Matériaux & Techniques **112**, 504 (2024)

https://doi.org/10.1051/mattech/2024029

Matériaux & Techniques

Special Issue on 'Circular Economy initiatives and solutions in the steel sector', edited by Valentina Colla and Ismael Matino

Available online at:
www.mattech-journal.org

Original Article

Open Access

An advanced simulation tool to support adoption of alternative non-fossil carbon sources in electric steelworks

Ismael Matino[1,*], Valentina Colla[1], Alice Petrucciani[1], Antonella Zaccara[1,2], Orlando Toscanelli[1], Aintzane Soto Larzabal[3], and Asier Zubero Lombardia[4]

[1] Scuola Superiore Sant'Anna – TeCIP Institute, Via Moruzzi, 1, Pisa, 56124, Italy
[2] Università di Padova, Dipartimento di Ingegneria Industriale, Padova, 35100, Italy
[3] Sidenor Investigacion Y Desarrollo SA, Barrio Ugarte, Basauri, 48970, Spain
[4] Sidenor Aceros Especiales, Barrio Ugarte, Basauri, 48970, Spain

Received: 31 May 2024 / Accepted: 14 November 2024

Abstract. In the European Green Deal background, electric steelworks are highly committed to decrease their environmental impact and greenhouse gas emissions. Among the different solutions, the use of alternative non-fossil carbon sources is promising for reducing both the environmental impact and the dependency from fossil energy and C-sources markets. The paper fits into this context and focuses on the application of an advanced model to support the investigations for the adoption of alternative non-fossil carbon sources in electric steelworks. The model is an update of a previous version allowing the simulation of a standard electric scrap route; model adaptations, validations and tests are described and showed. In addition, the first simulation results depict the possibility of obtaining a decrease between 3% and 20% of EAF CO_2 emissions by substituting fossil carbon. In parallel, a survey on the perception of the use of these kinds of tools from the European steel sector stakeholders was conducted. From the survey outcomes, it emerges an evident interest but also the need of models simple to be adapted, used, transferred and that can provide significant benefits. The adapted and used model try to fit with stakeholder requirements and to be a facilitator in the application of novel environmental friendly solutions in electric steelworks.

Keywords: electric steelworks / alternative non-fossil carbon / simulation tool / stakeholder survey / European Green Deal / steelmaking sustainability

1 Introduction

European industry is committed to contribute to the ambitious objective of the European Green Deal to make the European continent climate neutral by 2050 and to improve the leadership for clean products and technologies. Protection of human life, animals, plants and environment and an inclusive transition must be guaranteed in this period. Furtherly, recent geopolitical evolutions face Europe to high and volatile energy prices and push it to increase its energy independence. REPowerEU is the joint European action for more affordable, secure, and sustainable energy for achieving a rapid clean energy transition [1]. Therefore, joint cross-sectorial activities are required to maximize circular economy application and decarbonization of production processes. Main efforts are expected from energy and carbon intensive industries (ECII) to accelerate the switch to electrification and renewable hydrogen and enhance non-fossil carbon materials use and low-carbon manufacturing capabilities. The steel industry is one of the most ECII: EU steel industry is currently responsible for about 6% of total EU Greenhouse Gas (GHG) emissions with an amount of 221 Mt GHG per year including direct and indirect emissions [2]. Most emissions (almost 75%) come from the reduction of iron ore in the fossil carbon-based Blast Furnace (BF) route; the remaining part is linked to further fossil C-material usages for heat production (including heat losses), power generation, and materials transportation [3]. Important GHG reductions can be achieved by moving to C-lean steelmaking processes based on Direct Reduced Iron (DRI) and Electric Arc Furnace (EAF), accompanied by the substitution of fossil fuels and C-materials, with improved heat recovery and flexible heat management. In this context, EAF-based steelmaking plays a fundamental role, considering its standard scrap-based production route and its role in the evolution of the integrated route. In addition, in Europe, EAF is considered strategic for the application of Carbon Direct Avoidance (CDA) and

* Corresponding author: ismael.matino@santannapisa.it

Smart Carbon Usage (SCU) technologies, as highlighted in the ESTEP roadmap for improving the EAF scrap route [4].

Therefore, EAF steelmaking process needs to adapt to new challenges: change from fossil C and energy sources to bio-based and/or alternative non-fossil C and green H_2; use of different iron carriers from first grade scrap to more DRI and Hot Briquetted Iron (HBI) with various C-content and low-grade scrap; decrease of heat/energy losses with advanced/modular recovery technologies and advanced control systems; material valorization considering by-products changes.

In such a context, the European Union recently funded a project entitled "*Gradual integration of REnewable non-fossil ENergy sources and modular HEATing technologies in EAF for progressive CO_2 decrease*" (Ref. GreenHeatEAF) through the Horizon Europe research and innovation framework. GreenHeatEAF aims at demonstrating the integration of non-fossil fuels and alternative renewable C-sources in EAF process to decrease CO_2 emissions and dependence from fossil energy and C-sources markets, and promote circularity. The project addresses the challenges linked with these applications by combining pilot, on field (i.e. in real steelworks) and simulation investigations. Moreover, it is also devoted improving heat recovery solutions both from off-gases and slag considering the changes of their features with the introduction of hydrogen and/or biomass and different charge materials and modes. The present paper focuses on the simulation model adapted in this project for a comprehensive investigation of the effects both on the process, product and emissions of partial replacement of fossil carbonaceous fuels and materials with other alternative C-bearing renewable materials such as biomass, biochar, plastics or tires.

