DOI 10.36146/2026_03_71

Use of renewable and alternative carbon-bearing materials and hydrogen in the Electric Arc Furnace: simulations and pilot trials

V. Colla, I. Matino, O. Toscanelli, A. Soto Larzabal, A. Zubero Lombardia, T. Rodriguez Duran, J. Orre, E. Sandberg, M. Lundgren, M. Magnelov, D. Muren, P. Kwaschny, A. Zaccara

The achievement of C-lean and sustainable steelmaking processes is one of the challenges of the European Green Deal to target the climate neutrality by 2050. In this context, electric steelmaking is investigating alternatives to improve the sustainability of its production routes. The use of alternative carbon-bearing materials in electric arc furnaces and the replacement of natural gas with green hydrogen in related burners are two promising solutions. However, investigations are fundamental to assessing the viability of different technological solutions and their possible combination by avoiding unexpected process and product issues. Therefore, next to industrial trials, simulations are important to broaden the investigation, as they enable exploration of process configurations and the use of materials that are also quite far from conventional practices and that cannot be directly investigated through experiments for economic and practical constraints, such as material unavailability and high costs. The contribution focuses on the results of pilot trials and simulations done with an updated flowsheet model of the electric steelmaking route.

KEYWORDS: ELECTRIC STEELMAKING, ALTERNATIVE CARBON BEARING MATERIALS, HYDROGEN, EAF BURNERS, SUSTAINABILITY, MODELLING AND SIMULATION, PILOT TRIALS;

INTRODUCTION

The European steel sector is challenged by the ambitious objectives of the European Green Deal, which aims at achieving climate neutrality by 2050. Therefore, novel C-lean and sustainable steelmaking processes are being investigated through large-scale pilot projects, accompanied by studies on the possibility of improving operating practices and introducing new components in conventional routes. Moreover, Circular Economy and Industrial Symbiosis can further support the decarbonization process [1, 2] while reducing depletion of natural resources.

As far as the electric steelmaking route is concerned, many recent investigations focus on the replacement of fossil carbon-bearing materials fed to the Electric Arc Furnace (EAF) with renewable and/or Alternative Carbon-bearing Materials (ACMs) [3] from biogenic [4] and non-biogenic sources [5, 6]. Moreover, the use of green hydrogen to at least partially substitute Natural Gas (NG) in the EAF for heating purposes is intensively investigated [7,8].

Valentina Colla, Ismael Matino, Orlando Toscanelli
Scuola Superiore Sant'Anna, TeCIP Institute, Pisa, Italy

Antonella Zaccara
Scuola Superiore Sant'Anna, Pisa, Italy /
Università di Padova, Padova, Italy

Aintzane Soto Larzabal, Asier Zubero Lombardia
Sidenor Aceros Especiales, Basauri, Bizkaia, Spain

Tamara Rodriguez Duran
Sidenor I+D, Basauri, Bizkaia, Spain

Joel Orre, Erik Sandberg, Maria Lundgren, Marianne Magnelov
Swerim AB, Lulea, Sweden

David Muren, Pascal Kwaschny
Linde Sverige AB, Sweden

In this context the project entitled "Gradual Integration of Renewable non-fossil energy sources and modular heating technologies in EAF for progressive CO_2 decrease" (Ref. GreenHeatEAF – G.A. No. 101092328) aims at exploring and validating these decarbonization strategies through the integrated and synergistic use of pilot and demonstration trials, advanced digital simulations, and enhanced monitoring and control systems. In effects, while pilot trials are indeed fundamental to thoroughly assessing the industrial feasibility of the investigated substantial modifications in process operations [9, 10], they are costly and time-consuming, thus they cannot span the full range of possible process conditions of interest and possible input material mix and/or Hydrogen/NG blends. On the other hand, simulations through a validated physics-based model, although based on a virtual replica of the EAF which relies on assumptions and simplifications, enable exploring a wide range of scenarios and make detailed sensitivity analyses [11, 12]. Therefore, the combination of these two investigation approaches provides an ideal insight into the viability of potential modifications of consolidated industrial practices.

Within GreenHeatEAF, industrial trials were conducted to identify ACMs with characteristics that are similar to standard fossil carbon that do not affect process reliability nor product quality. The industrial tests also aimed to evaluate the handling characteristics and safety implications of using ACMs in EAF-based steel production. Pilot trials were conducted in a pilot EAF with a capacity of 10 tons [13] to assess both the effect of transition from NG to hydrogen as fuel in the burners and the effect of transition from fossil carbon to biochar. Simulations were carried out via a stationary flowsheet model of the EAF-based steelmaking route, which was updated to simulate the addition of pyrolyzed biomass, i.e. bio-carbon/biochar, plastic and tires in the EAF and the feeding of the EAF burners with hydrogen or NG/hydrogen blends [14].

This paper presents the methodology adopted for pilot trials and simulations, and overviews the most relevant results of both investigations, by highlighting the opportunities and barriers.

METODOLOGY

Pilot Trials

Pilot trials were conducted to evaluate both the effect of transition from NG to hydrogen as fuel in the burners and the effect of transition from fossil carbon to bio-carbon.

