Extending Cost-Benefit Analysis in Presence of Learning-By-Doing: Application to the Container Glass Industry in France

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May 2023

Abstract

Achieving carbon neutrality by 2050 for hard-to-abate industrial sectors necessitates the development of long-term strategies that involve investing in new low/zero-carbon technologies exposed to significant technological diffusion. While cost-benefit analysis is a widely accepted tool in economics, most empirical studies for industrial energy transition have overlooked dynamic externalities such as learning-by-doing and spillovers due to technological progress. In this study, we propose an extended cost-benefit analysis framework that integrates the economic impact of technological advances in terms of endogenous and exogenous learning and spillover effects within an industrial sector. The findings describe an optimal trajectory for carbon-neutrality of an industrial process within the container glass industry (for melting of glass in high temperature melting furnaces) in France that minimizes the overall social costs of the net-zero emission (NZE) transition by considering the sequencing of investment decisions for asset renewal and emphasizing the importance of the mechanisms of diffusion of technical progress in the industrial ecosystem.

Key words: Hard-to-abate Industrial Sectors, Carbon Neutrality, Net Zero Emission (NZE), Optimal Trajectory, Technology Diffusion, Learning-by-doing, Spillover, Glass Industry

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1. Introduction

To attain the Paris Agreement's goal of limiting global warming, the European Union's Green Deal aims to achieve climate neutrality by 2050, with a particular focus on the industrial sector. However, despite the urgent need to reduce emissions, the industrial sector has actually experienced faster emissions growth than any other sector over the past two decades, according to the Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2022). In 2019, this sector contributed to 24% (14 gigatons of carbon dioxide (CO2) equivalent (GtCO2-eq)) of the world's total greenhouse gas (GHG) emissions. If indirect emissions from electricity and heat production are taken into account, the share of GHG emissions from the industrial sector increases to 34%, as reported by IPCC. In France, the industry sector accounted for 70 MtCO2eq, or 24% of the country's national emissions in 2019 (IEA, 2021). France's National Low-Carbon Strategy (SNBC) aims to reach industrial carbon neutrality by 2050, which involves an 80% reduction of CO2 emissions compared to 2015 levels and a net decarbonization of the energy consumption of the industrial sector, as stated by the Ministry of Ecological Transition (Ministère de la transition écologique, 2020).

Currently, the decarbonization of so-called "hard to abate" industrial sectors is significantly falling short of the expected levels of emissions reduction, referred by IEA as "not on track" to achieve carbon-neutrality goals by 2050 (IEA, 2022). The term "hard to abate" is used to describe industries that rely on capital-intensive industrial processes emitting large amounts of GHG and air pollutants, and have large units with long life spans. The result is a high degree of rigidity in the entire production ecosystem (e.g. industrial processes, dedicated infrastructure for energy sources, and carbon capture and storage (CCS) systems). That means achieving carbon neutrality targets in those sectors require major technological breakthroughs through heavy investment. Despite the implementation of sectoral plans and fundings for pilot projects aimed at overcoming technological barriers, scaling up remains challenging, especially in the face of international competition. This challenge has become even more pressing due to the energy crisis and the increase in national reindustrialization plans. Furthermore, the risk of stranded assets in relatively new fossil fuel plants is a significant concern for investors, policymakers, and energy companies alike. With the increasing urgency to transition towards decarbonized industrial assets, previous investments in fossil fuel plants may become stranded if they become obsolete and uncompetitive in the rapidly changing energy market. This risk adds a layer of complexity to the issue of industrial decarbonization and requires careful consideration of energy policy and investment decisions. In addition, included in the European market for carbon quotas, companies in the sector have benefited from generous free allocations until recently, to limit carbon leakage that would have been caused by imports from countries with less stringent regulations. However, this protection has delayed industrial transformation, which is now encouraged under the New Green Deal as free allocations decrease over time. Nevertheless, carbon prices on the European Emission Trading System (EU-ETS) still do not reflect the true social cost of CO2 emissions. To achieve ambitious carbon neutrality goals, a comprehensive and systematic approach is needed to address not only technological barriers but also regulatory and policy-related barriers hindering scaling up. Addressing these barriers will accelerate the transition towards a sustainable and carbon-neutral future industry.

The transition path toward a carbon neutral industry requires a series of coordinated steps, and pilot (demonstration) projects are crucial initial steps in this regard. Pilot plants are test facilities that simulate real-world conditions to test and refine new technologies and processes. These pilot projects enable stakeholders to collect valuable data on the functionality of innovations, identify any weaknesses or limitations, and optimize designs for future large-scale deployment, a process commonly known as "learning-by-doing (LBD)". The knowledge gained from pilot projects can be shared across the industry to accelerate the diffusion of “learning spillovers”, leading to greater efficiency and cost savings across the sector. Investing in pilot projects is crucial for finding cost-effective solutions for achieving carbon neutrality in the long run, paving the way for a sustainable future. In fact, when evaluating decarbonization options, the key question should not necessarily be which short-term mitigation technology is the least expensive, but rather which actions taken today can minimize the total discounted cost of a “mitigation trajectory” both now and in the future. Vogt-Schilb et al.'s study argues that the conventional marginal-abatement-cost-curve (MACC) model, which proposes that emission mitigation efforts should be assigned to the least expensive abatement measure, fails to provide a clear indication of the optimal allocation of emission reductions across sectors and time periods; one must also take into account the future value of abatement capital when assessing abatement investment (Adrien Vogt-Schilb, 2018). This long-term focus is particularly important for pilot projects, , which can trigger innovation and spillovers that lead to significant dynamic effects. However, the low appropriability of the spillover impacts makes the private firms unwilling to fully fund their own demonstration projects. The study by Nemet et al. discusses the notion of the technology “valley of death” which refers to the underinvestment and premature deaths of otherwise promising innovations at the demonstration stage (Gregory F. Nemet V. Z., 2018). This valley of death is characterized by “high spillovers”, “large capital investment required”, “high technology risk”, and “uncertain demand”. The paper argues that the presence of knowledge spillovers necessitates public funding for demonstration projects that prioritize learning objectives. However, experiential learning, which involves knowledge creation by participants, implies that the private sector must also take an active role in developing new technologies and demonstration plants.

This paper contributes to design a Cost-Benefit Analysis (CBA) framework that incorporates the concept of learning-by-doing (LBD) and learning spillover to identify the first best trajectory for energy transition of the industrial sectors. Cost-benefit analysis is a widely accepted tool in economics to evaluate investment decisions. While there is a significant body of academic literature on conducting cost-benefit analysis, (Hanely, 1993) (Layard, 1994) (Sen, 2000) (European Commission, 2015), most studies have been conducted in a static environment that does not consider dynamic externalities like learning-by-doing and spillovers. On the other hand, the importance of the learning-by-doing has been recognized in the theoretical literature (Goulder, 1998) (Manne, 2005), (Thompson, 2010), (Popp et al., 2010), (Gillingham, 2018) (Stolper et al., 2022) and many empirical studies (IEA, 2000) (Hogan, 2014) (Gregory F. Nemet, 2020) but only a limited number of papers have formally integrated LBD into cost-benefit analysis. This paper aims to address this gap in the literature and provide a more comprehensive framework for evaluating the transition to a carbon-neutral industrial sector.

We propose a methodology based on the work of Meunier and Ponssard (Meunier, 2023), originally used to address decarbonization trajectories in the mobility sector (Ana Creti, , 2017). Our methodology builds upon these works to extend the analysis to the industrial sector. This methodology focuses on optimizing the total cost of the energy transition trajectory, which consists of three distinct phases: pre-transition, transition, and post-transition. In the pre-transition phase, only emitting technologies are available. The transition begins with the launch of a pilot project, followed by a delay period to allow for spillover cost reductions, and ultimately the decarbonization of other follower plants in the sector. During the transition phase, a combination of emitting and decarbonized technologies are employed. Once the sector's transition is complete, the investment in decarbonized technology is renewed indefinitely in the post-transition phase. The cost of the energy transition trajectory involves more than just the expenses associated with deploying and operating the technologies; it also considers the social cost of emissions. The social value of CO2 plays a crucial role in determining the most optimal launch date and delay. This value is mostly derived from integrated assessment modelling (IAM) that are not intertemporally optimized. However, with a "carbon budget" which is a finite resource stock (i.e. a given quantity of CO2 to be emitted by a specific time), our first-best trajectory assumes that the social cost of carbon should follow a Hotelling rule and increase in tandem with the social discount rate (Hotelling, 1931). Therefore, the social value of CO_2 is highly dependent on the choice of a social discount rate which is a crucial parameter that assigns a weight to future values of costs and benefits. By considering these factors, we can determine the optimal time to initiate the transition of the pilot project and the optimal delay to ensure that the total cost is minimized while achieving the desired outcome to be carbon-neutral before 2050.

This study also contributes to put forth an optimal energy transition trajectory for a segment within the container (or hollow) glass industry in France for packaging purposes. It represents an addition to the literature as it sheds light on the most socially effective trajectory to decarbonize an industrial process within the container glass industry. which is considered a "hard to abate" industry due to its energy and capital-intensive high-temperature melting furnaces (1200-1600°C). This industry is a critical component of the global supply chains for various major industries such as food and beverage, pharmaceutical, and cosmetic applications. France is the second-largest producer of glass in Europe and currently relies heavily on fossil fuels energy in melting furnaces. Therefore, developing a carbon-neutral trajectory for decarbonized furnaces is of strategic importance for France. To achieve this, the study applies the proposed cost-benefit analysis framework to data from all existing container glass furnaces in France, while also analyzing the spillover diffusion from a pilot project that is planned to practice decarbonized furnaces in this specific segment. We examine the sources of endogenous and exogenous learning in the context of the container glass industry. Endogenous sources of learning in this industry may include the development of new manufacturing techniques, improvements in the quality control process, or the accumulation of knowledge and experience gained from producing products over time. Companies within the industry may also learn from each other and share best practices (spillover impacts). Exogenous sources of learning for the container glass industry may include insights and innovations from related industries. Additionally, broader economic, social, or political factors could also impact the industry's learning and development, such as new environmental regulations or changes in consumer preferences and trends. The first best trajectory toward carbon neutrality is characterized in terms of the optimal launch time for the pilot plant and the optimal delay for the other following plants to maximize the benefits of spillovers. The aim of this paper is to develop a more robust cost-benefit analysis that can be utilized by state agencies, public authorities, energy suppliers, and industry stakeholders. The findings of this study provide policy recommendations to accelerate the industrial energy transition and prevent "carbon lock-in" considering the long-lived industrial assets.

The paper proceeds by detailing the methodology employed to enhance the cost-benefit analysis. Subsequently, we introduce hollow glass industry sector in France, and present the results of findings of implementing the methodology in this industry. Ultimately, we discuss the outcomes of the study and explore how public support mechanisms can effectively address the industrial energy transition while accounting for innovation and learning-by-doing.

2. Methodology

2.1. A two-plant sector cost benefit analysis with diffusion of technological progress

We consider a sector consisting of two identical emitting plants to be decarbonized. The question is how to sequence the decarbonization of the two plants. On the one hand, a delay in launch dates allow the second plant to benefit from the spillover coming from the first one; on the other hand, the delay increases emissions. The cost benefit framework introduced in Meunier and Ponssard (2023) will be used to solve this question.

Time is continuous going from $t=0$ to $t=+\infty$. Total emissions of the sector is E tons of CO_2 per unit of time. As the plants are identical, each fossil plant emits $E/2$. The social cost of carbon follows Hotelling's rule, $P(t)=P_0 e^{it}$, in which i stands for the social discount rate. For simplicity, operational costs of the fossil and the clean plants are assumed to be zero. Decarbonization is achieved through a capital investment f_0 the lifetime of is d. The two clean plants are launch in sequence, denote the first one the leader and the second one the follower. Let T denote the delay between the two plants. In the context of the NZE, the decarbonization must be permanent and the capital investment will be renewed accordingly for both plants.