Depending on C content and other chemical features, these materials can replace anthracite and coal generally used as energy sources or to generate foamy slag, by thus reducing fossil CO_2 emissions [5]. In addition, materials like biomass perfectly fit into the circular economy concept that "*the value of resources is indefinitely maximized, requiring that no irrecoverable waste occurs*" [6]. Some first discussions and investigations of the use of renewable carbon bearing materials can be found in literature from the beginning of this century. For instance, in 2001, Scaife [7] makes a presentation related to the opportunities of the use of forest biomass in iron and steelmaking, and, concerning EAF based steelmaking, he suggests the use of charcoal to replace fossil carbon used as slag foamer and recarburiser. Then several researches started during the years such as the one carried out by the Energy and Environmental Research Laboratory at McGill University more focused on the application of biomass in blast furnace as biomass-doped bio-coke and pulverized biomass [8]. Exemplary are also the investigations carried out by the RWTH Aachen University: first works [9,10] refer to the biochar quality requirements for their usage in EAF, to first trials on slag foaming and effects on EAF and product and to first economic analysis; interesting is also [11] where reduction of CO_2 emissions by the use of biogenic carbon in electric steelmaking was investigated obtaining an average CO_2 savings of about 29% in the considered European countries; then more specific analyses focused on reactivity of alternative carbon sources [12,13]. The interest in alternative and non-fossil C sources increases during the years depending also on the higher awareness to GHG emissions, environmental sustainability and circular economy. This is highlighted in some recent analyses related to the use of biomass and other alternative C-bearing materials in steelmaking [14–16]. A recent review on the topic [14] showed that in the EAF-based steelmaking route, biomass and its carbonization products can replace anthracite without negative effects on process reliability, steel quality and slag composition. However, differences in reaction sequences or conflicting results are observed concerning foamy slag formation due to different reactivities, physical properties (e.g. density), compositions and C content of biomass carbonates compared to hard coal. In [15], among others, the use of biomass in EAF-scrap-based route through a cogenerations system is analyzed including a biomass boiler, steam turbine and condenser. The system allows the production of electricity to be used in EAF by the biomass combustion and the production of superheated heat; heat recovery is also provided from hot exhaust gas. It is underlined that the process allows decreasing environmental impact and CO_2 emissions. The paper by Mapelli et al. [16] reviews several applications of renewable carbon sources in the steelmaking sector, highlighting that, although the promising results, there are still a lack of knowledge and some barriers (e.g. availability and cost of these materials) preventing their full scale industrial use. A very recent research work also explored the use of biochar to power a direct carbon fuel cell as an alternative and additional source of energy for the EAF [17]. The feasibility of four carbon materials as fuels in a molten hydroxide direct carbon fuel cell was tested: coke, electrographite, biochar and hydrochar. Concerning these last two materials, biochar powder appeared having higher power density value (23.5 vs 18.2 mW/cm^2) than hydrochar powder, both had lower penalties in terms of electrical performances if used as pellets with respect to coke and electrographite, and, in addition, it was found that hydrochar contains catalytic phases in its ash that can help in improving its electrical behavior. Preliminary evaluations of using these fuel cells for supplying at leat 10% of EAF annual electricity demand in Italy (i.e. 8400 kWh/y) gave a required amount of hydrochar of about 6.3 kton/year.

On the other side, different older literature works can be found concerning the use of tires to replace coke and/or anthracite in EAF. Exemplary is the work by Forez et al. [18]: laboratory and industrial trials demonstrate that shredded tires can substitute fossil-carbon in EAF but some technological rules has to be followed to avoid the decrease of performances and dangerous operating conditions. A further interesting study is the one carried out by Zaharia et al. [19] that analyses carbon/slag reactions for different coke/tires rubber blend by monitoring slag foaming, FeO reduction and off-gas emissions; from the study it seems that partial replacement of coke with tires rubber seems possible.

However, despite the consistent literature available on the topic, including also computational fluid dynamics analyses of the EAF behavior [20], uncertainties still exist concerning the effects of these materials on the behavior and evolution of the EAF-based steel production process regarding both process performance and product features, which limit their use. Therefore, further studies are being conducted on this subject, including ever more intensive industrial tests [21–23]. However, field tests involve risks and disruptions to the standard production plan, thus their exploration horizon is usually quite limited. Ad-hoc modelling and simulation tools can help to explore different scenarios and can be complementary to industrial trials to demonstrate the technical feasibility of the proposed solutions, in line with current trends of industrial research [24]. For example, Meier et al. showed through dynamic simulations the higher reaction rate of biomass compared to hard coal and used the model as a basis to investigate different strategies for controlling oxygen use in EAF [25,26].

This paper presents the Aspen Plus® flowsheet model adapted in GreenHeatEAF to analyze jointly the effects of using alternative C sources on the EAF process, on the obtained products and on the emissions. Model validation and test results which were obtained using industrial data are shown; the preliminary results of its usage for the purposes previously mentioned, and the description of further ongoing scenario simulation are also provided. Further required model evolutions are discussed, based not only on the accuracy of obtained estimates but also in the light of a first stakeholder survey conducted within the project to identify barriers and enablers for a wide adoption of modelling and simulation tools to investigate this topic in the European steel sector.

