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Two alternative fuels for the reduction of GHG emissions in the steel industry: biocarbon and hydrogen

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Abstract— Biocarbon obtained from pyrolysis and then pelletised using pyrolysis oils can be a useful fuel to substitute coke and coal used in the steel industry as reductants. A reduction of emissions of exactly 30% can be achieved. This depends also on the pyrolysis and pelletizing processes which are taken into consideration and the national electricity mix. We estimate that the reduction in emission can be further increase through coupling carbon capture and storage with biocarbon use. On the other hand, another alternative fuel which can be used in direct iron reduction (for example) is hydrogen. The production of hydrogen not always has a low impact and the technology is an important aspect to be considered. If hydrogen is produced from electrolysis also in this case the electricity mix of the country has an important role. The authors propose in this contribution a comparison between the impact of the final functional unit of steel produced using biocarbon with that produced using hydrogen. The analysis is performed through LCA focusing on the carbon footprint impact.

Keywords—biocarbon; hydrogen; Electric Arc Furnace, pellet, carbon footprint; LCA

I. INTRODUCTION

In recent years with increasing price of carbon credits in the ETS market and growing trends towards coal phase out [1], also the most important multinational companies in the steel sector are switching to a more green steel production. As examples, Arcelor Mittal has proposed its TORERO Plant [2,3]; while ThyssenKrup has developed a torrefaction plant for black pellet or biocarbon production [4]. The Technical Research Centre of Finland (VTT) has produced an interesting report in 2019 [5] in which it is declared a roadmap for the decarbonization of the steel industry in Europe and Finland. The possible evolution of the technology is reported in Fig. 1.

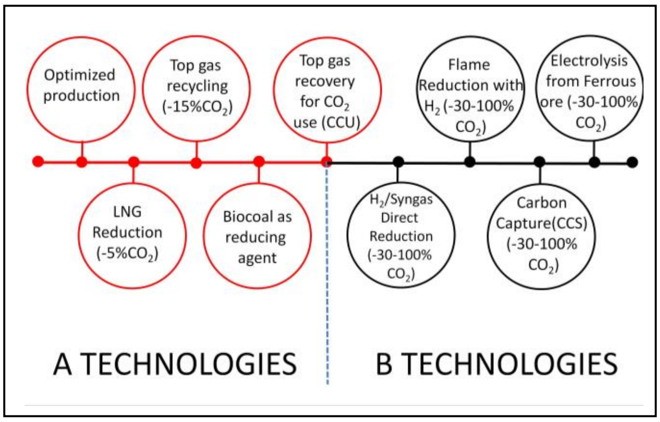

Fig. 1. Gree Steel production roadmap [5]

As it can be seen green coke or biocarbon are included as an “A-technology”, representing options which might be tested on a commercial scale on a large scale in the upcoming years. “B-technologies” can be considered instead, i.e. the use of hydrogen and electrolytic reduction. The roadmap towards the development of low-CO2 steel production technologies has been also proposed in [6-8].

Consequently, the objective of this paper is to give an overview of the initiatives developed through the collaboration of SINTEF Norway, University of Perugia (Italy), University of Agder (Norway), University of Tuscia (Italy), University of Aalborg (Denmark), Technical University of Denmark and Huazhong University of Science and Technology (China). The tests were initiated at the University of Perugia in collaboration with SINTEF (see Fig. 2) [9-12] and then joined with the experimental campaigns and methods developed at University of Agder [13,14] and Huazhong University of Science and Technology (HUST) [15,16]. Particular aspects in pelletizing modeling were analyzed by Aalborg University and Technical University of Denmark [17-18]. The present paper presents the results of technical optimization of pyrolysis oil content, pressure and temperature during the pelletization of a mixture of charcoal and pyrolysis oil. The developed process is based on three steps: vegetal biomass is pyrolyzed, the produced biocarbon is pelletized with pyrolysis oil as binder and the produced pellets are newly reheated. The optimization of the process was carried out based on three responses: strength, thermal strength and durability. In addition, an environmental feasibility analysis was performed together with the estimate of cost of production of biocarbon.

