Evaluation of Internal Slag Reuse in an Electric Steelmaking Route: Simulation Analyses through the EIRES Monitoring Tool

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Abstract

Electric steelworks can be included in the list of virtuous industries, as they recover end of life product (i.e. the scrap), but margins of improvement exist for the sustainability of their production process. In particular, an increased internal reuse of by-products (e.g. slags) can provide economic advantages reducing raw material exploitation (e.g. lime) and avoiding the disposal of waste, in-line with the ever more stringent environmental regulations. Although slags reuse can imply significant advantages, their internal recycling is sometimes hampered because of the variability of their composition, which might lead to not perfectly known process behavior and effects on the final product. The paper faces this problem and presents a study related to the analyses of process behavior and performance in the case of slags reuse in an Italian steelworks. An ad-hoc developed general purpose-monitoring tool was exploited to simulate and evaluate the technical feasibility of two case studies related to the replacement of lime and dolime with ladle furnace slag with or without the partial recovery of EAF slag. The effect of the two process modifications on the production route, the environmental and energy impacts and steel quality were evaluated through advanced simulation. In particular, the simulations demonstrates that lime and dolime replacement is possible by recovering only ladle furnace slag, as a small increase of 2.5% of required electric energy is compensated by a reduction of non-metallic raw materials of about 18% without negative effects on steel quality and metallic yield.

Keywords

Slag Recovery; By-products Management; Process Simulation; Steelmaking Sustainability.

1. Introduction

The steel produced through the electric route represents the 30% of the world production [1-2]. The main feeds of the process are steel scrap and electricity. The scrap is melt in the Electric Arc Furnace (EAF), where melting and scorifying agents (i.e. lime, dolime, silica sand) and iron alloys are also added in order to remove scrap contaminants and to achieve the desired steel composition, while a scorification process also takes place. Different kind of by-products and wastes are produced during the whole process, such as slags, off-gases, dusts and sludges. Therefore the EAF-based steelworks are committed to improve the sustainability of their production process in order to comply with the ever more stringent environmental regulations and to maintain its competitiveness.

An increased internal reuse of by-products can allow obtaining economic advantages, as it reduces raw material exploitation, avoids disposal of waste and, consequently, improves resource management [3]. This is also in line with one of the main topics treated in the Strategic Research Agenda of the European Steel Technology Platform [4] and it is also one of the pillars allowing to implement the concept of circular economy in the steelmaking sector [5]. The importance of this topic is reflected in different studies and applications related both to the electric that the integrated steel production route. For instance, several investigations were carried out to assess the possibility of the total recycling of Basic Oxygen Furnace (BOF) slag [6-7]: speciation and pre-treatment studies were done [8-9] in order to increase the knowledge of BOF slag features and to allow the separation of the slag in a magnetic and a non-magnetic fraction. Indeed, several research works demonstrated that the BOF non-magnetic parts could be used as fertilizer or amending material without affecting the groundwater pollution and having good vegetables yield [10-12]. On the other hand, the magnetic part can be reused in the steelmaking plant for instance to produce pellets as highlighted by the work of Kawatra et al. [13] and as investigated through a combination of simulation, optimization and pilot tests by Matino et al. [14].

In addition, treatments of oily mill-scales were investigated through simulation and pilot units in order to increase their reuse internally to the steelmaking plant [15].

Within the electric steelmaking route, the most important by-products in quantitative terms are the EAF and the Ladle Furnace (LF) slags. Recent Italian studies are examples of investigations focused on the stabilization [16], treatment and processing of electric steelworks by-products in order to maximize their reuse [17]. The process steps that allows the use of EAF slags and dusts in concrete production have been widely studied [18-21] together with the assessment of the features of the obtained product, which shows acceptable mechanic and chemical properties [22-23]. Recent studies suggest the use of EAF slag as reactive filter bed [24-25] and other investigations are more focused on the LF slag reuse [26-27]. However, only in some cases these by-products are directly reused in the steelworks as raw material substitute [17] and only a few field trials are in literature [28], although the internal reuse of this material could imply significant advantages due to their main compounds (e.g. CaO, Iron oxides). The reason of this fact is related to the variability of their composition, which might lead to not perfectly known effects on process behaviour, product yield and quality.

