewals**	**Years of Extra Maintenance**	**Year of Transition**
1	2010	2	4	2044
2	2012	2	3	2045
3	2013	1	17	2045
4	2013	1	17	2045
5	2013	1	17	2045
6	2013	1	17	2045
7	2014	1	16	2045
8	2014	1	16	2045
9	2014	1	16	2045
10	2014	1	16	2045
11	2014	1	16	2045
12	2015	0	9	2039
13	2016	0	9	2040
14	2016	0	9	2040
15	2017	0	8	2040
16	2017	0	8	2040
17	2018	0	8	2041
18	2019	0	7	2041
19	2019	0	7	2041
20	2019	0	7	2041
21	2020	0	6	2041
22	2020	0	6	2041
23	2020	0	6	2041
24	2020	0	6	2041
25	2020	0	6	2041

According to the individual plant-level CBA, we saw that the corresponding abatement cost is approximately 400 €/tCO_2 in contrast with the abatement cost of 200 €/tCO_2 resulting from our analysis. The subsidy for incentivizing the optimal launch of the pilots in 2023, under the conditions specified in Proposition 3 (cf. Section 3.2), represents 50% of the total discounted cash cost over their 15-year lifetime (the percentage x is obtained by solving $(1-x)\times 975/11.77 = 200\times 0.208$ (see Section 4.3), which gives $x = 50\%$).

Fig. 5 compares the optimal trajectory with a technical trajectory where the decarbonization of plants in the sector occurs right at the end of the technical lifetime of the furnaces, in the latest possible reconstruction before 2050, and there is no pilot phase to generate spillover in the sector. Fig.5 illustrates that in the technical trajectory (right Fig.5), the decarbonization of furnaces in the sector is postponed further, resulting in 14 Mt of CO_2 emissions from 2023 to 2050, which is 40% higher than the total emissions in optimal trajectory with 10 Mt of CO_2 emissions (left Fig.5). Furthermore, the total discounted cost of the technical trajectory, which does not benefit from spillover impact, is 16335 M€, approximately 6% higher than the cost of the optimal trajectory with the total discounted cost of 15438 M€.

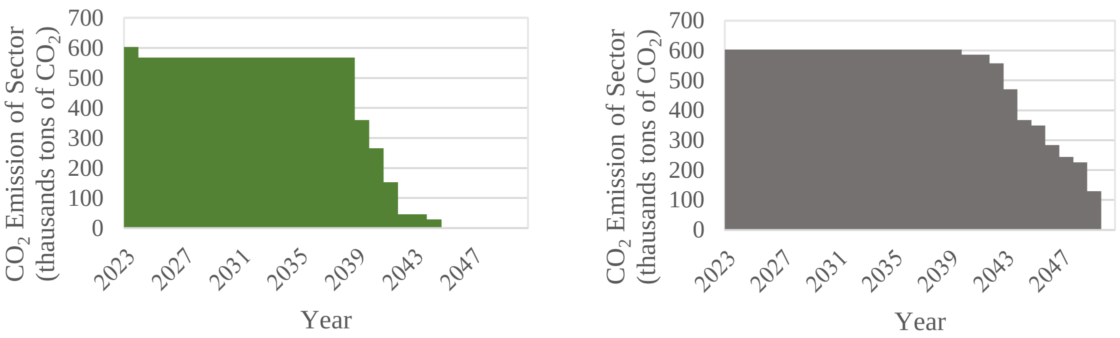

Fig. 5. Comparison of: (right) technical decarbonization trajectory with (left) optimal trajectory (λ=25%)

6. Sensitivity analysis

We do a sensitivity analysis of the optimal trajectory to the learning rate (*λ*)*,* the number of follower plants, and input energy prices (See Appendix B.2 for the sensitivity analysis to the maintenance costs of the extended assets). We show that the optimal launch date for the pilot converges quickly to 2023 as *λ* goes from 0 to 8%. Since our estimate is 25%, a much lower estimate would significantly affect the results. However, the optimal trajectory is quite robust to the number of follower plants, the input energy prices, and the maintenance costs.

6.1. Sensitivity Analysis to the Learning Rate and the Number of Followers

As the learning rate (introduced through the variable *λ*) increases, the third cost component (*F3*) decreases. As long as the spillover rate ν is connected to *λ* by the relation $e^{-\nu T}=1-\lambda,$ the third cost component of a follower will decrease as well, depending on the delay. In the base case, we assumed *λ*=25%. To analyze the impact of changing *λ* on the optimal strategy, we consider the range [0%, 100%].