The use of alternative fuels and carbon sources was tested in a pilot EAF available at Swerim's facilities in Lulea (Sweden), which has a capacity of 10 tons and was equipped with a CoJet-burner manufactured by Linde for these trials. The fundamental principle underlying CoJet technology is the use of an annular oxy-fuel flame shroud that envelops the primary supersonic jet, thereby generating a coherent jet capable of penetrating more deeply into the molten bath compared to a conventional supersonic jet [15]. The use of this type of burner is well established in EAF operations; however, the novelty of the present trials lies in feeding a suitably adapted CoJet burner with hydrogen over extended periods that was not previously investigated. The injected hydrogen is produced in the same experimental facility thanks to Swerim's high-pressure alkaline electrolyzer.

The carbon was injected in the pilot EAF via a pressurized carbon dispenser equipped with a roto-feeder and a supersonic wall-mounted carbon injector manufacture by Tallman Technologies using nitrogen as carrier gas. During the tests, carbon was also available for feeding from via the overhead bin. As emerged from previous experiments, the injectable particle size of the carbon material must not exceed 3 mm, and the moisture content must be lower than 5% to minimize the risk of clogging. In addition, the ash and volatile matter contents should be low to achieve a high fixed carbon content and to prevent adverse effects on the process. Based on this experience, the trials concerned:

1. Injection of bio-carbon to investigate the difference on slag foaming and slag reduction. Anthracite was used as reference carbon source.
2. Hydrogen use with Linde CoJet-burner by using Synthetic NG (SNG) as reference burner fuel.

Considering the ongoing transition of steel production towards more sustainable processes—characterised by the increasing use of Hot Briquetted Iron (HBI) and Direct

Reduced Iron (DRI), together with higher degree of continuous feeding—various iron carriers and charge mixes were employed in the tests to reflect expected variability of future EAF steelmaking operations, as follows:

1. Scrap charging with two-basket practice and carbon injection during the refining phase.
2. Scrap+HBI charging with one-basket practice and subsequent HBI feeding, and carbon injection during the HBI feeding phase and the refining phase.
3. Continuous scrap feeding and carbon injection used during the entire process.
4. Continuous DRI feeding, and carbon injection used during the entire process.

During the trials, anthracite was used as charge carbon in both the scrap and HBI charging campaigns. The experimental campaign comprised of 25 heats.

For each iron carrier and its corresponding process configuration, the following trial blocks were defined:

1. SNG-Anthracite, reference trials using SNG as burner fuel and anthracite as injected carbon.
2. H_2-Antrhacite using hydrogen as burner fuel and anthracite as injected carbon.
3. H_2-Biocarbon using hydrogen as burner fuel and bio-based carbon as injected carbon.

The described experimental design enables the assessment of the impact of substituting NG with hydrogen as burner fuel through the comparison of H_2- Anthracite with SNG-Anthracite and the evaluation of the effect of replacing fossil carbon with bio-carbon comparing H_2-Biocarbon with H_2-Anthracite.

The bio-carbon selected for the trials is wood-based charcoal with high carbon content, which is similar to fossil anthracite. Bio-carbon has lower density, volatile matter and ash content as Sulphur, see table 1, which provides the chemical composition (in wt%) of the adopted materials for injection. Photographic images of the bio-carbon and anthracite for injection are provided in figure 1.

Tab.1 - Properties of carbon materials used in the pilot trials.

CARBON ANALYSIS							
C (%)	S (%)	N (%)	H (%	Moisture (%)	Volatile matter (%)	Ash (%)	Density (g/cm³)
Anthracite, 0-3 mm, as injection carbon. Supplier Carbomax							
85.1	0.197	1.06	2.0	5.9	1.6	5.5	0.94
Bio-carbon, 0-3 mm, as injection carbon. Supplier Envigas							
89.1	0,023	0.22	2.8	3.2	4.8	1.1	0.64

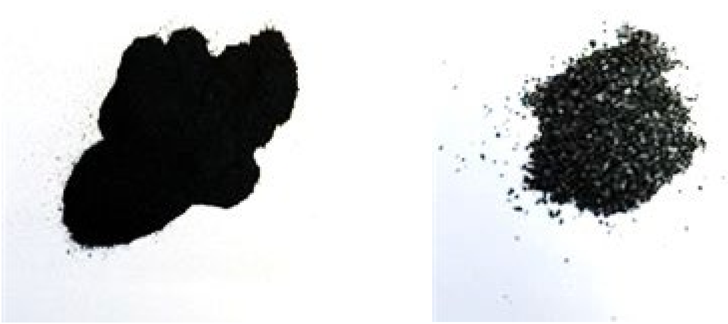

(a) (b)

Fig.1 - Photos of (a) bio-carbon, (b) injection anthracite 1-3 mm.

