Evaluations through Mass Flow Analysis of the production and management of steel slags in the province of Brescia (Italy)

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Nowadays, steel production is mainly carried out according to two different processes: integral and electric cycle. Both of these processes generate large amounts of slags that can be destined for treatment/recovery or disposal. In Italy, about 80% of steel production takes place through the electric cycle, in particular in the electric arc furnace (EAF), with a quantity of slag estimated at about 3.5 million tons per year. Most of the production is concentrated in the Northern Italy and in particular in the province of Brescia (Lombardy), which, by itself, is responsible for about 25% of the slag production from electric arc furnace at national level. Depending on the production process and management planning of the individual steel mill, the slag produced could be classified as a by-product or waste. At the moment, about 75% of the slag produced in the province of Brescia and classified as waste is destined for disposal in landfills. A greater reuse of steel slag could bring considerable benefits from both environmental and economic point of view (reduction in the exploitation of land and raw materials, lower greenhouse gas emissions, less space dedicated to landfills etc.). The research is therefore focusing on the study and implementation of different possible applications, in which this material could be a viable alternative to natural products (e.g. the reuse in geotechnical applications, for road construction, asphalt, concrete etc.). In order to fully understand the problem of the steel slag management on a territory, it is necessary to investigate and understand how this material is produced, treated and eventually reused. The Mass Flow Analysis is certainly a valuable tool to understand not only how producers interface with other companies involved in the steel industry (transporters, final users and/or disposers), but also to identify the most appropriate applications to ensure greater recovery of this material, thus limiting the amount destined to the landfill. Through the analysis of data available on regional scale and by means of accurate elaborations, this study aims to represent the "state of the art" concerning the production, management and destination of steel slags produced in the province of Brescia, useful to identify possibilities for improvement and implementation in the reuse of these types of materials.

Introduction

The global steel industry has seen a significant increase in production over the last 20 years, from 847.1 million tonnes in 2000 to 1,875.2 million tonnes in 2019. China has increasingly taken the lead in recent years, with a steel production accounting for around 50% of all steel produced internationally in 2019 [1].

Steel production can mainly take place according to two distinct processes, integral and electric cycle, and, depending on the geographical area considered, one method may be predominant over the other. The integral cycle is divided into two steps: the first step is the production of pig iron in the blast furnace from raw materials such as iron ore, coke, limestone and other minor additions. In addition to the primary material (molten pig iron), the so-called "*Blast Furnace Slag*" (or "*BFS*") is also tapped from the blast furnace, in a range of approximately 250-300 kg per tonne of pig iron produced. Depending on the cooling process and the treatments to which they are destined, these slags have different characteristics and can be reuse in various applications (e.g. partial replacement of the binder and/or the natural aggregate for the production of concrete, partial replacement of the clinker for the production of cement, production of lime from slag, etc.) [2]. The second step of the integral cycle consists in the production of steel in the oxygen converter from raw materials such as molten iron, steel scrap in small percentages, lime/dolomite and other minor additions. In addition to the primary material (molten steel), the so-called "*Basic Oxygen Furnace slag*" (or "*BOF*") is also tapped from the converter, in a range of approximately 100-150 kg per tonne of steel produced. This type of slag is mainly used as aggregate in road construction (as well as other minor reuses in concrete production or as an addition in fertilisers) [2].

The electric cycle is the main alternative to the integral cycle for steel production: it consists of a single step in the electric arc furnace starting from raw materials such as steel scrap (appropriately selected), pig iron in small percentages and other minor additions [2]. In addition to the primary material (molten steel), the so-called "*Electric Arc Furnace slag*" (or "*EAF*") is also tapped from the furnace, in a range of approximately 150-180 kg per tonne of steel produced. This type of slag is divided into two categories, depending on whether the steel produced is carbon steel ("*Electric Arc Furnace slag from Carbon steel*" or "*EAF-C*") or stainless/high alloy steel ("*Electric*

Arc Furnace slag from Stainless/high alloy steel" or "*EAF-S*") and is mainly used as aggregate for road construction or as a partial replacement of cement and/or natural aggregate in concrete [2].

The steel produced in both processes is then usually destined for secondary metallurgy operations in ladle furnace (e.g. desulphurization, degassing, changes in composition etc.). These steel refining processes give rise to another type of slag, called "*Ladle Furnace Slag*" (or "*LFS*"), in a range of approximately 30-80 kg per tonne of refined steel. Because of its characteristics and heterogeneity, which make it very difficult to reuse, this type of slag needs to be studied in depth [2].

