Comparison of novel ladle slag treatment and handling systems based on resource-efficiency metrics

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Abstract: Ladle slag is a by-product common to electric and basic oxygen steelmaking furnaces which is gaining increasing attention as a secondary material. Its main recycling path is internal to steelmaking process, since it can replace the lime used to remove impurities. However, storing and handling slag for internal recycling is problematic because cooled ladle slag soon becomes extremely dusty, determining harsh environmental conditions at the plant. Recently, a novel solution based on granulation of ladle slag was presented on the market, which could be integrated in the steelmaking process using diverse handling and storage systems. The implementation of such systems requires resources, specifically energy, but may produce benefits such as lower pollution from particulate emissions and easier storage, leading to lower material losses, reduced landfill disposal and savings of primary mineral resources. In this paper, three alternative treatment and handling systems are analyzed and ranked using ad hoc defined first level resource efficiency metrics. Results show that the best alternative in terms of carbon emission intensity is the more advanced configuration, which includes granulation within a casing and automatic transport with apron conveyors; however, open granulation with current handling systems apparently minimizes primary energy intensity. A possible cause for this discrepancy is that emission factors and primary energy consumption factors obtained from official sources refer to different years, and hence to a different electric energy generation mix. A clear ranking between the basic and the most advanced configuration cannot be obtained, but the resource efficiency evaluation leads to exclude the intermediate configuration (granulation within a casing and traditional materials handling) which is apparently dominated by the remaining alternatives.

Keywords: Resource efficiency, material handling, carbon emissions, dust dispersion, sustainable production

I. INTRODUCTION

In electric steelmaking, a mix of steel scrap, iron ore briquettes, and small quantities of chemical additives is processed to obtain steel products characterized by the desired chemical and physical properties. Depending on the additives used, and on the treatments required to obtain the final quality product, many by-products (steel slags) can be generated. After melting, molten steel is processed by secondary treatment processes performed in Ladle Furnaces (LF)[1]. Oxides resulting from this refining process are later adsorbed into the slag generated at the end of the treatment. After steel tapping from ladle, the slag residue is tipped into a pit at T>500°C, and it cools down rapidly in ambient conditions, reaching ambient temperature within 48 hours. LS residue is rich in lime (typically about 50% by weight) and hence in Ca.

An increasing interest on the reuse of LS in the last six years has been reported in literature [2]. While relatively few papers deal with the environmental impact of ladle slag, the bulk of literature focuses on slag generation mechanisms, composition, and size. One research objective is facilitating slag management since this has a strong impact on recycling options.

LS disposal in landfill generates atmospheric dispersion in air and potential leaching of toxic metals into the soil [3][4]. Given the significant amount of ladle slag - about 4 million tonnes/year considering only the EU [5] - the 80% of which is disposed into landfill [6], a few recycling routes have been proposed and implemented as prototypes or at the industrial scale [2].

The three main LS recycling routes described in literature include:

- use of ladle slag by the concrete industry as partial or full replacement for cement [2];
- use as geo-filling material or for soil stabilization [1];
- recycling of powdered LS by injection in the electric arc furnace [7].

While the first routes are more prototypal, the latter is adopted at some steelmaking sites. Injection of powdered LS into the EAF can replace the lime commonly used as additive. Although less performing than lime (which is 90% in CaO and can react completely in the EAF), powdered LS can be fully reused within the process, with significant savings of lime [8] and landfill disposal minimization.

Critical environmental issues related with LS handling and storage operations exist both in traditional LS management and new recycling practices. LS contains dicalcium silicate ($2CaO \cdot SiO_2$), commonly known as belite or briefly C_2S, which may be found in several allotropic phases depending on temperature, cooling rate and chemical composition of the slag. When ladle slag is cooled in still air, belite switches from α and β phases (stable at high temperature) to γ-phase, stable at room temperature. The transition between β and γ phases is associated to a ~10% increase in volume leading to crystal shattering with fine dust generation [9]. This is the reason why most of ladle slag (95%) is less than 2mm in size, and ~60% is less than 63µm in size. Due to the particle size distribution, slag particles can be easily raised and dispersed. LS heap storage in open air and bulldozer handling operations enhance this effect. Handling operations (including transferring, material loading and unloading and removal of steel scabs from the heap) generate dust lifting, and specific atmospheric conditions (wind and rain) promote dispersion causing also direct erosion of slag heaps.