Simulations

The model used for the simulations is developed in Aspen Plus® V11 and allows simulation of all the common steps of standard electric scrap-based steelmaking route from charging mix preparation to continuous casting through the combination of standard process blocks, customized calculators, and design specification units [11, 12]. The modular modelling framework considers key physical and chemical phenomena in the EAF process. It estimates molten steel quantity, temperature, and composition at different stages, as well as slag characteristics, electricity demand, and overall mass and energy balances. Since the model is based on input parameters and tuning data that are regularly measured in industrial practice, it can be easily calibrated, validated, and adapted across different steel plants and steel grades. Its modular structure also enables targeted modifications, as in this work to evaluate the replacement of fossil carbon in slag foaming and the substitution of natural gas in EAF burner operations.

For the planned investigations, alternative carbon-bearing materials were modelled as non-conventional solids starting from suppliers' data. Furthermore, related streams and new unit blocks were added to the original version of the model, and some were modified to allow the use of these materials and simulate their effects. Literature and industrial data—coming from plant standard operations and collected during field trials—were used for the scope. In particular, literature data [16–18] together with industrial results from an initial set of field trials—focused on replacing the quantity of anthracite added to an industrial EAF through the 5th hole for slag foaming—were used to tune the model. The calibrated model was then tested against industrial data not used during the tuning phase. The tuning and validation procedures, as well as the test results, are deeply described in [14]. For instance, the relative percentage error ranges of the tests—i.e., (simulated value-actual value)/(actual value) %—for tapped steel amount is between 5.22% and 9.95%.

Similarly, considering literature data, new streams and unit blocks were included in the model for allowing the use of hydrogen (or blend with NG) in EAF burners and consider related effects. Specifically, it was necessary to add design specification blocks to manage gas flows to ensure the same energy input regardless of the gas mixtures used.

The adapted flowsheet model was used to perform scenario analyses aimed at assessing the effects of using alternative carbon-bearing materials and/or hydrogen on both process performance and key product characteristics (e.g. composition).

1. Alternative carbon-sources: the simulations allowed to include effects not considered in industrial trials (e.g., electricity demand, fossil CO_2 emissions, steel composition, slag mass quantity) and to test a greater number of alternative materials, thereby complementing pilot and industrial tests, which focused mainly on foaming performance and safety issues, aspects not considered in the simulations. Specifically, simulations permit to evaluate the impact of replacing only the anthracite charged through the 5th hole of the EAF for starting the slag foaming—which represents less than 15% of the total fossil carbon input—while ensuring a fixed carbon input or energy supply, as well as the effect of the replacement of the entire amount of carbon needed for slag foaming (anthracite + foaming coal). In addition, sensitivity analyses are performed to evaluate the effect of the contents of different biochar compounds.
2. H_2 usage as burner fuel: the simulations examine the gradual substitution of NG used under standard operating conditions with H_2, while maintaining an equivalent total energy input to the EAF. Key process indicators—including EAF off-gas composition, steel chemistry, and relevant operational parameters (e.g., electrical energy demand, slag quantity, and slag composition)—are systematically monitored. Furthermore, the simulations encompass the entire secondary metallurgy to evaluate whether the current Vacuum Degassing (VD) practice is adequate to mitigate potential adverse effects on tapped steel quality, particularly those associated with increased hydrogen content.

EXPERIMENTAL AND SIMULATION RESULTS

Results of the pilot trials

The results from the trials were evaluated with respect to yield of injected carbon, slag foaming quality, steel chemistry, slag chemistry and dust and off-gas generation.

Figure 2 shows the total carbon yield for each heat. The carbon yield is calculated using output from the HSC model described by J. Orre et al [19]. The average carbon yield is 53% for anthracite (excluding the heat with negative carbon yield) and 42% for the investigated biocarbon. This is equivalent to a replacement factor of 1.25 for carbon in anthracite with carbon in the investigated bio-carbon, i.e. 25% more carbon atoms are needed for bio-carbon injection.