Fig. 6 displays *s(λ)* and the average *D(λ)* over that range. As *λ* increases, the optimal launch date of the pilot *s(λ)* decreases from 18 years (2041) to zero (year 2023) as soon as *λ* is above 10%. The delay for the launch of the followers *D(λ)* jumps to 16 years as *λ* gets to 10 %, then decreases progressively to 7 years as *λ* approaches 100%. This sensitivity analysis provides interesting benchmarks to question the credibility of our calibration; the optimal strategy critically depends on *λ* over the range [0%, 25%]. Consequently, we pursue the sensitivity analysis on this restricted range.

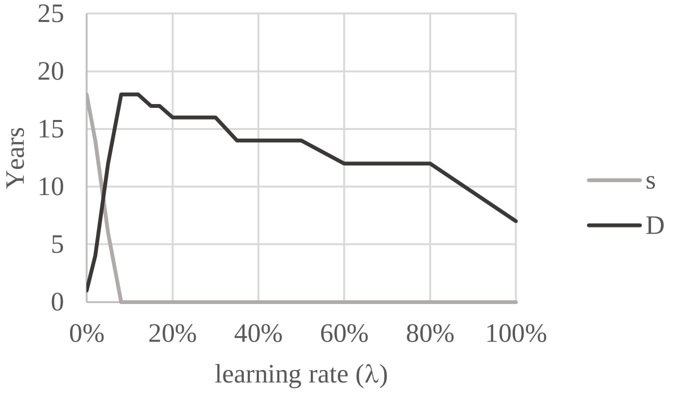

Fig. 6. Sensitivity of the optimal trajectory to the learning rate (λ)

Fig. 7 shows the total social discounted cost (including the emission costs) and the total emissions associated with the optimal trajectories as a function of *λ.* The total discounted cost decreases from 16530 M€ to 14750 M€ (7% reduction) over that range.

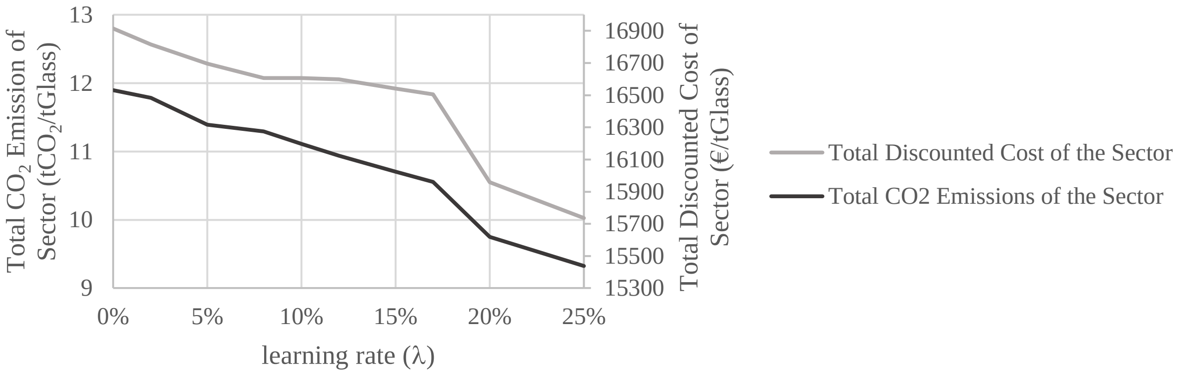

Fig. 7. Total cost and emissions of the optimal trajectories associated with each learning rate

Fig. 8 displays the optimal launch date of the pilots as a function of the number of plants that benefit from spillover (assuming λ = 25%). The follower plants are introduced sequentially according to the date of the latest reconstruction year (Table 10). It is seen that 13 plants are enough to advance the launch date to 2023.