With a total steel production of about 23 million tonnes (2019), Italy is the second largest producer in Europe after Germany and not considering Turkey (which is not classified in the "EU28" countries in the World Steel Association statistics [1]). Of these 23 million tonnes, approximately 19 million tonnes (80%) came from electric arc furnace production, making Italy the largest producer of electric arc furnace steel in Europe (not including Turkey, as mentioned above). Considering a production range of 150-180 kg of electric arc furnace slag (EAF) per tonne of steel produced, slag amounted to around 3.25 million tonnes in 2019 (to which must be added around 1 million tonnes of slag from secondary metallurgy processes, assuming that all the steel undergoes refining).

Almost all electric arc furnaces and ladle furnaces are located in Northern Italy and in particular in the Lombardy region (where there are 19 steel mills). Figure 1 shows the location of the steel producers (blast furnaces, basic oxygen converters and electric arc furnaces) in Italy in 2019, including non-operational sites, with a focus on the Lombardy region.

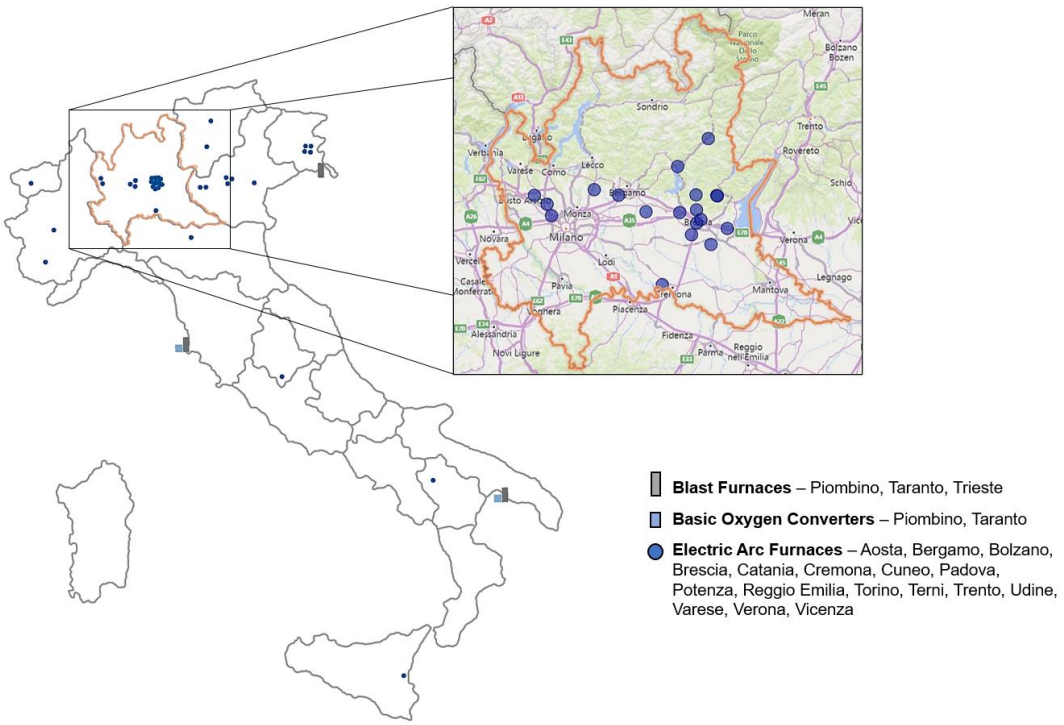

Fig. 1 Location of the steel producers (blast furnaces, basic oxygen converters and electric arc furnaces) in Italy in 2019, with a focus on the Lombardy region. Image modified and adapted from [3]

The most virtuous province concerning the Italian steel sector is undoubtedly the province of Brescia (in Lombardy), which has 11 steel mills located on its territory, contributing approximately to the 25-30% of the national steel produced and refined. In parallel with the steel production, there is also the production of a large quantity of slags (EAF and LFS), with values around 1.1 million tonnes in 2019. Unfortunately, a considerable part of these slags is not recovered and is still disposed in landfills, despite their good performance properties and the various fields of reuse that have been almost consolidated and studied, generating numerous problems in the management of the material.

