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EXPERTISES

Industrial decarbonization in Dunkirk: oxy-combustion

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1. Strategic context and alignment with the ZIBAC program

This study is part of the ZIBAC (Low-Carbon Industrial Zones) program, which is integrated into the France 2030 investment plan— a €54 billion initiative designed to accelerate the energy and environmental transition of France's industrial regions. The Dunkirk industrial-port zone is a priority area in this strategy, as it alone accounts for approximately 13.7 MtCO2/year, or nearly 20% of France's industrial emissions.

Faced with the carbon neutrality targets set for 2050, manufacturers in the region are developing several decarbonization solutions that combine energy efficiency, process electrification, waste heat recovery, the use of renewable energy, and CO2 capture technologies. Among these solutions, oxy-combustion appears to be a particularly promising technology for industrial processes that consume large amounts of steam.

The principle of oxy-combustion is based on replacing air with pure oxygen during combustion. This removal of atmospheric nitrogen results in flue gases composed mainly of water vapor and CO2, with a CO2 concentration that can be 8 to 9 times higher than that observed in conventional combustion. This high concentration significantly facilitates CO2 capture and utilization operations while reducing nitrogen oxide (NOx) emissions.

The study conducted for GRDF thus aims to assess the technical, economic, and regional feasibility of deploying oxy-combustion boilers in the Dunkirk industrial zone. It also seeks to identify potential synergies between oxygen producers, industrial steam consumers, and stakeholders capable of utilizing the captured CO2 in order to establish a future regional decarbonization sector. This study complements several industrial projects already underway in the region, notably the Ch0C pilot project as well as the industrial trials planned at the Villers-Saint-Paul platform starting in 2025.

2. Study objectives and analytical methodology

The primary objective of the study is to assess the potential of oxy-fuel boilers for decarbonizing industrial steam use in the Dunkirk industrial and port area. Steam production currently accounts for nearly 45% of the gas volumes distributed by GRDF to industry, making it a major lever for reducing CO2 emissions.

The methodology adopted is based on three complementary areas. The first involves conducting a technological benchmark of the various components necessary for the operation of an oxy-fuel boiler. The study specifically compares various air separation technologies (ASU), flue gas treatment systems, and CO2 capture processes. Several oxygen supply technologies are examined, including cryogenic separation, adsorption processes, polymer membranes, and chemical loops.

Cryogenic separation is currently considered the most mature technology for producing oxygen on a large scale with a purity of over 99%, but it requires significant energy consumption, ranging from 200 to 350 kWh per ton of oxygen produced. Membrane technologies, on the other hand, are simpler and less expensive but generally produce oxygen-enriched air rather than pure oxygen. ITM membranes, still under development, operate at temperatures above 700°C and represent a promising avenue for improving the energy efficiency of oxy-combustion systems.

The second focus of the study is a regional analysis of the Dunkirk industrial zone to identify manufacturers likely to use this technology, potential oxygen suppliers, and possible uses for the captured CO2. Oxy-combustion boilers are primarily intended for industrial facilities with a thermal capacity ranging from 1 to 20 MW. Oxygen requirements vary significantly depending on the boiler's capacity, ranging from less than 10 tons of O2 per day for a 1 MW boiler to approximately 250 tons per day for a 30 MW facility.

The study also shows that food processing companies are particularly well-suited candidates for this technology, as they generally combine significant steam requirements, CO2 consumption in their industrial processes, and oxygen needs.

Finally, the third focus aims to define an action plan enabling the launch of an initial industrial project and the gradual development of an oxy-combustion sector across the Dunkirk region. This approach also includes studying CO2 transport infrastructure as well as opportunities for the economic utilization of captured CO2. According to the report, the price of feedstock CO2 currently ranges between €150 and €200 per ton of CO2, and a 5 MW oxy-combustion boiler could generate over one million euros in annual revenue from captured CO2.

3. Principles and operation of oxy-fuel boilers

Oxy-combustion is based on a simple principle: replacing the air used in conventional combustion with pure oxygen. In conventional combustion, air is composed mainly of nitrogen, which significantly dilutes the flue gases produced and makes CO2 capture more complex. By removing this nitrogen from the combustion process, oxy-combustion produces flue gases composed mainly of water vapor and highly concentrated CO2.