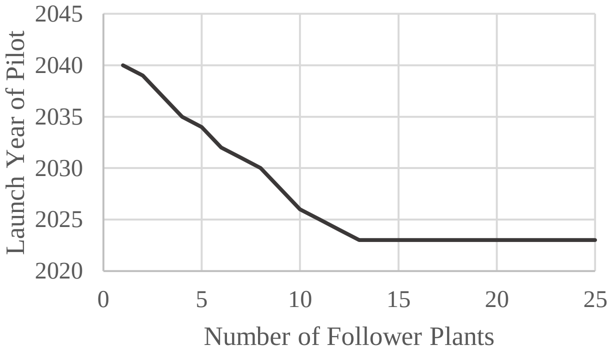

Fig. 8. Impact of the number of follower plants on the launch date of the pilot project (λ=25%)

6.2. Sensitivity Analysis to the Input Energy Prices

The input energy prices impact the total cost of the furnaces, either emitting or decarbonized technology. Regarding the evolution of the NG price, we assess three scenarios. In the 'Base Energy Cost (BEC)' scenario, we maintain the NG price at an average of 60 €/MWh in France (Eurostat, 2022). However, in the 'Low Energy Cost (LEC)' scenario, we assume the NG price is as low as 12€/MWh, a value projected for Europe in 2050 by the IEA Net Zero Emissions (NZE) scenario due to an estimated rapid decline in natural gas consumption (IEA, 2022). Conversely, in 'High Energy Cost (HEC)', we consider a rise in NG price to 120 €/MWh, a price observed during the European energy crisis in late 2021 when natural gas prices surged due to a combination of factors, including increased demand, low storage levels, and reduced supply from Russia. Regarding the evolution of electricity prices, given that natural gas accounts for 40% of the hours during the year as the marginal power producer setting the electricity market price in France (ADEME, 2018), we define three scenarios aligning with 'Base Energy Cost (BEC)', 'Low Energy Cost (LEC)', and 'High Energy Cost (HEC)'. We estimate the electricity prices in these scenarios at 120 €/MWh, 80 €/MWh, and 180 €/MWh, respectively. In Appendix B.1, we further detail the calculations of the input energy prices and provide the total discounted costs of input energy over a lifetime of NG and hybrid furnaces. In addition, we show the breakdown of the incremental cash cost over the lifetime of the decarbonized furnace (f_1, f_2, and f_3) in both short-term and long-term perspectives for the three input energy price scenarios in Appendix B.1.

We find that the impact on the total discounted incremental cost is more significant for the low energy cost scenario (LEC) than for the high energy cost scenario (HEC). In LEC, the incremental cash cost over the lifetime of a plant increases by 13% in the short term and 19% in the long term. This makes the substitution less attractive, which may postpone the launch date by 3 to 5 years for values of λ lower than 12 %. For higher values of λ, the launch date is not affected (see Fig. 9. Left). For HEC, the situation is the reverse. The incremental cash cost over the lifetime of a plant decreases by 1% in the short term and 2% in the long term. This reduction makes the substitution more attractive, which may advance the launch date. Fig. 9. Right shows that the change in the launch date of the pilot is about one year and that there is no change if λ is higher than 8%.

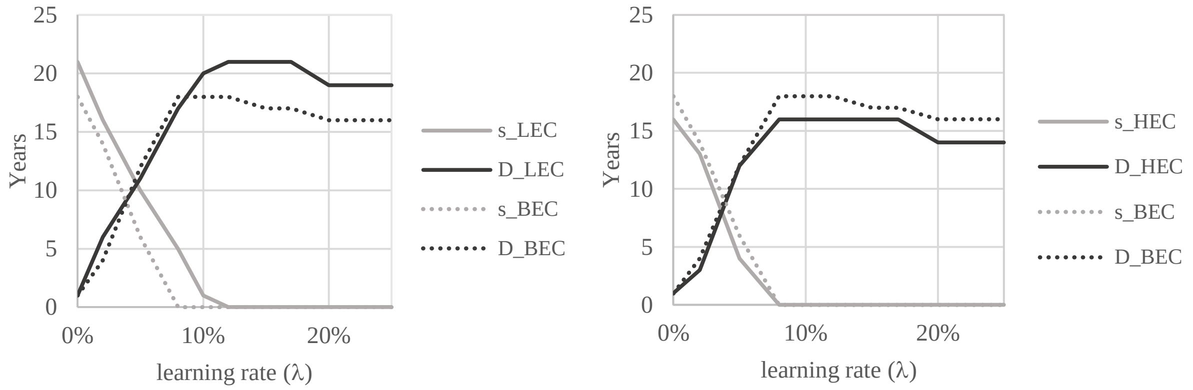

Fig. 9. Sensitivity of optimal trajectory to learning rate (λ) for (Left): Low Energy Cost (LEC) scenario, (Right): High Energy Cost (HEC) scenario

7. Discussion on the Results

The robustness of our result, as shown in the sensitivity analysis, strongly depends on two sets of assumptions. The first set concerns our formalizing technical change through exogenous progress and learning-by-doing. (Grafström and Poudineh, 2021) issued a word of caution regarding the application of commonly adopted learning curves. They highlight several concerns surrounding these curves, including the uncertainty in the impact of past cost reductions on future projections, difficulties in specifying the learning curve accurately, and the volatility of price ratios over time. These critics underscore the complexity of accurately projecting learning curves and highlight the need for careful consideration when employing them in our analyses. We identified the range for the learning rates that affects the optimal trajectory to guide further analysis.

