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Retrofitting strategies for improving the energy and environmental efficiency in industrial furnaces: A case study in the aluminium sector

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ABSTRACT

This study aims to analyse some of the most relevant issues that the energy intensive industry needs to face in order to improve its energy and environmental performance based on innovative retrofitting strategies. To this end, a case study based on the aluminium industry, as one of the most relevant within the European energy intensive industry has been thoroughly discussed. In particular, great efforts must be addressed to reduce its environmental impact; specifically focusing on the main stages concerning the manufacturing of an aluminium billet, namely alloy production, heating, extrusion and finishing. Hence, an innovative DC (direct current) induction technology with an expected 50% energy efficiency increase is used for retrofitting conventional techniques traditionally based on natural gas and AC (alternating current) induction. A life cycle assessment was applied to analyse three different scenarios within four representative European electricity mixes. The results reported reductions up to 8% of Green House Gases emissions in every country. France presented the best-case scenario applying only DC induction; unlike Greece, which showed around 150% increment. However, the suitability of the new DC induction technology depends on the electricity mix, the technological scenario and the environmental impact indicators. Finally, environmental external costs were assessed with comparison purposes to evaluate the increase of energy and environmental efficiency in existing preheating and melting industrial furnaces currently fed with natural gas.

1. Introduction

Energy intensive industries, including sectors such as che7micals, steel, aluminium, cement, ceramics and paper, are responsible for great environmental, economic and social impacts. About 3% of world's total energy is used in industrial sectors and the world power demand represented around 60 billion MW in 2015 [1]. Unfortunately, there is usually strong overlap of interest for energy-intensive industries and climate change goals [2]. Many efforts are focused on decarbonising the manufacturing industry by means of key actions such as fuel switching to less carbon intensive fuels, carbon capture and storage and alteration of the product design taking into account the lifecycle of the product [3]. So they are continuously facing new challenges in order to increase the efficiency, reliability and flexibility of their processes. However these changes disrupt the production or require sometimes high investment or an in-depth renovation process [4]; thus retrofitting strategies arise as promising and more cost-efficient actions in industrial plants. Most notably, industrial furnaces have been the focus of multiple researches as one of the most energy intensive processes [5], representing more than 40% of the energy consumption in European industry sector [6].

The main goals of retrofitting strategies are focused on addressing radical improvements in the competitiveness and energy, environmental and cost performance, which can be implemented at component, process, system, and organizational level [7]. To that end, the development of improved designs based on new materials and/or technologies, alternative feedstocks, equipment and the integration of permanent monitoring and control systems into new and existing furnaces seem to be essential instrument to meet the demands. A retrofitting action should be carefully weighed against the benefits and costs of new

Abbreviations: A, Acidification; AC, Alternating current; AD, Abiotic depletion; ADF, Abiotic depletion (of fossil fuels); Al, Aluminium; CO_2 eq., Equivalent carbon dioxide emissions; DC, Direct current; E, Eutrophication; EC, External costs; ECF, External cost conversion factor; EI, Environmental impact indicator; FWE, Fresh water aquatic ecotoxicity; FR, France; GHG, Greenhouse gases; GR, Greece; GWP 100a, Global warming (100 years); HT, Human toxicity; IT, Italy; LCA, Life Cycle Assessment; LCC, Life Cycle Costs; LCI, Life Cycle Inventory; MAE, Marine aquatic ecotoxicity; NG, Natural Gas; ODP, Ozone layer depletion; PO, Photochemical oxidation; S, Scenario; SP, Spain; TE, Terrestrial ecotoxicity

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equipment that incorporates the most energy-efficient technologies available or eco-innovative designs considering the whole life cycle from a very early stage. In that sense, the overall objective of this work contributes not only to seek strategies to update the mainly old-aged furnaces, but also to initiate a path to ensure a successful design in case of new furnaces. This path includes a review gathering options which comprises (i) incremental improvements to existing technology and materials, and (ii) the application of significant process changes using innovative technologies that are technically reliable and have the potential to become commercially ready in the medium term. Among the wide variety of retrofitting opportunities, the present paper evaluates especially the feasibility of an innovative technology in the aluminium sector. This case study aims to assess the sustainability and efficiency in terms of environmental, energy and economic impact, by analysing a selection of the most appropriate methodologies and key indicators.