This paper faces this problem and presents a simulation study related to the analysis of process behaviour, performance and steel composition in the case of EAF and LF slags reuse in an Italian steelworks. The importance of simulation in the assessment of new plant configurations, process integration solutions and process route modifications was widely verified in several exemplar works carried out by Matino et al. [29], Alcamisi et al. [30] and Porzio et al. [31]; for this reason, process simulation is also the basis of this study. The work presented in this paper was developed within the European project entitled “Environmental Impact Evaluation and Effective Management of Resources in the EAF Steelmaking (EIRES)” and was carried out exploiting two modules of the developed EIRES general purpose-monitoring tool. In this way, the effect of process modification on the production route, the environmental and energy impacts and the steel quality were evaluated before the real implementation.

The remainder of the paper is organized as follows: Section 2 presents the EIRES general purpose monitoring tool; in Section 3 the simulated case studies are discussed and results are shown, while Section 4 includes some concluding remarks.

2. Overview of EIRES General Purpose Monitoring Tool

Plant modifications, process changes or new production route can affect the sustainability of an electric steelworks. The impossibility to evaluate in advance all the effect of such modifications often represent a major obstacle for plant staff for the implementation even of limited plant trials related to innovative approaches or technologies. On the other hand, modifications and experiments are needed in order to find new solutions which can decrease environmental or energy impacts and increase the competitiveness of the plant. To solve this issue, a general-purpose monitoring tool was developed during the EIRES project, which is schematically represented in Figure 1.

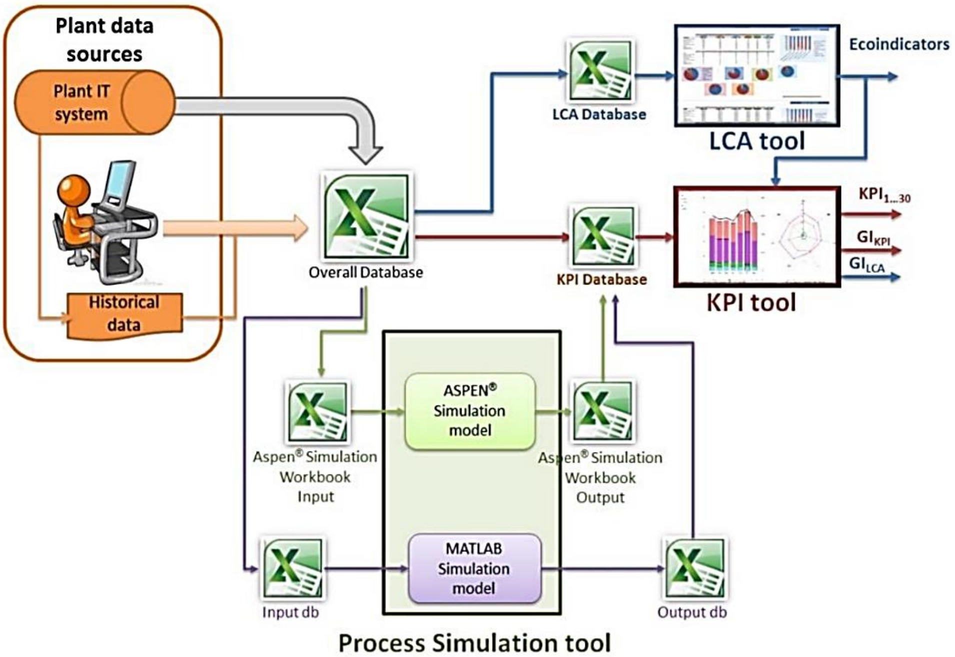

Fig.1 Overall structure of the EIRES general-purpose monitoring tool

The tool allows monitoring the behaviour of the plant in terms of sustainability in common and un-common scenarios and making online evaluations or offline simulations. The tool also monitors the product quality in terms of steel composition, which is a fundamental aspect for a steelmaking company.