II. METHODOLOGY

A. *Analysis of biocarbon pellet carbon footprint*

Based on both: the results of the optimization analysis, previous experience on coal densification [19] and on pyrolysis plants at the University of Perugia [20], a plant layout for the production of biocarbon pellet was developed [21]. The layout of the plant is proposed on Fig. 2a. To design the mass and energy balances of the reactor the following assumptions have been made:

- the yields of pyrolysis products are distributed in the following way: 1/3 char, 1/3 biooil, 1/3 pyrogas;

- in the volatiles burner an air to fuel ratio of about 4 is considered, as reported also in [22];

To simulate the impact of the plant the following processes were considered:

- “Heat, central or small-scale, natural gas {GLO} |market group for | Alloc Rec, U”; taken from Ecoinvent 3.3 database; this process was chosen because it contains an average of the impact of producing heat at a global level;

- in the case of electricity it was chosen to make a sensitivity analysis on different electricity mixes composition: EU, Italy, Norway and China. This will be explained further in the section about the sensitivity analysis further on in the work.

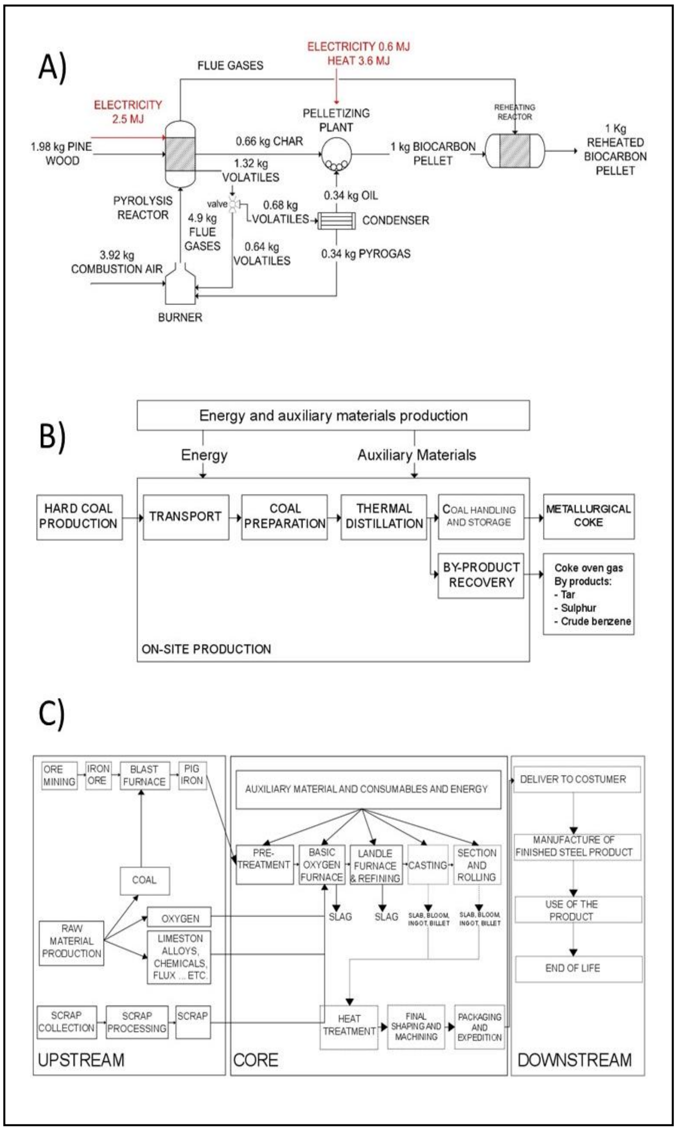

Fig.2 a) Biocarbon production process layout, based on pyrolysis – pelletization - reheating [23], b) Coke production system boundaries [24], c) System boundaries in steel production [25]

Many studies have taken into consideration the impact of coke production, which varies depending on the technology and on the country also. Each country has in fact a different Energy mix which can influence coke production. In this case the project “Coke {GLO} |market for| Cut-off, U” was chosen, which belongs to the Ecoinvent 3.5 database. The system boundaries are reported in Fig. 2b, as taken from [24]. The life cycle of coke starts from coal extraction, which is followed by transport and thermal distillation (which is the main process used in coke production, also called coking).