2 Material and methods

The investigation concerning the adoption of advanced modelling and simulation tools fostering the use of non-fossil energy and Carbon sources, and modular heating technologies in electric steelworks was conducted on a twofold level. On the one hand, an existing stationary flowsheet model of the electric steelmaking route up to the continuous casting [27] was adapted to simulate the use of alternative C-sources in the EAF. On the other hand, a brief survey was carried out in the European steel community to collect feedback and useful indications for making such tool best-fit the demands of the steel sector, easily deployable and transferable across the European steel sector. The survey covers not only the model application concerning the study on the use of alternative C-sources, but also the adoption of alternative non-fossil energy sources and modular heating technologies, as this is the broader scope of the GreenHeatEAF project. Moreover, in the future, the same model will be further adapted to consider input of HBI and exploitation of multiple energy sources including Hydrogen as fuel in the burners.

2.1 Stationary flowsheet model

A stationary flowsheet model developed in Aspen Plus® and validated with several industrial data of different steelworks, representing a standard scrap-based EAF route and allowing process and related impact evaluations [27], was adapted for simulating the use of alternative non-fossil C sources in the EAF. The starting model was already upgraded different times during the years [28] considering the increased amount of available data and following the steelworks and related operator needs. Indeed, the model was developed to be straightforwardly adapted and improved with data generally available in steelworks (e.g. different feeds, energy consumptions, temperatures, steel compositions). Furthermore, it can be easily exploited by operator thanks to ad-hoc developed Excel based graphical user interfaces, where required inputs can be inserted and outputs can be visualized and smoothly interpreted since they belong to standardly monitored variables.

The model version then adapted in GreenHeatEAF consists of a combination of several Aspen Plus® internal unit blocks (e.g. mixer, reactors, heaters, separators) with customized ones and ad-hoc calculators and design specs units to consider all the steps of the scrap-based steelmaking process and to reproduce the different involved phenomena as the sum of effects in terms of both mass and energy flows and balances, chemical and physical transformations, reactions and thermodynamic equilibria and transformations. The considered process steps (corresponding to different model sections) are the following: charge and melting; additions in the EAF, slagging and tapping; additions before secondary metallurgy and transportation of the ladle; ladle furnace (LF) treatment; vacuum degassing (VD) treatment and final stages of secondary metallurgy; receipt of steel in tundish and starting of continuous casting. While, phenomena considered belongs to the following typologies: melting, oxidation, reductions, tapping, refining, degassing, heat exchange. The inputs required from the model for each section/units are well known process parameters including charge streams (e.g. scraps amount and type, amount of non-metallic standard charge materials), process conditions (e.g. desired temperature at tapping), amount of used fuels (e.g. natural gas), injections flowrate (e.g. oxygen), amount of Fe-alloys or of further additions, pressure (e.g. in VD). On the other side, main outputs are liquid steel amount and chemical composition (in terms mainly of C, Mn, Si, P, S, Cr, Ni, Mo, Cu, Al, Fe mass fractions, H_2 concentration) in the different process steps, slags amount and composition (in terms mainly of SiO_2, FeO, Al_2O_3, CaO, MgO, MnO, Cr_2O_3, TiO_2, P_2O_5, V_2O_5, Na_2O mass fractions), required electric energy, distribution of different kind of exploited energies, CO_2 emissions, efficiencies (e.g. metallic yield). More detailed information on the model is provided in [27,28].

The first adaptation steps consisted in the modelling of the alternative non-fossil carbon sources: a list of them was selected based on their features and availability in Europe and includes biomass, biochar, tires (only rubber), plastic and subcoal. Data coming from providers was exploited and missing values (i.e. H and O content) were calculated with an ad-hoc developed auxiliary model for fitting known High Heating Calorific Values. The alternative C-bearing materials were modelled as Non-Conventional Solids (NCS), namely materials that are not pure chemical species, for which generally there is a lack of equilibrium

Table 1. Percentage relative error of simulated alternative non-fossil C sources.

ID	Type	Fixed C [wt. %]	HHV real (from supplier specification) [kcal/kg]	HHV percentage relative error ((simulated-real)/real)%
1	Biochar	87.7	8048	0.0%
2	Biochar	62.2	6115	0.4%
3	Biochar	64.0	5786	−3.6%
4	Biochar	80.0	6446	1.4%
5	Biochar	70.0	5776	0.0%
6	Biochar	41.3	5307	0.9%
7	Biomass	20.4	4481	0.0%
8	Biomass	13.9	4529	0.0%
9	Biomass	20.3	4802	0.0%
10 (Ref.)	Biochar	80.0	7214	0.0%
11	Biochar	95.0	8264	0.0%
12	Tires (only rubber)	28.7	8938	0.0%
13	Plastics	97.2	8084	−16.8%
14	Subcoal	48.0	4691	0.0%
Ref. Fossil C	Anthracite	84.0	8250	0.0%

and physical property data. A NCS is characterized in terms of empirical factors called component attributes representing component composition by one or more sets of consituents. In particular, the following analyses were exploited for defining the NCS:

- Ultimate analysis, referring to the dry basis composition of the NCS in terms of ash, carbon, hydrogen, nitrogen, chlorine, sulfur and oxygen;
- Proximate analysis, referring to the content of moisture, ash, fixed carbon (mass fraction of non-volatile solid carbon residue remaining after a combustible particle is heated and the volatile matter is expelled) and volatile matter;
- Sulphur analysis, referring to the type of sulphur compounds (here approximated as organic).