Both learning-by-doing and spillover are introduced. At the n^{th} renewal of the leader, the capital investment cost decreases so that:

$$f_n= f_\infty+(f_0- f_\infty)\,\mu^{n} \qquad (1)$$

In which f_∞ stands for the long-term investment cost and $\mu<1$ a parameter standing for LBD. Denote F_1 the total discounted cost over an infinite horizon. It writes:

$$F_1 = f_\infty / (1 - e^{-id}) + (f_0- f_\infty) / (1 - \mu\, e^{-id}) \qquad (2)$$

We assume that a spillover rate $\nu<1$ induces a decrease in the capital investment cost for the follower which depends on the delay T, and can be written as $e^{-\nu T}$. Future renewals for the follower also benefit from the LBD rate μ so that the total discounted investment cost F_2 be written as

$$F_2 = e^{-\nu T}\,[f_\infty / (1 - e^{-id}) + (f_0- f_\infty) / (1 - \mu\, e^{-id})]= e^{-\nu T}F_1 \qquad (3)$$

The transition path will involve several stages:

- A pre-transition stage in which the two fossil plants are operating.
- A deployment stage with the duration of T starting with the launch of the pilot plant at time s, and in which both the pilot plant and one of the two fossil plants are operating.
- A fully decarbonized stage starting at time $s+T$ and in which both decarbonized plants are operating.

The total cost of the transition path can be written as:

$$\Gamma(s,T)= \int_0^{s} e^{-it}\, P(t)\, E\, dt + \int_s^{s+T} e^{-it}\, P(t)\, E/2\, dt + e^{-is} F_1 + e^{-i(s+T)}\, e^{-\nu T} F_1 \qquad (4)$$

The first two terms correspond to the emission costs, and they can be simplified since $P(t)=P_0e^{it}$, so that expression (4) may be simply written as:

$$\Gamma(s,T)= P_0\, E\, s+ P_0\, E\, T / 2 + e^{-is} F_1 + e^{-is}\, e^{-(i+\nu)T} F_1 \qquad (5)$$

The optimal transition trajectory is obtained through minimizing $\Gamma(s,T)$. The following proposition holds.

Proposition: *The optimal delay* T^* *and the optimal launch time* s^* *are given by:*

$$T^* = \frac{1}{(i+\nu)} Ln(\frac{i+2\nu}{i}) \qquad (6)$$

$$s^* = \frac{1}{i} Ln(\frac{2i(i+\nu)}{i+2\nu}\,\frac{F1}{P_0E}) \qquad (7)$$

Proof

Setting the first order derivatives with respect to s and T, we get:

$$\delta\Gamma(s,T)/\delta s= P_0\, E - i\, e^{-is}\, C_1\, (1 + e^{-(i+\nu)T}) = 0$$

$$\delta\Gamma(s,T)/ \delta T= P_0\, E/2 - e^{-is}\, (i + \nu)\, C_1\, e^{-(i+\nu)T} = 0$$

This system of equations may be rewritten as:

$$P_0\, E\, e^{is} = i\, F_1\, (1 + e^{-(i+\nu)T})$$

$$P_0\, E\, e^{is} = 2\, (i + \nu)F_1\, e^{-(i+\nu)T}$$

Solving for $e^{-(i+\nu)T}$ gives (6) and replacing $e^{-(i+\nu)T}$ by this value in the first equation gives (7).

As the second cross derivative is positive the corresponding values for s^* and T^* give a minimum:

$$\delta^2\Gamma(s,T)/\delta s\, \delta T = i(i + \nu)\, e^{-is}\, e^{-(i+\nu)T} F_1 >0$$

Observe that the social cost carbon at time at the optimal launch date s^* is such:

$$P(t) = P^0 e^{is} = \frac{2i(i+\nu)}{i+2\nu}\frac{F_1}{E} = \left[1+\frac{i}{i+2\nu}\right] i \frac{F_1}{E} \qquad (9)$$

As could be expected the optimal launch time is a decreasing function of the spillover rate ν. Nothing can be said about the dependence on ν of the optimal delay T^*. The next section presents a numerical illustration.

2.2. A numerical illustration

The values of the parameters are given in Table 1.

Table 1. Values of the parameters for the numerical illustration

Parameter	**Denotation**	**Value**	**Unit**
Total Emission of the Sector	E	0.02	MtCO$_2$
Initial Carbon Price	P_0	200	€/tCO$_2$
Social Discount Rate	i	3%	-
Current Investment Cost of Decarbonized Technology	c_0	100	M€
Minimum Projected Long-Term Investment Cost of Decarbonized Technology	c_∞	60	M€
Lifetime of the Decarbonized Technology	d	15	years

It is reasonable to anticipate a correlation between the spillover and the learning-by-doing rates. In this illustration, we assume that $e^{-\nu d/T} = \mu$.This means that if the delay (d) is equal to the lifetime of the pilot plant ($T=d$), then the cost reduction that the follower plant captures from spillover is equal to the cost reduction achieved through learning-by-doing after one investment cycle. With this calibration, $e^{-\nu d}$ decreases from 1 to μ, as T increases from 0 to d.

Using the proposition, we can draw the graph which depicts the values of s and T as a function of the learning rate μ (see Figure 1). The optimal launch time is decreasing with the learning rate: the more the investment cost decreases due to LBD, the earlier the optimal launch date (which is always true as can be seen in relation in (4), since ν is increasing as μ decreases). However, the delay is not a monotonous function of the LBD rate. The optimal launch determined by the LCC is also shown in Figure 1.

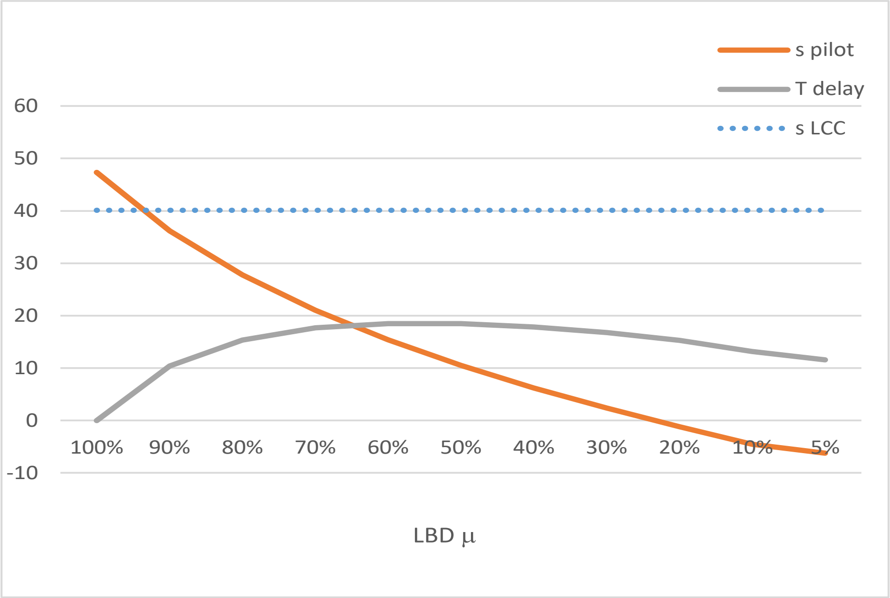

Figure 1. A numerical illustration of the optimal trajectory

The sources of learning in a specific industry or sector can be classified as either endogenous or exogenous. Endogenous sources of learning refer to the knowledge and expertise that is developed within the industry itself, including innovations, advancements, and accumulated best practices. Exogenous sources of learning, on the other hand, refer to knowledge and expertise that is developed outside of the industry, such as insights from academic research, other industries, or the broader economic, social, or political context. The following section will delve into the sources of endogenous and exogenous learning in the context of the hollow glass industry. This section provides a more detailed examination of the various factors and processes that contribute to learning and innovation within the industry. Examining the sources of learning in this industry provides us with insights into broader patterns of innovation and knowledge creation that could be relevant to other industries and contexts as well.

3. Application to the hollow glass sector

3.1 The sector

The glass manufacturing industry represents the difficulties encountered by "hard to abate" industrial sectors in transitioning to low-carbon operations due to energy-intensive high-temperature furnaces (1200-1600°C), capital-intensive production infrastructure, and a fiercely competitive market with limited margins on existing products, while also being a vital component of the global supply chains for several major industries. The European Union (EU) is the world's biggest producer of glass 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 own production, with about 80% of the glass produced being consumed within the EU. France is the second European producer of glass behind Germany with more than 80 furnaces spread over about 50 sites (Glass Alliance Europe (GAE), 2021). The majority of the energy consumed in the French glass sector is derived from fossil fuels, with 74% of the energy coming from natural gas and 4% from fuel oil in 2018, as shown in Figure 2. Electricity accounted for 22% of the energy mix in the same year. The sector consumed over 11 TWh of energy in 2018, which represents approximately 3% of thermal energy and 2% of electrical energy consumed by French industries. This level of energy consumption resulted in the emission of 2.7 MtCO2 in 2018, which accounts for roughly 4% of the total national greenhouse gas emissions (ADEME, 2021).

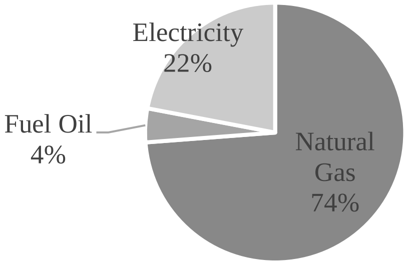

Figure 2. Energy consumption of the glass industry in France in 2018 (Capilla, 2021)

The development of a carbon neutrality trajectory for the glass sector is of particular strategic interest. The emissions from the glass sector in France is subject to the European Industrial Emissions Directive, which applies to glass manufacturing facilities with a melting capacity exceeding 20 tons per day, and the Best Available Techniques reference document BREF adopted by the European Commission in December 2001 (European Commission, 2021). Despite the fact that the majority of glass trade within Europe is destined for domestic consumption, manufacturing of all types of glass products has been placed on the EU ETS Carbon Leakage[4] List (CLL) and considered at significant risk of carbon leakage for fourth trading period of EU ETS (2021-2030) (European Commission, 2019). This policy will continue in phase 4 of EU ETS (2021-2030), but based on more stringent criteria and improved data. The CE Delft's ex-post investigation found that allocated free allowances for the glass industry exceeded emissions in the first and second trading periods (2005-2012), but allocation has been below verified emissions since the third period, providing incentives for mitigation activities (Bruyn et al, 2015). CE Delft's research suggests that free allocation may not be suitable for future European climate policies, as carbon border adjustment mechanisms could be used to ensure the price of imports reflects their carbon content, accelerating the phasing out of free allocation in the end of current EU ETS phase. Elimination of free allocations of emissions is an incentive accelerating the energy transition and technological change in the glass sector. ADEME has published its initial Sector Transition Plan "Glass STP", a 360° technical, economic and social vision of the sector's challenges (ADEME, 2021). Hence, formulating a trajectory for achieving carbon neutrality within the sector holds significant strategic importance.

The focus of this study is on the hollow glass segment, which is one of the sub-sectors of the glass industry. The glass industry is highly diversified with various applications, leading to specialization among players in different market segments. The requirements and fields of activity of glassmakers vary greatly depending on the final product. Glass products are generally classified into five major categories: hollow/container glass, flat glass, fiberglass, specialty, and domestic glass. The container glass sub-sector plays a crucial role in critical industries such as food and beverage, medical, pharmaceuticals, and perfume supply chains. This sub-sector accounts for the largest share of volume production in Europe, with a percentage of 61.7% (as per Figure 3), and in France, it holds a share of 74% (as per Table 2). The production volume of hollow glass industry has been maintained almost constant during the past 10 years (Figure 4). An independent consumer research survey commissioned the European Container

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[4] Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints (European Commission, 2022). To safeguard the competitiveness of industries covered by the EU ETS, sectors and sub-sectors exposed to a significant risk of carbon leakage are given a higher share of free emission allowances compared to other industrial installations

Glass Federation (FEVE) carried out among more than 10000 consumers across 13 European countries in 2020, revealed that 75% of people view glass as the best packaging material due to the high recyclability of glass, along with a growing consumer awareness of its environmental credentials (European Container Glass Federation (FEVE) , 2020). At the same time, 46% of Europeans state that they have significantly decreased their consumption of plastic packaging to prevent littering in the environment. As Figure 5 shows the decrease in the European production volume of plastics in the recent years, glass container market will remain favorably influenced from the stringent regulations against plastic usage. Furthermore, glass packaging preserves the quality of the containing product and cannot be easily substituted by other packaging materials such as paper, metal, and plastics.