This technology is now one of the three main categories of CO2 capture processes at the source, alongside pre-combustion and postcombustion. Historically used in industrial sectors requiring very high temperatures, such as steelmaking and glass manufacturing, it is now the subject of in-depth studies for industrial boilers fueled by natural gas. One of the main advantages of oxy-combustion is the significant increase in CO2 concentration in the flue gas.

The report indicates that this concentration can be 8 to 9 times higher than that observed in conventional combustion, which greatly simplifies CO2 capture and purification operations. This technology also helps limit NOx emissions by removing atmospheric nitrogen during combustion. However, oxy-combustion also presents certain major technical challenges. The main difficulty concerns the supply of pure oxygen, the production of which requires significant energy consumption.

The system must also incorporate specific equipment to control combustion temperatures that are higher than in a conventional boiler.

4. Technological architecture of an oxy-combustion system

An industrial oxy-fuel combustion system relies on three main technical functions: oxygen supply, the combustion system, and flue gas treatment. Each of these functions requires specific equipment and plays a decisive role in the technical and economic performance of the facility.

The first function concerns oxygen supply. Three main strategies are considered in the report. The first involves installing an air separation unit (ASU) directly on-site to produce the oxygen needed for combustion locally. The second consists of purchasing oxygen directly from an industrial supplier such as Air Liquide. Finally, a third solution involves recovering oxygen co-produced by certain industrial processes, notably electrolysers used for hydrogen production.

The combustion system itself also requires several modifications compared to a conventional boiler. Combustion in pure oxygen generates much higher flame temperatures, which necessitates the integration of a flue gas recirculation (FGR) loop. This loop recycles a portion of the flue gases to reduce the temperature inside the boiler ans preserve the materials. In certain industrial sectors such as glass manufacturing, this recirculation also reduces natural gas consumpion by 15 to20%.

The burner must also be specifically adapted to the characteristics of oxy-combustion in order to account for differences in temperature, combustion rate, and flame stability. Despite these adaptations, the report notes that the differences compared to a conventional boiler remain relatively limited, which opens up the possibility of retrofitting certain existing facilities.

The third function concerns flue gas treatment and CO2 capture. Although in theory the flue gases from oxy-combustion are mainly composed of water and CO2, their actual composition depends on several parameters such as the purity of the oxygen used, the quality of the fuel, and the combustion conditions. Depending on the end use of the CO2, various stages of purification, drying, compression, or liquefaction may be necessary.

Quality requirements are particularly high for food and beverage applications, especially for the production of carbonated beverages or food preservation, where quality standards impose very strict limits on impurities present in the CO2.

5. Oxygen supply technologies

The oxygen supply is one of the most critical factors in the operation of an oxy-fuel boiler, as it directly affects energy efficiency, the quality of the captured CO_2, and the facility's operating costs. Oxygen requirements vary significantly depending on the boiler's capacity. The report estimates that a 1 MW boiler requires less than 10 tons of O2 per day, while a 30 MW facility may require up to 250 tons of O2 per day. Several technological solutions are currently available to produce or supply this industrial oxygen.

Cryogenic separation is currently the most mature technology for large-capacity facilities. This technology relies on the liquefaction of air followed by fractional distillation to separate oxygen from nitrogen. It produces oxygen of very high purity, generally exceeding 99%. However, it has a particularly high energy consumption of between 200 and 350 kWh per ton of O2 produced. Cryogenic units also require significant investment and have relatively long commissioning times. They are particularly relevant for industrial facilities exceeding 20 MWth.

PSA (Pressure Swing Adsorption) and TSA (Temperature Swing Adsorption) processes offer a more suitable alternative for mid-sized facilities. These systems operate using adsorbent materials capable of selectively trapping certain gases prior to regeneration. PSA technologies generally achieve oxygen purities between 93% and 99% while offering lower capital costs than cryogenic systems. However, their performance is limited for very large industrial capacities.

Membrane technologies offer another approach to oxygen separation. They use semipermeable membranes to separate gases based on their diffusion rates. Polymer membranes have the advantage of being simpler, more compact, and less expensive than cryogenic processes. However, they generally produce enriched air containing only 30 to 50% oxygen rather than pure oxygen, which limits their use in certain demanding industrial applications.