The second set concerns the critical impact of some input prices, particularly the connection over time between the electricity and natural gas prices. While we primarily relied on the grey literature and professionals' interviews to calibrate technical change, the electricity and natural gas prices are at the center of many available studies to provide scenarios. Unfortunately, these scenarios display a large spectrum of ranges that depend on unpredictable geopolitical factors. We oversimplified our calibration through constant long-term future prices and showed that our result depends on the ratio between these prices. We considered these prices interdependent and modeled the dependency based on the expected cost structure of the production mix for electricity. Further research should be done to analyze how the evolving public policy for the energy transition in electricity production will affect the price ratio.

There is another source of uncertainty on top of the calibration of these two sets of assumptions; it concerns our formalization of the demonstration phase. We consider this phase as a deterministic process. It is preferable to allow for several uncertain milestones unrelated to the learning rate associated with future renewals. The spillover process could be directly aligned with the outcomes achieved at successive milestones.

These caveats suggest that our framework should be further enlarged to accommodate uncertainty and rely on options theory to evaluate the irreversible decisions associated with the launch of a demonstrator. It would be interesting to see if the significant difference between our result and the one obtained with traditional valuations prevails in such extensions. This paper identifies a significant first step in providing a relevant valuation of demonstrators depending on confirming this difference.

8. Policy Implications

We have shown that the decarbonization trajectory could be implemented through a subsidy for the firm operating the pilot plant, conditional on the transfer of knowledge through the industry, and that no further intervention would be needed to launch the follower plants at their optimal delays. This simple public policy is based on several assumptions that we review. There is a carbon tax that fully internalizes the CO_2 and environmental cost; firms make their valuation using the public rate of discounting, the demand facing each firm is inelastic, and there are no market interactions between the firms. Moreover, there are no transaction costs for the transfer of knowledge. On top of these assumptions, the public agency has complete information on the costs of the emitting and the clean technologies. Altogether, these assumptions are admittedly extreme.

Still, our analysis provides some recommendations for designing a public policy to facilitate the launch of demonstrators. The first recommendation is to elicit proposals in which the CBA encompasses the spillover to the sector. The firm's selection could be made through a competitive tender emphasizing this perspective. Several characteristics would be explicated in the proposals: a launch date, a subsidy, the potential benefits to followers, the transfer mechanism, and, most importantly, consistency with NZE at the sector level. In order to encourage the transfer of knowledge, the total subsidy to the selected firm could be spread along the sequence of launches. In this way, the pilot is incentivized to transfer the accumulated knowledge and have it adopted by the follower. It is not unrealistic to assume that a public agency has sufficient technical expertise to compare such proposals. Such an approach would significantly differ from most selection processes, which focus on horizons of 10 to 15 years. Recently, Carbon Contracts for Differences (CCfDs) have been promoted for decarbonizing the hard-to-abate sectors (see (IEA, 2023)). These contracts are similar to those used to promote the deployment of renewable electricity by giving a fixed guaranteed resale strike price independent of the electricity market price fluctuations. Such a mechanism indirectly encourages firms to make a CBA on that limited period. While the fluctuations of the EU-ETS CO_2 price could be a factor that discourages breakthrough innovation, this study suggests that public policy should significantly enlarge its scope of analysis.

Yet, another critical issue should be considered in designing relevant public policies in hard-to-abate sectors. These sectors are characterized by their oligopolistic structure. The barriers to entry come, among other things, from the capital intensity and the high level of fixed costs. Breakthrough technologies may increase fixed costs, inducing a higher market concentration. A better understanding of the strategic implications between environmental and competition policies would be worth studying. Further research on this topic would be welcome.