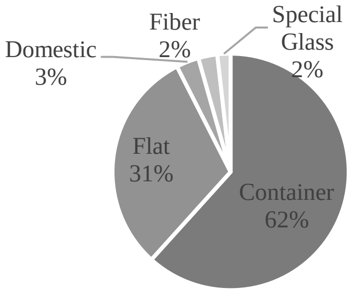

Figure 3. Share of different glass sub-sectors in the EU (Glass Alliance Europe (GAE), 2022)

Table 2. Classification of French Glass Industry (ADEME, 2021)

Type	Number of Plants	Total Production (t/y)	Share of the Production Volume	Average Production per Plant (t/y)
Container glass	33	3 298 537	74%	~ 100 000
Flat glass	6	1 080 654	17%	~ 180 000
Fiberglass	7	381 686	8%	~ 55 000
Specialty glass	6	36 672	1%	~ 6 000
TOTAL	**52**	**4 797 549**	**100%**	-

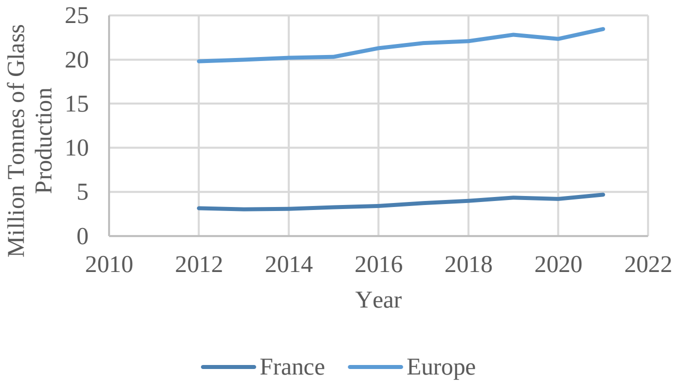

Figure 4. Container Glass Production in France and Europe (European Container Glass Federation (FEVE), 2022)

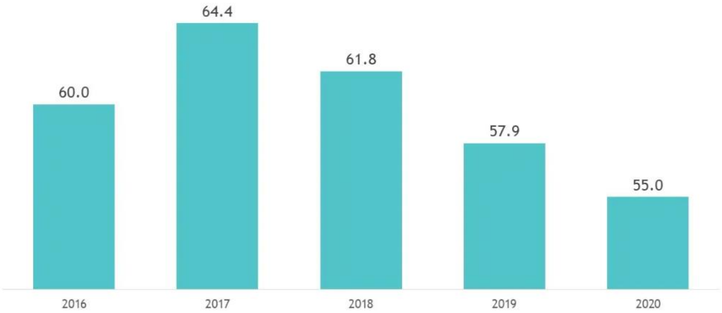

Figure 5. Decrease in Production Volume of Plastics in the EU (European Container Glass Federation (FEVE), 2022)

The paper segments the hollow glass sub-sector based on the coloring of the end-use product. Specifically, in the hollow glass industry, different colorings of glass could be obtained depending on the residual impurities in the molten glass. The so-called flint (or clear) and super-flint (or ultra-clear) container glass require a special sand with very low iron oxide levels and are characterized by their transparency, brilliance and luster. These types of container glass have limitation in use of recycled glass (called “cullet”) resulting into more energy required to melt and react the batch materials and increasing the emissions. In France, a significant number of the container glass production sites (about 73%) are dedicated to clear and ultra-clear glass (Figure 6). Figure 7 depicts the number of constructed furnaces in France in this specific segment of hollow glass industry. According to the Glass Global Database, in 2020, there have been 49 clear and ultra-clear hollow glass furnaces constructed in France. The database reveals that the furnaces in this industry have an average technical lifetime of 15 years. This means that there are only two furnace lifetimes left before the 2050 carbon-neutrality target must be met. As such, it is imperative to consider this limited timeframe when planning and implementing decarbonization strategies in the industry. While early decarbonization may result in stranded assets, extending the lifetime of the assets can lead to additional maintenance costs. Striking a balance between decarbonization and asset management is critical to ensure the sustainability and profitability of the hollow glass industry.

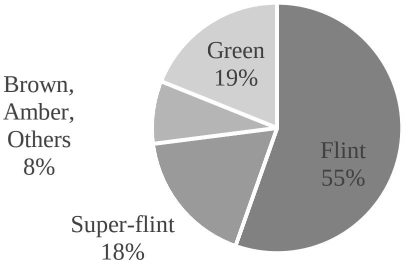

Figure 6. Different Colorings of Container Glass in France (Database from Glass Global for the year 2020)

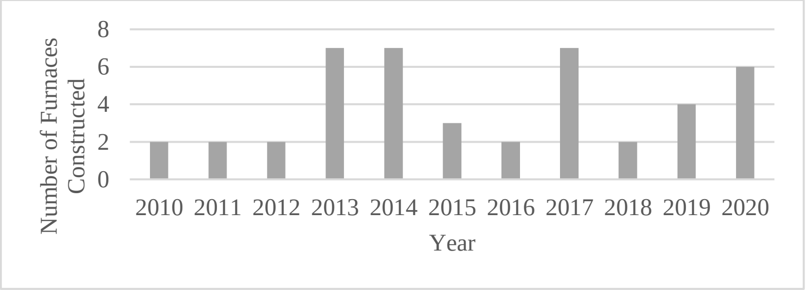

Figure 7. Constructed Clear and Ultra Clear Container Glass Furnaces Per Year (49 Furnaces in Total) (Database from Glass Global for the year 2020)

3.2 The pilot project

This paper assesses a pilot project that aims to decarbonize the energy consumption of a natural-gas fired furnace in the clear and ultra-clear hollow glass sector in France. The outputs of this pilot project could be ultimately applied to the furnaces throughout the sector. As such, it is essential that the demonstrator furnaces selected for this project are representative of the sector's characteristics. The industrial sites for a R&D pilot project have been selected by ENGIE Future Industry Lab in partnership with hollow glass manufacturers, based on the evaluation of macro criteria such as the diversity of furnaces' technology, environmental constraints, land potential of the industrial sites, etc. According to this evaluation, decarbonization of five existing furnaces (out of 49 existing furnaces in France) for the production of clear and ultra-clear hollow glass has been selected and the data has been collected from the manufacturers. Table 3 demonstrates the values of glass production, energy consumption, emissions, and the launch date of these selected furnaces. It is demonstrated that the panel of the chosen furnaces cover a wide range of configurations, and the current performances of these furnaces are consistent with the state of the art that is measured on a large scope of furnaces in the world.

Table 3. The technical information of the reference fossil-based furnace

	Furnace 1	**Furnace 2**	**Furnace 3**	**Furnace 4**	**Furnace 5**
Glass Production (tGlass/day)	55	110	150	175	330
Year of Last Reconstruction	2015	2015	2016	2016	2021
Annual NG consumption of the Furnace (GWh/year)	42	50	42	65	129
Annual CO2 Emission (tCO2/year)	7597	9117	7597	11776	23313
Annual NOx Emission from Combustion (tNOx/year)	27	33	27	42	84
Annual SOx Emission from Combustion (tSOx/year)	11	13	11	17	34
Annual CO Emission from Combustion (tCO/year)	0.04	0.04	0.04	0.06	0.1

Scope 1 and 2 GHG emissions[5] are primarily related to the energy input into the furnace. Scope 1 emissions arise from the combustion of fossil fuels, while scope 2 emissions come from the use of electricity. The melting furnaces, which operate at temperatures between 1200-1500°C, are the largest energy consumers in the glass industry. These furnaces use combustion-heating of fuels, direct electrical heating, or a combination of the two to melt the glass. As shown in Figure 8, melting furnaces in France have accounted for approximately 75% of the total CO2 emissions in the hollow glass industry (ADEME, 2021). There is also the so-called process GHG emissions, through the decarbonation of lime and sodium carbonate present in the batch composition. The furnace also generates process GHG emissions through the decarbonation of lime and sodium carbonate present in the batch composition, which account for about 20% of the total emissions. However, due to the low-carbon electricity mix in France, the indirect emissions from power consumption (scope 2 emissions) constitute only a small share (5%) of the total emissions. Considering the high volumes of energy consumption, the glass melting process in furnaces is the most important lever in the decarbonization of the hollow glass sector.

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[5] Scope 1 emissions are direct greenhouse emissions that occur from sources that are controlled or owned by an organization (e.g., emissions associated with fuel combustion in boilers, furnaces, vehicles). Scope 2 emissions are indirect GHG emissions associated with the purchase of electricity, steam, heat, or cooling.

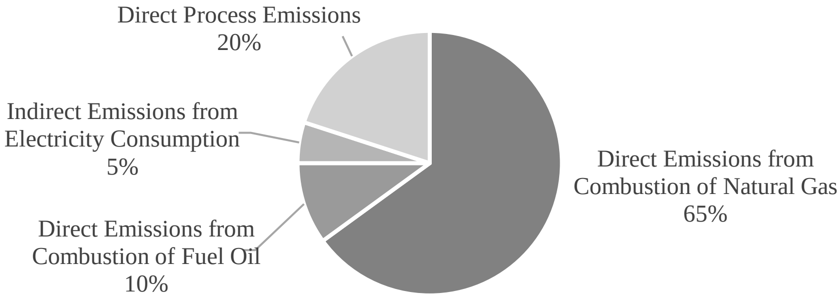


Figure 8. Sources of Emission in French Glass Sector (ADEME, 2021)

The hollow glass furnaces, which are constructed from refractory materials, are designed to operate continuously for approximately 15 years without any interruption. Any disruption to this thermal process that causes a drop in temperature, even for a few hours, can have severe consequences. These include the complete collapse of the refractory materials due to rapid thermal contraction, the risk of hot glass leakages that pose a threat to the operating staff and could result in fire or explosions, the solidification of the liquid glass inside the furnace, and the impossibility of restarting the furnace. Such damage to the furnace would have detrimental effects not only on the container glass industry but also on its entire value chain. The cascade effect to the food, beverage, pharma, and cosmetic industry would directly result in incapability of filling in hollow glass. This characteristic of hollow glass melting furnaces highlights the significance of the pilot projects aimed at testing the innovative technologies and energy solutions for the decarbonization of the entire sector.

Low or zero-carbon alternatives for melting the glass include hydrogen (H_2), electricity, or biofuels. Given that the availability of biomass is a concern as a sought-after alternative in other sectors, it is not usually considered as a promising alternative in the hollow glass sector (DNV.GL, 2015). All-electric furnaces are advantageous in terms of efficiency, however, they are currently in use for smaller size of furnaces (less than 150 tons of daily glass production) and there is no established electric furnace that produces the full production volume of large size furnaces (Eurotherm, 2019). Decarbonized hydrogen is viewed as a promising supplement to the carbon-neutrality of this industrial process. Hydrogen is compatible with the current gas furnaces on the large scale. Furthermore, the on-site production of H_2 through electrolysis provides the supplementary values of ancillary services as well as the co-production of heat and oxygen (to be valorized directly at oxy-fuel furnaces). Nevertheless, hydrogen is facing several challenges. The current cost of production of hydrogen (either on-site or transported from centralized facilities) is currently not competitive to the wholesale market price of electricity. Furthermore, for on-site production of clean hydrogen through electrolysers, a part of energy is lost due to the efficiency of electrolysers to convert electricity to hydrogen. Therefore, the choice of technology for decarbonizing glass melting processes depends on the size of the furnace, the geographical features, including the availability and cost of fuel, and the potential of long-term cost reduction of the components.