The report also discusses ITM (Ion Transport Membrane) technology, which is still in the industrial development phase. These membranes operate at high temperatures, generally above 700°C, and theoretically enable oxygen purity levels exceeding 99%. They could reduce energy consumption by approximately 60% compared to conventional cryogenic processes. Despite this significant potential, this technology remains limited today by constraints related to mechanical strength and material costs.

Finally, chemical loops represent a particularly innovative emerging technology. This process directly combines oxygen separation and combustion through a redox cycle involving metallic materials. The theoretical performance is promising, with a potential 40–70% reduction in energy consumption associated with air separation. However, this technology remains at the laboratory stage and still requires significant research before large-scale industrial application.

In Dunkirk, several supply strategies are being considered. In the short term, sourcing from Air Liquide appears to be the simplest solution to implement, despite the high costs associated with the supplier's dominant position in the region. In the medium term, utilizing the oxygen co-produced by H2V's future electrolysers could be a more competitive alternative. The second electrolyser, scheduled to come online in 2029, could notably enable the recovery of high-purity oxygen for oxy-combustion processes.

6. CO_2 capture and treatment technologies

CO_2 capture is one of the key benefits of oxy-combustion boilers. By using pure oxygen during combustion, the flue gases produced have a high concentration of CO_2, which greatly simplifies the separation and purification processes compared to conventional combustion.

The report distinguishes three main categories of CO2 capture technologies: pre-combustion, post-combustion, and oxycombustion.

Pre-combustion involves converting the fuel to produce a mixture rich in hydrogen and CO2 prior to combustion. This technology offers good energy efficiency but requires heavy and complex infrastructure, including gasifiers and chemical conversion units, which significantly increases investment costs.

Post-combustion relies on capturing CO_2 directly from the flue gas after combustion. This solution is currently the most widely used in industry, but it has several limitations when applied to industrial boilers, particularly due to the low concentration of CO_2 in conventional flue gas and the significant presence of nitrogen and impurities.

Oxy-combustion thus emerges as a particularly attractive alternative, since the flue gases produced contain mainly CO2 and water vapor. This high concentration significantly reduces the complexity of the separation steps. On the other hand, this technology requires the installation of an air separation unit (ASU), which accounts for a significant portion of the system's energy and economic costs.

The report then identifies several families of capture technologies that can be used in conjunction with oxy-combustion.

Absorption processes use liquid solvents capable of selectively capturing CO2 prior to a thermal regeneration phase. This technology is currently the most industrially mature, but it involves significant energy consumption due to solvent regeneration.

Adsorption processes operate on a similar principle but use solid adsorbent materials. These technologies offer potentially lower energy consumption but remain limited for certain high-capacity industrial applications.

Membrane technologies, on the other hand, use selective membranes to separate CO2 from other gases present in flue gas. They offer advantages in terms of compactness and modularity but still require improvements to achieve high levels of purity.

Finally, cryogenic processes rely on cooling CO2 to its anti-sublimation temperature in order to separate it in solid form. This solution can produce very high-purity CO2 but remains highly energy-intensive.

Flue gas treatment also depends heavily on the final quality of CO2 required. For food and beverage applications, EIGA standards impose extremely strict limits on impurities present in CO2. Additional steps for drying, purification, compression, and liquefaction are then necessary to obtain CO2 compatible with food or sensitive industrial uses.

The report also emphasizes that the quality of the oxygen used directly affects the quality of the CO2 produced. Oxygen containing traces of nitrogen can lead to the formation of NOx in the flue gas, thereby increasing the need for downstream purification.

From an economic standpoint, CO2 is now a valuable resource in certain industrial markets. The prices cited in the report range from €120 to €150 per ton of CO2 for certain industrial uses, such as dry ice production, and from €180 to €200 per ton of CO2 for food-grade CO2. For a 5 MW oxy-fuel boiler, the revenue potential could exceed one million euros per year depending on the quality of the CO2 produced and the available markets.

7. <u>Industrial opportunities in the Dunkirk area</u>

The development of an oxy-combustion industry cluster in the Dunkirk industrial-port zone relies on the creation of a true industrial ecosystem that brings together oxygen producers, industrial steam consumers, and entities capable of utilizing captured CO2. The report emphasizes that the economic viability of such a model depends heavily on the ability to create local synergies among these various stakeholders.