The EIRES decision support tool is composed of three main modules that can be distinguished in the Figure 1: a Life Cycle Assessment (LCA) tool, a Key Performance Indicator (KPI) tool and a Process Simulation tool. All of them are connected to a database that allows importing historical, real time or further external data; the other modules are linked to each other through intermediate databases manageable through MS Excel®. The LCA tool provides information about the sustainability of the plant in terms of eco-indicators, while the KPI tool provides the value of some KPIs defined in [32] in order to follow the evolution of the environmental, energy and resources performance of the steelworks during common process or in case of modifications. The KPI tool also allows aggregating the ecoindicators obtained by LCA tool and each KPIs in two different global indexes, which are useful to have a global view of the sustainability of the steelworks. The Process Simulation tool is composed of two alternatives: a sort of "virtual electric steelmaking plant" developed through flowsheeting modelling with Aspen Plus® V.8.4 and a mathematic model developed in Matlab® environment and representing itself the whole route of electric steel production. This sub-tools can be fed either with real (current), historic or synthetic data or with set-by-user inputs and provide as outputs parameters which are normally monitored. Such parameters, by themselves or in form of KPIs (after that they are processed by the KPI tool) can give information of the impact behaviour of the production process, which is useful especially in case of un-common situations or plant/route modifications. Each EIRES module can be used both as a stand-alone tool and linked to the other ones.

In the work presented in this paper the Aspen® process simulation tool and the KPI tool were exploited. In particular, the Aspen®-based tool is composed of three sub-modules: a production process model, a fumes network models and a water network model; only the production process model was used in the presented case study. The production process model allows simulating the different steps of a real production route monitoring each mass and energy stream and transformation:

1. Electric Arc Furnace
    - Charge
    - Melting
    - Oxygen addition
    - Furnace opening
    - De-Slagging
    - Refining
2. Ladle Furnace
    - Refining
    - De-Slagging
3. Vacuum Degassing (VD) if required and composition refining
4. Continuous Casting (CC)

The model was validated for 11 steel families that includes steel grades with similar features; after the model validation, the prediction error lies below the 2% for some parameters (e.g. the EAF electric energy, steel quality and amount, temperatures during the process), while for other ones (e.g. amount of dust) the error is bigger, but still lower than a threshold value identified together with the plant staff as representative of the desired model output reliability. More information about the model and the modelling phases are in [33-34]. The input listed in Table 1 are required to compute two different types of outputs (Table 2):

- Output required for KPIs calculation (“Output for KPIs”)
- Output needed for process monitoring (“Output for monitoring”)

Table 1 Aspen®-based production process model required inputs

EAF
Scrap Charge (different scrap types)
Non-Scrap Charge (e.g. lime, anthracite)
Burners (natural gas, oxygen)
Other additions (blowing graphite, oxygen)
Fe-Alloys during tapping
Temperature after melting (or EAF electric power)
Time of EAF Power ON
LF
Fe-Alloys
Argon Volume Flow
Temperature input in VD/CC (or LF electric power)
Time of LF Power ON
VD
VD Pressure
Argon Volume Flow
CC
Fe-Alloys after VD and before CC
T before starting casting

Simple MS Excel® sheets linked to the model by Aspen Simulation Workbook® represent the human machine interface (HMI) of the model. In this way, also user with poor expertise of process modelling software can exploit the Aspen-based model; in addition, data are simply exported in the other tools (e.g. KPI tool).