In this pilot project, for the reference case (Figure 9), the natural gas and oxygen are externally supplied to the oxy-fuel furnace for the combustion process emitting CO2, Sulfur Dioxide (SOx), Nitrogen Dioxide (NOx), and Carbon Monoxide (CO). However, in the pilot project, the reference NG-fired furnace should be replaced by a one of studied decarbonized technologies; full-electric (Figure 10), hybrid (Figure 11), and hydrogen furnaces (Figure 12). Due to the high energy consumption of the glass melting process, all technologies require a connection to high voltage electricity from the grid with Guarantees of Origin (GO). The full-electric furnace utilizes imported electricity to supply an electric furnace, and is limited to smaller-sized furnaces with production capacities lower than 150 tons of glass per day. The hybrid furnace, on the other hand, can operate on any ratio of electricity and gas up to 20% electricity/ 80% gas, but can only perform switches between ratios very rarely, usually once a year. For the pilot project, 80% of the supplied electricity will be consumed directly in the furnace for electrical heating, while the remaining 20% will be used to operate an on-site electrolyzer for producing low-carbon hydrogen and oxygen coproduct, which will be used directly in the oxy-fuel furnace. To minimize the footprint, a high pressure storage solution will be used for storing the large quantities of hydrogen required to compensate for a failure of the electrolyzer. The hydrogen-based technology relies entirely on imported electricity from the grid to operate the on-site electrolyzer. Both hybrid and hydrogen technologies are applicable for both small and large-sized furnaces.

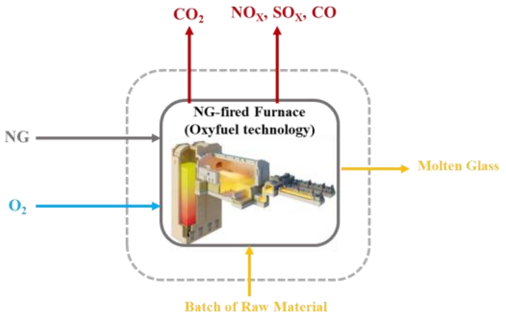


Figure 9. The schematic of the reference fossil-based furnace

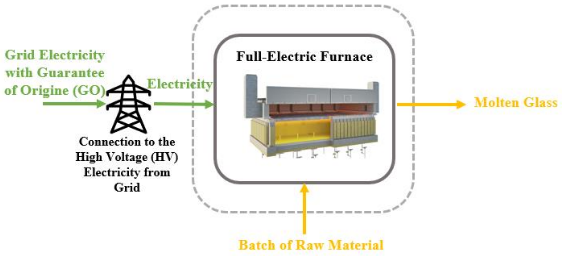


Figure 10. The schematic of the full-electric furnace technology

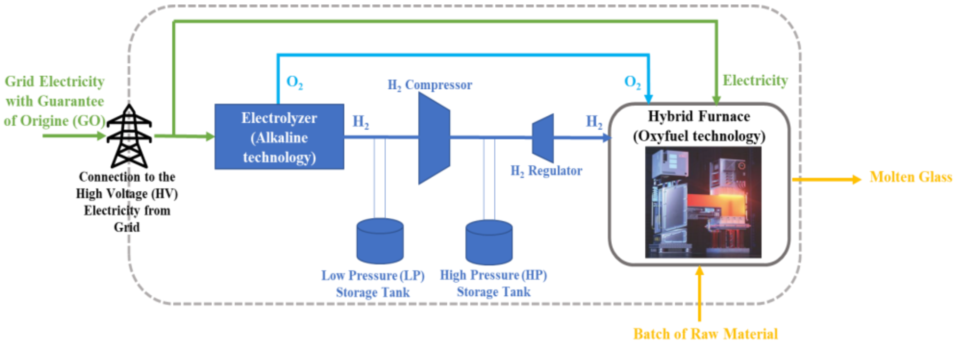


Figure 11. The schematic of the decarbonized hybrid furnace

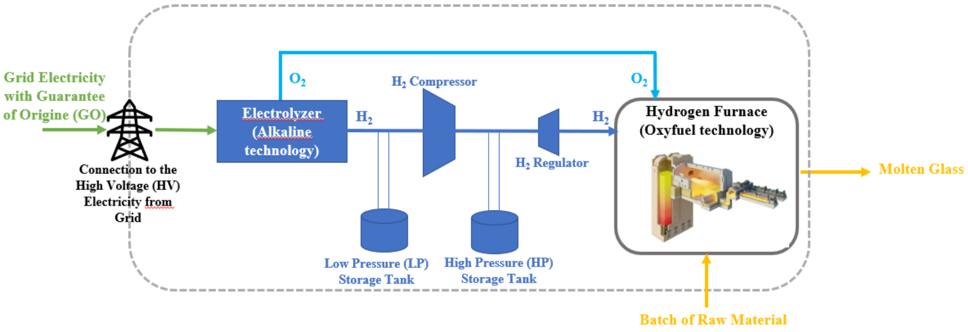


Figure 12. The schematic of the decarbonized hydrogen furnace

3.3. Specific assumptions regarding the cost-benefit analysis of the sector

The social value of carbon: In order to adhere to the theoretical framework, we adopt the Hotelling assumption that presumes the social value of CO2 will increase in accordance with the social discount rate (assumed to be 3.2% in France). For this purpose, we fix the social value of CO2 in 2030 to be 250 €/tCO2 based on the official trajectory value established by Quinet (Quinet, 2019). These factors point to the present social value of CO2 being approximately 195 €/tCO2 (as shown in Figure 13).

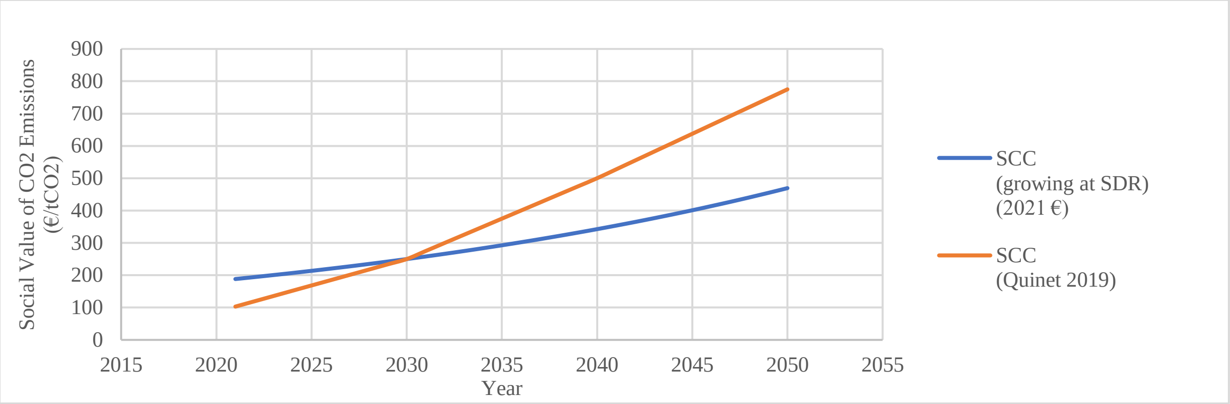


Figure 13. Social Value of CO2 growing at social discount rate

The social value of air pollutants: This paper uses the methodology of the Environmental Prices Handbook (Bruyn, 2018) to monetize the benefits of the abatement of air pollutions (NOx, SOx, and CO) from the combustion of natural gas in the reference case (Table 4). As recommended by the handbook, we consider a constant value of the air pollutants over the years.

Table 4. Environmental Damage Cost of Air Pollution: Environmental Prices Handbook (Bruyn, 2018)

Pollutant	**Lower Value (€$_{2015}$/t)**	**Central Value (€$_{2015}$/t)**	**Upper Value (€$_{2015}$/t)**
Carbon Monoxide (CO)	38.3	52.6	91.8
Nitrogen Oxides (NOx)	9970	14800	22100
Sulfur Oxides (SOx)	8300	11500	17900

Considerations regarding assets lifetime: In gas-based furnace technologies (i.e. NG, H_2, and hybrid furnaces), the technical lifetime typically ranges from 12 to 15 years, which are assumed to be 15 years for the purposes of this study. By contrast, the lifespan of full-electric furnaces is considerably shorter, estimated at around 6 to 8 years, with a 6-year lifespan assumption in this study.

In scenarios where emitting assets, (i.e. NG furnaces), launch decarbonization after 15-year with an extended lifetime of the emitting technology, additional maintenance costs are factored in. Conversely, if the emitting technologies launch decarbonization prior to the assumed 15-year lifespan, they will be subject to the risk of stranded assets and incur additional costs. Stranded assets are assets that have become uneconomic before the end of their useful life, here as a result of technological advancements, consist of the direct costs related to the dismantling, removal, and disposal of the asset as well as any associated environmental remediation or restoration costs. In this study, a simple assumption was made to estimate the additional maintenance costs associated with extending the lifetime of a particular asset. Specifically, it was assumed that the additional maintenance costs would increase in proportion to the number of years that the asset remained in service beyond its original technical lifetime. In addition, an assumption was made to estimate the stranded costs associated with an asset that is retired before the end of its technical lifetime. It was assumed that the stranded costs would increase in proportion to the number of years remaining until the end of the asset's technical lifetime. The assumptions made aimed to provide a simple and straightforward way to estimate the additional maintenance costs and stranded costs of extending or retiring an asset prematurely. Although not all complexities were considered, they serve as a starting point for analysis. Further research can refine these assumptions and develop more detailed models for cost estimation.

Assumption on recycling rate: The present study refrains from assuming a specific recycling rate for clear and ultra-clear container glass due to the high level of purity of the raw material in this segment. It is important to note, however, that the recycling rate for clear glass can vary depending on the region and the specific recycling program in place. Therefore, further investigation may be required to determine the actual recycling rates in the considered segment. Nonetheless, this inquiry is beyond the scope of the current study, which focuses on analyzing the economic and environmental implications of decarbonization trajectories for the furnaces.

Cost Decomposition: The cost breakdown of the reference case, the natural gas fired furnace, and its comparison to decarbonized technology of furnaces (full-electric, hybrid, and hydrogen) for small and large sizes are depicted in Figure 14 for one lifetime of each furnace. For the decarbonized technology, the primary cost component is the operational cost of electricity. However, we identified two technological bricks for the full-electric technology (including electric furnace and High Voltage (HV) electricty connection), and five technological bricks for the hybrid and hydrogen technologies (comprising of the hybrid furnace, electrolyzer, hydrogen compressors, storage tanks, and HV grid connection). Each technological component includes both equipment and installation CAPEX (such as engineering, command and control, start-up expenses, contingencies, etc.), as well as annual operational and maintenance (O&M) costs. The cost of fuel consumption and O&M costs make up the OPEX in the cost-benefit analysis.

In this analysis, we take the average electricity price for 2022 in France as 120€/MWh and the average natural gas (NG) price as 60€/MWh, based on data provided by Eurostat. It should be noted that the electricity price includes the Guarantee of Origin (GO), which confirms the renewable origin of the electricity produced. The cost of connecting to a HV grid can vary depending on various factors such as the distance to the nearest HV substation, the capacity of the connection required, and the availability of infrastructure in the local area as well as the local regulations and the policies of the grid operator. According to a report by the French Energy Regulation Commission (CRE), the cost of connecting to the French HV grid varies from €30,000 to €80,000 per MW. Our study employs an Alkalin electrolyzer technology with a cost of 1505€/KW in 2021. The hydrogen compressor and storage tanks are calculated based on the study by U.S. Department of Energy Hydrogen Program (DOE).

