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Quantification of energy and environmental impacts in uncommon electric steelmaking scenarios to improve process sustainability

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HIGHLIGHTS

- Application of an ad-hoc developed Decision Support Tool for electric steelworks.
- An EAF route model allows global view simulations.
- Quantification of scrap type influence on production sustainability.
- Identification of a viable modification of the standard route.
- Monitoring of environmental sustainability of the electric steelmaking route.

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ABSTRACT

The electric steel production is in line with the circular economy concept due to the reuse of scrap. However, being energy intensive industries with a significant environmental impact, electric steelworks can increase their competitiveness and environmental sustainability through an adequate management of resource and energy. The paper presents a work related to the quantification of electric energy consumption and environmental impact of unconventional electric steelmaking scenarios while simultaneously monitoring the steel composition. The exploitation of an ad-hoc developed Decision Support Tool highlights that scrap quality strongly affects the monitored energy and environmental parameters (quantified in terms of Key Performance Indicators and aggregated in a Global Index). Moreover, the developed simulations pointed out that the removal of Fe-alloy addition during EAF tapping allows reducing slag and improving the yield by preserving also the steel quality while slightly increasing the electric energy consumption: in countries where the price and the emissions related to the production of electricity are low, this can be a good compromise to improve the environmental sustainability of the sector. The study shows that also limited modifications of the well-known electric steelmaking process could help to increase the sustainability of this energy intensive industrial production route.

1. Introduction

The electric steelmaking route exploits scrap as raw material for steel production by melting it in the Electric Arc Furnace (EAF). This production is therefore perfectly in line with the concept of Circular Economy, which nowadays is very popular in the international technical and scientific community, as end-of-life steel products are fully recycled, being steel a material, which can be endlessly melted and reused. Examples can be found in literature of the efforts that are spent in order to increase and promote the circular economy in the steel industry, such as described by Yin and Zhang in [1] related to the Chinese situation. In addition, Reh in [2] provides a relevant demonstration of the fundamental role of process engineering in the diffusion of the circular economy concept with a focus on the steel industry.

Moreover, the electric steelmaking constitutes the route for steel production, which is experiencing the greatest spread in the recent years and which, according to forecasts, could gain noticeable market shares with respect to the integrated cycle of steel production. In effect, the EAF production route shows economic advantages in the production of some categories of steel products (e.g. long products for the construction sector) and the continuous development in this field allows increasing the EAF product quality range, such as highlighted in [3]. Noticeably, the increased level of

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Nomenclature

Abbreviations
CC Continuous Casting
DST Decision Support Tool
EAF Electric Arc Furnace
EIRES Environmental Impact Evaluation and Effective Management of Resources
KPI Key Performance Indicator
LCA Life Cycle Assessment
LF Ladle Furnace
ORC Organic Rankine Cycle
SF Steel Family
VD Vacuum Degassing

Symbols
CS_i Case study No. i ($1 \leq i \leq 6$)
G_{LCA} Global LCA-based index
Fe-All_{EAF} Fe-alloy addition in the ladle during EAF tapping
Fe-All_{LF} Fe-alloy addition at the LF station
Fe-All_{VD} Fe-alloy addition after VD station

Variables
EE_{EAF+SM} Consumption of electric energy in the EAF and in the secondary metallurgy [GJ]
MC Amount of metallic charge [t]
QTY_{CO2} Amount of emitted CO_2 [kg]
SL_{EAF} Amount of slag produced in the EAF stage [kg]
SL_{EAF+LF} Overall amount of produced slag [kg]
SL_{LF} Amount of slag produced in the LF stage [kg]
SS Amount of produced solid steel [t]
$KPI_{normalized}$ Normalized KPI

Functions
G_{KPI} Global KPI-based index
KPI_2 Specific electric energy consumption [$GJ/t_{solidsteel}$]
KPI_5 Direct specific carbon dioxide emission [$kg_{CO2}/t_{solidsteel}$]
KPI_{14} Metallic yield [%]
KPI_{15} Specific EAF slag production [$kg_{EAFslag}/t_{solidsteel}$]
KPI_{18} Specific LF slag production [$kg_{LFslag}/t_{solidsteel}$]
KPI_{21} Specific total output slag [$kg_{slag}/t_{solidsteel}$]
KPI_{SCORE} KPI Score

lifestyle in some emerging countries increased the consumptions of goods, which will lead to an increased amount of produced scrap to recycle: Li et al. in [4] discussed the fact that a bigger amount of scrap will increase the EAF steelmaking share in China. For instance, in China Chen et al. expect that the EAF steelmaking share could increase from about 10%, in 2010, to about 45%, in 2050 [5].