The percentage relative error between High Heating Value (HHV) simulated and real (from supplier specification) values is reported in Table 1.

New streams were then added to the previous model version for considering the use of alternative C-bearing material directly as part of the basket feed, added to the 5th hole, and/or injected in EAF. Further modifications concern additions, tuning and modifications of model unit blocks and reactions according to the indications found in literature [9,10;12–14;21–23;25,26;29–31] and to the information coming from real Sidenor industrial data of 280 tested heats with the substitution of anthracite added to the 5th hole (used for starting the foaming slag formation) with the biochar 10.

2.2 Stakeholders survey

The basic idea behind the survey was to gather information and feedback from the main stakeholders, namely steel producers, plant providers, hydrogen, and biomass suppliers, on the general interest in the adoption of non-fossil energy and Carbon sources and heating technologies as well as on the perceived usefulness and knowledge on the use of modelling and simulation tools in this context. To this aim, a survey was prepared using the SurveyMonkey online tool and launched in November 2023. The survey also took advantage of the opportunity provided by some dissemination actions implemented on some project results, which fostered the creation of contacts and the spreading of exemplary applications, helping to raise awareness of the potentials of these tools. To encourage participation, the survey was kept very compact, with a compilation time of about 5 min.

The survey is composed by a total of 12 questions and is articulated into the following four main sections:

- The first section entitled "*Premise*" does not contain any questions but briefly introduces the GreenHeatEAF project and the purpose of the survey. In this introduction, a short explanation was provided concerning to scope of the project dealing with biomass/biochar adoption and modular heating solutions, which comprises modular regenerator and ceramic heat exchanger for heat recovery from EAF off-gases, latent heat recovery from slags, hybrid heating, based on both fuel gases from the steelmaking process and incorporation of electricity from renewable sources, integrated management of heating capacities.
- The second section entitled "*Basic information on the respondent*" contains 2 questions collecting in an anonymous form a few personal data on the respondent, i.e. the country and type of company/institution where He/She works.
- The third section entitled "*Modelling and simulation on GreenHeatEAF topics*" contains 8 questions aimed at assessing the general interest of the respondent in the adoption of alternative non-fossil energy and Carbon sources and heating technologies, the current and

Table 2. Tests percentage relative errors of some of the monitored variables.

Variable	Test relative error ((simulated-real)/real)%
Tapped Steel amount	[+5.22%, +9.95%]
Desired Liquid Steel (DLS) amount	[+8.83%, +12.56%]
EAF Electric Energy	[−7.21%, +10.47%]
LF Electric Energy	[−6.51%, +35.60%]
EAF slag amount	[−3.84%, +7.82%]
LF Slag amount (based on average industrial estimate)	[−2.78%, +46.76%]

potential interest in the company/institution of the respondent in using modelling and simulation tools to investigate this topic, the main perceived intensifiers for and barriers to the adoption of modelling and simulation tools and the professional experience of the respondent on this topic. Among the 8 questions, 5 are single choice questions, 1 allows multiple choice and 3 also allow inserting free text to justify and explain the answer and/or provide more detailed information on a voluntary basis.

– The fourth section entitled "*Intensifiers and barriers for any kind of model*" conveys 2 final general multiple-choice questions concerning the main perceived factors which can amplify or hamper the transferability of any kind of modelling tool, and both questions also allow inserting free text to motivate the provided answer, although it is not mandatory.

The survey was spread across the European steel sector through the contact networks of the European Steel technology Platform (ESTEP) and all the project partners.

3 Results

3.1 Model validation and tests

The adapted flowsheet model described in Section 2.1. was validated and tested for different steel families (i.e. groups of similar steel grades) with the available industrial data. Then it was used for conducting scenario investigations related to the use of alternative C-sources.

The validation was carried out by simulating average steel families heats and comparing simulated results (e.g. related to steel composition and amount, slag composition and amount, required energy) with the relative average industrial data.

Then, using a different dataset from the validation one, model was tested by simulating some random heats and comparing real industrial data with simulated results.

The ranges of tests percentage relative errors (i.e. (simulated value-real value)/(real value) %) for some of the monitored variables are reported in Table 2.

Generally, highest errors are related to families having lowest amount of available data that requires more assumptions and cannot allow an appropriate validation of the model. While for LF slag, the comparison is done with an average industrial estimation because no data are available for each heat; for this reason, the related upper error extreme is higher. An example of simulation test result is shown graphically in Figure 1 for a heat related to Alloyed Quenched & Tempered (Q&T) family: on the left side real (measured) and simulated values of some monitored variables are compared; on the right side the corresponding values of the relative error are shown. Concerning steel and slag compositions, the highest values of the error generally refer to compounds whose contents are very low and, thus, are more affected by measurement errors and scrap composition variability.