9. Conclusion

In this paper, we analyze strategies for the energy transition of an industrial sector requiring breakthrough technologies to achieve the NZE objective in 2050. The trajectory involves a phase in which the technology is implemented at a pilot plant, followed by a second phase in which knowledge is disseminated throughout the sector. Based on a relevant CBA, we identify the optimal sequence for launching the pilot and the follower plants. Our approach allows for the quantification of the long-term benefits of the pilot accruing to the industry.

The energy transition for the hollow glass industry in France is used as a case study to exemplify our approach. Previous studies on the demonstration phase remained inconclusive in triggering public support, suggesting the need to take a larger perspective. We calibrate our general framework and show that considering a learning rate of λ=25%, this larger perspective generates an abatement cost of 200 €/tCO_2 compared to a value higher than 400 €/tCO_2 in the previous studies. The optimal sequencing of the second phase would span over 2039 and 2045 to benefit from the spillover generated by the first phase. It considers the costs associated with early or late adoption of the new technology compared to the technical lifetimes of each plant. The sequencing is consistent with the NZE objective to achieve full decarbonization in 2050. The total discounted cost of the transition of the sector is reduced by 10% compared with a traditional approach in which the transition of each plant would be studied independently, while the total sector emissions are decreased by 40%. This shows beneficial effects of optimizing the transition on decreasing both costs and emissions. Under the conditions specified, subsidizing 50% of the total discounted cash cost of the pilot project over its 15-year lifespan is justifiable to incentivize its optimal launch in 2023.

Data availability

Data will be made available on request.

Acknowledgement: This work was supported by ENGIE SA, the Chair Energy Prosperity (hosted by the Risk Foundation of the Louis Bachelier Institute), and EPEE (Center for Economic Policy Studies of University of Evry). This paper benefited from comments of participants to the following conferences: International Conference of Innovation and Climate Change Governance, Paris, France, May 19-20, 2022; 43rd edition of the IAEE International Conference (IAEE 2022), Tokyo, Japan, July 31- August 4, 2022, and: International Conference on Sustainability, Environment, and Social Transition in Economics and Finance (SESTEF), Paris, France, December 2022. The authors also acknowledge receiving direct comments from Ludovic Ferrand (CRIGEN's Future Industry Lab, ENGEI Research and Innovation), Guy Meunier (INRAE, AgroParisTech, Paris-Saclay Applied Economics), and Juan-Pablo Montero (Instituto de Economía, Pontificia Universidad Católica de Chile).

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Appendices

Appendix A. Overview of Glass Industry

Appendix A.1. Emission Profile of the European Glass Industry

The ex-post investigation of the European glass industry found that during the initial and second trading periods (2005-2012), allocated free allowances exceeded sector emissions (Cludius et al., 2020). However, from the third period onward, allocations have fallen below verified emissions. This shift has incentivized mitigation activities, resulting in a downward trend in emissions (a 10% decrease in emissions in 2019 compared to 2005 levels), as shown in Fig. A. 1.

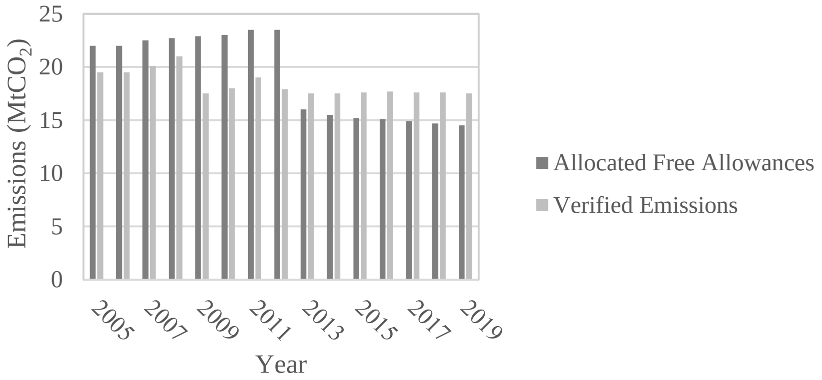

Fig. A. 1. Allocated free allowances and verified emissions of glass industry for the EU ETS 2005-2019 (Zier et al., 2021)

Appendix A.2. Production of Container Glass in France

Table A. 1 shows the distribution of glass production across various segments of the sector in France, with the container glass segment holding the largest share, accounting for approximately 75%.

