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Special Issue on "Overview, state of the art, recent developments and future trends regarding Hydrogen route for a green steel making process", edited by Ismael Matino and Valentina Colla

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EDITORIAL

Editorial for the Special Issue: Overview, state of the art, recent developments and future trends regarding Hydrogen route for a green steel making process

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The steel sector shows a not negligible impact in terms of CO_2 emissions, despite important and continuous improvements. The Greenhouse Gases (GHG) emissions coming from the steel industry currently correspond to about 6% of the total emissions of the European Union (EU) with an amount of 221 Mt GHG per year through direct and indirect emissions. Therefore, the steel industry is fully committed to investigate and implement novel technological solutions for reduction of CO_2 emissions, by providing its contribution to the ambitious goals of EU, which targets the achievement of European climate neutrality by 2050.

The European Steel Technology Platform (ESTEP) in its Strategic Research Agenda gives the highest priority to technologies and solutions favoring C-lean steel production, and recently launched the Clean Steel Partnership, a Public-Private Partnership, which supports the EU leadership in transforming the steel industry into a carbon-neutral one, fully in line with the European Green Deal.

In this context, Carbon Direct Avoidance is one fundamental CO_2 mitigation pathway, while steel production based on hydrogen is one of the key factors to improve the green footprint of steel industry, being also strictly linked to low carbon hydrogen production, norm and standardisation. The synergic use of low-C hydrogen instead other fossil fuels in both routes, Blast Furnace (BF) – Basic Oxygen Furnace (BOF), and Direct Reduction (DR) – EAF, and the complementary role of these routes can significantly contribute to the decrease of the GHG overall emissions.

To disseminate knowledge concerning hydrogen-based technology for the steel production, ESTEP organised in spring 2021 a thematic workshop to discuss the state of the art, the most recent developments and trends related to hydrogen-based technologies to be used within the steel sector. The four-days workshop, entitled "H2GreenSteel" was organised in the form of four virtual sessions of about 4 h of duration per day, where a total of 27 presentations and keynote lectures were provided by expert researchers in the field coming from both industry (hydrogen and steelmaking producers as well as plant providers) and academia. Each session included a round table, where the audience and the lecturers held interesting discussions concerning the future evolution of the steel production cycle, the most promising research outcomes which are already available and the gaps which need to be filled. In addition, in the first and last sessions appreciated and interesting lectures were provided by the ESTEP Secretary, the European Commission Head of Unit (DG RTD C3) and the Director of Clean Planet (DG RTD, unit C).

The present special issue collects a selection of the themes discussed during the above-mentioned Workshop, which were provided on a voluntary basis by the authors and passed a further peer-reviewing test. Therefore, the focus is on hydrogen-based route for greening the steelmaking process.

To introduce the content of this special issue, two review papers provide fundamental principles and relevant considerations on hydrogen steelmaking. In particular, in "Hydrogen steelmaking, Part 1: Physical chemistry and process metallurgy", the mechanisms of reduction by pure hydrogen of the iron oxide grains and pellets is analyzed at the microscopic level. Moreover, a kinetic model of the reduction of a single pellet based on the experimental findings is proposed together with a mathematical model for simulating the reduction by pure hydrogen in a shaft furnace, which can be very useful to design a future installation. The proposed analysis shows that using pure hydrogen, the reduction kinetics are faster and can end with fully metallization, the direct reduction process would be simpler, and the shaft furnace could be squatter. In "Hydrogen steelmaking, Part 2: Competition with other Net-Zero steelmaking solutions – Geopolitical issues", the gains in terms of CO_2 emissions are quantified and the

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whole route is compared to other zero-carbon solutions. Furthermore, further issues are discussed, such as the foreseen hydrogen demand compared (and possibly in competition) with other future hydrogen usages, the carbon footprint and associated costs, the maturity of the various processes, and some geopolitical issues.