If we consider the steel sector, we can think that about 200 kg of coke are needed to produce a ton of steel. The system boundaries typical of steel production are reported in Fig. 2c. These are taken from the draft Product Category Rule “BASIC IRON OR STEEL PRODUCTS & SPECIAL STEELS, EXCEPT CONSTRUCTION STEEL PRODUCTS”, Draft, DATE 2019-10-08. This can be downloaded directly from the Environdec Website (https://www.environdec.com/), where Environdec (also known as International EPD® System) is a global programme for environmental declarations based on ISO 14025 and EN 15804. An EPD on steel production has been for example already published by Outokumpu Oy, the biggest steep producer in Europe and certifiedby another program operator (this time from Germany, Institut Bauen und Umwelt e.V.).

To analyse the processes reported in Fig. 2c the following dataset was considered from Ecoinvent 3.5: "Steel, low-alloyed {RoW} |steel production, converter, low-alloyed| Cut-off, U". This process takes into consideration the production of unalloyed steel using ferrochromium, ferronickel, molibdenite, oxygen liquid, pig iron and ferromanganese. Pig iron is produced in the blast furnace from from iron pellet and sinter iron, using coke. Coke is the reductant used to produce both sinter and pig iron. Also, some small quantities of coal are used in pig iron production. In Fig. 2c the process indicated with dotted lines are not included in this study because we chose to focus our attention on the raw material, further operations will be the same for both: conventional steel and steel produced with biocarbon pellet, indicated with the name "green steel".

B. Analysis of hydrogen production carbon footprint

Dealing with the analysis of the impact of steel production from hydrogen, we have to take into consideration the publication of Bhaskar et al. 2020 [26], in which the system presented in figure 3 is studied.

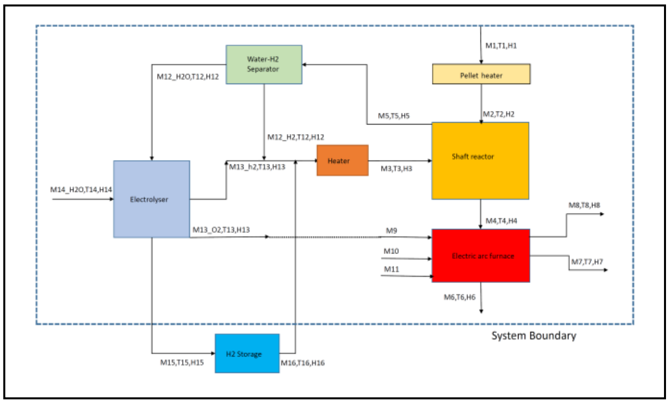

Fig.3 Hydrogen direct reduction shaft furnace coupled with an electric arc furnace [26]

The system shown in figure 3 is based on Hydrogen Direct Reduction of Iron Ore (HDRI) coupled with an Electric Arc Furnace (EAF). So reduction of iron happens using hydrogen in a moving bed shaft furnace. The direct reduction of the iron pellet is an endothermic reaction which needs energy to heat up the furnace temperature. Temperature should be maintained around 800°C and should not overcome 900°C to avoid sintering of the pellet [27].

The mass and energy balances of the HDRI furnace are shown in figure 4.