The aim of this work is therefore to investigate and analyse the supply chain that deals with the management of steel slags in the province of Brescia, from the producer to the final user and/or disposer, identifying the mass flows of these materials within the province, as well as the incoming and outgoing flows. This research aims not only to study the slag flows, but also to obtain a representation of the current situation regarding the reuse and reutilization of these materials in production processes for which they are suitable, with a view to their full exploitation and following the principles of the circular economy (increasing recovery, recycling and reuse of

materials that would otherwise be destined for disposal, reducing land consumption, areas used for landfills, atmospheric emissions, etc.). This study was possible thank to the consultation of a regional database (MUD) and the processing of data obtained through Mass Flow Analysis, as described in the following paragraphs.

Data analysis – Methodology

According to Italian legislation (Legislative Decree 152/2006 and subsequent amendments and updates [4]) and depending on the choices made by each steel mill, the slag produced can be classified either as "waste" or as "by-product", with consequent differences in terms of management and treatment. The Lombardy region, through the ARPA ("*Agenzia Regionale per la Protezione dell'Ambiente*"), provides a database called MUD ("*Modello Unico di Dichiarazione ambientale*"), consisting of a set of declarations that all producers, transporters, treatment/recovery plants and disposers of waste must submit every year and in which waste is distinguished according to type, producer, origin and source [5]. For each of the 12 provinces of Lombardy, the database is divided into 29 tables, that can be exported in the desired format or consulted with special software, each containing one or more information and identified by two letters. Depending on the purpose of the research and the waste of interest, and using special filters, the database provides the desired information. The sections consulted for this research were:

- Section AA – "*Company and Local Unit Master Data*", containing the master data of each company that has submitted the annual declaration of waste production, management, treatment or disposal. Among the most important data in this section, in addition to the name and the address of the company, there is the CIU ("*Codice di Identificazione Univoca provinciale*"): this is a code assigned to each declarant so that it can be easily and immediately identified in the other sections of the database;
- Section BA – "*Waste Communication*", containing, for each reporting company, the main information on waste produced, managed, treated or disposed (total quantities produced and destined for third parties, stocks, etc.), subdivided by EWC code;
- Section BB – "*Attachments to Section BA*", containing information on incoming and outgoing flows from each company. This section is subdivided into three different modules: module "*RT*" – "*waste received from third parties*", module "*DR*" – "*waste delivered to third partied*", module "*TE*" – "*waste transported by third parties*" and, for each module, the quantity of waste, the name and the address of the sender or receiver company are indicated;
- Section BD – "*Waste management, disposal operations*", containing information on waste destined for disposal: quantities, name and address of the destination company and disposal category (in accordance with Annex B of Legislative Decree 152/2006 [4]);
- Section BE – "*Waste management, recovery operations*", containing information on waste destined for recovery: quantities, name and address of the destination company and recovery category (in accordance with Annex C of Legislative Decree 152/2006 [4]).

The distinction between the different types of waste in the database is made possible by the assignment of an EWC code (from the European Waste Catalogue [6]), i.e. a sequence of three pairs of two digits, "*class*", "*subclass*" and "*category*", so that the waste can be identified according to production sector, production process, type and characteristics. As regards the steel slags examined in this study, they were classified by the producers using the following EWC codes:

- 10.02.01 – "*Waste from the processing of slag*";
- 10.02.02 – "*Unprocessed slag*";
- 10.09.03 – "*Furnace slag*".

The MUD database is an excellent tool for reconstructing the steps that a waste undergoes when it passes from the producer to the final user and/or disposer. However, this study was not only limited to the consultation of the data, but also aimed at simplifying their visualization: to this end, the data were first extrapolated and superfluous information were removed. This was followed by further processing, in order to represent and identify, in a quicker, simpler, more intuitive and interactive manner, all possible information contained in the database for the type of waste of interest.

Results obtained by consulting the MUD database

The province of Brescia is located in the eastern part of the Lombardy region and is the most virtuous province in Italy as regards the steel sector. There are 11 steel mills on its territory, equipped with one or more electric arc furnaces and one or more ladle furnaces, depending on the company's management system. The total steel

production in the province of Brescia has undergone a significant increase in the last 10 years, reaching about 6 million tons in 2019. In parallel to this steel production, high quantities of slag are also generated, reaching about 825 thousand tonnes of electric arc furnace (EAF) slag and 285 thousand tonnes of ladle furnace (LFS) slag in 2019, for a total of about 1.1 million tonnes.