A further useful analysis is presented in "Decarbonisation of the steel industry: A techno-economic analysis", where potential and constraints for the implementation of green hydrogen, generated via electrolysis in the direct reduction process are analyzed. A comparison among the hydrogen-based steel production route fed with green hydrogen, the traditional blast furnace route and the natural gas-based direct reduction is proposed, based on the outcome of the EU-funded H2FUTURE Project, in which a 6 MW PEM electrolysis system is tested. The CO_2 reduction potential for the various routes together with an economic study is analyzed, and the corresponding hydrogen and electricity demands for large-scale adoption across Europe are presented to rate possible scenarios for the steelworks of the future.

A dominating idea for hydrogen exploitation in steelworks is its exploitation in blends with natural gas as a fuel for industrial furnaces. This topic is treated in "Feasibility study for the utilization of natural gas and hydrogen blends on industrial furnace", where technical aspects and general issues related to the use of mixtures of hydrogen and natural gas in industrial processes are analyzed, by considering, in particular, the usage of such blends in industrial burners for treatment furnace as well as the effects on oxidability and descaling susceptibility of forged material. A blend with 30% of hydrogen content does not require hardware modifications, causes a moderate scale growth without detrimental effect on the scale removability and does not produce any noticeable negative effect on other process parameters or product quality.

The investigation of the effect of the same blend is deepened in "Development and testing of flameless burner fed by NG/H_2 mix., where a research activity is described, which includes CFD analysis and experimental tests to verify the proper working of a 2.0 MW industrial flameless burner fed with the above-mentioned mixture of natural gas and 30% hydrogen. CFD results fully agree with experimental data, showing that the burner can properly operate without any modification on the combustion process and on NO_x emissions.

On the other hand, research efforts are also being devoted on limiting the consumption of natural gas by feeding the burners with 100% hydrogen. On this subject, in "Rolling mill decarbonization: Tenova SmartBurners with 100% hydrogen", the Tenova SmartBurner technology is presented; it is based on TSX recuperative flameless for reheating applications ready to use hydrogen as fuel (up to 100%), with NO_x reached in the operative range from 100% natural gas to 100% hydrogen, far lower than the next envisioned limits (80 mg/Nm^3 at 5% of O_2 with furnace temperature at 1250 °C).

On the same topic, "Effects of H_2 combustion on scale growth and steel surface quality in reheating furnaces" describes an experimental activity to assess the effects of the combustion atmosphere by simulating reheating and heat treatment process on two steels grades, one for line pipe production and one for casing production, showing remarkable differences for scale growth and adherence related to C and Ni contents. In the experiments heating of a 20 mm thick pipe at 920 °C and reheating process at 1230 °C for 180 min were simulated and two possible combustion atmospheres were considered, which showed different values of water concentration and corresponding to 100% natural gas and 100% hydrogen. Very limited differences were observed in the behavior of the two steel grades, and an increase in scale thickness is observed for the reheating in an atmosphere with 100% hydrogen, where the interface between scale and steel appears complex and entangled.

Finally, in "Hydrogen role in the valorization of integrated steelworks process off-gases though methane and methanol syntheses" a completely different but still very valuable usage of hydrogen to reduce CO_2 emissions related to the integrated steel production cycle is considered, namely hydrogen enrichment of process off-gases for their valorization though methane and methanol syntheses. In particular, stationary scenario analyses are described, which showed that the required hydrogen amount is significant and existing renewable hydrogen production technologies are still far away from satisfying the demand in an economic perspective. Moreover, an ad-hoc developed Dispatch Controller (DC) is described for managing hydrogen intensified syntheses in integrated steelwork, which considers both economic and environmental impacts in the cost function to be optimized. Dynamic tests through the DC application showed that the hydrogen costs highly affect the DC decisions, by underlying the need for big scale green hydrogen production processes and dedicated green markets for hydrogen-intensive industries, which can ensure demands satisfaction and can pave the way for a C-lean and more sustainable steel production.

For the reader's information, the program of H2GreenSteel Workshop is given in the Appendix A.

Acknowledgments. The European Steel technology Platform (ESTEP) is gratefully acknowledged for having organized and hosted the Workshop, during which the topics treated in this special issue were presented, and for having co-funded the open access publication of some papers, when the authors agreed to have their papers publicly available.