The study identified several categories of industrial companies potentially interested in oxy-combustion boilers. The most relevant sectors are primarily food processing, beverages, glass manufacturing, and certain industrial processes that consume large amounts of steam. These industries generally have thermal requirements ranging from 1 to 20 MW, which corresponds to the operating range targeted by the oxy-combustion boilers studied in the report.

The agri-food sector appears to be particularly well-suited for the deployment of this technology. These manufacturers combine several advantageous characteristics: significant industrial steam requirements, regular CO_2 consumption in their processes, and, in some cases, oxygen needs. This configuration makes it possible to consider models for the local utilization of CO_2 directly on-site or among neighboring manufacturers.

Interviews conducted with several manufacturers in the region also reveal a strong commitment to decarbonizing industrial activities. Several solutions are currently being considered by manufacturers: biomass boilers, electrification, waste heat recovery, solar energy, and hydrogen. However, the report highlights that oxy-combustion offers a major advantage in terms of operational flexibility.

This issue of flexibility is particularly evident in the case of Coca-Cola in Socx. The industrial site produces approximately 370 products across 8 production lines and currently has three Babcock Wanson boilers, each with a capacity of 6 tons of steam per hour, as well as a fourth 4 t/h boiler that is currently offline. Forty percent of the steam produced is used for cleaning the lines, and 60% for sterilizing equipment.

The site has extremely high flexibility requirements, with power fluctuations ranging from approximately 1 MW to 15 MW in less than three minutes. This constraint makes it difficult to use certain alternative technologies, such as biomass or certain electric solutions.

The report indicates that several decarbonization solutions were studied and then rejected by Coca-Cola:

* biomass boilers cannot handle significant load fluctuations;

* electrification is limited by the saturation of the local power grid;

* the use of hydrogen requires large areas of land as well as additional safety requirements;

* wind power solutions are limited by urban planning constraints;

* geothermal energy lacks suitable local resources.

In this context, oxy-combustion has been identified as the most suitable solution to simultaneously meet the site's needs for flexibility, decarbonization, and industrial continuity. Coca-Cola thus emerges as the first potential oxy-combustion boiler project identified in the Dunkirk region.

The report also highlights the strategic role of future applications for captured CO2. Several local manufacturers already use CO2 in their processes, notably for the production of carbonated beverages, the inerting of industrial lines, food preservation, and the production of dry ice.

In the longer term, new opportunities could emerge through the development of CO2 mineralization or geological storage projects, notably via the Northern Lights project in the North Sea. However, these solutions impose high technical requirements regarding the purity of the CO2 as well as its liquefaction prior to maritime transport.

Finally, the study highlights that the development of the Dunkirk CO2 Hub could play a decisive role in the emergence of a large-scale oxy-combustion sector. The first CO2 pipeline transport infrastructure is planned to be operational starting in 2027 to connect local manufacturers to future CO2 storage and utilization solutions.

8. Utilization and applications of captured CO_2

CO_2 utilization is a key factor in the economic viability of an oxy-fuel boiler project. Several manufacturers based in the Dunkirk area already use CO_2 in their industrial processes, particularly for the production of carbonated beverages, food preservation, the inerting of production lines, and the manufacture of dry ice.

The report identifies several potential CO_2 consumers in the region, including Coca-Cola, Blédina, and Carbonord. These manufacturers use high-quality CO_2, particularly for food and beverage applications that require compliance with strict standards such as EIGA standards. This requirement involves implementing additional steps for purification, drying, and sometimes liquefaction of the CO_2 before its industrial reuse.

The market price of CO_2 varies significantly depending on the required quality and end use. The report indicates prices ranging from €120 to €150 per ton of CO_2 for certain industrial uses such as dry ice production, while food-grade CO_2 can reach €180 to €200 per ton of CO_2. In the case of an oxy-fuel boiler of approximately 5 MW, the potential value of the captured CO_2 could exceed one million euros per year, representing a major economic driver for industrial projects.

Beyond direct industrial applications, geological CO_2 storage solutions are also being developed on a European scale. The Northern Lights project, located in the North Sea, represents one of the main prospects for CO_2 sequestration for industrial companies in Dunkirk. However, this type of infrastructure imposes significant technical constraints, particularly regarding the purity of the CO_2, its liquefaction, and maritime transport conditions to prevent corrosion of the facilities.

The development of future opportunities related to CO_2 mineralization or permanent storage could thus help enhance the economic viability of oxy-combustion projects while contributing to the carbon neutrality goals of the Dunkirk region.