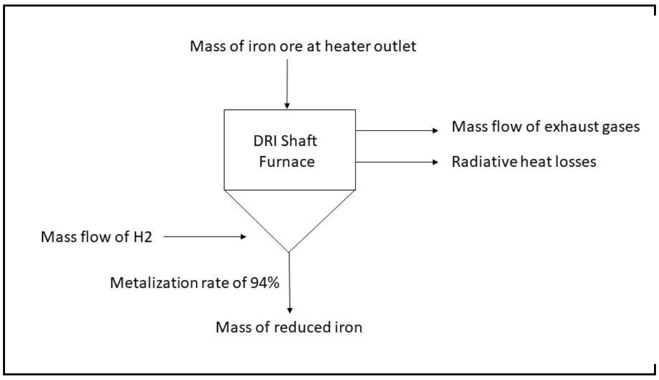

Fig.4 Mass balances of HDRI [26]

The furnace shown in figure 4 it is a contercurrent gas solid reactor in which iron pellet is fed from the top and hydrogen from the bottom. The output of the reactor is metallic iron which is produce with a metallization rate of 94%.

Dealing with the waste gas stream, this is composed by a mixture of H2 which is not reacted and steam. The exhaust gases have a temperature of 275°C-400°C [28].

III. RESULTS

In this section the results of the carbon footprint analysis of steel produced from biocarbon and from hydrogen are presented and compared

A. Steel produced froom biocarbon

The carbon footprint of 1 kg of biocarbon pellet is shown in Fig. 5 and compared with that of coke.

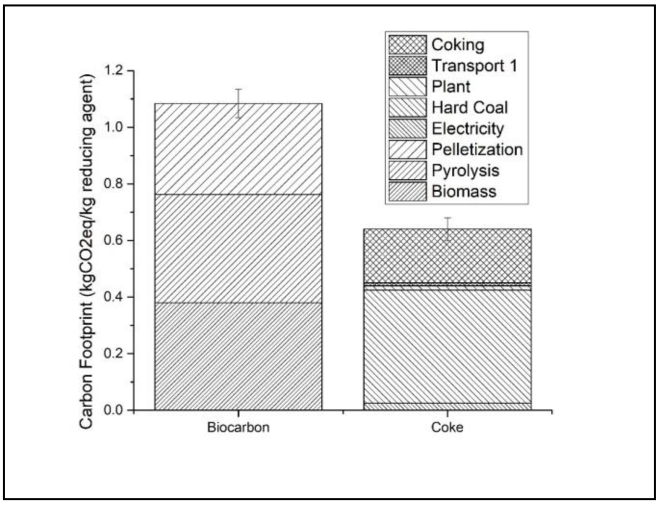

Fig.5 Carbon Footprint of Biocarbon Pellet versus Coke

It can be seen that the total carbon footprint is about 1 $kgCO_2eq/kg$ of biocarbon pellet. The impact is almost equally distributed between three processes: wood collection, transport and chipping, pyrolysis and pelletization. The total carbon footprint of biocarbon pellet is comparable with that of charcoal, reported in the database Ecoinvent 3.5, and indicated with the de nomination "Charcoal {GLO} |market for| Cut-off, S". This has an impact of 1.43 kgCO2eq/kg, so the biocarbon pellet produced with an integrated process has a slightly lower impact than charcoal produced with conventional reactors. Coke production impact is reported also in Fig. 5. We can see that the impact of coke is generally lower than that of biocarbon pellet. So, we can infer from this that the production of biocarbon pellet is linked with some environmental burden, it is the use phase which is convenient for the biocarbon pellet because it is not associate di GHG emissions, on the contrary of the use phase of coke. The most impacting phases are linked with hard coal extraction, coking and the use of electricity during the process.

The impact of pig iron production is shown in Fig. 5.