The fraction of ladle slag lost in environment (atmosphere and soil) is a main pollution concern for local communities and surrounding plants; it also negatively affects working conditions and productivity at the steelworks due to dusting, indoor air quality degradation and health effects.

The aim of this paper is to evaluate alternative approaches for LS treatment systems under testing by Italian steelmaking companies to identify the best promising. A specific case study is described in section 2; resource-efficiency performance indicators proposed in section 3 are calculated to compare and rank proposed alternatives. Results are discussed in section 4 and future research developments are summarized in section 5.

II. CASE STUDY DESCRIPTION

Current and proposed LS treatment processes implemented in the steelmaking plant are sketched in Figure 1. Configuration 0 represents the handling, storage, and recycling process in use at the steelmaking site, whereas alternative configurations denoted as A, B, and C, respectively, differ in the pre-treatment and handling processes as described below.

A. Handling, storage, and recycling process in use

LS, once solidified and partially cooled, is removed by bulldozers from the pouring area; wheel loaders are used to transfer LS to an open-air heap located outside the steel plants. The larger steel pieces are then removed from the heap using a grapple handler. Ladle slag cools down and then is loaded into the recycling plant by means of a bulldozer. The slag inside the recycling plant is transferred automatically using conveyor belts and it is processed to remove the steel parts and to obtain two separated flows. A vibrating screen separates the fine particles (below 6 mm) from the coarse particles. Fine particles are pneumatically transferred to storage silos to be injected into the Electric Arc Furnace (EAF) as partial replacement of the lime. Coarse particles are loaded into the scrap basket and then poured into the EAF.

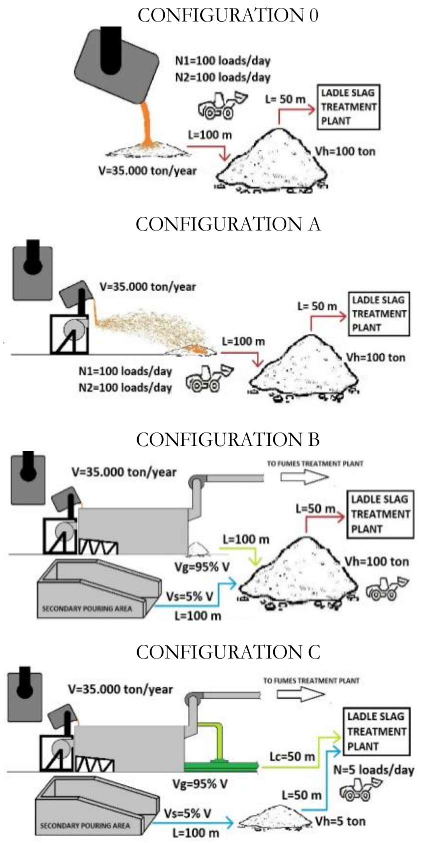

Fig. 1. Sketch of current ladle slag management process (Configuration 0) and proposed alternative configurations.

B. Innovative alternatives for LS handling systems

A few alternatives have been proposed in literature to avoid the formation of fine particles from ladle slag. Some include the use of additives [10]: yet, since LS should be re-used inside the process, variations in chemical composition should be avoided. Other recent and more promising solutions focus on the control of those parameters affecting the allotropic state, such as the cooling rate [11], aimed at blocking the meta-stable β-phase transition of belite at room temperature. Specifically, a cooling method was recently developed [12] by which the nebulization and granulation of the ladle slag is obtained using a fan. The granulated material obtained is composed of spherical particles of few mm in size and agglomerates as shown in Figure 2. Quenched slag particles are bigger and heavier than particles generated with the normal cooling process, reducing the dispersion potential of ladle slag. Moreover, they are stable, i.e. they do not react with humidity and do not undergo any further allotropic transformation. Configuration A identifies plant operation including the pre-treatment (quenching) process. Ladle slag is poured from the ladle into an intermediate heated vessel of about 5 m^3, where homogeneous granulation is promoted by an automatic tilting system. Local natural gas burners are used to maintain the container at an assigned temperature, which both guarantees a smooth handling of the LS, and preserves the refractories of the container by avoiding excessive temperature oscillations. No modifications are introduced in relation to the material handling, with the granulated slag transferred by bulldozer to the open-air heap.