In the present research, not only the overall production data, but also the slag flows in the province, from the producer to the final treatment/recovery plant and/or disposer, were analysed by consulting the MUD database for the year 2017 (last available update). In 2017, the total slag production in the province of Brescia amounted to approximately 1.07 million tonnes (considering both EAF and LFS slags). To this must be added the stocks stored at the steel mills until the end of 2016, which have contributed to the increase in the amount of slags to about 1.1 million tonnes. These slags were then transferred to the other operators in the steel chain, where they underwent treatment and recovery operations or disposal in landfills. Figure 2 shows the location of the province of Brescia in Lombardy and a focus on the location of steel mills, treatment/recovery plants and disposal plants in the provincial territory.

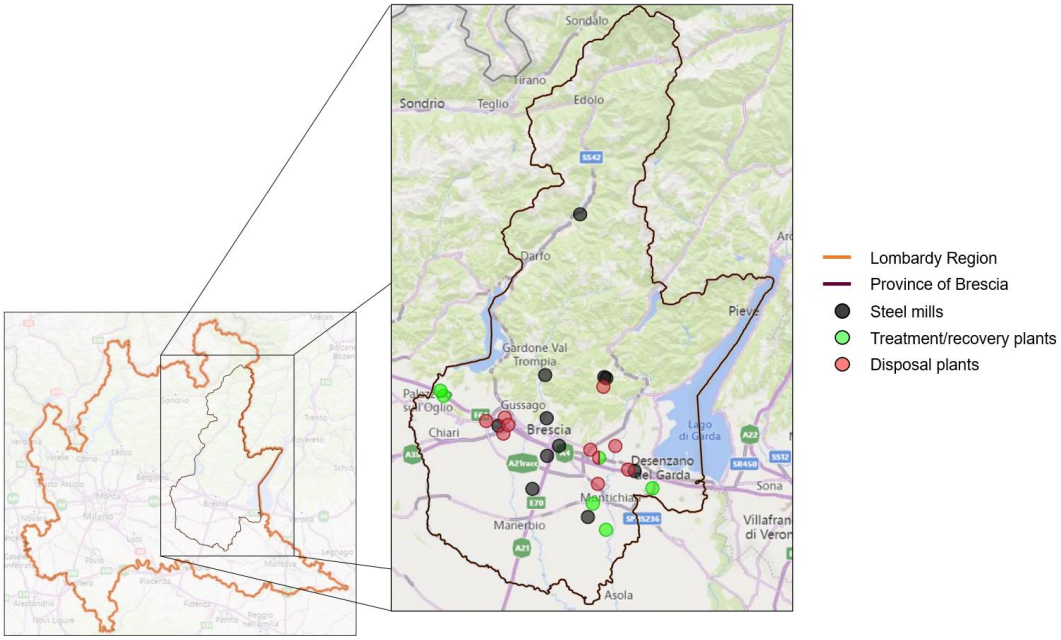

Fig. 2 Location of the province of Brescia in Lombardy with a focus in the location of steel mills (in black), treatment/recovery plants (in green) and disposal plants (in red) in the provincial territory

Further analysis and processing of the data made it possible to map the flows of steel slags produced in the province of Brescia, highlighting both the quantities that remain within the province and those destined for recovery and/or disposal outside the province. Figure 3 shows an example of processing through which it was possible to identify the quantities of slag produced and destined for treatment operations at recovery plants, located both inside and outside the province. Figure 4 shows the same data processing, but with reference to the slag produced and destined for disposal in landfills located both inside and outside the province. In these figures, the steel mills are identified with different coloured circles for better distinction, and a thicker line corresponds to a larger quantity of slags going to a recovery and/or disposal plant.