Nevertheless, the model fits for the purpose as, generally, for the tested heats the simulation errors are below 15% (i.e. the acceptable threshold considering the available data) for most variables. Furthermore, continuous updating of the model is provided for all the GreenHeatEAF duration due to expected higher amount of new data; this is expected to allow improving model accuracy and robustness.

The model is currently adopted for making different investigations on the substitution of fossil carbon sources with alternative ones; among the C-sources listed in Table 1, only the ones with fixed carbon higher than 40% and tires are considered in the investigations.

In particular, the ongoing scenarios are related to:

a. Simulations of some heats by adding different alternative C-sources to the 5^{th} hole, by ensuring the same amount of fed fixed C or of supplied energy in each case.
b. Sensitivity analyses on some heats by changing in a range of ±25% the content of C, S and moisture of biochar 10 (see Tab. 1) added to the 5^{th} hole.
c. Simulations of some heats by replacing fossil coal injected in EAF with the biochar 10 and ensuring the same amount of overall fed fixed C or of supplied energy.

Fig. 1. Example of simulation results of a tested heat related to Alloyed Q&T family: left. absolute values (labels on the Y axis are not shown for confidentiality reasons) of some monitored variables; right. corresponding relative errors.

It is important to consider that in scenarios a. and b. the amount of substituted fossil carbon is less than 15% and therefore the effects are less evident with respect to the simulations c. where fossil carbon is completely substituted.

Among preliminary results and in line with literature results and data [11,32], it emerges the significant decrease of EAF CO_2 emissions by using alternative non-fossil C-sources: from a maximum of about 3% for simulations a. to a maximum of about 20% for simulations c. without any detrimental effect on the process and the product. It seems that this reduction in the simulation is linked to the different features of these materials (e.g. in terms of composition of volatile part) and to the different reactions conditions/behavior that are created in the EAF with respect to anthracite. Moreover, the use of tires seems to generally lead to a decrease of required EAF electric energy (e.g. in simulations a., a maximum of about 12% of required EAF electric energy is obtained) but causes the highest S content in tapped metal (tires contains the highest amount of S with respect to the other considered C-sources).

Regarding sensitivity analyses b. almost linear correlations appear existing for main monitored parameters (e.g. EAF electric energy, C and S content in tapped metal, EAF slag) with respect to C, moisture and S content in considered biochar.

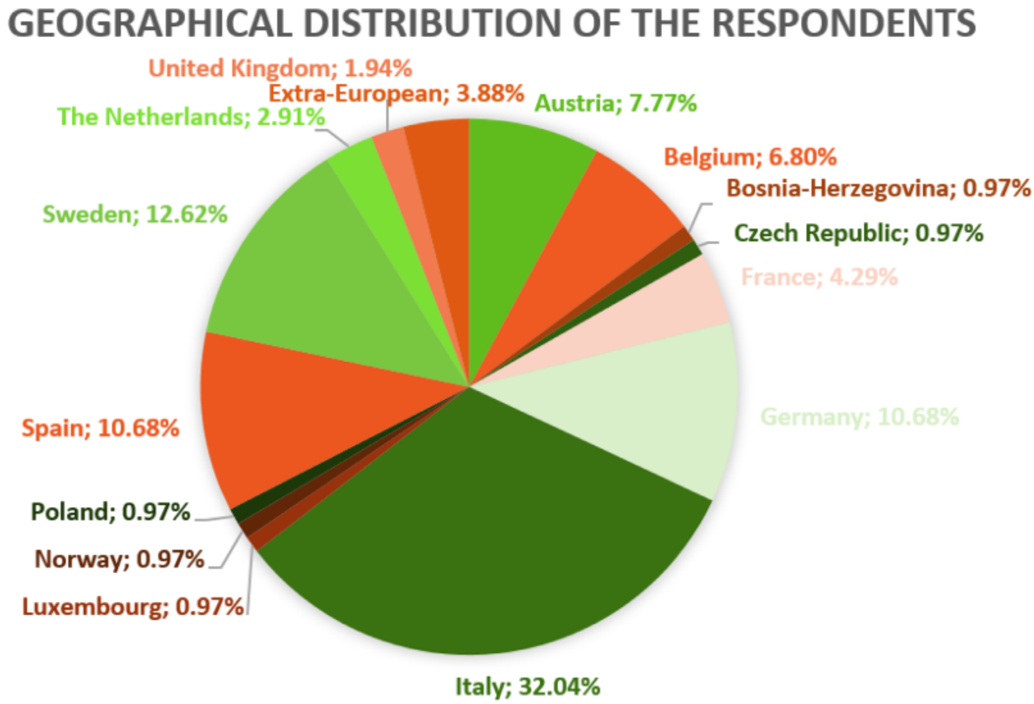

Fig. 2. Distribution of the survey respondents per country.

However, these are only the first results and simulations are still ongoing to obtain clearer results and understanding of involved phenomena, especially for some of the monitored parameters (e.g. C content in tapped metal, EAF metallic efficiency) that are not clearly affected by the alternative C-bearing materials. Furthermore, for tires, other simulations are required for understanding the effects of their partial usage mixed together with anthracite and/or with other alternative non-fossil C-sources.