Table 2 Aspen®-based production process model computed outputs

Unit Operation	Output for KPIs	Other Output
EAF	Electric Energy (or Temperature after melting)	Mass of Steel Temperature of Steel Composition of Steel (also H_2 content) Composition of Slags Mass and Composition of Fumes and Dusts before the fumes treatment
	Chemical Energy	
	Energy from Burners	
	EAF slag	
	Metallic Charge	
	Non-Metallic Charge	
LF	Electric Energy (or Temperature input in VD/CC)	
	LF slag	
	Metallic Charge	
	Non-Metallic Charge	
VD		
CC	Desired Steel	
	Output for KPIs	

Although the model was conceived especially to monitor the sustainability (environmental, energy and resource impacts) of electric steelworks, it allows controlling also the process itself in terms of production yield and product quality. This is relevant for the purposes of the steelworks, which aims at keeping the same quality standard levels, i.e. at producing high quality steel through "greener" process routes.

3. Case studies: simulation of internal reuse of slags

Nowadays in the considered Italian electric steelworks only small amount of slags are reused in the process, as their composition is not continuously monitored and the process behaviour once such highly variable material is fed back is not completely known. However, previous simulations [34] of one of the most produced steel family, whose composition is reported in Table 3, suggested that EAF and LF slags have the compositions depicted in Figure 2.

Table 3 Composition of the simulated steel family (underlined values are included)

Steel Alloy Content [wt %]					
C	**Si**	**Mn**	**Cr**	**Ni**	**B**
0.12÷0.25	≤0.5	0.9÷1.6	≤0.25	≤0.25	≤0.0008

LF slag appears a valid replacement of lime, dolime or silica sand, which are normally used as scorifying compounds, and EAF slag contains a significant amount of both ferrous and calcium oxides. In order to evaluate the viability of such recycling solution, the two previous described modules (i.e. Process Simulation Tool – Aspen-based production process model and KPI Tool) were used to evaluate the behavior of the production process in terms of sustainability, process yield and steel quality in the following two different scenarios for slags reuse:

- Replacement of lime and dolime by total LF slag recovery (CS 1)
- Replacement of lime and dolime by total LF slag recovery and partial recovery of EAF slag (CS 2)

In the first case study the produced LF slag was completely reused in the process, but only a part of lime/dolime was replaced. In the second case study EAF slag was added to the LF slag in order to completely replace the lime/dolime.

The original process simulation model does not allow the use of slags as feed of the EAF furnace, therefore the simulation was carried out through a very simple model adaptation which is depicted in Figure 3.