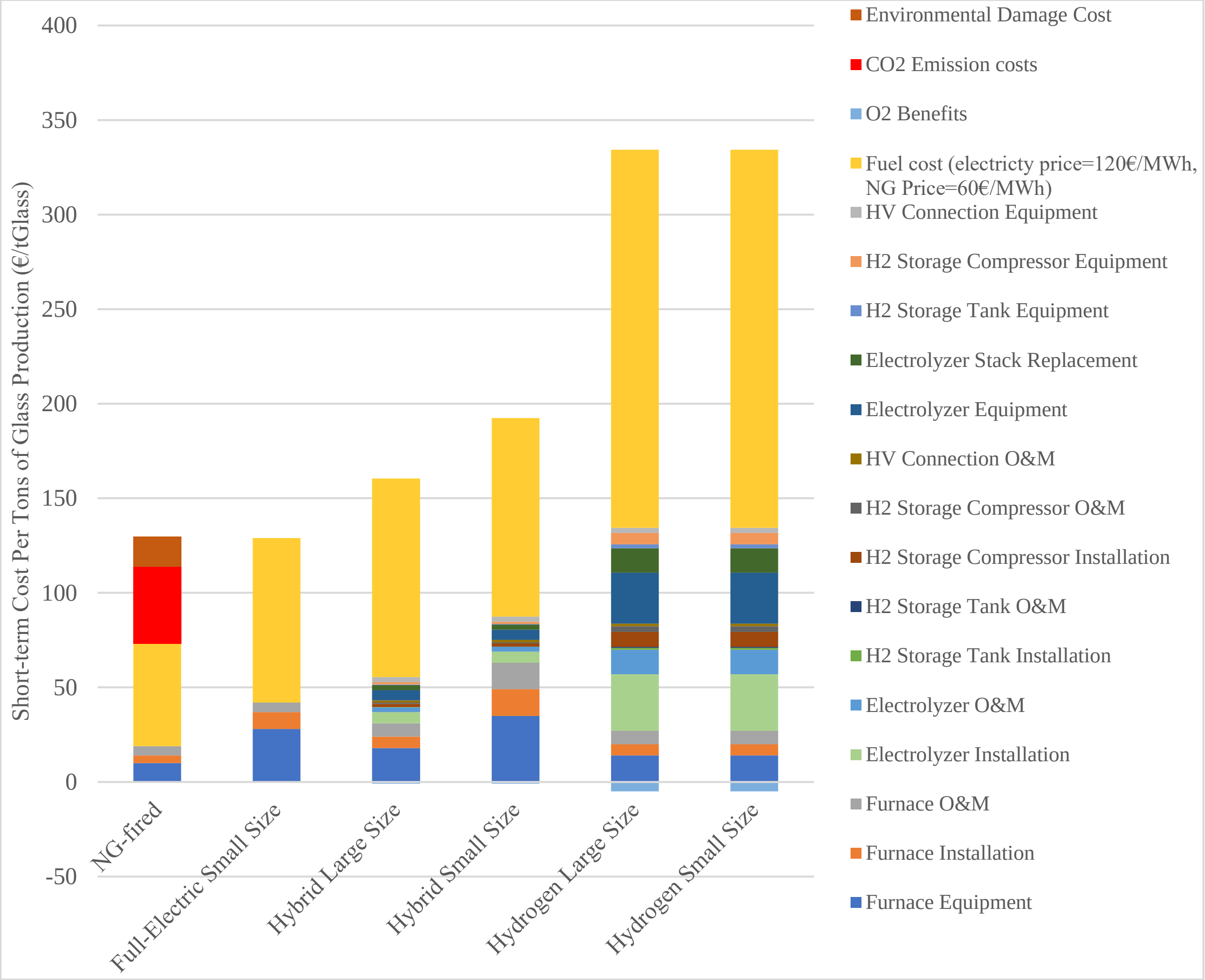


Figure 14. The short-term cost decomposition of different technologies

Endogenous and Exogenous Technical Change: The long-term cost components of the technologies would be subjected to both endogenous and exogenous learning impacts. The technologies used for the electrolyzer, hydrogen compressor, and storage tanks, as well as connection to HV electricity, are commonly used in other sectors with mass production beyond the glass industry. Therefore, we can consider the equipment cost of these components as sources of exogenous learning to our model. The Net Zero Emission (NZE) scenario of IEA projected a 85% reduction in the equipment cost of the electrolyzer by 2050 compared to its current value. Also, IEA Energy Technology Perspectives 2020 report states that cost reductions of up to 70% for hydrogen storage technologies are possible by 2050 through the deployment of larger-scale systems, improvements in the manufacturing process, and the development of new materials. Regarding the cost of HV grid connections while improvements may be made in terms of efficiency and infrastructure expansion, it is unlikely that this cost component will decrease significantly in the future. On the other hand, there are also sources of endogenous learning. For example, the equipment cost of decarbonized furnaces and the installation and O&M costs could decrease due to the cumulative deployment of new technologies within the sector. We assume that the cost of the decarbonized furnace will eventually reach the cost of the current natural gas-fired furnace in the long term. The current and the projected cost of each component of hybrid technology for the large size furnaces is shown in Figure 15.

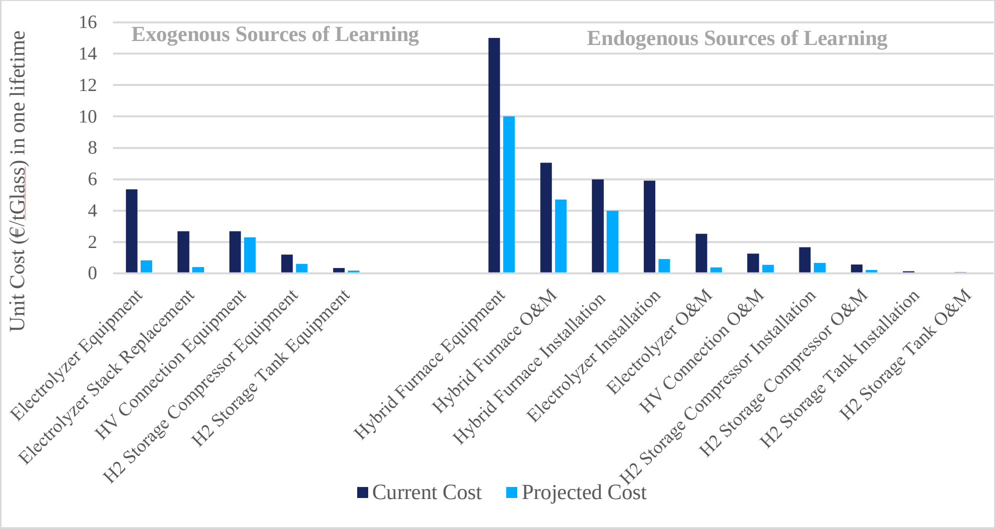


Figure 15. Exogenous and endogenous sources of learning for hybrid technology for large furnaces

According to the theoretical framework, the impact of endogenous learning is factored in after each investment cycle (15 years for a hybrid furnace and 6 years for a full-electric furnace). While investments in decarbonized technology continue indefinitely, each cost component will eventually reach a minimum projected long-term cost. When endogenous learning spillover does not occur, each furnace launches the decarbonized technology at the current assumed cost. However, if there is endogenous learning spillover from the pilot project to the follower projects, the follower projects' cost could be reduced based on the time delay between the pilot and the follower. Since exogenous learning in this model is contingent upon the level of deployment in other sectors, it is considered an external factor and outside of the control of the specific sector being studied in the model. We assume that exogenous learning occurs over time and is explicitly anticipated to happen through the progression of time. For instance, it is assumed that the equipment cost of electrolyzers will decrease linearly to reach the minimum projected price by 2050 according to the IEA NZE scenario, after which it will remain constant.

The discounted cost function to be minimized: The objective of the social planner is to minimize the sector's overall cost as specified in Equation (5). This equation could be extended to Equation (10), when there are several producing units in the sector:

$$\Gamma = \int_0^S e^{-it}(c_e + P_t)Edt + \int_S^{S+T} e^{-it}[(c_e + P_t)(E - a_t) + c_t a_t]dt + \int_{S+T}^{\infty} e^{-it} c_t a_t dt \qquad (10)$$

Where c_e is the cost of emitting technology per unit of CO_2 emission, P_t is the social cost of CO2 emission, E is the total amount of CO2 emission of the sector, a_t is the amount of CO_2 abatement at time t, and $c_t$is the cost of decarbonized technology at time t. Prior to the implementation of the pilot project, the sector only consists of natural gas (NG)-fired furnaces that involve the expenses of deploying the emitting technology and the costs incurred due to emissions from all units. Following the pilot project's launch at time s, only the pilot units are decarbonized, with a cash cost of deploying the decarbonized technology. The other furnaces continue to emit for a duration of T before they are decarbonized. Upon the completion of the delay period, the other furnaces adopt the decarbonized technology and benefit from a cost reduction that spills over from the pilot project. The decarbonized technologies will be renewed after each investment. The aim of this study is to determine an optimal trajectory, which is defined by the pilot launch time and the delay time values.

3.3 Results and Sensitivity Analysis

The Choice of Decarbonized Technology: The selection of decarbonized technology depends on the size of furnaces, as discussed in Section 3. It has been found that full-electric furnaces are inadequate to transfer sufficient heat for large size furnaces, i.e., those with a production capacity of more than 150 tGlass/day. Therefore, the considered decarbonized technologies for such furnaces are only hybrid (80% electricity-20% hydrogen) and fully hydrogen furnaces. However, full-electric technology is technically feasible for small size furnaces, i.e., those with a production capacity of less than 150 tGlass/day. In order to minimize the total social cost of the decarbonization trajectory, it is essential to identify the most competitive technology pathway in the long-run for each segment.

Although the short-term deployment cost of hybrid technology is currently lower than that of hydrogen technology for large size furnaces, it is crucial to justify whether this cost comparison will remain the same in the long term, considering the spillover impact. Figure 16 demonstrates that the spillover rate has a more significant effect on the cost of the hydrogen technology pathway due to the higher cost-reduction potential of various components, including electrolyzer and storage systems. Despite this, the minimum cost of the H2 pathway remains higher than the hybrid pathway. Even if fully hydrogen technology is utilized for both small and large size furnaces, resulting in a higher cost-reduction for the hydrogen pathway due to its deployment in the other segment, the cost of the hydrogen technology still remains higher than the hybrid technology pathway. Similar argument applies to small size furnaces, as shown in Figure 17. Even if there is a high spillover rate for H2 and hybrid technologies, the full-electric technology pathway remains the most competitive option in the long term. Therefore, in this setting for large furnaces the hybrid technology is selected while for small furnaces the full-electric technology is deployed. In the following section, we explain how to determine the optimal trajectory in a segment using the hybrid technology pathway for the large size furnace segment as an example.