3.2 Results of the survey

The survey remained open for 6 weeks and 103 respondents from quite a wide range of countries compiled it. The geographical distribution of the respondents is shown in Figure 2. Italy, Sweden, Germany and Spain are the most represented countries, as these countries hold a relevant number of steel companies and are highly represented in the GreenHeatEAF consortium. As largely expected, almost half of the respondents work in a large company (see Fig. 3), as the survey was spread in the steel community and most steelworks belong to such category. However, also the academic community working in the steel sector actively participated with more than 20% of the respondents. Respondents belonging to other kind of company work mostly in consultancy companies but also in trade unions and institutions of the European Union.

More than 90% of the respondents state that their companies or institutions are investigating or planning to investigate the adoption of alternative non-fossil energy and C sources and heating technologies (see Fig. 4a). Modelling and simulation tools are used more frequently to investigate the adoption of renewable energy sources and heating technologies rather than the use of renewable C-sources (see Fig. 4b).

Among the respondents who indicated an ongoing use of modelling and simulation tools to investigate the adoption of renewable energy sources and heating technologies, 96% indicate that internal solutions are developed for this purpose mostly in Python, Matlab, Simulink, Excel and C (Julia, C++, C#, Fortran and Delphi are also mentioned by a few respondents), while 58% indicate the use of commercial tools, mostly Aspen Plus, Ansys Fluent and Comsol (gPROMS, OpenFOAM, ThermoCalc and SimuCalc are also mentioned by a few respondents).

Similarly, although in smaller numbers, among the respondents who indicated an ongoing use of modelling and simulation tools to investigate the adoption of renewable C sources, 82% indicate that internal solutions are developed mostly in Python, Matlab, Simulink and C (C++, C# and Delphi are also mentioned by a few respondents), while 62% indicate the use of commercial tools, mostly Aspen Plus, Ansys and Fluent (with a few mentions for gProms, FactSage, Comsol, ThermoCalc and OpenFOAM).

About 78% of the respondents declare a potential interest of their company/institution in modelling and simulation tools to investigate or implement the adoption of alternative non-fossil Carbon and energy sources and heating technologies, but almost half of the respondents state that they never applied models for these purposes.

The ranking of the main barriers to the use of modelling and simulation tools to investigate or implement the adoption of non-fossil C and energy sources and heating technologies is shown in Figure 5.

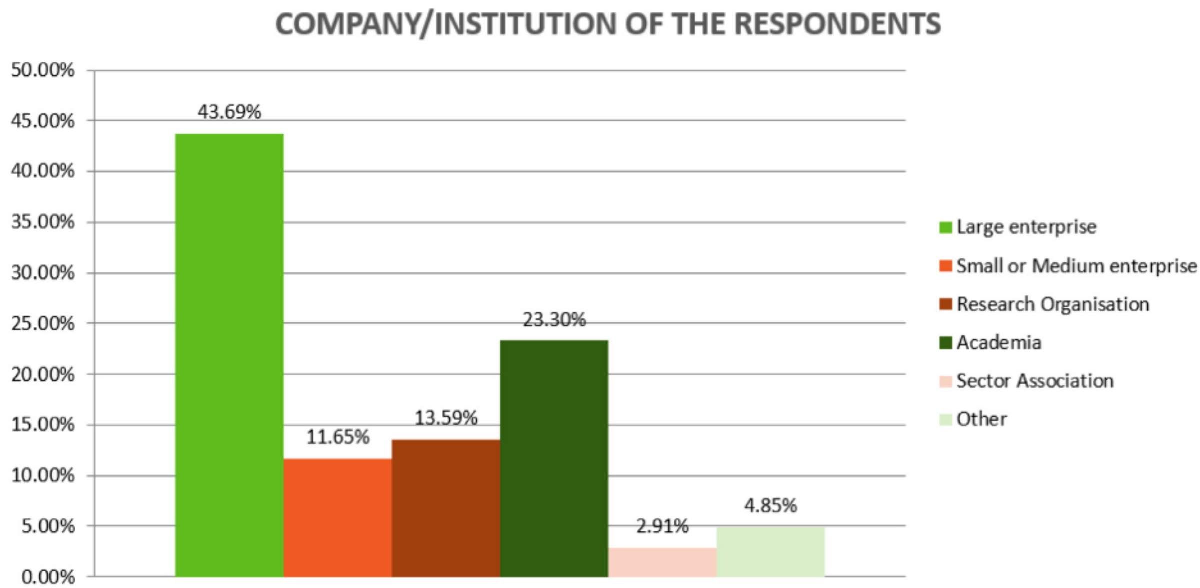

Fig. 3. Distribution of the survey respondents per type of company/institution.