Table A. 1. Segmentation of *French Glass Industry* (ADEME, 2021b)

Type	Total Annual Production (tons of Glass)	Share of the production volume	Average Annual Production per Plant (tons of Glass)
Container glass	4 170 125	74%	100 000
Flat glass	1 080 654	19%	180 000
Fiberglass	381 686	6%	55 000
Specialty glass	36 672	1%	6 000
Total	**5 669 137**	**100%**	-

Glass packaging preserves the quality of the containing product and cannot be easily substituted by other packaging materials such as paper, metal, and plastics. Moreover, glass containers are expected to enjoy a continuing advantage over plastic containers due to the increasingly stringent regulations against plastic usage. Altogether, the production volume of hollow glass has been maintained almost constant during the past ten years (see Fig. A. 2) and is expected to remain stable in the future according to an independent consumer research survey commissioned the European Container Glass Federation (FEVE) (FEVE, 2020).

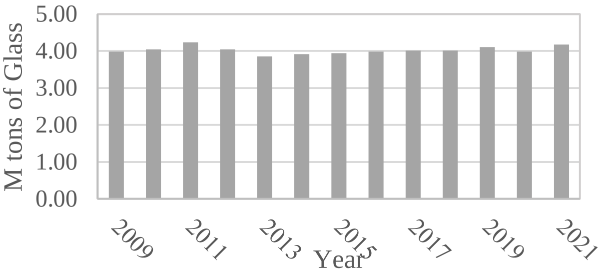

Fig. A. 2. Annual Container Glass Production in France from 2009 to 2021 (Capilla et al., 2022)

The production capacity for high-quality (clear and ultra-clear) container glass constitutes over 80% of France's hollow glass production capacity, totaling around 3.5 million tons of glass. As illustrated in Fig. A. 3, 49 operating furnaces in 2020 were constructed or reconstructed since 2010, with an average expected technical lifetime of 15 years (GlassGlobal, 2020). Fig. A. 4 depicts the market share of each container glass manufacturer firm, determined by their total furnace capacity.

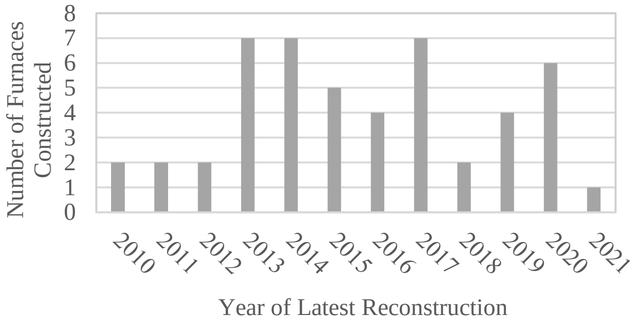

Fig. A. 3. Constructed High-Quality Container Glass Furnaces Per Year (49 Furnaces in Total) (GlassGlobal, 2020)

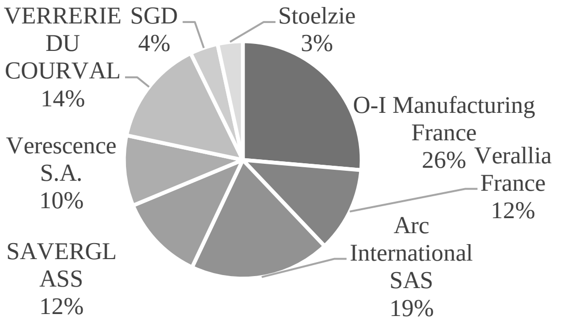

Fig. A. 4. Market Share of the High-Quality Container Glass Producers in France (based on total furnaces capacity) (GlassGlobal, 2020)

Appendix A.3. Overview of Demonstration Decarbonization Programs

In 2020, the European Container Glass Federation (FEVE) initiated the Furnaces for Future (F4F) project, a collaborative effort involving 19 leading container glass companies, constituting over 90% of European production (FEVE, 2021). The project aimed to deploy hybrid furnaces dedicated to container glass production, with Ardagh Group playing a key role in construction and project beneficiary designation at their German facility to capitalize on the scalability of the technology within the sector. Despite advancing to the second stage of the EU Innovation Fund call, the F4F project ultimately failed to secure the funding (FEVE, 2021), leading to independent national pursuits. In Germany, Ardagh Group independently pursued furnace construction under the NextGen project, securing support from German state aid provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Competence Centre on Climate Change Mitigation in Energy-Intensive Industries (KEI) (ArdaghGroup, 2022). Other German partners, including Stoelzle, Weigand-Glas, and Horn Glass Industries, also received BMWK German state aid for the ZeroCO$_2$Glas hybrid furnace project (Stoelzle Glass Group, 2022). In France, the two glass producers of the F4F project, SAVERGLASS and

VERESCENCE, established a separate French consortium for the "VERCANE-Carbon Neutral Glass Melting" project. This project was supported by ADEME in 2021 for the preliminary study of the transition solutions for the high-quality container glass sector (ADEME, 2022).