Fig. 2 – Granulated ladle slag.

In configuration B, the granulation phase is performed in an enclosed casing to minimize open air operations, further reducing dust dispersion. The casing is designed to create the ideal thermo-fluid dynamic conditions for the solidification of nebulized slag drop and to confine the processing area to increase safety and environmental protection. A suction system, powered by a fan, is used to remove heat and to convey the dusty fumes to the treatment system. In this configuration, a secondary pouring area of full ladle capacity is provided to temporary store LS in case of downtimes of the granulation line or unexpected safety issues. Material handling is still performed using bulldozers.

In configuration C, ladle slag is automatically transferred to the slag treatment plant using an apron conveyor; this reduces dust emissions produced by bulldozer loading/ unloading operations. In this way, all the processes are confined during systems uptime and dust dispersion is expected to be drastically reduced. In the following, a model to estimate dust emission reduction will be introduced.

Different handling systems have different energy requirements, which should be accounted for when evaluating environmental benefits and costs of technical alternatives. Preliminary tests performed on granulated slag confirm that operations of the slag recycling plant will not be affected by changes introduced by configurations A, B, and C. Consequently, the components of the recycling subsystem (cooling part, pneumatic and belt conveyors, screens) will be not included in the resource-efficiency analysis, which is exclusively focused on comparing pre-treatment and handling systems.

III. METHODOLOGY

The transition to more resource efficient production systems implies the need for quantitative indicators, capable to trace resource consumption and associated impacts with production and consumption systems [13].

There is no standardized definition of resource efficiency in literature, and just a few guidelines supporting the definition of appropriate performance indicators. Kalliski and Engel [14] define resource efficiency as “a multi-dimensional entity that encompasses the performance with respect to energy and material as well as environmental aspects”. According to [15], resources are the environment, land, air, water, materials, and energy required to make a desired product. Elsewhere [16] the scope is restricted to materials and energy utilized to obtain the desired products. Two classes of metrics are identified in literature to characterize resource efficiency, which in [13] are referred to as “level 1” and “level 2” efficiency. Efficiency at level 1 is the ratio between the useful outputs or benefits and the inventoried flows, which includes natural resources, industrial resources, waste as resources or emissions. Efficiency at level 2 is defined as the ratio between benefits and environmental impacts. The latter can be evaluated at so called midpoint impact level (e.g. climate change or abiotic resource depletion) or aggregated as endpoint impacts (e.g. human health). In case of waste as resources, environmental impacts can also be used to quantify the benefits related to the reused/recycled waste, which are credited to the considered product as avoided impacts otherwise produced by other production systems. Unlike in [16], the authors of [13] include monetary values and flows among potential indicators. Some authors [17] point out that the integration of resource efficiency indicators based on material flow analysis and of GHG emission accounting is not trivial, and it is not even mandatory under the EU ETS scheme but gives a substantial boost to the identification and evaluation of systemic solutions and resource efficiency strategies for reducing emissions.

Eight principles are introduced by [16] to support the definition of resource-efficiency indicators for large scale chemical and petrochemical plants. Some of them are relevant for our assessment as well. Indicators should be based on material and energy flow analysis. Within the system boundaries, the indicators need to be directionally correct, i.e. improvements of the indicators demonstrate better process performance. Eco-intensity indicators, defined by inverting corresponding eco-efficiency indicators, can be used equivalently to eco-efficiency indicators, depending on users’ preferences, particularly to simplify the aggregation over different contributions due to having the same basis (product output).

A. Definition of resource efficiency indicators

Based on these principles, three resource efficiency indicators have been defined for alternative configurations of the pre-treatment and materials handling systems. The systems boundaries include the processes schematized in orange in Figure 3, which shows how the recycled ladle slag entering the EAF contributes to the overall calcium balance and reduces the need for lime consumption.