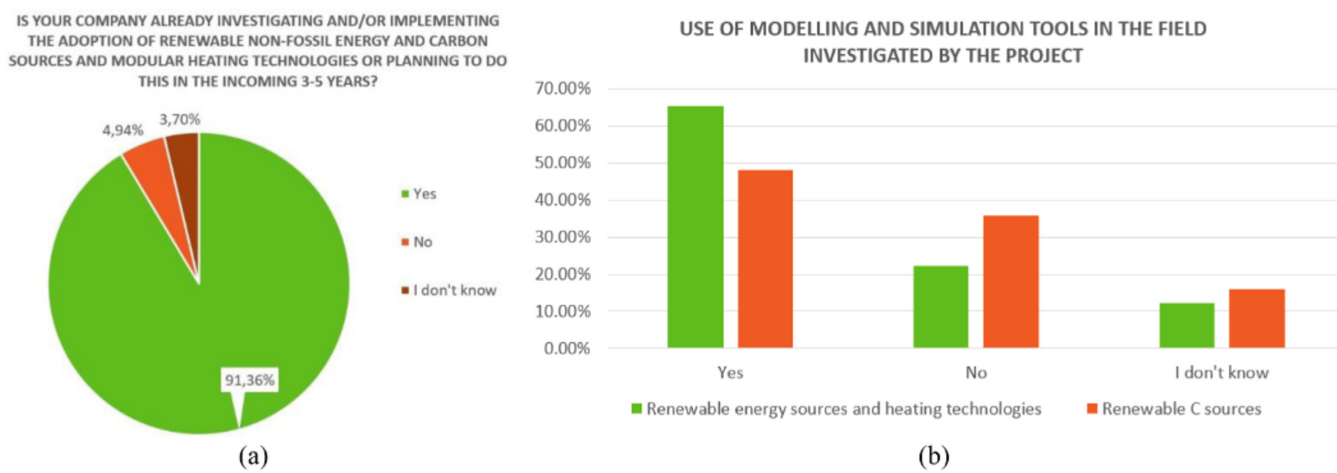

Fig. 4. a) Ongoing activity or plans of the respondents' companies or institutions concerning the adoption of alternative non-fossil energy and C sources and heating technologies; b) use of modelling and simulation tools for these topics.

Other identified barriers are:
- lack of credible roadmaps and plans imposed by governments;
- unclear path towards reaching the goals;
- poor model reliability in complex applications;
- difficulties in the validation of the model outcomes due to lack of relevant plant/process data;
- difficulties in modelling, foreseeing and elaborating all the anomalous events and/or deviations that happen during the production process;
- poor representativity of the process complexity and limited cases definition;
- poor capability to represent many aspects, such as market availability.

The main factors that can favor transferability of any kind of model are identified in the evident benefits in savings of resources, materials, energy and emissions reduction, model simplicity and usability, as well as evident benefits for product quality and increased yield (see Fig. 6a). Other mentioned enablers are model maintainability and documentation availability to ensure a reliable long-term use of the model. The main barriers to model transferability are identified in the difficulty to gather internal data for model tuning and customization, the lack of adequate skills to run the model and interpret its results and the cost of purchasing the modelling environment (see Fig. 6b). Other barriers are identified in:
- Lack of adequate documentation accompanying the model and ensuring its maintainability and long-term use.

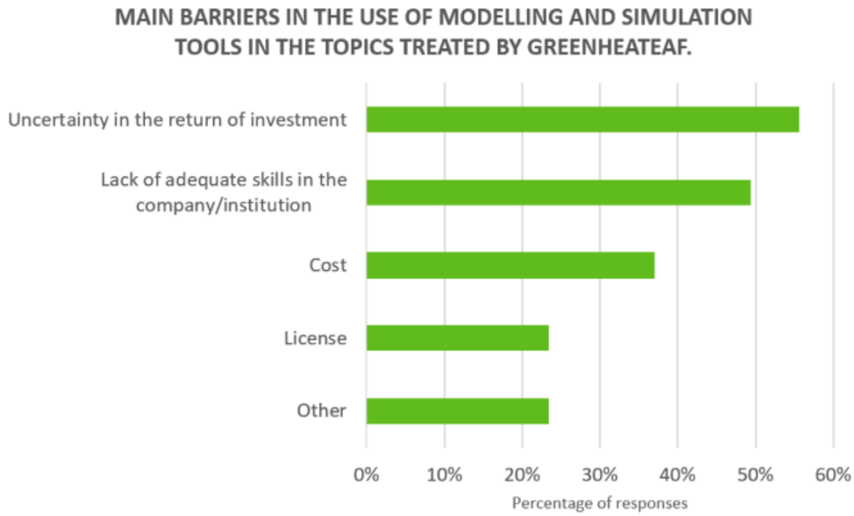

Fig. 5. Main barriers in the use of modelling and simulation tools to investigate or implement the adoption of alternative non-fossil C and energy sources and heating technologies.

