H_2-READY BURNERS FOR STEEL INDUSTRY DECARBONIZATION: ACHIEVEMENTS AND CHALLENGES

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Abstract
The steel industry, a pillar of the global economy, faces the crucial challenge of reducing greenhouse gas emissions while meeting the growing steel demand. This article explores steelmaking processes, their carbon footprints, and the decarbonization strategies in place, focusing on the role of hydrogen (H_2) and the innovative technologies for a sustainable transition of the production stages that involve transforming the raw steel into various finished products (DOWNSTREAM process). In fact, while liquid steel production (UPSTREAM process) is reducing its carbon footprint, the influence of the downstream process is growing, requiring a transition to sustainable heating solutions. Carbon Direct Avoidance (CDA) through low-carbon H_2 combustion is a promising approach to eliminate CO_2 emissions at the source. However, large-scale implementation faces technological, economic, and regulatory challenges. This paper presents Tenova's "H_2-ready" combustion system development and its role in facilitating the steel industry's energy transition and decarbonization while highlighting open challenges in H_2 adoption at an industrial scale.

Introduction
The steel industry contributes 10% of global CO_2 emissions [1,2], making its decarbonization essential to meet European Green Deal climate targets [Figure 1]. Several decarbonization strategies can be leveraged to align with the European Green Deal and the NetZero pathway, including Carbon Capture and Usage (CCU), Smart Carbon Usage through efficiency improvements, and Carbon Direct Avoidance (CDA) [3]. Concerning UPSTREAM, H_2 can partially or totally replace fossil sources, such as coal or natural gas, as a reducing agent thanks to the Direct Reduction Process (DRP). By using H_2 produced by water electrolysis, powered by low-CO_2 energy, the DRI/EAF process can reduce the specific emission by one order of magnitude, achieving near-zero emissions (< 100 kg_{CO2}/t_{steel}) [Figure 2]. Regarding DOWNSTREAM, today carbon intensity of reheating and heat treatment furnaces ranges from 80 to 350 kg CO_2 per tonne of steel. This is already a significant source of emissions for the scrap-based route (EAF) and, in the future, will also become significant for the new primary route (DRI/EAF) [4]. Therefore, the use of

H_2 in substitution to fossil fuel, in addition to the role of reducing agent, represents a promising CDA strategy to achieve the steel sector decarbonization, provided that the associated technical and economic challenges are addressed effectively.

H_2 in combustion systems

The substitution of carbon-based fuels (such as natural gas, NG) with H_2 in industrial combustion systems presents several challenges. First, given the high cost as well as the limited and fluctuating availability of low-carbon H_2, industrial burners must be fuel-flexible, meaning they should be able to operate with any NG-H_2 mixture. Moreover, achieving significant CO_2 reduction necessitates high H_2 concentrations in the fuel mixture, with a significant impact on the combustion phenomena, thus demanding a new burner design.

H_2 combustion exhibits a higher adiabatic flame temperature, leading to increased NO_x emissions due to the thermal pathway [5]. An effective strategy for mitigating the temperature peaks associated with H_2 combustion is the adoption of flameless combustion [6-7]. In this regime, fuel and oxidizer are mixed in a way that promotes a kinetically controlled and volumetrically distributed reaction that results in a more homogeneous temperature distribution [Figure 3] and a subsequent significant reduction in NO_x formation by suppression of the thermal NO_x. In Tenova, an iterative process involving advanced Computational Fluid Dynamics (CFD) modeling, experimental validation, and engineering optimization has resulted in a robust portfolio of industrial burners capable of seamlessly switching between NG and H_2 without operational interruptions [8-9]. Experimental measures conducted by Tenova in the test facility confirm that NO_x emissions remain below Best Available Techniques (BAT) [10] limits across the full NG-H_2 mixture range when flameless combustion is employed [Figure 4]. These features are essential for securing long-term CAPEX protection in a capital-intensive sector like steel, which has 20 to 30 years investment cycles, and at the same time for managing OPEX to ensure a competitive value proposition in the global market.

H_2 employment at the industrial scale: open challenges

While the feasibility of H_2 combustion in industrial burners has been established, several open challenges remain for large-scale deployment, requiring further investigation to enable the full integration of H_2 into industrial processes.