The materials flows considered include the ladle slag management process previously represented more in detail in Figure 1, the LS flows dispersed in the atmosphere as fine particulate and the lime flows entering the EAF as additive of Ca. As the evaluation concerns the pre-treatment and handling process, whose purpose is to reduce dust emissions, particulate emission reduction was assumed to be the only benefit of this subsystem, that is its desired output. The ratio of the additional resource flows required by the pre-treatment and handling systems to the benefits achieved thereby has been defined as eco-intensity indicators, which have been preferred to eco-efficiencies for ease of aggregation. Indicators have been thus defined as increments from the baseline according to equations 1 to 3.

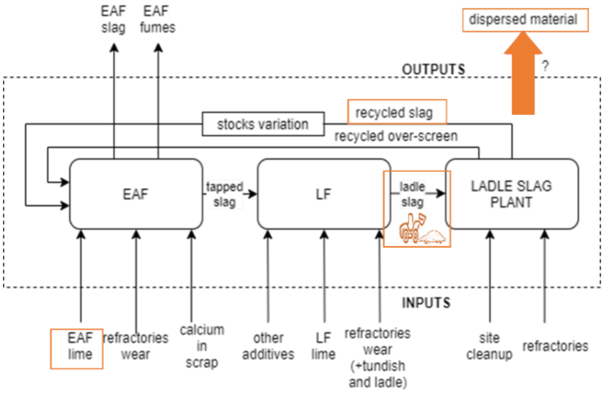

Fig. 3. Calcium related material flow balance in electric steelmaking with ladle slag recycling and system boundaries of resource efficiency indicators.

An effectiveness indicator AD_j is also introduced, which is defined as the ratio of air dispersed LS dust in each novel configuration j to the quantities dispersed in configuration 0. A preliminary check of effectiveness should be performed before resource efficiency assessment, assuring that ineffective technology options leading to null or additional dust emissions are preliminary excluded from the analysis. This implies that, for effective technologies, AD_j is always lower than 1, and the denominator of equations 1 to 3 is always positive. Equation 1 yields the Primary Energy Intensity indicator for each novel configuration j (PEI_j), which accounts for the primary energy required as fuel for materials handling, as electricity for materials handling (suffix h) and as electricity consumed by LS treatment systems (suffix t).

$$PEI_j = \frac{PEIel\_t_j + PEIfuel\_h_j + PEIel\_h_j - PEIfuel\_h_0}{PM_0 - PM_j} \tag{1}$$

Similarly, an Energy related Carbon equivalent emission Intensity indicator $ECO2I_j$ and an Energy and Materials related Carbon emission Intensity indicator $EMCO2I_j$ are defined by equations 2 and 3, respectively. Both are a function of fuel and electricity related carbon equivalent emission factors, but the latter also accounts for indirect carbon equivalent emissions associated with lime consumption (eq. 3).

$$ECO2I_j = \frac{ECO2el\_t_j + ECO2fuel\_h_j + ECO2el\_h_j - ECO2fuel\_h_0}{PM_0 - PM_j} \tag{2}$$

$$EMCO2I_j = \frac{ECO2el_{t_j} + ECO2fuel_{h_j} + ECO2el_{h_j} + ECO2lime_j - ECO2fuel_{h_0} - ECO2lime_0}{PM_0 - PM_j} \tag{3}$$

To calculate the value of these indicators, models have been used to quantify Particulate Matter (PM) emissions, primary energy consumption and carbon emissions as clarified below.

B. Quantification of particulate matter emissions

Emission models [18][19][20] developed by the Environmental Protection Agency (EPA) of the USA have been adopted to quantify the dispersion of particulate matter under different configurations. As shown in Table 1, particulate emissions from LS heaps derive from three activities or phenomena, that are drop operations from and to LS heaps, LS transport, and erosion of heaps by wind. The dispersion related to drop operations is the one that occurs during bulldozer handling activities of loading and unloading and during the removal of the large steel part from the heap performed by a grapple handler. The expression for the drop operation emission factor, and the emission factors related to the other mechanism of material dispersion are listed in Table 1.