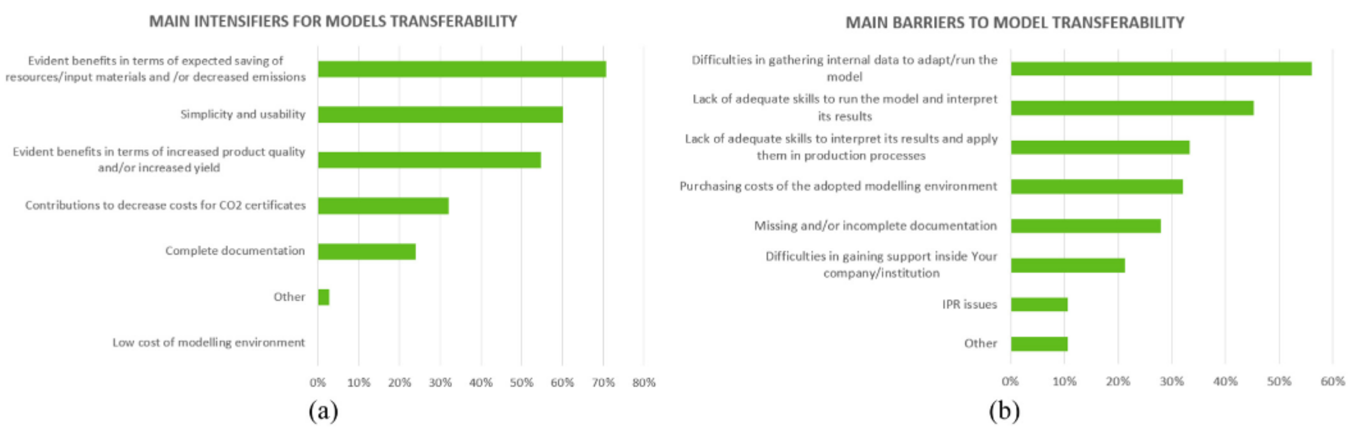

Fig. 6. a) Main intensifiers and b) barriers to transferability of any kind of model.

– Excessive time needed to adapt the model and achieve an adequate accuracy.
– Lack of internal resources dedicated to models' usage and adaptation.
– Lack of trust in models that were initially developed in or for other companies.

4 Discussion

The survey outcomes show that people are encouraged to use modelling and simulation tools when their environmental benefits clearly show up. The first results of the model simulations are in line with this aspect. Indeed, benefits of alternative non-fossil C-sources in terms of reduction of CO_2 emissions are shown by simulation results. And these findings have been obtained without expensive and large number of industrial tests. Obviously, industrial tests are required for the final proof, but simulations can guide in avoiding risky and unuseful investigations.

On the other hand, one of the most relevant perceived barriers is the difficulty in gathering the data required to run the model. In this sense, the above-described model shows the relevant advantage of using "standard" data, i.e. data that are normally collected and easy to find/input by the user (as explained in section 2.1). Moreover, the model can be fed via simple and widely spread Excel sheets, which facilitates data collection (see section 2.1). However, the survey also highlights a major problem of the steel sector, which refers to an existing gap on data "standardization" especially for assessments related to environmental sustainability of technologies and solution. This issue goes far beyond the scope of GreenHeatEAF, as it probably deserves a long-lasting and in-depth investigation on its own, but it highlights that models' transferability also passes through a clear definition of the meaning of the data required and input and provided as output by the model and a straightforward and not ambiguous interpretation of the results of simulations. Therefore, in its final version to be provided at the end of the GreenHeatEAF project, a "manual for use" will be provided together with the model to facilitate its usage. This also meets another demand clearly highlighted by the survey, i.e. the availability of an adequate documentation which enhances model usability and provide clear guidelines for its adaptation, fine-tuning and maintenance also beyond the project lifespan.

5 Conclusion

Advanced simulation models can be powerful tools for supporting the investigation of novel applications in the steelmaking fields. The perception of European steel sector stakeholders was shown in the paper on the use of modelling and simulation tools for investigating the effects of using non-fossil energy and Carbon sources and heating technologies in electric steelmaking. The interest is evident but also the related barriers to their usages. In parallel, an existing model of EAF scrap route was adapted for allowing the simulation of alternative C-sources use in EAF. It reflects “what the stakeholders want” and “what is less explored with simulations”. The first results show the model potential and the benefits of substituting fossil anthracite in EAF. However, several other trials are provided for obtaining more general results. In addition, the model will be further improved to also allow the investigations of hydrogen exploitation in place of methane as heating source, the use of DRI/HBI and to bring it ever closer to the stakeholders’ needs.

Acknowledgments

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*” (Ref. GreenHeatEAF), Grant Agreement No. 101092328, that has received funding from the Horizon Europe framework programme of the European Union, which is gratefully acknowledged. The sole responsibility of 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.

Funding

This research was funded by the European Union through the Horizon Europe framework programme, Grant Agreement No. 101092328, in the context of the project entitled “*Gradual integration of REnewable non-fossil ENergy sources and modular HEATing technologies in EAF for progressive CO_2 decrease*” (Ref. GreenHeatEAF).

Conflicts of interest

The authors have nothing to disclose and have no conflicts of interest.

Data availability statement

Data associated with this article cannot be disclosed due to confidentiality constraints.

Author contribution statement

Conceptualization, I.M. and V.C.; Methodology, I.M and V.C.; Software, I.M., V.C, A.P, A.Z., O.T.; Validation, I.M., V.C., A.P, A.Z., O.T; Formal Analysis, I.M, V.C, A.S.L., A.Z.L.; Investigation, I.M., V.C., A.Z., A.S.L., A. Z.L.; Resources, V.C.; Data Curation, I.M., A.Z., A.S.L.; Writing – Original Draft Preparation, I.M. and V.C.; Writing – Review & Editing, A.P, A.Z., O. T., A.S.L., A.Z.L.; Visualization, I.M. and V.C.; Supervision, V. C., A.S.L., A.Z..L.; Project Administration, V.C; Funding Acquisition, V.C and I.M.

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Cite this article as: Ismael Matino, Valentina Colla, Alice Petrucciani, Antonella Zaccara, Orlando Toscanelli, Aintzane Soto Larzabal, Asier Zubero Lombardia, An advanced simulation tool to support adoption of alternative non-fossil carbon sources in electric steelworks, Matériaux & Techniques **112**, 504 (2024)