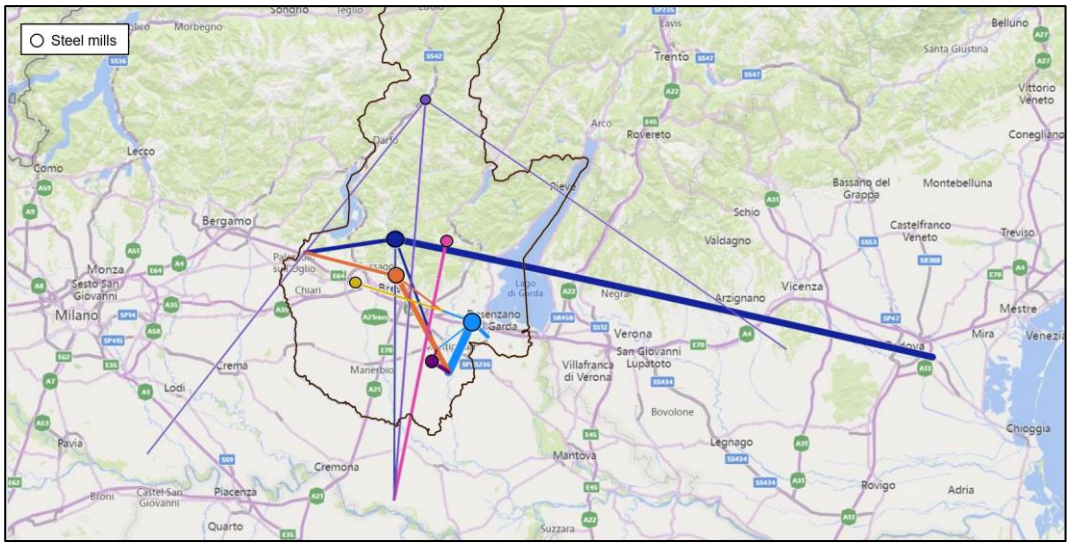

Fig. 3 Example of processing showing the quantities of slag produced and destined for treatment operations at recovery plants, located both within and outside the provincial territory (steel mills are marked with different coloured circles for better distinction)

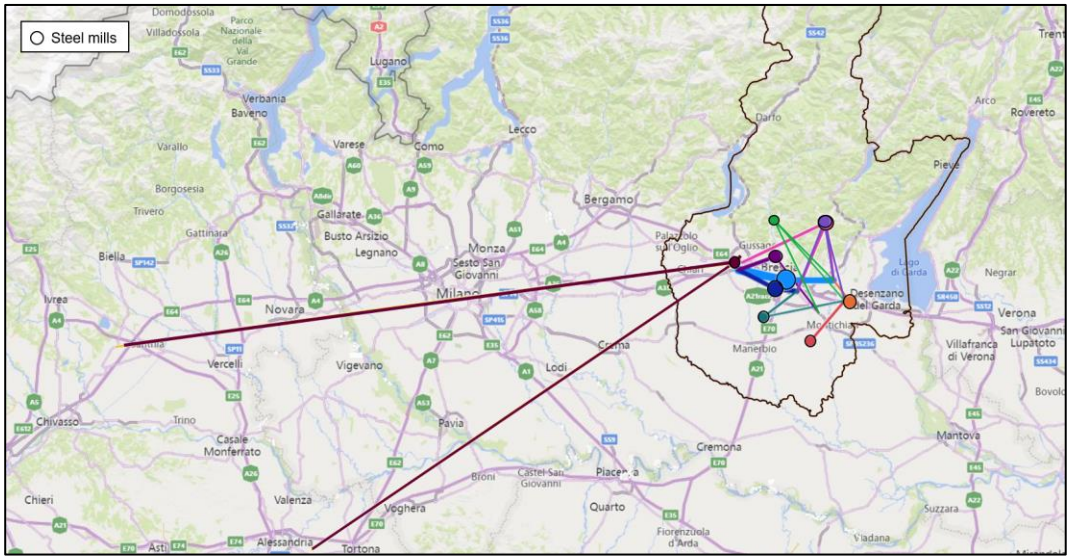

Fig. 4 Example of processing showing the quantities of slag produced and destined for disposal in landfills located both inside and outside the province (steel mills are marked with different coloured circles for better distinction)

Given the large amount of data analysed and processed, deriving from the consultation of the MUD database for the year 2017, a summary of the quantities of steel slags produced in the province of Brescia and destined for recovery and/or disposal operations, both inside and outside the provincial territory, is shown in Figure 5. The total production of slag from electric arc furnace (EAF), added to that of slag from ladle furnace (LFS), amounted to just over 1 million tonnes in 2017. If the stocks present at the end of 2016 and still stored in the steel mills are added, the amount of slags to be sent to third parties for recovery and/or disposal operations reached approximately 1.1 million tonnes.