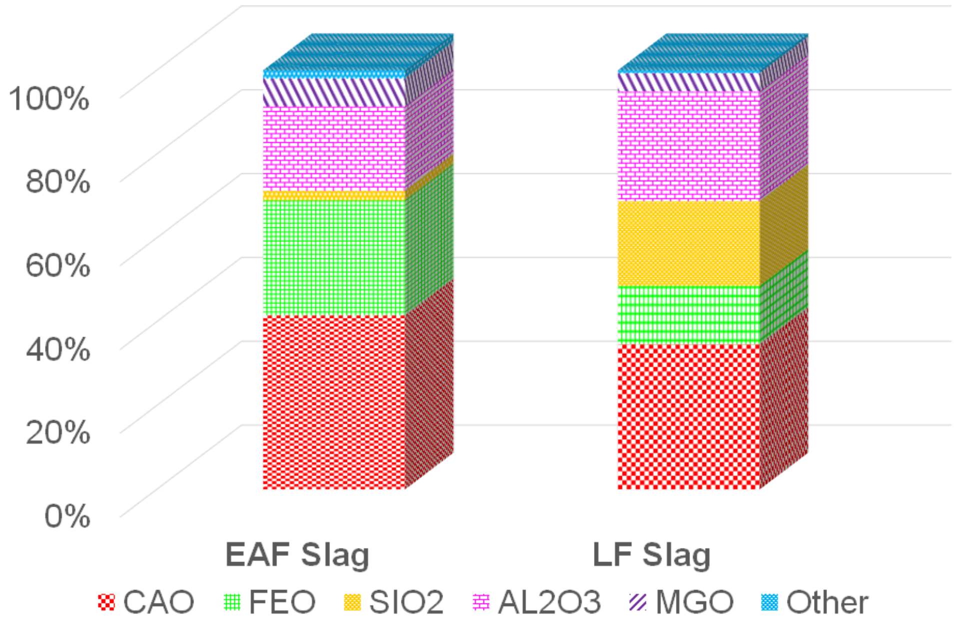

Fig. 2 Simulated composition of EAF and LF slags

From the “Output for monitoring” of the simulations, the two proposed process modifications negligibly affect the desired steel composition, although obviously the composition of obtained slags are in the both cases different from the recycled ones. On the other hand, the “Outputs for KPIs” of the model are then fed to the KPI tool to compute the following KPIs [32]:

- KPI_2 required electric energy (ratio between the electric energy consumed in steel production and the amount of produced steel);
- KPI_{12} specific non-metallic charge materials (ratio between weight of non-metallic charge materials and the amount of produced steel);
- KPI_{14} metallic yield (percentage ratio between produced steel and the amount of metallic charge);
- KPI_{15} specific EAF slag (ratio between the amount of EAF slag and the amount of produced steel);
- KPI_{18} specific LF slag (ratio between the amount of LF slag and the amount of produced steel);
- KPI_{21} total amount of slag (ratio between the total amount of produced slags and the amount of produced steel).

The environmental and energy impacts of the considered case studies are represented in Figure 4 in forms of radar diagrams.

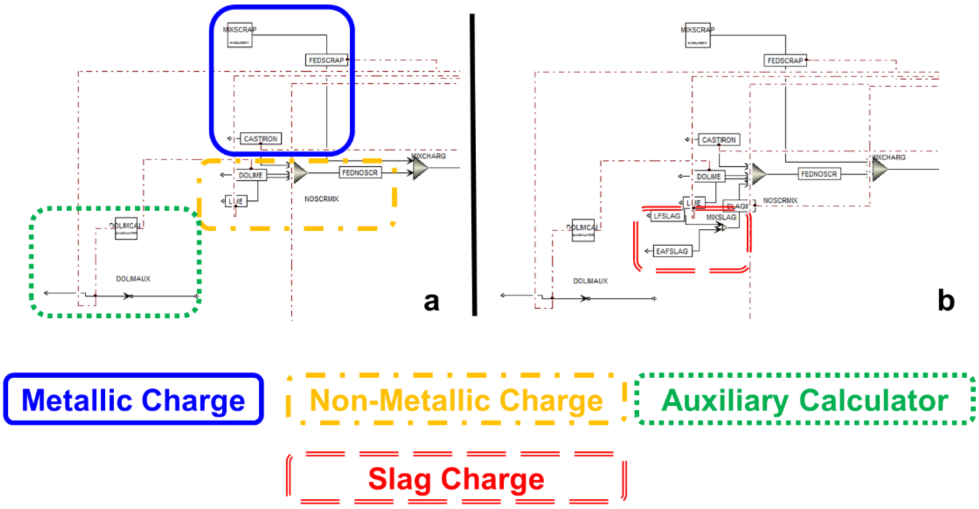

Fig. 3 EAF charge phase of the Aspen® based production process model: a. standard route; b. modified route

The simulation study demonstrates that lime and dolime replacement with slag is possible but only in the case of LF slag recovery (CS 1): a reduction of non-metallic raw material feed (*KPI_{12}*) of about 18% is obtained in this case without affecting the metallic yield (KPI_{14}) or the steel quality. Despite some negative outcomes, such as an increase of about 2.5% of required electric energy (*KPI_2*) and of produced slags (especially EAF slag), such solution appears to be a good compromise between process efficiency and increased by-product reuse. On the other hand, the use of EAF slag together with LF slag allows a reduction of about 55% of specific non-metallic charge materials due to the complete replacement of lime and dolime. However, the use of EAF slag significantly increases the required electric energy (*KPI_2*) (+7%), due to the big amount of matter to be melted with respect to the standard operating practice. Moreover, in the CS 2 the production of slags considerably rises, with a consequent increment of the related management costs.