TABLE I
EPA MODELS FOR DUST EMISSION

Source	Equation
Drop operations	$E_D = 0{,}0016 \cdot k \cdot \frac{\left(\frac{U}{2{,}2}\right)^{1{,}3}}{\left(\frac{M}{2}\right)^{1{,}4}}$
Transport	$E_T = (k \cdot (sL)^{0{,}91} \cdot W^{1{,}02}) \cdot (1 - \frac{P}{4 \cdot N})$
Wind erosion	$P_W = 58 \cdot (u_s - u_{thr})^2 + 25 \cdot (u_s - u_{thr})$

The parameters influencing the drop operation dispersion are the average wind speed (U), the moisture content of the material handled (M) and the size of the particles handled (corresponding to a coefficient k). This emission factor is then multiplied by the material handled, relative to each drop operation, and, as a result, the total dust dispersion is determined. Transport model allows to define how much material is lifted from the ground due to bulldozers traffic. The variables affecting the emission are the Silt Load (sL) that is the quantity of material deposited on a unitary surface, the weight of the vehicle transiting (W), the period of rainy days (P), the total period considered (N) and the material particle size (adopting a coefficient k). The emission factor obtained from the model is then multiplied by the total distance travelled by the vehicles within a set amount of time to calculate the dust emission associated to this mechanism. Lastly, the potential of wind erosion depends on the heap surface wind speed (u_s) and on a threshold wind speed (u_{thr}). This potential is referred to a unitary heap surface and is multiplied by the associated heap surface, calculated with reference to a conical heap shape facing a frontal wind gust, and by a coefficient that considers the material particle size (k) to obtain the amount of material lost in t/year. The total mass of particles by size class, which is required in the models to determine coefficients k, is derived from the physical slag characterization trials performed at the plant for LS and for pre-treated LS: the change in particle size distribution produced by the pre-treatment procedure is highlighted in Figure 4.

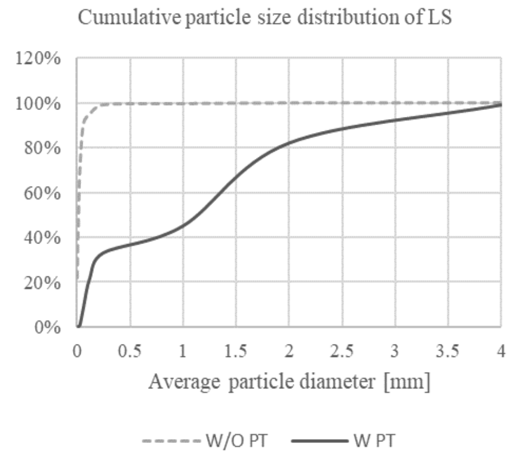

Fig. 4. Grading curves of ladle slag with and without pre-treatment

C. Quantification of additional energy demand

To determine the energy consumption of each configuration, the power demand by each component should be first evaluated. Table 2 summarizes the power ratings Pel attributed to each component and the criterion adopted to quantify them. The energy consumption is calculated by assuming a utilization factor uf and a working schedule of the component. Based on expected working schedule of subsystems and on historic data on equipment availability, recorded at the steelworks for the equipment studied or for similar components, the equipment runtime rt is estimated. The corresponding energy consumption is then evaluated according to equation 4.

$$EL_k = Pel_k \cdot rt_k \cdot uf_k \tag{4}$$

The primary energy demand from fuel consumption for materials handling is estimated based on historic diesel fuel consumption by bulldozers in litres. This is assumed to remain unchanged in all but the last configuration, where an apron conveyor is introduced instead. A further energy demand and carbon emission source is represented by natural gas burnt at the tiltable container. The gas consumption is estimated based on the analogous process of ladle heating, by assuming an equal consumption per unit volume. Values of natural gas flows for the existing system are currently recorded by meters installed on the line feeding the ladle burners. The energy calculated is converted into Tons of Equivalent Oil (TOE) using official conversion factors reported by the Italian Ministry for Economic Development [22] i.e. 1,08 TOE/t diesel oil, 0,82 TOE/(1000*Nm^3 natural gas), and 0,23 TOE/MWh$_{el}$, respectively.