The high H_2O concentration in the combustion atmosphere has potential implications for both the product being processed and the furnace refractory material. In the case of metal processing, an elevated H_2O concentration can enhance oxidation kinetics, leading to the formation of thicker and more adhesive scale layers on the metal surface. This phenomenon can directly affect product quality and yield [11-12], necessitating a deeper understanding of process adjustments required to mitigate excessive oxidation. Additionally, furnace refractory materials may experience degradation due to prolonged exposure to high water vapor concentrations, potentially affecting their performance and service life [13-14], raising maintenance-related concerns. The effects of prolonged H_2 exposure on insulation materials, burner blocks, furnace linings, and gas ducts are not yet fully understood [15]. Finally, ensuring a secure and economically viable H_2 supply is another critical factor influencing industrial adoption. The cost of low-carbon H_2 remains largely dependent on electricity prices, and the feasibility of H_2-based industrial operations is contingent on the availability of affordable and stable H_2 supplies [16]. The large-scale deployment of H_2 requires robust infrastructure for H_2 generation, transportation, and storage.

In such a context and intending to address the lack of long-term operational data under continuous industrial operation, Tenova takes part in several demonstration projects involving the H_2 value chain from utilities to technology providers, up to end users. T3 Dalmine Zero Emission Project [17]: an initiative that integrated a 500kW containerized electrolyzer supplied by Snam with a Tenova "H2 ready" combustion system installed in an industrial furnace at the TenarisDalmine production site. Horizon Europe HyTecHeat project [18]: a demonstrator at the Tenova site in Castellanza that combines the TenovaLAB pilot furnace with the innovative 1.2 MW De Nora alkaline electrolyser (DragonFly®). powered by photovoltaic energy, and a 30 bar H_2 storage system supplied by Snam [figure 5]. LIFE H2Reuse project [19] that aims to mitigate the impact of the bright annealing process at the DMV production site by reusing waste H_2 from the annealing process as fuel. Horizon Europe SYRIUS project [20] in which a 4.2 MWel solid oxide electrolyser (SOEC) supplied by Baker Hughes will be integrated to feed with H_2 the new Tenova H_2 Ready furnace for slab heating at AST in Terni, using the steam generated by recovering heat from the furnace fumes.

By leveraging these experiences, Tenova aims to generate critical insights and lessons learned that will partially fill the described gap and contribute to the development of best practices for H_2 adoption in industrial combustion applications.

Conclusion

The transition to a low-carbon steel industry is not only an environmental necessity but also an opportunity to modernize and strengthen the competitiveness of the sector. CDA through low-carbon H_2 combustion is a promising approach to eliminate CO_2 emissions at the source for the re-heating and treatment furnaces process in the downstream process. Tenova has developed its portfolio of "H_2-Ready" combustion systems and is investing in knowledge-building initiatives to support the long-term integration of H_2 into industrial applications to overcome the open challenges in the extensive use of H_2 as fuel in the steel industry. Process control, monitoring, and management strategies of integrated systems, particularly in the context of fluctuating renewable electricity availability, are areas that require structured research and development efforts. Establishing predictive maintenance strategies tailored to H_2-fired systems will also be crucial to ensuring operational reliability and minimizing unforeseen downtimes. Additionally, regulatory frameworks have not fully adapted to accommodate H_2 as an industrial fuel [21].