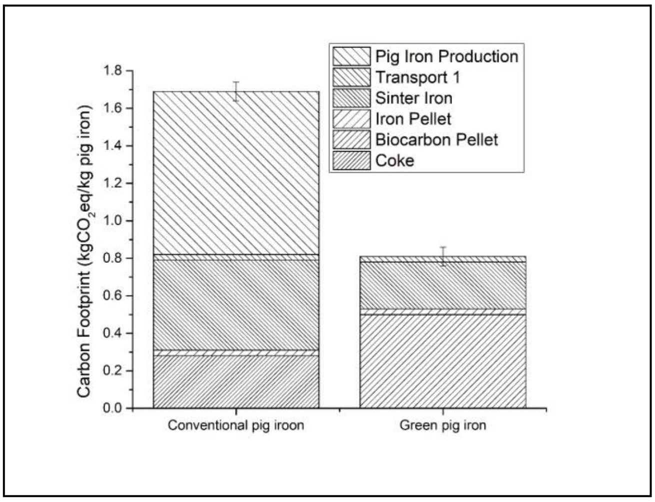

Fig.6 Carbon footprint of conventional pig iron versus green pig iron

We see from Fig. 6 how the most impacting processes are: coke production, sinter iron production and pig iron production. Where the process “pig iron production” comprises the emissions of coke combustion to reduce iron.

We see from Fig. 6 also that the carbon footprint of green pig iron is about 0.92 $kgCO_2eq/kg$ of pig iron. The main impacts in green pig iron production are the following:

- biocarbon pellet production accounts for 55% of the total impact;

- sinter production accounts for 32% of the total impact;

- iron pellet accounts for 5% of the total impact;

- transport accounts for 8% of the total impact.

In this case the use of biocarbon pellet can reduce the carbon footprint of pig iron of 46%.

When the biocarbon pellet is used to substitute the coke used for pig iron production and also the sinter, substituting also a small part of hard coal, this can decrease the carbon footprint of pig iron and so also that of steel. We speak in this case of “green” pig iron and “green” steel.

Fig. 7 shows the carbon footprint of conventional unalloyed steel, produced using conventional pig iron.

We see that, if the carbon footprint of pig iron is about 1.71 $kgCO_2eq/kg$ of material that of conventional steel is about 2.31 $kgCO_2eq/kg$ of material.

The main contribution to conventional unalloyed steel carbon footprint are: ferronickel production, which accounts for about 18% of the total impact and obviously pig iron, which accounts for 67% of the total impact.

The emissions released by the steel production process are quite reduced and currently equal to 4% of the total carbon footprint. Liquid oxygen production and ferrochromium production account respectively for 3.6% and 3.02% of the total impact.

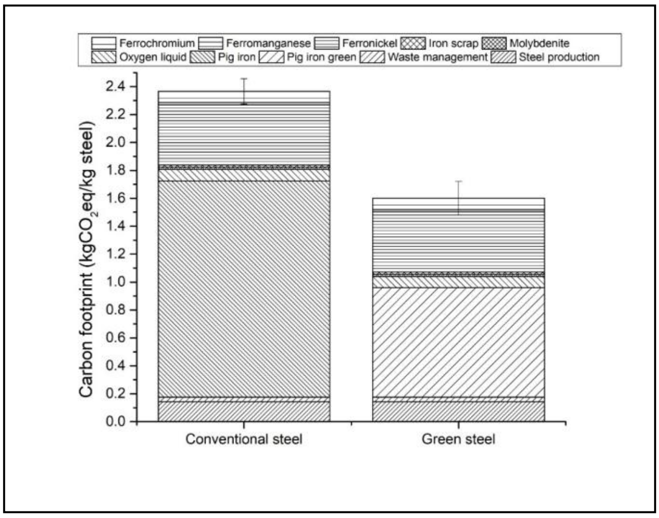

Fig.7 Carbon footprint of conventional steel versus green steel

From Fig. 7 it can be seen that the impact of unalloyed green steel is due to:

- green pig iron, which accounts for 49% of the total impact;

- ferronickel, which accounts for 27% of the total impact;

- ferrochromium, which accounts for 5% of the total impact;

- oxygen liquid, which accounts for 5% of the total impact;

- steel production (which comprehends also steel production emissions), which accounts for 9% of the total impact on the carbon footprint;

- ferromanganese, iron scrap, molybdenite and waste management, which account for the remaining.