Appendix A: Program of H2GreenSteel Web-Workshop

Session 1: Low carbon Hydrogen production and supply chain

Opening Lecture: Klaus PETERS, ESTEP SG

Opening Lecture: Jane AMILHAT, European Commission, Head of Unit (DG RTD C3)

H2FUTURE Green Hydrogen, H. WOLFMEIR, voestalpine

Development of a complete value chain for green hydrogen for industrial use in a high-temperature steel process in the northern part of Norway, S. NÆVERMO-SAND, CELSA Nordic, and G.M. BREKKE, Statkraft

Keynote Lecture: Mike GRANT, Air Liquide, Tying it all Together – Hydrogen Supply and Use for a Carbon Neutral Steel Industry

Comprehensive view of sustainable hydrogen production routes for green steelmaking, N. JÄGER, ThyssenKrupp

Outlook into the Hydrogen cycle in EAF Steelmaking, A. LANARI, SMS Group, and S. MAGNANI, Paul Wurth Italia S.p.A

Session 2 – Part I: Hydrogen metallurgy and related up/down streams processes issues

Keynote Lecture: Thomas BÜRGLER, voestalpine, Developments and trends in green steelmaking at voestalpine

Hydrogen steelmaking, Part 1: Physical chemistry and process metallurgy, F. PATISSON, Université de Lorraine – IJL

Hydrogen steelmaking, Part 2: Competition with other zero-carbon steelmaking solutions and geopolitical issues, J.P. BIRAT, IF Steelman

Hydrogen role in the valorisation of integrated steelworks process off-gases through methane and methanol synthesis, I. MATINO, Scuola Superiore Sant'Anna

Hydrogen plasma smelting reduction – Carbon-free steelmaking, A. SORMANN, K1-MET GmbH

Influence of H_2–H_2O content on the reduction of acid iron ore pellets in a CO–CO_2–N_2 reducing atmosphere, A. ABDELRAHIM, Oulu University

Development and testing of flameless burner fed by NG/H_2 mix, U. Zanusso, SMS Group, and I. Luzzo, Rina

Rolling mill decarbonisation: Tenova SmartBurners with 100% Hydrogen, A. DELLA ROCCA, Tenova

Session 2 – Part II: Hydrogen metallurgy and related up/down streams processes issues

Keynote Lecture: Alexander REDENIUS, Salzgitter, Green Steelmaking 2.0–SALCOS + ENERGIRON

Numerical analysis of a shaft furnace for hydrogen reduction of iron oxide pellets, H. SAXEN, Abo Akademi University

Effects of H_2 combustion on scale growth and steel surface quality in reheating furnaces, G. JOCHLER, Rina

The DR-OSBF route for production of Virgin Iron Units, P. STAGNOLI, Tenova

Hydrogen use in a Midrex Direct Reduction Plant, R. MILLNER, Primetals

Technologies for use of hydrogen in melting, heating and reheating, J. VON SCHEELE, Linde Technology

Green Hydrogen for decreasing the fossil fuels exploitation in electric steelmaking route: one of the identified priority intervention areas of the ESTEP roadmap for an improved EAF scrap route, V. COLLA, Scuola Superiore Sant'Anna

Greening the steel industry with hydrogen, A. SASIAIN CONDE, K1-MET GmbH

Session 3: Norm and Standards relevant for Hydrogen application in steelworks & Session 4: Hydrogen safety, availability and market and related legislation and social impact

Opening Lecture: Rosalinde VAN DER VLIES, European Commission, Director – Clean Planet (DG RTD, unit C)

Keynote Lecture: Renzo VALENTINI, University of Pisa, Materials safety with respect to hydrogen-induced problems

Feasibility study for the utilization of natural gas and hydrogen blends on industrial furnaces, I. LUZZO, Rina, and A. GAMBATO, Snam Rete Gas

Green Hydrogen for steel processing, J.-C. BIDAUT, John Cockerill

A review on kinetics of iron ore reduction by Hydrogen, A. HEIDARI, University of Oulu

Hydrogen direct reduced iron and steel production in Norway with grid-connected electrolysers for Hydrogen production, A. BHASKAR, University of Stavanger

Hydrogen demand and feasibility for the Italian electrical steel industry, A. DI DONATO, Rina

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