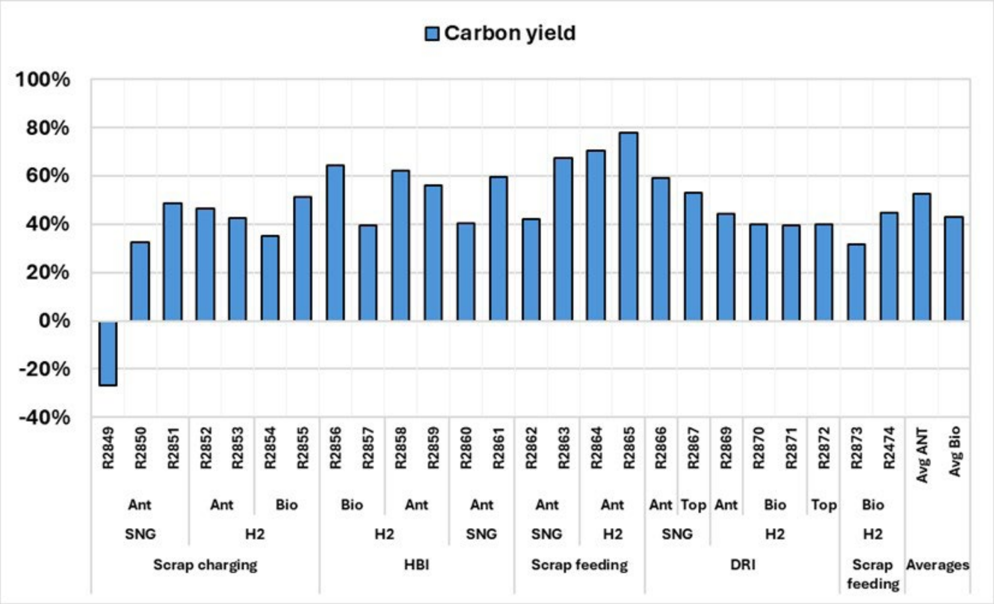


Fig.2 - Carbon yield to slag reduction.

The slag foaming was assessed by visual inspection when the slag door of the EAF was opened for sampling. The following classification of the slag foaming performance was adopted:

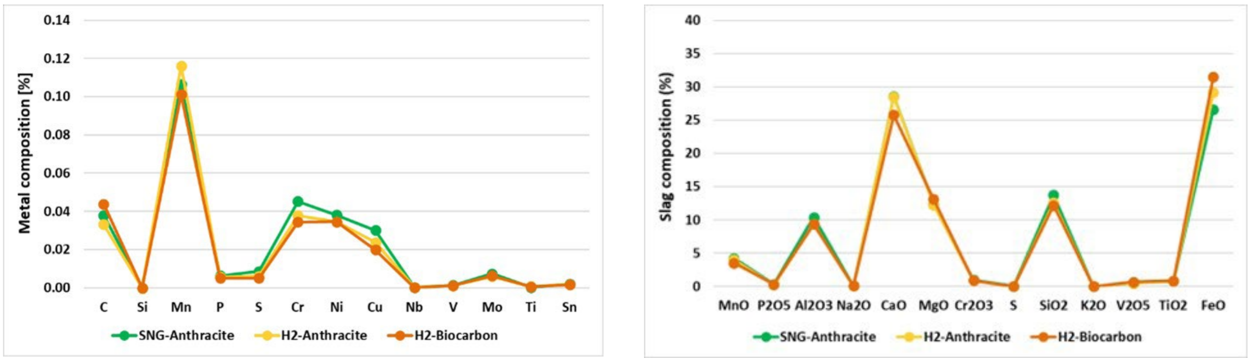
1. bad, if the arcs are clearly visible in the furnace;
2. OK, if the arcs in the furnace are not visible and the slag is not at the level of the slag door when the furnace is in horizontal position;
3. good, if the arcs in the furnace are not visible and the slag is at the level of the slag door when the furnace is in horizontal position or inclined towards the steel tapping side.

Table 2 reports the average values of qualitative results of slag foaming assessment for the three trial blocks described before under different process conditions. The inspection showed that the foaming is good and equivalent for all the different CoJet fuels and injected carbon sources

Tab.2 - Average slag foaming quality for the different trial blocks.

SNG-Anthracite	H_2-Anthracite	H_2-Biocarbon
2.4	2.9	2.8

Metal and slag chemical composition was assessed during the trials (see figure 3), and the results showed that no significant effects were observed on steel and slag chemical compositions in relation to use of hydrogen. However, the FeO content of the slag was generally higher for the bio-carbon heats (34% compared to 28% for the anthracite heats). Consequently, the iron losses to slag (and removal of oxidizable impurity elements as Mn and Cr to slag) were higher for the bio-carbon heats. The Sulphur content of the steel was also slightly lower for the bio-carbon heats, which can be explained by the lower Sulphur content of the bio-carbon than the anthracite (see table 1).

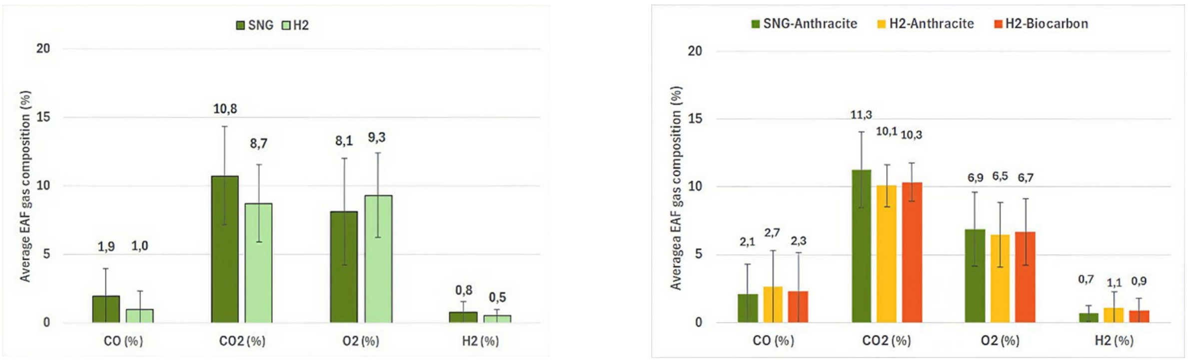


(a) (b)

Fig.3 - Chemical compositions (wt%) of a) Average tapped metal; b) Average EAF slag.