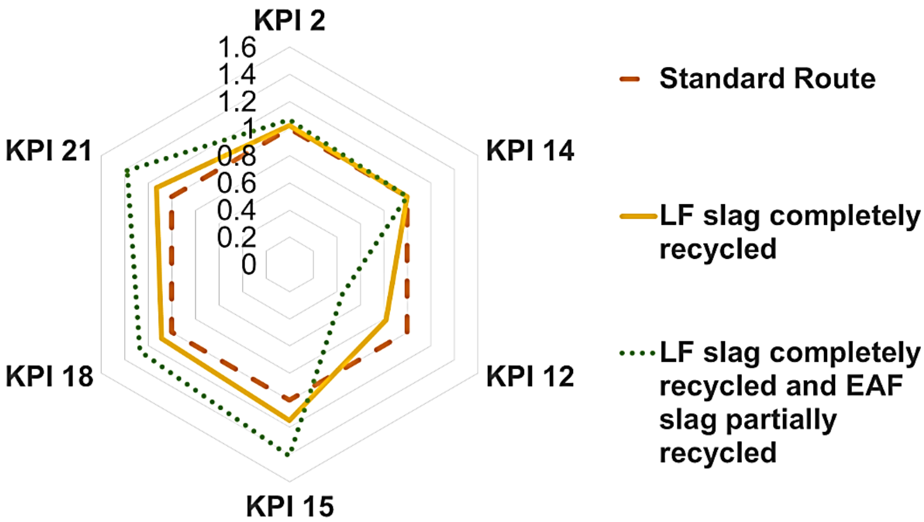

Fig.4 Radar diagram of obtained results: KPI_2 – required electric energy, KPI_{12} – specific non-metallic charge materials, KPI_{14} – metallic yield, KPI_{15} – specific EAF slag, KPI_{18} – specific LF slag, KPI_{21} – total amount of slag.

4. Conclusions

The main by-product produced in the electric steelworks are slags: EAF and LF slags, whose features and compositions are often discontinuously monitored. Simulation studies were carried out through a general-purpose monitoring and simulation tool developed within the EIRES European project, which allowed a deeper analysis of the composition of the slags related to different produced steel families. Considering one of the most produced steel family in an Italian steelworks, slags appear having high amount of valuable compounds, such as CaO, MgO, which make them suitable to replace some of the common used non-metallic raw materials (lime and dolime), which are used in EAF furnace as scoryfing agents. Two simulated case studies were presented evaluating the possibility of reuse of LF and EAF slags in the considered steelmaking plant. The steel quality and the production yield were monitored and the results were fed to the KPI module of the EIRES tool in order to assess the effect of such modification in terms of environmental and energy impacts. The study proves that the LF slag could be a good material to replace partially lime and dolime, while maintaining a good steel quality and yield. The non-metallic raw material is reduced of about 18% and the related increase of 2.5% of required electric energy is acceptable. On the other hand, EAF slags significantly increase the required electric energy and the amount of produced slags, thus this solution is not economically and environmentally viable.

The analysis proposed in the paper represents only a starting point for deeper studies focused on the maximization of the internal reuse of by-products and wastes in the electric steel cycle, to the final aim of increasing the environmental sustainability of the production process.

The proposed simulation-based approach exploiting the EIRES tool provides useful indication and information on non-standard scenarios preliminarily to real plant implementation, by allowing an early identification of most promising solutions to undergo real experimentation/implementation, by avoiding risky and economically cumbersome plant trials related to non-viable options.

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