Figures and Tables

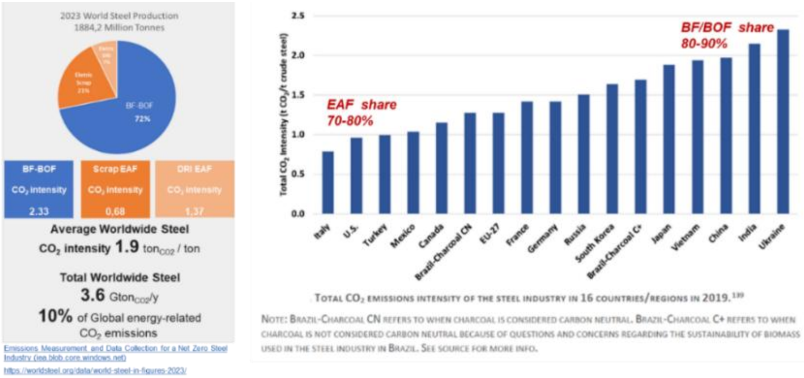

Figure 1. The carbon footprint of the steel industry

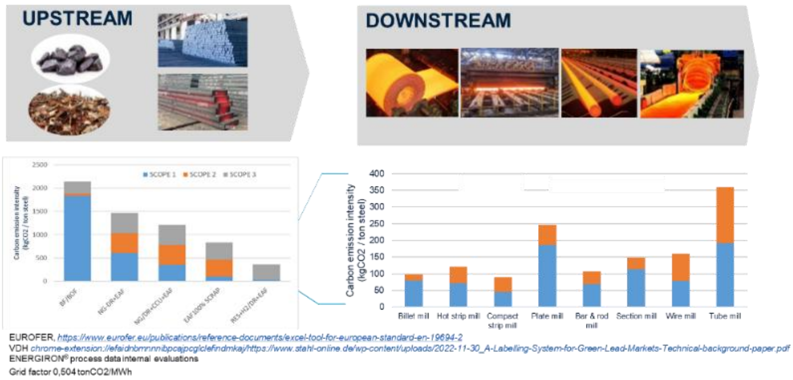

Figure 2. A transition path for the steel sector

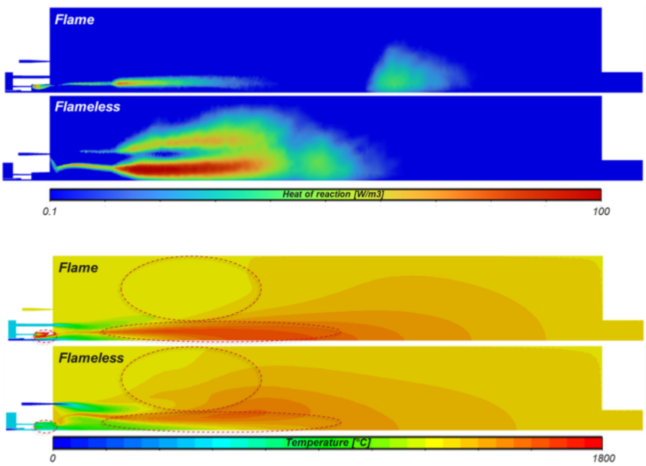

Figure 3. Heat-of-reaction (top set) and temperature (bottom set) contours of a flame (top) vs. flameless (bottom) combustion regimes in a Tenova lateral flameless (TSX) burner.

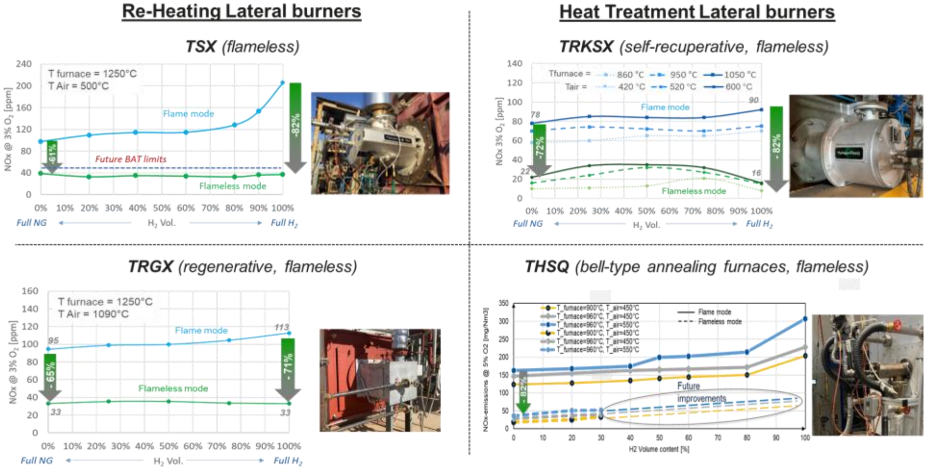

Figure 4. Examples from Tenova's fuel-flexible H_2-ready burners portfolio with related NO_x emission reported as ppm @3%O_2 under flame and flameless regimes over the whole CH_4-H_2 mixture range.

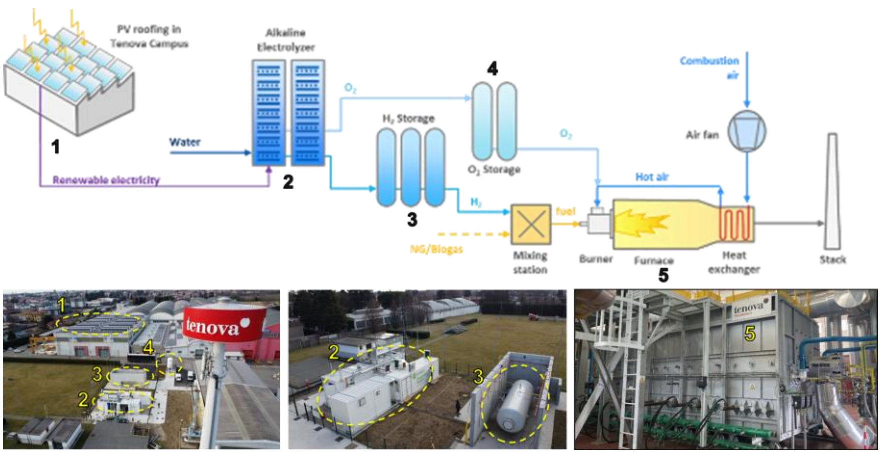

Figure 5. Sketch and photos of the demo-case installation at TenovaLAB in Castellanza [3]. The whole H_2 value chain is covered from green electricity production (1) and H_2 generation via a 1MW water electrolyzer (2) to H_2 storage (3) and combustion in industrial furnaces (5).

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