TABLE II
POWER DEMAND OF EQUIPMENT USED IN DIFFERENT CONFIGURATIONS

Config.	Component	Power	Evaluation
0	Bulldozer	177 kW	Existing component
A	Bulldozer	177 kW	Same as config. 0
	Granulation fan	315 kW	Based on preliminary design
	Tiltable container	55 kW (tilter) + 250 kWt (preheater)	Based on preliminary design
B	Bulldozer	177 kW	Same as config. 0
	Granulation fan	320 kW	Same as config. A
	Tiltable container	55 kW (tilter) + 250 kWt (preheater)	Same as config. A
	Casing components	50 kW	Based on preliminary design
	Suction fan	150 kW	Based on preliminary design
C	Bulldozer	177 kW	Same as config. 0
	Granulation fan	320 kW	Same as config. A
	Tiltable container	55 kW (tilter) + 250 kWt (preheater)	Same as config. A
	Casing components	50 kW	Same as config. B
	Suction fan	150 kW	Same as config. B
	Apron conveyor	5 kW	Based on preliminary design

D. Quantification of additional and avoided carbon equivalent emissions

Energy related carbon emissions, both direct (fuel consumption) and indirect (electricity consumption) are calculated with official emission factors from ISPRA (2020), which amount to 1,972 $tCO_2eq/(1000*Nm^3$ of gas), 3,16 tCO_2eq/t of diesel oil and to 276 gCO_2/kWh of electric energy, respectively.

To evaluate avoided emissions from reduced lime consumption an emission factor of 1,092 tCO_2eq/t of lime has been derived from [21], which accounts for average carbon equivalent emissions in quicklime production in Europe considering emissions from process, combustion, and from related electricity consumption. The impact of lime transport from producers to the steelworks is not considered here, although internal recycling of LS as lime substitute has the additional advantage of avoiding external transport with trucks.

IV. RESULTS AND DISCUSSION

Figure 5 and Figure 6 report the results of the application of the EPA model to estimate dust dispersion. Figure 5 shows that total emissions in resulted to be mainly caused by “drop operations” (d.o.). For brevity, only dust emissions from d.o. are hence reported in detail in Figure 6, for all configurations.

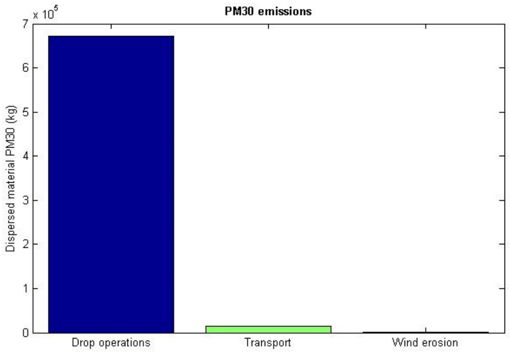

Fig. 5. Yearly dust emissions from different sources for current LS management practices (configuration 0)

We observe that all the proposed configurations are very effective in reducing LS dust dispersion. As confirmed by the effectiveness indicator *DD* represented in Figure 7, in configuration A dust dispersions drop to less than 30% of the dispersions in the baseline configuration 0. In configuration C they are further reduced to less than 5% of the baseline, and almost 900 t/year of LS dust emissions could be avoided. Figure 6 also shows that the primary energy consumption is maximum for configuration B, due to the combined effect of the hydraulic units, electric motors and vibrating engines used to move LS within the casing and of the suction fan which is required evacuate air and heat from the casing. It is interesting to observe that, based on all the eco-intensity indicators reported in Figure 7, the decrease in dust dispersion associated with enclosing the handling system within a casing, although significant, does not justify the additional energy demand required for managing the closed system. On the other hand, the advantages of opting for an enclosed system are fully grasped if the LS handling is automated with a cased apron conveyor, which is loaded and unloaded in closed environments, thereby avoiding dispersion from drop operations. Interestingly, configuration C has the best carbon emission intensities, although only slightly better than configuration A, but is only second best in terms of *PEI*. Consistent with this finding, in Figure 8 we observe that energy related carbon emissions (represented by the sum of grey, yellow and blue bars in Figure 8) are, as expected, in line with primary energy demand patterns observed in Figure 6, with less evident differences between configurations A and B and more evident differences between configurations B and C.