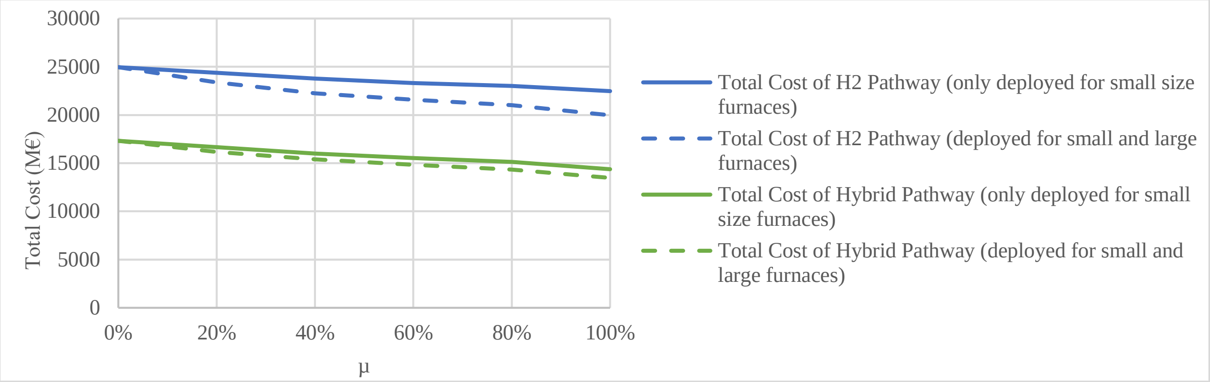


Figure 16. Feasible Technology Pathways for Large Size Furnaces

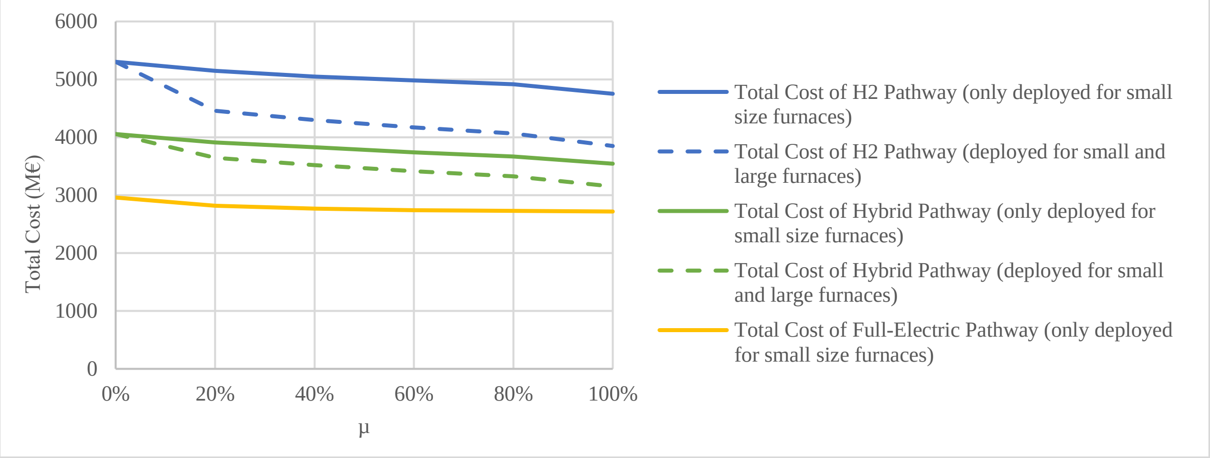


Figure 17. Feasible Technology Pathways for Small Size Furnaces

In this simulation, we have established two scenarios to evaluate the decarbonization project in the segment. The first scenario, labeled as the "optimal scenario," involves launching a pilot project before the follower projects with a delay period. This approach allows for learning from the pilot project, making necessary adjustments before scaling up. However, the follower projects have the freedom to choose their launch date while an extra cost is added whenever the emitting assets are stranded or extended. The second scenario, however, referred to as the "technical scenario," involves launching the decarbonization project for all furnaces in the segment right after the end of their technical asset lifetime. Therefore, in this case, the assets do not have the freedom to choose the launch date of decarbonized technology and will only follow the technical lifespan of the existing emitting technologies.

Determination of the Optimal Trajectory:

The determination of the optimal trajectory for the segment can be characterized by its pivotal value of spillover rate. Figure 18 depicts the dependence of the optimal trajectory on the spillover rate, which is a key parameter in the decision-making process for launching pilot and follower projects. Our analysis indicates that, when the spillover rate is low (below 10%), the optimal strategy is to postpone the pilot project launch without introducing a delay between the pilot and follower projects. However, for moderate spillover rates (between 10% and 25%), launching the pilot project earlier and incorporating a delay between pilot and follower projects is preferable. When the spillover rate reaches a critical threshold of 25%, launching the pilot project as soon as possible while incorporating a 13-year delay between the pilot and follower projects is the optimal strategy. At higher spillover rates (above 25%), the optimal trajectory is largely unchanged as the minimum projected long-term cost has already been reached, and any further spillover effects are negligible. Therefore, we identify the spillover rate of 25% as the critical value, beyond which the optimal strategy is to launch the pilot project immediately and introduce a 13-year delay to minimize the total cost of the segment.

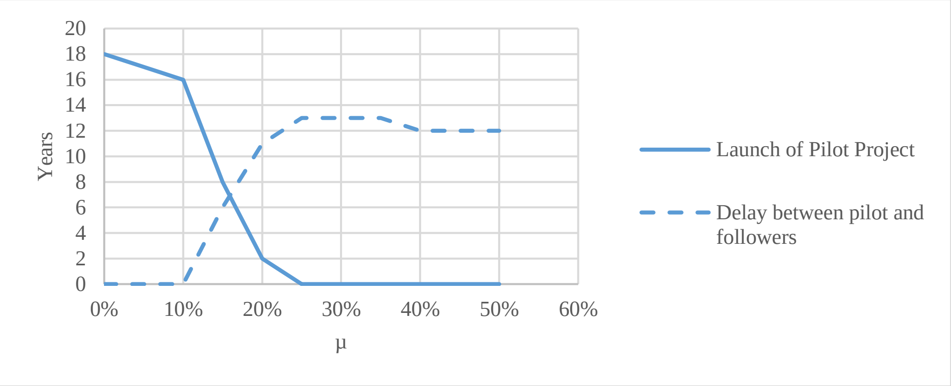


Figure 18. Optimal trajectory for decarbonization of large size furnaces with hybrid technology

Figure 19 displays the total cost and total emissions associated with the optimal trajectories for different values of spillover rates. The optimal trajectory corresponding to a spillover rate of 25% leads to a reduction of approximately 5% in the total cost of the segment for the time horizon of 2023-2050, inclusive of both cash cost and emissions cost, compared to the optimal trajectory with no spillover impact. Specifically, the total cost of the segment is reduced from 17.3 b€ to 16.5 b€. Furthermore, the optimal trajectory for this spillover rate is associated with a reduction of around 30% in the total amount of CO2 emissions generated by the segment over the same time horizon, compared to the optimal trajectory with no spillover impact. In particular, the total CO2 emissions of the segment are reduced from 10 MtCO2 to 7 MtCO2.

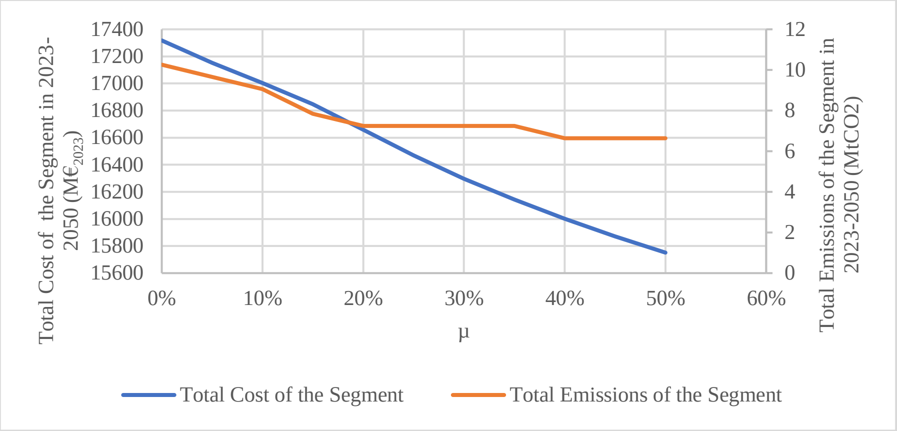
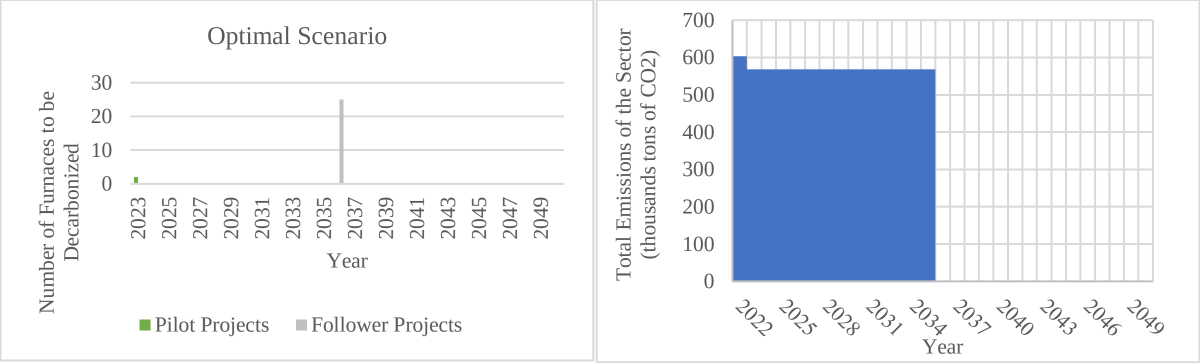
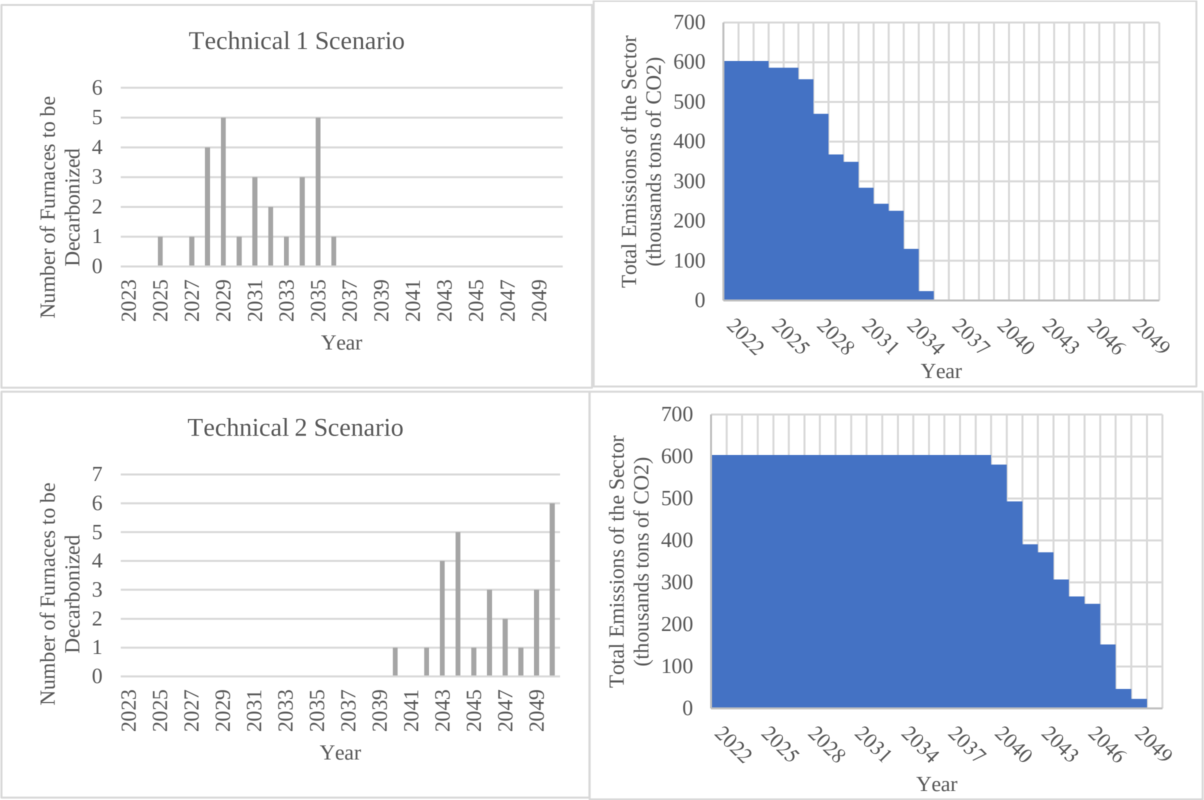


Figure 19. Total cost and emissions of the optimal trajectories associated with each learning rate

Comparison of Optimal and Technical Scenarios:

Assuming a spillover rate of 25%, Figure 20 provides a comparison between the "optimal" and "technical" scenarios regarding the decarbonization schedule of the segment and the associated CO2 emissions trajectory over the 2050 horizon. For the technical scenario, only two distinct trajectories are available to align with the Net Zero Emission (NZE) targets and achieve decarbonization of the segment before the year 2050. These trajectories are labeled as "technical 1" and "technical 2" scenarios. Under the "technical 1" scenario, all furnaces will undergo decarbonization at the end of their present asset lifetime, whereas in "technical 2," the furnaces will invest in the emission technology once more and only launch the decarbonization project after their second investment cycle. Investing in emitting technology after the second renewal within this particular segment is no longer aligned with the goal of achieving net-zero emissions before 2050.