Appendix B. Assumptions and Details of the Sensitivity Analysis

Appendix B.1. Input Energy Prices

It is essential to carefully consider the electricity price in relation to natural gas prices. In European markets, natural gas prices often influence electricity prices because the gas turbines are usually the marginal power producers. A marginal power producer is the last production unit required to meet demand in the merit order system, which determines the wholesale market price (CRE, 2021). The marginality of a production unit can be very different from its share of annual electricity production. For instance, while the share of gas-based power production in the French electricity mix is less than 1% (compared to 70% nuclear), gas turbines were the marginal producer 40% of the time during 2019. A reference case of ADEME scenarios forecasts that the duration of marginality of gas technologies will remain dominant by 2050. Fig. B. 1 illustrates the marginality duration of different power producer technologies by 2050, as predicted in the reference case of ADEME (ADEME, 2018).

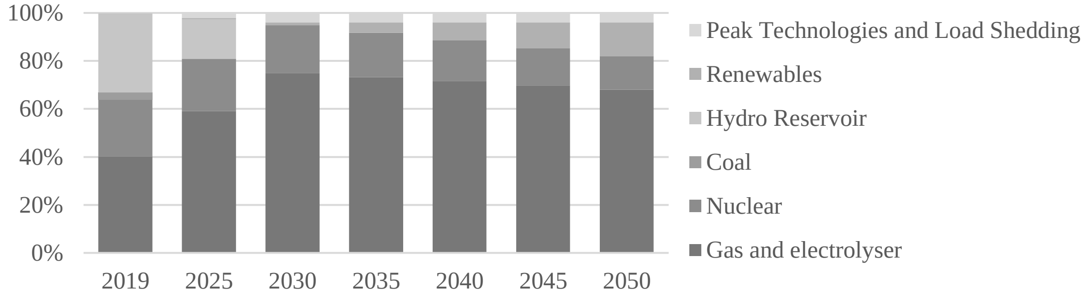

Fig. B. 1. The marginality duration in the French electricity market by 2050, ADEME reference scenario (ADEME 2018): The nuclear technology will be less present as the marginal sector technology while renewable technologies (including run-of-the-river hydro) will grow in terms of both production and marginality. The reduction in overcapacity leads in particular to more hours of marginality in peak thermal technologies. Furthermore, industrial load shedding will appear through which industrial electricity consumers accept to adjust temporarily their electricity consumption upon request against a financial compensation. ADEME assumes that reservoir hydraulic centers will eventually disappear from marginality figures particularly due to the drop in energy demand and lack of rainfalls. Coal sector will have zero marginality after 2025.

We suggest that the average electricity price in each year (*t*) could be calculated as:

$$P_E^t = \sum_s MD_s^t \times MC_s^t$$

Where *s* indicates the power producer technology, MD_s^t is the marginality duration of power producer *s* in year *t*, and $MC_S^t$is the marginal cost of power production through technology *s* at year *t*. The marginal cost of the gas power production technology at the year *t* (MC_{Gas}^t) is dependent on the gas market price (P_{Gas}^t), the thermal efficiency of Combined Cycle Gas Turbine (CCGT) plant (η_{CCGT}), the emission factor of the gas plant (η_{CCGT}), as well as the price of the CO$_2$ emission (P_{CO2}^t). It writes:

$$MC_{Gas}^t = \frac{1}{\eta_{CCGT}}\left(P_{Gas}^t + \beta_{CCGT} P_{CO2}^t\right)$$

The thermal efficiency (η_{CCGT}) and the emission factor of the CCGT plant (β_{CCGT}) are assumed to be constant at 60% and 0.429 tCO$_2$/MWh, respectively (RTE, 2023). Taking these assumptions, the electricity price associated with each case are presented in Table. B. 1.