As shown in Figure 5, about 73% of the slag was unfortunately destined for disposal in landfills, just over 775 thousand tonnes. The remaining part, about 27% (285 thousand tonnes), was sent to recovery plants to undergo treatments in order to obtain a material that can be reused in the applications for which it is suitable. Comparing the destinations for recovery with those for disposal, it can be seen that 75% of the recovered slags remained in plants located in the province (about 213 thousand tonnes) and the remaining 25% was sent to treatment plants located outside the province. As for the slags for disposal, almost all of them (99.5%) were sent to landfills located within the province and only a small part was sent outside the province (just under 4,000 tonnes).

It was also possible to identify the flows of slag produced by steel mills located outside the province of Brescia and imported into the province, which amounted to just under 190,000 tonnes. Figure 5 shows that 99% of these was destined for disposal and only 1% was destined for recovery, thus increasing the total amount of slag disposed and recovered in the province of Brescia in 2017 from slightly more than 775 thousand tonnes to approximately 960 thousand tonnes and from 285 thousand tonnes to slightly less than 290 thousand tonnes, respectively. The percentage ratio between the total amount of slag disposed and the total amount of slag recovered in the province of Brescia has therefore increased from 73-27 (%) to 78-22 (%).

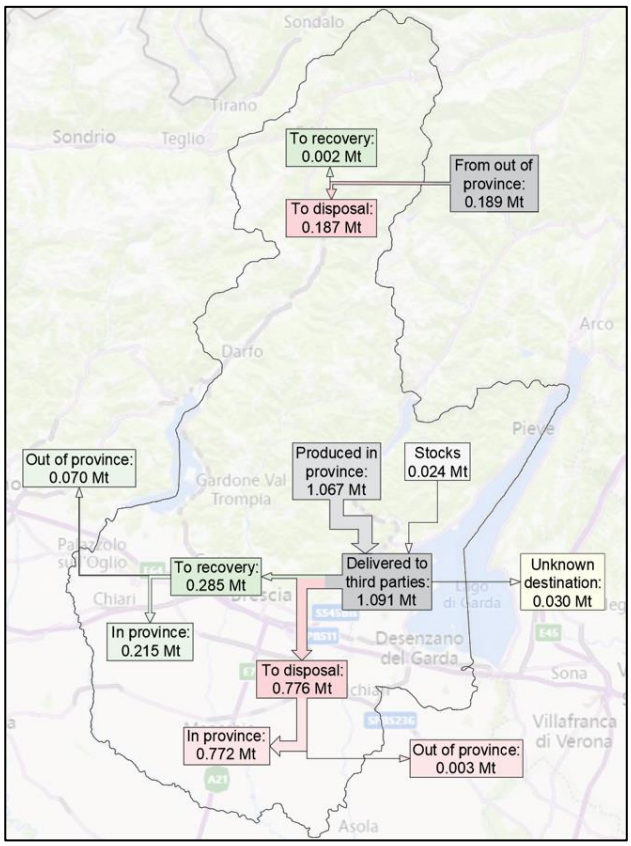

Fig. 5 Summary of the quantities of steel slags produced in the province of Brescia and destined for recovery (in green) and disposal (in red), both inside and outside the provincial territory (expressed in million tonnes)

Weaknesses points of the MUD database

Once tapped from the furnace and subjected to preliminary treatments (e.g. characterisation of composition, cooling, solidification, etc.), the slags produced can be classified in two different ways, depending on company choices and availability:

- Slags classified with the status of "waste" (definition according to art. 183, paragraph a) of Legislative Decree 152/2006 [4]): they are subjected to the attribution of an EWC code by the producer, who is also required to fill in the MUD database annually, declaring quantities, production and destination. They will then be stored in the steel mill to then be destined for recovery operations ("End of Waste", according to art. 184-ter of Legislative Decree 152/2006 [4]) or disposal in landfills;
- Slags classified with the status of "by-product" (definition and conditions according to art. 183, paragraph qq) and art. 184-bis of Legislative Decree 152/2006, respectively [4]). Compliance with the conditions of art. 184-bis, with the addition of the registration to the ECHA ("*European Chemicals Agency*") and CE marking, allows the slags classified as "by-product" to be placed on the market and to be reused in sectors where they are most suitable, without undergoing "End of Waste" recovery operations.