Also, it is important to mention that the impact of hydrogen on the metal composition cannot be evaluated since the content of hydrogen was not measured in the melted metal. This aspect was therefore investigated by simulations, as showed in section "Results of the simulations".

The EAF-gas composition in terms of volume percent of CO, CO_2, O_2 and H_2 was continuously measured during the trial campaign. Figure 4a compares tests with H_2 as fuel with SNG, while figure 4b shows the average EAF gas composition for the different burner fuels and the different carbon sources. The average gas composition in burner mode was calculated using data from periods when the burner was operating during the scrap charging trials and the HBI feeding trials. Figure 4 shows that using H_2 instead of NG as fuel has a positive effect in terms of CO_2 emission reduction, while no significant difference was observed on EAF-gas composition between anthracite and bio-carbon.



(a) (b)

Fig.4 - a) Average gas composition for different burner fuels; b) Average gas composition for the different burner fuels and the different carbon sources.

Finally, possible differences in dusts compositions were assessed. During the trials, the weight of off-gas dust, collected in barrels after the bag house filter, were recorded for each heat. Furthermore, the chemical composition of the collected dust samples was analysed. Although the variations in dust chemistry and amount were quite high during the tests due to variations in zinc and alkali contents of the charge materials, the difference in dust chemistry for use of bio-carbon and anthracite were insignificant.

Results of the simulations

Table 3 summarises the results of the two main simulated scenarios. Concerning the effects of the use of alternative carbon-sources as foaming materials, the variations of the following monitored variables have been included in the table: EAF specific electrical energy consumptions, specific CO_2 emissions and slag, and contents of C and S in tapped steel. The use of H_2 in EAF burners is assessed, among others, by monitoring the content of H_2 in liquid steel during tapping and after VD, to complement pilot and industrial trials that do not monitor this aspect.

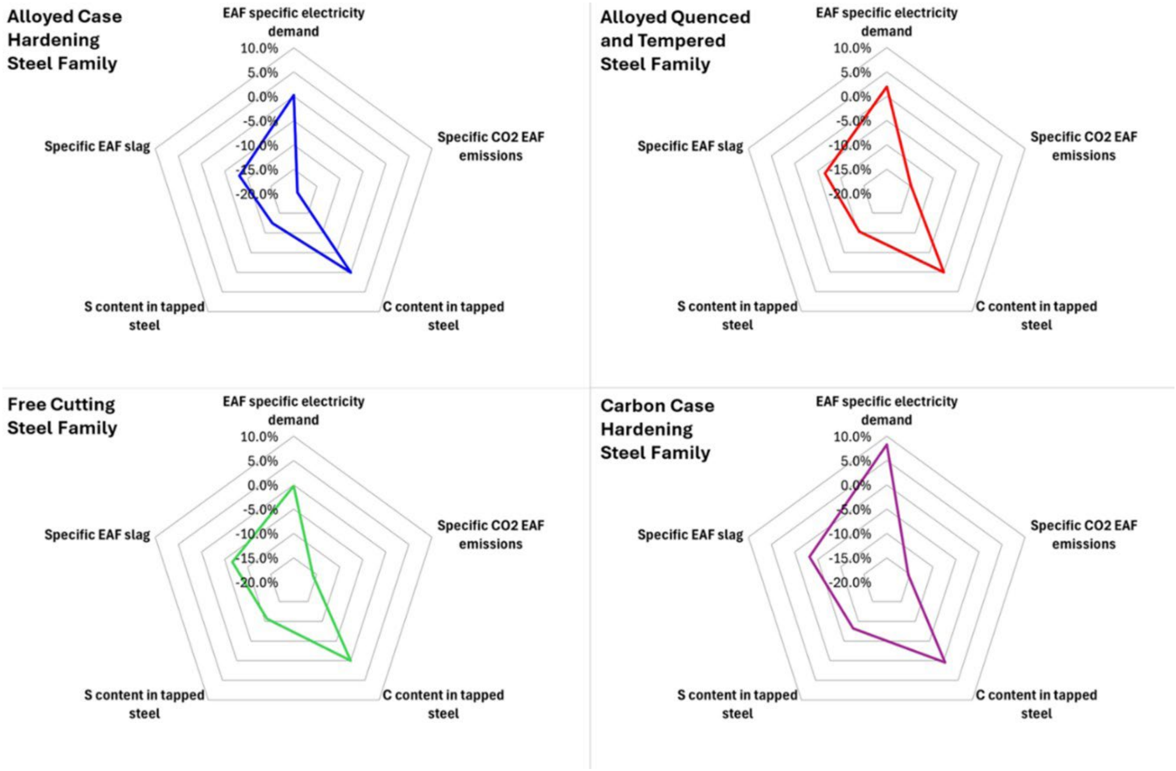
The results are reported in terms of range of variation with respect to reference conditions, considering the whole explored range, and all the simulated heats and considered materials.

Tab.3 - Overview of the results of the simulations.