Table. B. 1. Input Prices in Energy Cost Scenarios

Scenario	NG price	Electricity price
Low Energy Cost (LEC)	12 €/MWh	80 €/MWh
Base Energy Cost (BEC)	60 €/MWh	120 €/MWh
High Energy Cost (HEC)	120 €/MWh	180 €/MWh

Table. B. 2 details the discounted input energy costs over a lifetime of emitting and hybrid furnaces for the three scenarios. Meanwhile, Table. B. 3 provides a breakdown of the incremental cash cost over the lifetime of the decarbonized furnace (f_1, f_2, and f_3) in both short-term and long-term perspectives for the three input energy price scenarios. The table also presents the percentage share of each cost component in the total discounted incremental cost. Notably, f_1, which is not influenced by learning impacts and maintains consistency in the long term, is the sole cost component affected by input energy prices.

Table. B. 2. Discounted cost of the energy inputs for the NG-fired and hybrid furnaces

Parameter	Scenario	Discounted Cost	Unit	Assumption	Source
NG Consumption Cost of Emitting Furnace	BEC	810	€/tGlass	Case Base Average NG Price in France in 2022: 60 €/MWh	(Eurostat, 2022)
	LEC	165	€/tGlass	Low Input Price Case: 12 €/MWh	IEA NZE Scenario (IEA,2022)
	HEC	1620	€/tGlass	High Input Price Case: 120 €/MWh	Authors' estimation
Electricity Consumption Cost of Hybrid Furnace	BEC	1560	€/tGlass	Average Electricity Price in France 2022: 120 €/MWh	(Eurostat, 2022)
	LEC	1050	€/tGlass	Low Electricity Price: 80 €/MWh	(ADEME , 2018) + Authors' Estimation
	HEC	2355	€/tGlass	High Electricity Price: 180 €/MWh	

Table. B. 3. Breakdown of the cost components for the three energy input price scenarios

	Short-term			**Long-term**		
	LEC	**BEC**	**HEC**	**LEC**	**BEC**	**HEC**
f_1	285 €/tGlass (36%)	150 €/tGlass (15%)	135 €/tGlass (14%)	285 €/tGlass (39%)	150 €/tGlass (25%)	135 €/tGlass (23%)
f_2	150 €/tGlass (14%)	150 €/tGlass (15%)	150 €/tGlass (16%)	30 €/tGlass (4%)	30 €/tGlass (5%)	30 €/tGlass (5%)
f_3	675 €/tGlass (60%)	675 €/tGlass (70%)	675 €/tGlass (70%)	420 €/tGlass (57%)	420 €/tGlass (70%)	420 €/tGlass (72%)
Total	**1110 €/tGlass (100%)**	**975 €/tGlass (100%)**	**960 €/tGlass (100%)**	**735 €/tGlass (100%)**	**600 €/tGlass (100%)**	**585 €/tGlass (100%)**

Appendix B.2. Sensitivity Analysis to the Adjustment Costs

Table C.1 illustrates the impact of varying the maximum maintenance cost level after 30 years of the furnace's lifetime (refer to Section 4.2) on the optimal trajectory. The range considered spans from 4% (no additional cost) to 50% of the initial equipment cost, with a fixed learning rate of 25%. In this range, where the spillover impact is maintained at a high level, there is no effect on the optimal launch date for the pilot plants, ensuring their launch as soon as possible in 2023. However, minor adjustments are observed in the launch dates of the subsequent decarbonized follower plants. Comparing these outcomes to the initial assumption (maximum increase of 25% of equipment cost for maintenance), when the maintenance cost of emitting assets remains low (4% of the equipment cost), the industry prefers to prolong the use of their existing emitting technology as long as possible. This extension is constrained by the requirement to decarbonize before 2050. Conversely, if the maximum maintenance cost is relatively high (50% of the equipment cost), the industry shows a preference to reinvest in emitting technology rather than extending the lifespan of the current assets. Again, this preference results in a longer delay between the pilot and followers compared to the initial assumption of a maximum increase of 25% of the equipment cost for maintenance.

Table C. 1. Sensitivity of the optimal trajectory (λ=25%) to the maintenance cost of the extended emitting assets

Launch Data	4% Equipment Cost	25% Equipment Cost	50% Equipment Cost
Pilot	s=0 (year 2023)	s=0 (year 2023)	s=0 (year 2023)
Followers	$s+Dj$ =25 (year 2048)	16≤ $s+Dj$ ≤22 (years 2039-2045)	20≤ $s+Dj$ ≤25 (years 2043-2048)