In particular, the aluminium sector represents an important part of the European industrial value chain and nowadays aluminium is the most produced non-ferrous metal [8]. The advantageous and well-known properties of this alloy have recently spread its application in the last decades; mainly due to its strength, durability, flexibility, malleability, thermal and electrical conduction combined with its low weight [8]. In 2013, the European production[1] exceeded 4.2 million tonnes of aluminium and, in particular, the extruded aluminium production was above 3 million tonnes and emitted more than 2 $MtCO_2$ eq. [9,10]. Although the aluminium industry has reduced its CO_2 emissions by more than 53% since 1990 and the recycling rates have extensively increased [11], much more effort is needed to fulfil the low-carbon and resource-efficient agenda. Consequently, the European Aluminium Industry's Sustainability Roadmap towards 2025, launched by European Aluminium Association (EAA) [12], aims to commit within a sustainable development and seeking innovative technologies along the aluminium value chain. Therefore, these growing environmental requirements lead the industries towards reengineering and retrofitting challenges meant to increase productivity, cost-effectiveness, energy and resource efficiency and design for lightweight recyclable materials [13].

Environmental and economic assessments are a key part for evaluating the introduction of a new process or technology, since many polices are pursuing to mitigate future climate change risks by developing strategies and technologies to reduce emissions and fossil fuels. There are several indicators to measure these emissions and therefore their impacts on the environment. For instance, CO_2, sulphur or methane emissions lead to local problems related to air or soil quality and water pollution. These local environmental impacts have a significant economic dimension, as they may prove to be a decisive growth limiter in a particular location. Technical and design aspects must be combined with environmental and economic considerations for assessing novel technologies, processes and products. Consequently, the strategy should be based on an optimum environmental and economic performance assessment to evaluate environmental impacts of the new involved processes.

To do so, the European aluminium industry supports the use of the life cycle assessment methodology (LCA) [14] as a holistic environmental system analysis method, in order to promote the sustainability and life-cycle thinking [15]. In fact, LCA has already been widely used in the aluminium industry [16]:

- to make commercial strategies
- to identify the most relevant processes regarding both energy and environmental optimization and supply chain management
- to communicate the overall environmental performance

Nevertheless, as Liu and Müller [17] presented in their review, the aluminium industry LCAs are typically accomplished from generic data, which is sometimes inaccurate, due to geographical, temporal, and technological variations; and whose coverage for some processes is still very low, so some relevant information may go undetected. To minimize these effects through the LCA approach, the life cycle inventory (LCI) of the proposed innovative technological scenarios was developed from experimental tests and then completed and compared using literature data. Finally, these results were quantified in monetary terms considering environmental externalities required for further studies framed into environmental the life cycle costs (LCC) methodology [18].

2. Comprehensive overview of retrofitting actions in the energy intensive industries

In search of opportunities to improve energy efficiency and reduce greenhouse gas (GHG) emissions in energy intensive industries [19,20], the iron and steel sectors have been pioneers by proposing and implementing a wide range of practices and technologies not only along Europe but also worldwide [21]. Already in the 19th century, iron and steel industries developed and installed techniques of waste energy recovery [22]. In fact, Worrell, van Berkel [23] gathered many examples of energy efficient measures applied in the industrial sector, such as new technologies and processes, conversion to cogeneration, fuel switching and recycling. Furthermore, Beer, Harnisch [24] reported that the global energy efficiency in the steel sector would be improved near a 30% by 2020 using existing technologies.

Furnaces and ovens are considered to be the most energy consuming equipment, not only in steel sector, but also in other energy intensive industries. They include a very wide variety of equipment encompassing the range from the smallest laboratory ovens (1 kW h) up to the biggest cement kiln consuming up to 0.61 TWh of primary energy per year [25]. Due to the large amount of energy consumed traditionally based on fossil fuels [5], considerable GHG are emitted to the atmosphere along with other critical environmental impacts.

In this line, large efforts to improve the energy efficiency in industrial sector mainly focused on various energy savings strategies such as management, technologies and policies have been reported during the last years [1]. To this end, refurbishment actions in specific operational system based on integrated solutions combining different technologies and approaches can be considered as innovative and efficient strategies. However, despite the efforts to change the current trend, the International Energy Agency [26] reports that industry is half as energy efficient as it could be according to the thermodynamic laws. So, the opportunities to enhance the performance and reduce the environmental impact are still very high.

On the one hand, energy and resource-efficient designs and eco-innovative thinking foster the sustainable development and green transformation. These approaches offer an opportunity for building new furnaces and ovens with the best available technology and improved performance; but investment costs or operational might be a constraint. On the other hand, retrofitting is regarded as a profitable alternative; nevertheless, the performance of these actions is not always possible [27]. There are restrictions regarding the life spam of the rest of unchanged components or is limited by the space available for a larger structure [28]. Even so, retrofitting actions can help the industries to accomplish the global commitments towards energy efficiency and low carbon production strategies, without compromising their production rates and economic balance. Hence, it is worth noting the numerous benefits of a proper retrofit strategy, which can be summarised as:

[1] The values corresponding to Europe encompasses the EU, Albania, Belarus, Bosnia-Herzegovina, Iceland, Macedonia, Moldavia, Norway, Serbia-Montenegro, Turkey and Ukraine.