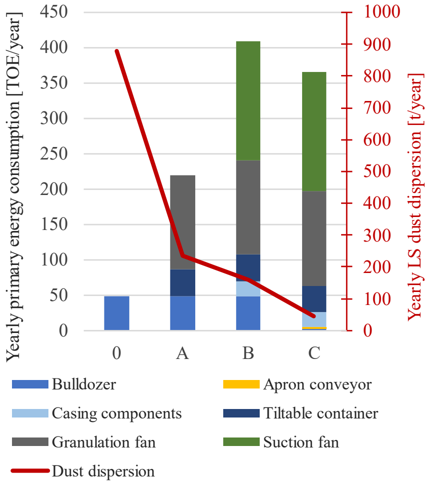

Fig. 6. Yearly primary energy consumption and dust dispersion for each pre-treatment and material handling option

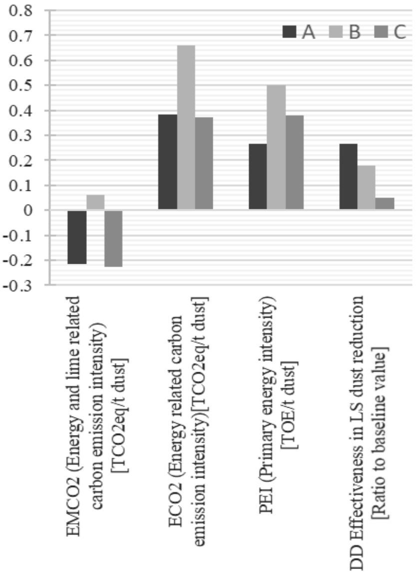

Fig. 7. Eco-intensity indicators and effectiveness indicator DD for each pre-treatment and material handling option

Differences between configurations can be mainly attributed differences in electricity consumption, particularly for the suction fan required if a casing is used. As the amount of carbon emitted to the atmosphere is directly proportional to the amount of fossil fuel combusted, the fact that total carbon equivalent emissions are less affected than primary energy demand by substantial changes in electricity demand implies that the weight of fossil fuel-based electricity generation is higher in the electricity related primary energy consumption factor (dating back to 2014 [22]) than in the corresponding carbon equivalent emission factor as of 2020. On the other hand, electrification of LS handling in option C avoids diesel oil combustion and partially compensates additional emissions to support operations in a closed environment. The most striking result emerges from the assessment of total carbon equivalent emissions, including the indirect emissions from lime consumption (Figure 8), as well as of the corresponding eco-intensity indicator $EMCO_2$ (Figure 7).

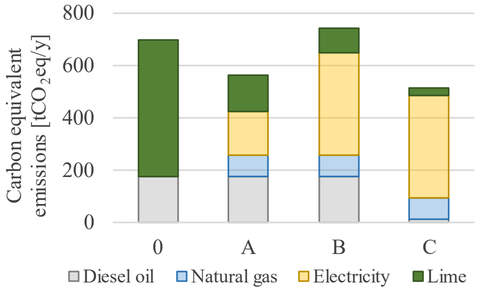

Fig. 8. Yearly primary energy consumption and dust dispersion for each pre-treatment and material handling option

The lime that potentially could be saved by adopting configuration A is about 372 ton/year, which is just about 1% of current total quicklime and dolomitic lime consumption at this steelmaking plant. This quantity is enough to outweigh the increase in carbon equivalent emissions caused by the additional energy demand by the pre-treatment and handling systems. This is mainly due to the high carbon emission intensity of lime production processes, which makes LS dust dispersion avoidance and consequent recycling particularly advantageous.

V. CONCLUSIONS

Some novel LS pre-treatment and handling options at electric steelmaking plants have been compared by introducing eco-intensity indicators based on primary energy and carbon emissions. The efficiency indicators alone do not allow a clear ranking of alternatives, but they help in excluding dominated solutions such as configuration B in our case study. A combined analysis of efficiency and effectiveness indicators leads to preferring configuration C, where a fully automated and electrified material handling system reduces the use of diesel fuelled vehicles and enhances recycling enough to outweigh the indirect emissions from the additional electric energy required for its operation. Further research will be devoted to developing a broader multicriteria framework considering monetary flows as well, to obtain a clearer ranking of technology options.