Nevertheless, electric steelworks are energy intensive industries, which exploit electric energy as main energy supply, thus the energy costs affect the final conversion cost. Additionally, electric steel production has a not negligible environmental impact related to wastes, water consumption, direct (e.g. dusts) and indirect (e.g. CO_2) atmospheric emissions. Therefore, electric steelworks are focusing their efforts to monitor their impact and to improve energy efficiency through, for instance, an optimal exploitation of the cheapest energy portion (e.g. chemical energy) while jointly minimizing wastes and emissions, with benefits for the environmental sustainability of the whole production cycle.

In the past, some research activities were developed in order to monitor and quantify energy efficiency and to forecast energy savings in the steelmaking field, such as highlighted by the works of Poggi [6], Langley [7] and Price et al. [8] for cases studies in Italy, UK and China respectively.

Nowadays energy efficiency and environmental impact are of primary interest for the steelworks and different kind of research works were carried out. The monitoring of the current energy and environmental impacts are the main topics of [5,9]: in these research works, investigations of current and future energy exploitation and emissions production are developed in order to evaluate possibility of improvements. On the other hand, the research of the factors that mostly affect the energy efficiency and the environmental impact and the investigation of new ways for their improvement is the work carried out by Cullen et al. in [10]. Several possibilities for energy recovery and utilization in an integrated way are discussed and economically assessed in [11]. Moreover, different energy saving technologies, including front-end control, processing control and end-treatment technologies, are analysed in Chinese studies such as [4,12,13] by focusing on the required investments, operation costs and benefits related to energy savings and emission reduction. Although the high technological level reached in the steel sector and the continuous process progresses, these studies demonstrates that potentials for plant sustainability improvements exist. The identification of strategies for reducing greenhouse gas emissions and energy exploitation are object of the studies of Ling et al. [14] and of Karali et al. [15], respectively, for cases study in China and U.S.. With the same objective, Milford et al. developed a work in which a global mass flow analysis is combined with process emissions intensities in order to forecast future emissions in the steel sector under all abatement options, finding that energy and material efficiency have a complementary role in the reduction of CO_2 emissions [16]. In a recent study Karali et al. [17] further analysed the effect of technological changes on energy efficiency in the steel sector by incorporating technological learning into the adopted model. Zhang et al. in [18] introduced an innovative techno-economic model in order to evaluate potentials for energy savings and consumptions reductions through a synergy technology promotion and structure adjustment in some scenarios related to the Chinese steel sector. A further relevant work of Amado et al. [19] is more focused on the identification of variables affecting the energy exploitation in EAF steemaking: a particular data-mining algorithm was used in order to obtain a ranking list of the most relevant variables with respect to energy consumption in the EAF melting process. In [20] a production-planning tool composed of three modules, one of which was based on a genetic algorithm, was exploited in order to optimize the production conditions. The latest trends in EAF optimization are analysed in [21], where the effect of chemical energy input intensity is pointed out. An interesting study on the energy efficiency and on the identification of energy saving potentials in EAF steelmaking was carried out by Kirschen et al., who found that an efficient use of natural gas in EAFs helps the maximization of material and energy conversions and the minimization of greenhouse gas emission [22].

Other research works are focused on a particular innovative technology or modification of the standard operating practice. The exemplar work of Teng et al. [23] presents a new generation of electromagnetic stirrer that allows a lower energy consumption through a more homogeneous melt bath and the enhancement of the heat and mass transfer in the EAF. The importance of the mixing of steel melt is also discussed in [24], in which a direct bottom gas purging is proposed, which allows obtaining higher productivity and lower production costs due to the improvement of energy efficiency. The application of Organic Rankine Cycle (ORC) power