	Simulation Aim	Reference	Monitored Variable	Variation range
1. Alternative C-sources	Replacement of fossil carbon used for slag foaming process with alternative carbon-bearing materials	Use of fossil carbon in slag foaming process (anthracite for starting + foaming coal)	EAF specific electricity demand	[-9.4% +8.3%]
			Specific CO_2 EAF emissions	[-19.2% -0.9%]
			Specific EAF slag	[-8.7% +1.3%]
			C content in tapped steel	[-7.2% +2.3%]
			S in tapped steel	[-12.5% +16.2%]
2. H_2 usage as burner fuel	Gradual replacement of NG with H_2 in EAF burners (step of 10% of NG energetic contribution)	Full NG use in EAF burners	H_2 in tapped steel	[+1.1% +170.4%]
			H_2 in liquid steel after VD	[+0.8% +79.8%]

In scenario 1, the high values of electricity consumption reductions are connected to the use of tires at fixed carbon fed, while the increases of required electric energy are generally related to the full replacement of fossil carbon with biochar. They depend on the lower Higher Heating Value (HHV) of almost all the considered biochars compared to reference anthracite and to their moisture content. However, the extent of such increase depends on the produced steel family (i.e. group of similar steel grades) and related operating practices. Obviously, higher fossil CO_2 reductions are achieved when global replacement of fossil carbon compared to replacement of anthracite only. Moreover, higher decreases in slag amount refer to full replacement of fossil carbon, while slight increase of slag amount has been observed with biochars having higher carbon content. Finally, a reduction in carbon content is obtained by using tires in simulation at fixed supplied energy, and high Sulphur content reductions refer to full replacement of fossil carbon with biochar, while Sulphur content increases if tires are used. As anticipated, full fossil carbon replacement yields the most significant variations. Figure 5 depicts the specific results of some simulations where fossil carbon is entirely replaced by one of the considered biochar (80% wt. of fixed C and 7.4 kWh/kg of HHV), while ensuring the same fed carbon as the reference case. The results shown relate to four simulated heats belonging to different steel families; they are reported in terms of variations of the variables considered in table 3 with respect to the reference heat. It can be observed that, although similar trends, the extent of the obtained variations in monitored variables depends on the produced steel family and consequently on operating conditions used in related productions.

In scenario 2 an increase of H_2 content in tapped steel is observed in all simulations. Besides the values reported in table 3, a typical obtained trend is depicted in the illustrative figure 6, where an example is shown of the extent of H_2 variations in steel in case of gradual replacement of NG in EAF burners. Specifically, with full replacement of NG in EAF burners, hydrogen content in tapped steel, while remaining within the ppm range, more than doubles compared to the reference heats where only NG is fed to EAF burners. However, simulations also show that this increase does not affect the final product, as it can be handled by current VD procedures, that are always capable of ensuring that the required specification is met in obtained steel.


Alloyed Case Hardening Steel Family

Alloyed Quenced and Tempered Steel Family

Free Cutting Steel Family

Carbon Case Hardening Steel Family

Fig.5 - Examples of results obtained during simulations of heats belonging to different steel families and aimed at full replacement of fossil carbon with biochar.

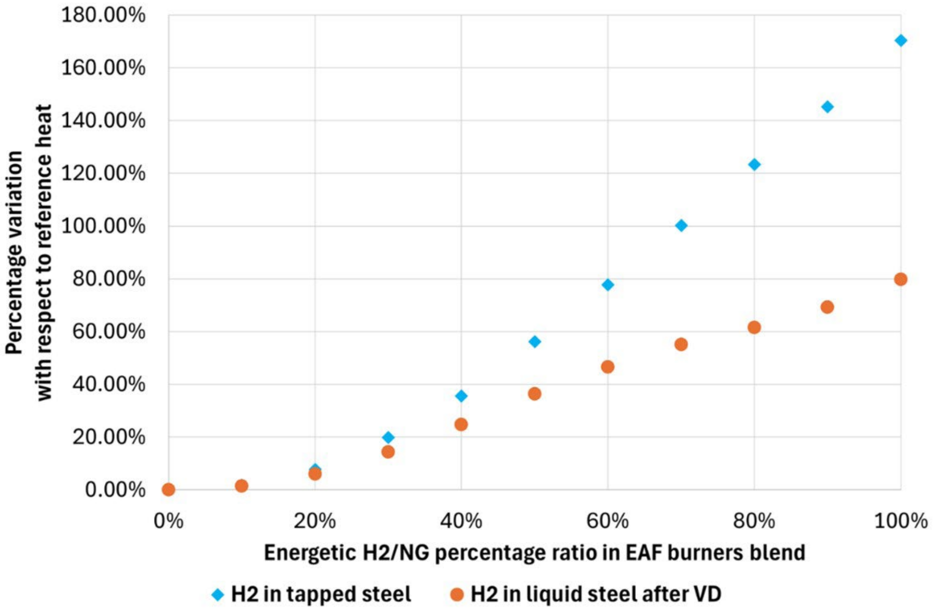


Fig.6 - Example of variations of hydrogen in steel obtained in simulations of the gradual NG replacement with H_2 in EAF burners.