9. <u>Pilot project planned at Coca-Cola</u>

The study identifies the Coca-Cola site in Socx as the leading candidate for an oxy-fuel boiler project in the Dunkirk industrial zone. This industrial site produces approximately 370 beverage products across eight production lines, requiring significant amounts of steam for cleaning, sterilization, and inerting operations.

The site currently has three Babcock Wanson boilers with a capacity of 6 tons of steam per hour, as well as a fourth boiler with a capacity of 4 t/h that is currently not in operation. Approximately 40% of the steam produced is used for cleaning the lines, and 60% for sterilization operations.

One of the site’s main constraints involves the very sharp fluctuations in load required to operate the production lines. Thermal demand can vary from approximately 1 MW to 15 MW in less than three minutes, which requires a high degree of flexibility from the steam generation systems. This constraint significantly limits the integration of certain decarbonization alternatives, such as biomass boilers or certain electric solutions.

Coca-Cola has explored several alternative solutions, but they all have significant limitations:

* Biomass boilers do not meet the site’s flexibility requirements;

* electrification is limited by the constraints of the local power grid;

* hydrogen solutions require additional safety and land-use constraints;

* geothermal solutions lack suitable local resources;

* the installation of wind turbines remains limited by urban constraints.

In this context, oxy-combustion appears to be a particularly suitable solution, as it allows for high operational flexibility while facilitating the capture of CO_2 produced during combustion. The site also consumes approximately 6,500 tons of CO_2 per year for beverage carbonation and production line inerting. The proposed project would involve converting an existing boiler into an oxy-combustion system to capture the emitted CO_2 and then reuse it directly in the site's industrial processes after purification.

This pilot project represents a strategic step toward demonstrating the technical and economic feasibility of oxycombustion on an industrial scale in the Dunkirk region.

10. Prospects for the development of an oxy-Combustion industry

The development of an oxy-combustion sector in the Dunkirk industrial-port zone requires coordination among several industrial players in order to simultaneously establish the oxygen supply, industrial heat production, and the utilization of captured CO_2.

In the short term, the oxygen supply could primarily be provided by industrial suppliers already established in the region, notably Air Liquide. This solution would quickly meet the needs of the first industrial projects despite relatively high supply costs.

In the medium term, new opportunities could emerge thanks to the development of hydrogen-related projects in the region. The report specifically mentions the possibility of utilizing the oxygen co-produced by future electrolysers intended for hydrogen production, particularly those in the H2V project scheduled to begin in 2029. Another prospect under consideration involves the creation of shared air separation units (ASUs) to reduce oxygen supply costs across multiple industrial facilities.

The development of an initial pilot project is an essential step in demonstrating the technical, economic, and environmental viability of this technology. According to the report, the success of an initial industrial demonstrator could facilitate the gradual emergence of a genuine regional network of industrial players focused on oxy-combustion and CO_2 capture.

In the longer term, the sharing of CO_2 transport infrastructure, the development of the Dunkirk CO_2 Hub, and future geological storage solutions could help establish a genuine regional decarbonization sector based on oxy-combustion.

RÉSUMÉ

This study assesses the potential for deploying oxy-fuel boilers in the Dunkirk industrial and port area, a region responsible for approximately 13.7 MtCO2/year, or nearly 20% of France's industrial emissions. Conducted as part of France 2030's ZIBAC program, it analyzes the technical, economic, and regional feasibility of this technology for decarbonizing industrial heat applications.

Oxy-combustion relies on the use of pure oxygen instead of air during combustion, enabling the production of flue gases with a high concentration of CO2 and simplifying carbon capture and utilization operations. The study examines the various oxygen supply technologies, flue gas treatment systems, and associated CO2 capture processes.

The regional analysis highlights the potential of the food and beverage industries, whose simultaneous demand for steam and CO_2 supports the development of a local oxy-combustion ecosystem. The market opportunities for captured CO_2 represent a significant economic driver, with potential revenue of up to €200/tCO_2 depending on the application.

The Coca-Cola site in Socx has been identified as a suitable initial pilot project due to its high steam requirements and significant industrial flexibility constraints. Finally, the study emphasizes that the development of an oxy-combustion sector in Dunkirk will depend on the establishment of infrastructure for oxygen supply, CO2 transport, and the utilization or storage of captured carbon.

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