Technical 1 Scenario

Technical 2 Scenario

Figure 20. The decarbonization schedule and total emission trajectories for the three scenarios

The results presented in Figure 21 clearly indicate the importance of transitioning towards decarbonization pathways in the segment. The figure shows that if the segment continues with Business As Usual (BAU), i.e., using NG-fired furnaces, the increasing emission costs will eventually make it the most expensive trajectory despite having lower annualized cash costs than hybrid technology paths.

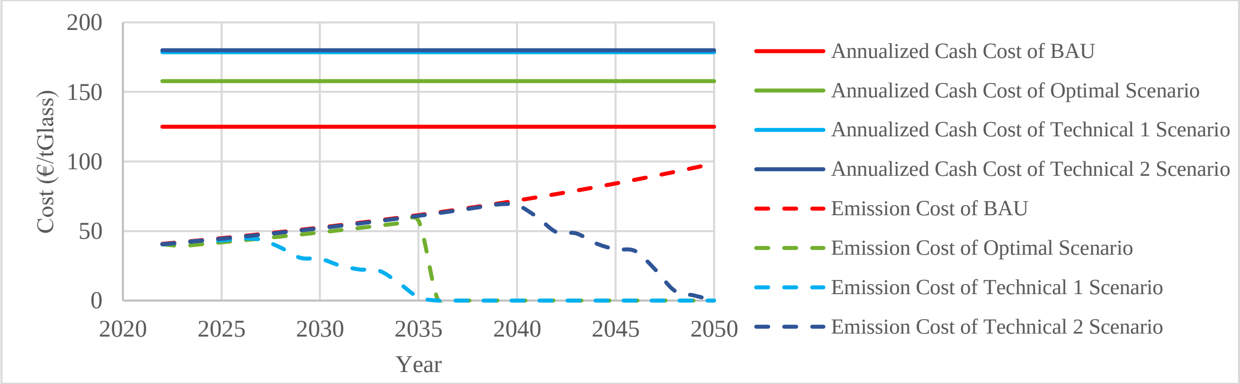


Figure 21. The cash cost and emission costs of the three scenarios compared to BAU

The comparison of the three scenarios in terms of their trade-offs between emission costs, cost reductions from endogenous and exogenous learning, and the extra cost of stranded/extended assets provides important insights into the decision-making process. The analysis revealed that the total CO2 emissions in the Optimal scenario are higher than those in the Technical 1 scenario but lower than those in the Technical 2 scenario. These findings are depicted in Figure 20, which visually represents the total CO2 emissions over time for each scenario. As a result, as presented in Table 5, the total emission cost of the Optimal scenario remains between those of the two Technical scenarios. Concerning the cost of stranded/extended assets, as illustrated in Table 6, both Technical scenarios are designed to coincide with the end of the asset lifespan for each furnace, resulting in a lack of additional cost. In contrast, the Optimal scenario involves the installation of new plants before or after the end of the old ones' lifespans, leading to the inclusion of stranded/extended asset costs. This additional cost consideration should be weighed against the potential benefits of the Optimal scenario. Regarding the learning impacts, the Optimal scenario benefits more from exogenous learning than Technical 1, as the Optimal trajectory postpones the decarbonization of follower furnaces that become less costly in the future. On the other hand, it benefits less than Technical 2, as the Technical 2 trajectory further postpones the emission mitigation of all furnaces. However, spillover effects of the endogenous learning from the demonstration phase in the Optimal scenario lead to a significant reduction in costs that outweighs the additional costs of this trajectory. Consequently, the overall costs of the Optimal scenario exhibit a lower total discounted cost in comparison to the both Technical scenarios.

Table 5. Decomposition of the total costs for the three scenarios

Scenario	**Total Discounted Cost**	**Total Cash Cost**	**Total Emission Cost**	**Cumulative emissions**
Optimal	16469 M€$_{2023}$	14294 M€$_{2023}$	2174 M€$_{2023}$	7.24 MtCO$_2$
Technical 1	17094 M€$_{2023}$	15353 M€$_{2023}$	1741 M€$_{2023}$	5.63 MtCO$_2$
Technical 2	17132 M€$_{2023}$	13123 M€$_{2023}$	4009 M€$_{2023}$	14.55 MtCO$_2$

Table 6. The added cost of stranded/extended assets vs the reduced cost due to spillover and external

Scenario	**Added cost of stranded/extended assets**	**Reduced cost due to exogenous learning**	**Reduced cost due to endogenous learning and spillover impact (μ=25%)**
Optimal	505 M€$_{2023}$	-487 M€$_{2023}$	-1268 M€$_{2023}$
Technical 1	0 M€$_{2023}$	-407 M€$_{2023}$	-823 M€$_{2023}$
Technical 2	0 M€$_{2023}$	-490 M€$_{2023}$	-514 M€$_{2023}$

Figure 22 illustrates the abatement cost curve of the segment for the "Optimal" trajectory, as well as the Levelized Cost of Carbon (LCC) proposed by Baker and Khatami (Erin D. Baker, 2019). The Optimal trajectory entails abating approximately 35 tCO2 with the CO2 social cost set at 200€/tCO2 in 2023 within the demonstration (pilot) phase, while the remaining CO2 emissions of approximately 568 tCO2 will be abated with the CO2 social cost set at 300€/tCO2 in 2036. In contrast, the LCC approach disregards dynamic factors such as learning and spillover, leading to an estimation that the total abatement potential of the segment (603 tCO2) would require a higher cost of approximately 800€/tCO2. This finding highlights the significance of incorporating dynamic considerations into policy and strategy design aimed at achieving decarbonization goals. Thus, policymakers must prioritize the inclusion of dynamic factors to ensure more realistic and effective mitigation strategies.

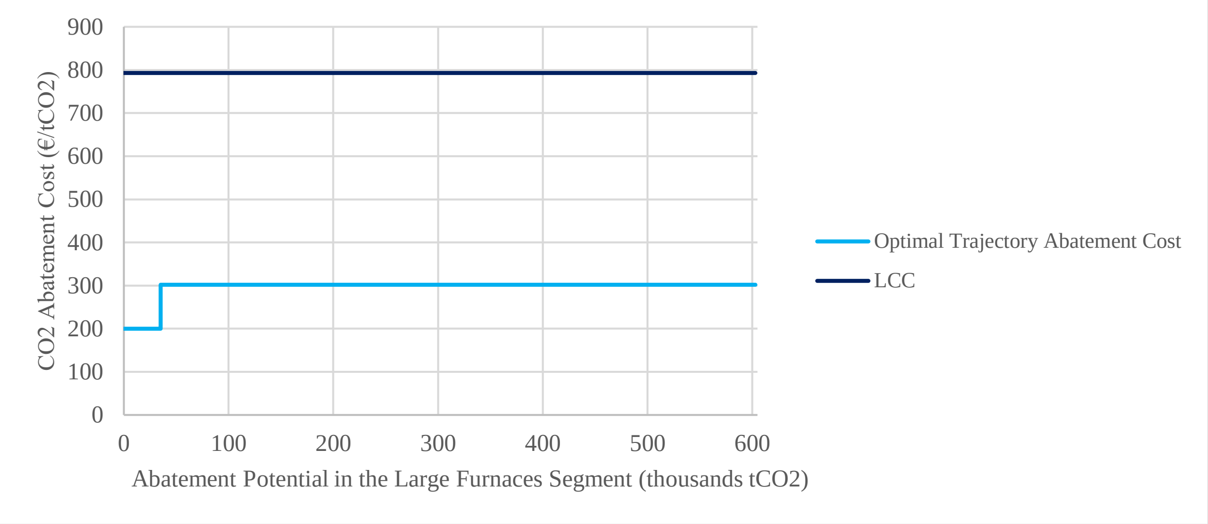


Figure 22. The segment abatement curve comparing optimal trajectory and Levelized Cost of CO2 (LCC)

In Figure 23, the optimal decarbonization trajectory is compared to France's National Low-Carbon Strategy (SNBC) (Ministère de la transition écologique, 2020). SNBC trajectory is a top-down approach that assumes a linear reduction in CO2 emissions across an aggregated industrial sector to achieve carbon neutrality by 2050 through a net decarbonization of the energy consumption. These hypothesis fail to capture the dynamic features of the energy transition. The Optimal trajectory, on the other hand, provides a more precise and sector-specific decarbonization path that considers the different industrial segments' unique characteristics within an bottom-up approach. Although the figure implies emitting more CO2 within the Optimal trajectory compared to the SNBC approach, the Optimal trajectory's precision ensures that the net-zero emission goal is still achievable by 2050.

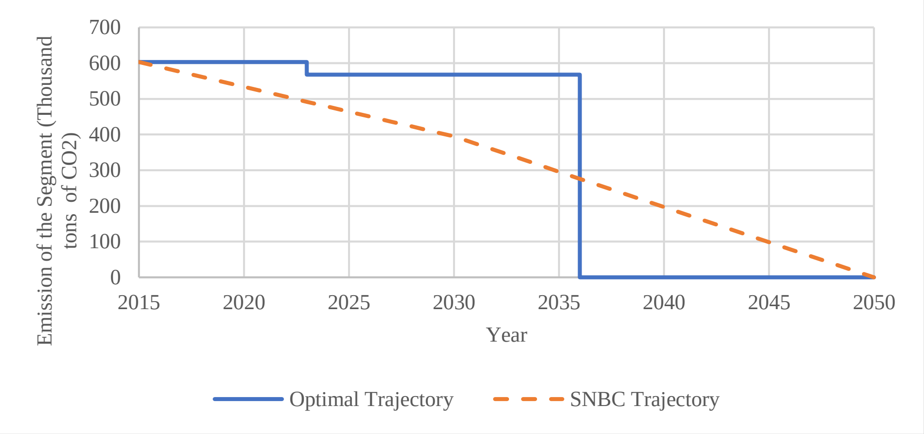


Figure 23. optimal decarbonization trajectory compared to France's National Low-Carbon Strategy (SNBC)

Sensitivity Analysis to the Input Prices

Conducting a sensitivity analysis of the optimal trajectory to input prices of natural gas and electricity is crucial to better understand how changes in input prices may affect the optimal trajectory. Although this section does not attempt to define price trajectories to track the fluctuations and price cycles that characterize commodity markets in practice, it is essential to observe the impact of extreme cases when input prices change in both higher and lower directions. By doing so, we can make informed decisions on how to adjust the optimal trajectory accordingly.

The Optimal trajectory presented so far considered current natural gas and electricity prices of 60€/MWh and 120€/MWh, respectively, referred to as the Current Price Case. To better understand the impact of extreme scenarios, we considered two additional cases: a High Price Case and a Low Price Case. In a High Price Case, natural gas price increases 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. Conversely, in a Low Price Case, input price of natural gas is assumed to decrease to 12€/MWh, a value projected for Europe in 2050 by IEA Net Zero Emission (NZE) scenario[6] due to a predicted rapid decline in natural gas consumption.

It is essential to carefully consider the electricity price in relation to natural gas prices, as in European markets, natural gas prices can often influence electricity prices because the gas turbines are usually the marginal power producers. Marginal power producer is the last production unit required to meet demand in the merit order system, which determine 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. Figure 24 illustrates the marginality duration of different power producer technologies by 2050 as predicted in the reference case of ADEME.