CONCLUSIONS AND OUTLOOK

The pilot trials in Swerim's EAF were conducted successfully and the following conclusions can be drawn.

1. In the pilot trials carbon in fossil anthracite was replaced by carbon in bio-carbon with a replacement ratio of 1.25, providing the following outcomes.
    - The slag foaming was mostly good, and no significant difference arises between trials with injection of anthracite and biocarbon.
    - The use of bio-carbon led to a decrease in Sulphur content in slag and metal due to lower Sulphur input compared to anthracite.
    - No significant difference arose on the composition of EAF off-gas and dust between trials with injection of anthracite and the investigated bio-carbon. No substantial difference was expected since the contents of carbon and Hydrogen are similar, although bio-carbon has slightly higher Hydrogen content.
    - Some further process optimization considering the total carbon and Oxygen input to the furnace may be investigated. For example, reduced oxygen injection could reduce the need for bio-carbon for slag reduction without negative effects on the slag foaming or FeO content due to higher gas generation per carbon atom provided by the bio-carbon than the anthracite.
    - The reasons for the lower yield of carbon in bio-carbon (42%) compared to anthracite (53%) may be further investigated. Factors likely to contribute to the lower carbon yield of bio-carbon are material properties like higher volatile content, lower density and smaller particle size.
    - Adaption of production methods for improving bio-carbon properties for use with standard injection systems at EAF steel plants, or adaption of standard injection systems for use of bio-carbon could improve the carbon yield and reduce the replacement ratio for bio-carbon.
2. H_2 was used with a 1:1 energy replacement ratio between SNG and H_2 [19]
    - There were no significant measured differences on steel, slag, dust and off-gas composition. However, simulation indicated significant higher H-content in the steel when using hydrogen injection.
    - Further investigation of the actual Hydrogen content in crude steel when using hydrogen injection and its effect on the final steel quality is of interest for future work.
    - It is confirmed that CO_2 emissions are higher in SNG-based heats compared to H_2-heats.

The simulations investigated substitutes of fossil carbon with similar or lower characteristics of used anthracite; generally, they do not provide negative effects on process and product. Also, the replacement of the entire amount of foaming carbon (anthracite through the 5th hole + foaming coal) does not affect negatively the process performance or the quality of the liquid steel. In general, substituting fossil carbon in the foaming process with various types of alternative carbon-bearing materials can lower CO_2 emissions. The carbon and sulfur contents in tapped steel rise in proportion to their respective concentrations in the considered alternative carbon-bearing materials. In addition, electric energy demand increases with higher moisture contents and is also influenced by volatile matter content and HHV.

To sum up, the combination of pilot trials and simulation highlights that no major negative effects on the product are observed from the use of alternative C-bearing material, independently of the way they are introduced in the furnace. However, further parallel real industrial trials showed that an excessive amount of some of these materials may jeopardize operational safety and leads to poor slag foaming. Furthermore, it is possible to confirm that hydrogen can be used as burner fuels with benefit in terms of CO2 emissions. Large quantities of hydrogen fuel result in an increase of hydrogen content in liquid steel but standard VD operating practices appear adequate to mitigate this effect leading to a final hydrogen content meeting the given specifications for each considered steel family.

ACKNOWLEDGEMENTS

The work described in the present paper has been developed within the project entitled "Gradual Integration of Renewable non-fossil energy sources and modular heating technologies in EAF for progressive CO_2 decrease" (GreenHeatEAF – G.A. No. 101092328) that has received funding from the European Union through the Horizon Europe programme, which is gratefully acknowledged. The sole responsibility for the issues treated in the present paper lies with the authors; the Commission is not responsible for any use that may be made of the information contained therein.

REFERENCES

[1] European Commission, "Circular Economy Action Plan", accessed 15 January 2026, https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[2] V. Colla, T.A. Branca, R. Pietruck, S. Wölfelschneider, A. Morillon, D. Algermissen, S. Rosendhal, H. Granbom, U. Martini, D. Snaet, "Future Research and Developments on Reuse and Recycling of Steelmaking By-Products," Metals, 2023, vol. 13, no. 4., art. 676. https://doi.org/10.3390/met13040676

[3] T. Echterhof, "Review on the use of alternative carbon sources in EAF steelmaking". Metals, 2021, vol. 11, no. 2, art. 222. https://doi/org/10.3390/met11020222

[4] A. Cardarelli, M. Barbanera, "Substitution of Fossil Coal with Hydrochar from Agricultural Waste in the Electric Arc Furnace Steel Industry: A Comprehensive Life Cycle Analysis," Energies, 2023, vol. 16, No. 15, art. 5686. https://doi.org/10.3390/en16155686

[5] M. Bissoli, E. Malfa, E. Marchesan, L. Di Sante, M. Casa, P. Frittella, L. Salas, "Multi-material injection system to foster circularity: Valorization of recycled polymers from waste plastics in electric arc furnace," Thermal Science and Engineering Progress 2025, vol. 61, https://doi.org/10.1016/j.tsep.2025.103497