The total impact of green steel is about 1.6 $kgCO_2eq/kg$ of steel, which is 31% lower than that of conventional steel.

B. Steel production from hydrogen

Dealing with the carbon footprint of steel produced from hydrogen direct reduction, this is shown in figure 8. It has already been said how in the work of Bhaskar et al. 2020 [26], the impact assessment is performed mainly based on the energy consumption. So figure 8 presents how the impact is influenced by the electricity mix of different countries. If we consider the European electricity mix (to make the results comparable with those obtained for example with biocarbon), we obtain a final carbon footprint of 1101 $kgCO_2/tls$ (ton of liquid steel).

We can see how this final value is very promising, but is affected by some assumptions adopted in the Life Cycle

Assessment study, like the neglected impact of the infrastructures and plants used in the hydrogen production, compression and transportation and in the production of the steel. Besides in this case the contributions of the different life cycle steps are not clearly specified by the authors.

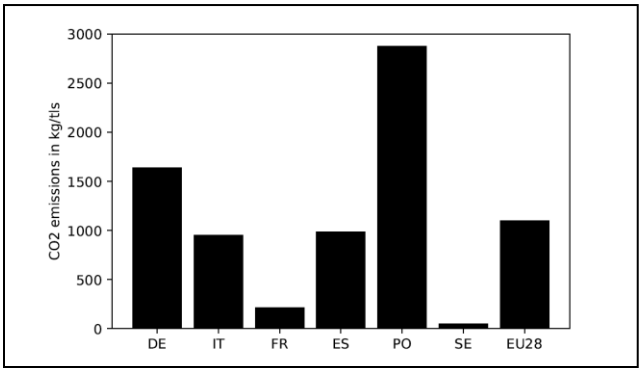

Fig.8 Carbon footprint of steel produced with hydrogen, based on different electricity mixes [26]

IV. CONCLUSIONS

Through the collaboration of SINTEF with University of Perugia, University of Agder, Tuscia University and Huazhong University of Science and Technology new methods have been developed to produce biocarbon pellet interesting characteristics of the final product have been achieved, in terms of hardness and durability.

The impact of unalloyed green steel is due to: green pig iron, which accounts for 49% of the total impact; ferronickel, which accounts for 27% of the total impact; ferrochromium, which accounts for 5% of the total impact; oxygen liquid, which accounts for 5% of the total impact; steel production (which comprehends also steel production emissions), which accounts for 9% of the total impact on the carbon footprint; ferromanganese, iron scrap, molybdenite and waste management, which account for the remaining. The total impact of green steel is about 1.6 $kgCO_2eq/kg$ of steel, which is 31% lower than that of conventional steel.

Electricity mix and raw materials obviously impact the whole life cycle. On the other hand, concerning the impact of electricity it is possible to limit it by increasing the efficiency of the pyrolysis and pelletizing plant.

Regarding the raw materials, the most convenient to use is waste lignin produced from the second generation bioethanol industry.

The process has to be still optimized by the economic point of view and energetic point of view. In fact the yields of solid products in the pyrolysis of biomass are much lower than those obtained from the pyrolysis of coal, for this reason the cumulative energy consumption in the case of biocarbon is often higher than that for coal.

Besides this, detailed methods for the characterization of the final biocarbon have to be developed, to be sure that its characteristics are really correspondent to those of coke.

Dealing with the production of steel by direct reduction with hydrogen, this technology appears to be surely interesting and can reduce further the carbon emissions, nevertheless it has still to be investigated the carbon emissions released by the final hydrogen infrastructure (considering production, compression and transport) and also by the HDRI and EAF infrastructures.

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