REFERENCES

[1] Yildirim, I. Z., & Prezzi, M. (2011). Chemical, mineralogical, and morphological properties of steel slag. *Advances in Civil Engineering*, 2011.
[2] Najm O., El-Hassan H., El Dieb A. (2021), Ladle slag characteristics and use in mortar and concrete: A comprehensive review, *Journal of Cleaner Production*, 288, 2021, 125584.
[3] Serjun, V.Z., Mladenovič, A., Mirtič, B., Meden, A., Ščančar, J., Milačič, R. (2015) Recycling of ladle slag in cement composites: Environmental impacts. *Waste Management*, 43, pp. 376-385
[4] Piatak, N.M., Parsons, M.B., Seal, R.R., II (2015) Characteristics and environmental aspects of slag: A review *Applied Geochemistry*, 57, pp. 236-266.
[5] Natali Murri A., Rickard, W.D.A., Bignozzi, M.C., Van Riessen, A. High temperature behaviour of ambient cured alkali-activated materials based on ladle slag. (2013) *Cement and Concrete Research*, 43 (1), pp. 51-61.
[6] Bocci, E. Use of ladle furnace slag as filler in hot asphalt mixtures (2018) *Construction and Building Materials*, 161, pp. 156-164.
[7] Guzzon, M., Di Sante, L., Malfa, E., Praolini, F., Bissoli, M. (2019). Secondary metallurgical slag granulation by forced air. *Proceedings of the 10th EUROSLAG Conference*, Thessaloniki
[8] Memoli, F., Mapelli, C., & Guzzon, M. (2007). Recycling of ladle slag in the EAF: A way to improve environmental conditions and reduce variable costs in steel plants. *Iron & Steel Technology* 4(2), 68–76.
[9] Shi, C. (2002). Characteristics and cementitious properties of ladle slag fines from steel production. *Cement and Concrete Research*, 32(3), 459–462.
[10] Branca, T. A., & Colla, V. (2008). Possible Uses of Steelmaking Slag in Agriculture: An Overview.
[11] Varanasi, S. S., More, V. M. R., Rao, M. B. V., Alli, S. R., Tangudu, A. K., & Santanu, D. (2019). Recycling Ladle Furnace Slag as Flux in Steelmaking: A Review. *Journal of Sustainable Metallurgy*, 5(4), 449–462.
[12] Guzzon, M., Malfa E., Bozzetti L., Bissoli M., Praolini F., Process and Apparatus for the Granulation of Slag deriving from Iron and Steel Production, WO2021156789A1, 2021
[13] Huysman, S., Sala, S., Mancini, L., Ardente, F., Alvarenga, R.A.F., De Meester, S., Mathieux, F., Dewulf, J.(2015) Toward a systematized framework for resource efficiency indicators. *Resources, Conservation and Recycling*, 95, pp. 68-76
[14] Kalliski, M., Engell, S. (2018) Real-time resource efficiency indicators for monitoring and optimization of batch-processing plants. *Canadian Journal of Chemical Engineering*, 95 (2), pp. 265-280
[15] Krämer S., Engell S. (2018) *Resource efficiency of processing plants*. Wiley-VCH Verlag GmbH, Weinheim
[16] VTT (2017) *Successful resource efficiency indicators*. https://publications.vtt.fi/pdf/technology/2017/T290.pdf
[17] Billy, R.G., Monnier, L., Nybakke, E., Isaksen, M., Müller, D.B. (2022) Systemic Approaches for Emission Reduction in Industrial Plants Based on Physical Accounting: Example for an Aluminum Smelter *Environmental Science and Technology*, 56 (3), pp. 1973-1982
[18] EPA. (n.d.). 13.2.5 Industrial Wind Erosion. 1–15
[19] EPA. (n.d.). 13.2.4 Aggregate Handling And Storage Piles.
[20] EPA. (n.d.). 13.2.1 Paved Roads. 1–15
[21] EuLA. (2014). Competitive and Efficient Lime Industry-Cornerstone for a Sustainable Europe-EXECUTIVE SUMMARY. 1–72. www.eula.eu.
[22] MISE, DM 27 marzo 2014. http://www.gazzettaufficiale.it/eli/gu/2014/04/07/81/sg/pdf
[23] ISPRA(2020). Rapporto 317/2020 http://www.isprambiente.gov.it/files2020/pubblicazioni/rapporti/Rapporto317_2020.pdf