[6] F. Cirilli, M. De Santis, L. Di Sante, D. Mirabile, L. Kieush, J. Rieger, J. Borlée, C. Brondi, D. Rov-elli, T. Echterhof, C. Thaler, N. Jaeger, K. Peters,·D. Snaet, V. Colla, I. Matino, M. Bissoli, E. Malfa, S. Möhring, G. Stubbe, R. Attrotto, A. Sorino, G.B. Landra, M. Bianchi, L. Bianco,·M. Chini, D. Gaspardo: "A Comprehensive Review of Secondary Carbon Carriers for Ironmaking and Steelmaking Processes: Industrial Utilization of Non-biogenic Materials in Steel Production," Journal of Sustainable Metallurgy, 2025, vol. 11, no. 4, p. 3343, https://doi.org/10.1007/s40831-025-01149-5

[7] J. von Schéele, "Pathways towards full use of hydrogen as reductant and fuel," Matériaux & Techniques, 2023, vol. 111 no. 4, art. 405. https://doi.org/10.1051/mattech/2023030

[8] M. Mostafa, A. Ashabi, A. Hryshcenko, I. O'callaghan, K. Bruton, D.T.J.O. Sullivan, "Green Hydrogen Penetration in Steel Industry Operations: A Year-long Modeling Case Study," 6th International Conference on Environmental Sciences and Renewable Energy - ESRE 2024, p. 566. https://doi.org/10.1051/e3sconf/202456603003

[9] C. Wang, Y.C. Lu, L. Brabie, G. Wang, "A Pilot Trial Investigation of Using Hydrochar Derived from Biomass Residues for EAF Process," Minerals, Metals and Materials Series 2023, p. 153. https://doi.org/10.1007/978-3-031-22634-2_15

[10] F. Cirilli, G. Baracchini, L. Bianco, "EAF long term industrial trials of utilization of char from biomass as fossil coal substitute," La Metallurgia Italiana 2017, vol. 109, no. 2, p. 13.

[11] I. Matino, E. Alcamisi, V. Colla, S. Baragiola, P. Moni, "Process modelling and simulation of electric arc furnace steelmaking to allow prognostic evaluations of process environmental and energy impacts," Matériaux & Techniques, 2016, vol. 104, no. 1, art. 104. https://doi.org/10.1051/mattech/2016004

[12] I. Matino, A. Petrucciani, A. Zaccara, V. Colla, M. Ferrer Prieto, R. Arias Pérez, "Characterization of EAF and LF Slags Through an Upgraded Stationary Flowsheet Model of the Electric Steelmaking Route," Metals, 2025, vol. 15, no. 3, art. 279. https://doi.org/10.3390/met15030279

[13] I. Heintz, E. Mousa, G. Ye, "Development of Fossil-Free Technologies for the Metallurgical Industry—Swerim Pilot and Industrial Experiences," Minerals, Metals and Materials Series 2023, p. 55. https://doi.org/10.1007/978-3-031-22634-2_5

[14] I. Matino, V. Colla, A. Petrucciani, A. Zaccara, O. Toscanelli, A. Soto Lazabal, A. Zubero Lombardia, "An advanced simulation tool to support adoption of alternative non-fossil carbon sources in electric steelworks," Materiaux et Techniques 2024, vol. 112, no. 5, art. 504. https://doi.org/10.1051/mattech/2024029

[15] W. Mahoney, A. Deneys, P. Mathur, S. Warty, "The Critical Role of Hydrogen in Linde's Coherent Jet Technology," AISTech - Iron and Steel Technology Conference Proceedings 2023, p. 566. https://doi.org/10.33313/387/065

[16] R. Robinson, L. Brabie, M. Pettersson, M. Amovic, and R. Ljunggren, "An empirical comparative study of renewable biochar and fossil carbon as carburizer in steelmaking. ISIJ International 2022, vol. 62 no. 12, p. 2522, https://doi.org/10.2355/isijinternational.ISIJINT-2020-135

[17] M. Mayyas, R. K. Nekouei, and V. Sahajwalla, "Valorization of lignin biomass as a carbon feedstock in steel industry: Iron oxide reduction, steel carburizing and slag foaming" Journal of Cleaner Production 2019, vol. 219, p. 971, https://doi.org/10.1016/j.jclepro.2019.02.114

[18] L. Kieush, J. Schenk, A. Koveria, G. Rantitsch, A. Hrubiak, and H. Hopfinger, "Utilization of renewable carbon in electric arc furnace-based steel production: comparative evaluation of properties of conventional and non-conventional carbon-bearing sources", Metals 2023, vol. 13, no. 4, art. 722. https://doi.org/10.3390/met13040722

[19] J. Orre, E. Sandberg, M. Magnelöv, "Effects of H2 as energy source and biocarbon injection in EAF," Proc. of the 7th European Steel Technology and Application Days ESTAD 2025, Verona (Italy), October 6-9, 2025 vol. 2, p. 173.

TORNA ALL'INDICE >