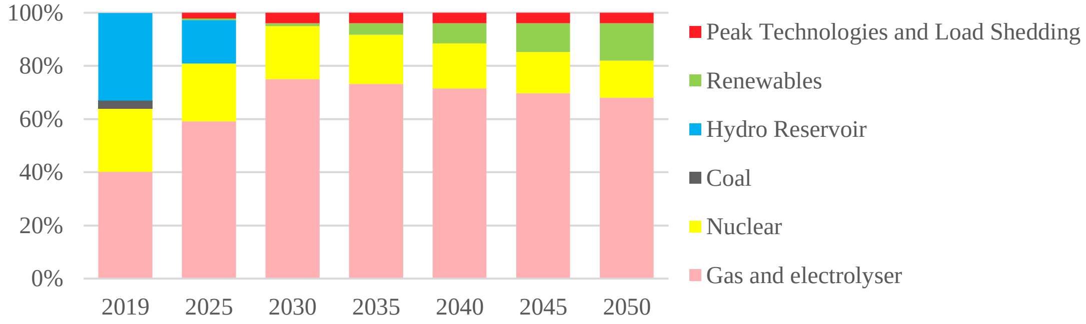


Figure 24. The marginality duration in the French electricity market by 2050, ADEME reference scenario (ADEME 2018): The nuclear technology will be less present as the marginal sector technology while renewable technologies (including run-of-the-river hydro) will grow in terms of both production and 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.

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[6] IEA scenarios model an energy system in equilibrium, in which energy prices follow a relatively smooth trajectory to balance supply and demand, and where energy markets, investment, technologies and policies all evolve in a mutually consistent direction.

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

$$P_E^t = \sum_s MD_s^t \times MC_s^t \tag{11}$$

Where s indicates the power producer technology, MD_S^t is the marginality duration of power producer s at 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 CO2 emission (P_{CO2}^t).

$$MC_{Gas}^t = \frac{1}{\eta_{CCGT}} (P_{Gas}^t + \mu_{CCGT} P_{CO2}^t) \tag{12}$$

The thermal efficiency (η_{CCGT}) and the emission factor of the CCGT plant (η_{CCGT}) are assumed to be constant at 60% and 0.429 tCO2/MWh, respectively (RTE, 2022). Taking these assumptions, the electricity price associated with each case are presented in Table 7.

Table 7. NG and electricity prices in different sensitivity cases

Case	NG Price	Electricity Price
Low Price Case	12 €/MWh	80 €/MWh
Current Price Case	60 €/MWh	120 €/MWh
High Price Case	120 €/MWh	180 €/MWh

Figure 25 depicts the sensitivity of the optimal trajectory to various input price scenarios, as determined by different values of µ, which represents the combined effect of endogenous learning and spillover impacts. Notably, Table 7 reveals that the deviation of prices in the extreme cases from the Current Price Case is asymmetric. Additionally, the alteration of natural gas (NG) prices does not result in a linear change in electricity prices, as Equation 11 implies. These factors account for the non-symmetrical shape of the curves observed in the sensitivity analysis in Figure 25. Nonetheless, the results presented in this figure can be evaluated in three distinct areas:

In the first area, where µ ranges between 0% and 10% representing a low level of endogenous learning and spillover, a delay between the launch of pilot and follower projects is not justified for any of the price cases due to the minimal impact of spillover benefits. However, in the High Price Case, an earlier launch of decarbonization is necessary (16 years delay to launch for High Price Case when µ=0). Although the high electricity prices may appear discouraging for implementing decarbonization via electricity/electrolyzers, the much higher NG prices compared to the current values provide greater incentives to transition from NG-based emitting technology. Conversely, this is not the case for the Low Price Case, where NG prices are too low to encourage early adaption, and the segment prefers to postpone the launch of decarbonization (23 years delay to launch for High Price Case when µ=0).

The second area of Figure 25 corresponds to µ values ranging from 10% to 30%, indicating a medium level of endogenous learning and spillover impact. For the High Price Case, fuel consumption costs constitute the main cost component in the total cost of the trajectory. As the fuel costs are not subject to learning impacts, in High Price Case the spillover impact is not strong enough to justify the delay between pilot and followers. In contrast, for the Low Price Case, CAPEX and operational costs of the technological bricks account for a larger share of the total cost. These cost are the cost components subject to learning and spillover. As a result, the optimal trajectory in this case is characterized by advancing the launch of pilot project while making a longer delay between the pilot and follower projects. Consequently, contrary to the first area of the graph, the optimal trajectory for the High Price Case is to launch decarbonization later than in the lower price cases. For instance, with µ=20%, the pilot is launched with a 13-year delay in the High Price Case, followed by the immediate launch of followers.

However, in the Low Price Case, the pilot is launched in 2 years, and a 15-year delay is introduced after the pilot for launching the followers.

The third region of the figure pertains to values of μ exceeding 30%, indicating a strong level of endogenous learning and spillover impact. In this range, the spillover impact is robust enough for all cases to launch the pilot project immediately and have the maximum possible delay between the launch of pilot and follower projects. As previously mentioned, for the Low Price Case, the importance of the spillover impact justifies longer delays between pilot and followers.

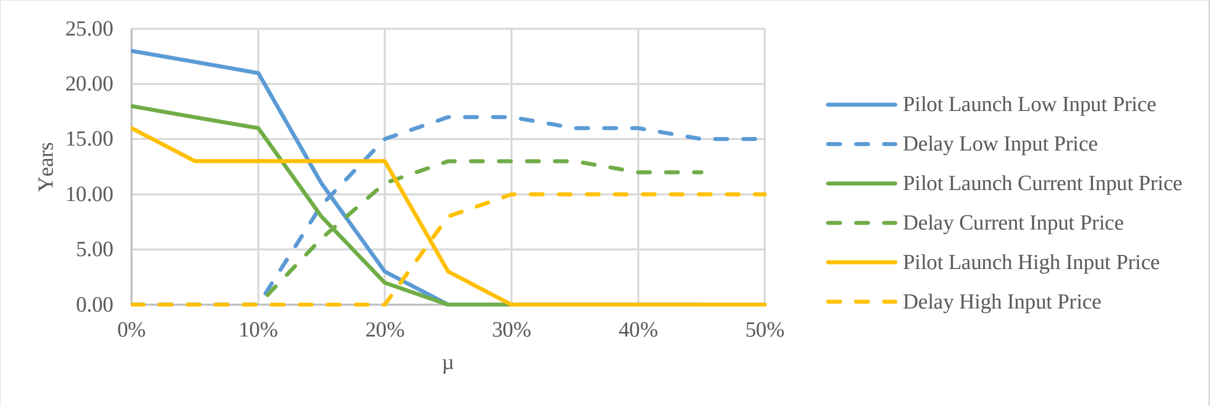

Figure 25. Sensitivity analysis of the optimal trajectory for different input prices

In conducting a cost-benefit analysis of industrial sectors, considering the results of sensitivity analysis to input prices is crucial, especially with regard to the role of natural gas in decarbonization. Firstly, natural gas is a crucial input in numerous industrial sectors, and the price of low or zero-carbon alternatives must become competitive with natural gas prices. Secondly, natural gas plays a critical role in the evolution of electricity prices since gas turbines will remain a marginal power production technology in the merit order system for the next several decades. As such, electricity can serve as a direct input that can replace natural gas or an indirect input to produce clean hydrogen through electrolysis. Finally, there may be a ripple effect on the market price of carbon on the EU-ETS, which is the reference for evaluating the private benefits of the decarbonization process. It is worth noting that decreasing scenarios for natural gas prices are less likely, as acknowledged by the IEA NZE scenario, which suggests that additional investments are required to compensate for Russian supplies that have no clear route to market after the breakdown of the energy relationship with Europe.

4. Discussion and the areas for further research

Unlike static cost analysis that focuses solely on direct emission reductions in the short-run, this framework reflects the long-term cost of adopting a green strategy. Our findings indicate that from a social standpoint, the optimal trajectory for the industrial energy transition is characterized by a demonstration phase, which costs less than the trajectories that delay action until the end of the technical lifetime of emitting assets. This supports the argument made by Nemet et al. (Gregory F. Nemet V. Z., 2018) about the necessity of public funding for demonstration projects due to the presence of spillovers. Our framework highlights the importance of considering the dynamic effects and the need for supporting the pilot projects as the main creators of technological advances in achieving a socially optimal trajectory toward the industrial energy transition. We identify three crucial factors that will enable successful implementation of a certain carbon neutrality pathway.

The first key factor is the essential role of experimentation in triggering radical changes. By applying approaches similar to those used for research and development to more economic or organizational problems, the planner can, in partnership with all the relevant actors, set in motion an initial click of action at a limited cost. More fundamentally, this incremental approach also has the advantage of producing feedback that, if properly integrated into the construction process, will allow for indispensable adjustments to the overall strategy.

The second factor is that, beyond the public funding, a new mode of interaction is required between economic actors, aimed at replacing opportunistic behavior with cooperation. This cooperation can only be achieved by including a significant bottom-up component that allows for the consideration of constraints and complexity that are sometimes ignored by the classic top-down approach. In the container glass industry, for example, this bottom-up approach has been reflected on a segment scale by mobilizing several players toward creation and share of the knowledge for the development of new decarbonized technologies.

Finally, the third key factor is the development of new methodologies for strategic thinking, compatible with the required bottom-up approach. Using a methodology that aims to integrate all the issues into the collective reflection allows us to go beyond the simple case study and to have an approach that is potentially transferable to other breakthrough innovations. Rather than resorting to complex modeling based on opaque hypotheses with questionable results, a two-step approach, alternating qualitative and quantitative, allows for a more coherent representation of disruptive scenarios. This alternation includes a conceptual model, allowing the common knowledge necessary to develop a trajectory to be shared, and, in a second phase, a quantitative model intended to measure the commitments of the various stakeholders. This type of method, by offering a broader vision, facilitates the commitment of stakeholders to the implementation of the chosen strategy. In the decarbonization of "hard to abate" industrial sectors, this methodology was built on a reflection on the nature of technology transfers, learning effects and spillovers within a sector and on the implications of these transfers. It leads to a quantified strategy for planning the decarbonization of an entire sector. We argued that static costs provide an incomplete picture of the true costs of pilot action, which must include the dynamic consequences. Application of the model to the container glass industry in France shows that the effects of induced learning-by-doing and learning spillovers can make dynamic costs lower than a myopic static calculation. Most of the empirical studies focus on static costs, however, climate change is a long term problem, and the focus of policy must be on long-term solutions. The standard approach for policy-makers is to begin with the low-cost abatement options that rank better in Marginal Abatement Cost Curves (MACCs). However, this approach overlooks the potential interactions and spillover benefits among the mitigation actions. Ultimately, taking a more holistic and long-term view of decarbonization may require investments in higher-cost demonstration projects in the short term, but can result in significant benefits and cost savings in the future.

There are some further aspects that should be explored in order to solidify the implementation of the decarbonization policy. First of all, this study focuses on the first best trajectory from a social perspective. However, the issues of competition, equality of conditions of practice, and the dynamics of the industrial ecosystem and the market that this raises are not addressed at this stage. Beyond the numerical results, the implementation of the proposed optimal trajectory includes dimensions of collaboration and competition, regulation and public financial support. Also, there is ongoing discussion on the combination of carbon pricing and environmental taxes with the research subsidies for low-GHG technologies that might achieve dynamically efficient outcomes (Fischer et al., 2008), (Acemoglu et al., The Environment and Directed Technical Change, 2012), (Acemoglu et al., 2016). In addition, for basic industrial materials such as glass, the demand-pull policies are effective to incentivize the innovation. Such policies should take into account the issue of recycling which is not addressed within the scope of this study. The optimal interaction of public support mechanisms could be further investigated to become closer to first best trajectory through subsidies. Governments, as guarantors of commitments in the NZE transition, must help bridge the gap between the two public and private perspectives. Countries are actively positioning themselves on the various aspects of the NZE transition, with a set of measures ranging from support for technological innovation to the emergence of a regulatory framework combining environmental requirements and financial invitations, sometimes protectionist. It seems necessary to reflect on how to articulate interventions at different levels in the light of policies implemented at the international level.

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