The analysis of the MUD database can provide a lot of information on the production and destination of steel slags in a given territory. However, if one bases oneself solely on consulting the database, there is the risk of

obtaining a representation that is not the exact representation of the real situation of the steel industry, due to some weaknesses in the database layout, that, unfortunately, contribute to providing useful but incomplete data:

- The database contains information only on steel slags classified as "waste"; there is no information on slags classified as "by-products" (which, on further investigation, represent, on average, about 30-40% of the annual steel slag production);
- Although the database allows searches to be carried out using the EWC code of interest, it is not possible to distinguish between the quantities of slag from electric arc furnace (EAF) and slag from ladle furnace (LFS). This is due to the fact that the two types of slag are classified under the same EWC code by most of the steel mills operating in the area, despite the fact that they differ greatly in terms of chemical, physical and mineralogical properties, performance characteristics and fields of application and reuse [2];
- By analysing sections BD and BE of the database, only partial information can be obtained on the disposal and recovery of slag classified as "waste". In fact, disposal and recovery are only identifiable by the codes in Legislative Decree 152/2006, Annexes B and C of Part IV, from D1 to D15 for disposal and from R1 to R13 for recovery, respectively [4]. There is therefore no further information about the actual field of reuse of the examined slags (e.g. road construction, concrete mixes, etc.).

Given the above, further research was carried out in this study to "fill in" the weakness points in the database and provide a picture of steel slag management in the province of Brescia that is as close to reality as possible. In order to do this, the operators in the province were directly involved by sending questionnaires customised for each company, with the aim of obtaining more information about the part of slag classified as a "by-product", a subdivision of the slag produced between electric arc furnace slag (EAF) and ladle furnace slag (LFS) and an update of the data to the year 2020. This made it possible to outline a situation much closer to the real situation regarding the production, management, treatment, recovery and disposal of steel slag in the province, compared to consulting only the MUD database.

Impact of the slag classified as "by-product"

From the analysis and processing of the data obtained from the questionnaires sent to the operators of the iron and steel industry, and from the data obtained thanks to the sector consortia [7], it was possible, albeit in part, to fill the weakness points in the MUD database described above. Several comparisons were made between the total quantities of slag from electric arc furnace (EAF) and ladle furnace (LFS) production, as well as between slag classified as "waste" and "by-product" and between slag destined for recovery and slag destined for disposal. The time period taken into consideration was from 2013 to 2020, in order to obtain a realistic trend and representation of the production and management of the material in recent years within the province of Brescia.

Tables 1 and 2 show, respectively, the summary of the abovementioned data for slag from electric arc furnaces (EAF) and ladle furnaces (LFS):

Table 1 EAF steel and slag production in the province of Brescia, expressed in million tonnes, and subdivision of slag into by-product, waste for recovery and waste for disposal

EAF slag from Electric Arc Furnace in the province of Brescia					
Year	Steel production	EAF slag	EAF slag as by-product	EAF slag as waste - Recovery	EAF slag as waste - Disposal
	[Mt]	[Mt]	[Mt]	[Mt]	[Mt]
2013	4.81	0.70	0.21	0.33	0.25
2014	4.98	0.72	0.29	0.24	0.27
2015	5.32	0.72	0.39	0.12	0.27
2016	5.71	0.77	0.16	0.19	0.31
2017	6.05	0.83	0.18	0.24	0.46
2018	N/D*	0.82	0.09	0.32	0.42
2019	N/D*	0.82	0.14	0.33	0.35
2020	N/D*	0.67	0.12	0.37	0.18

* N/D: no data available

Table 2 Steel refining and LFS slag production in the province of Brescia, expressed in million tonnes, and subdivision of slag into by-product, waste for recovery and waste for disposal

LFS slag from Ladle Furnace in the province of Brescia					
Year	Steel production	LFS slag	LFS slag as by-product	LFS slag as waste - Recovery	LFS slag as waste - Disposal
	[Mt]	[Mt]	[Mt]	[Mt]	[Mt]
2013	4.81	0.20	0.0003	0.0007	0.29
2014	4.98	0.20	0	0.0004	0.23
2015	5.32	0.21	0	0	0.21
2016	5.71	0.26	0	~ 0	0.24
2017	6.05	0.28	~ 0	0.0003	0.28
2018	N/D*	0.28	0	0.0003	0.28
2019	N/D*	0.28	0	0.0002	0.28
2020	N/D*	0.23	0	0.0001	0.23

* N/D: no data available

Figure 6 shows a summary of Tables 1 and 2 above, with a comparison between the production of slag from electric arc furnace (EAF) and slag from ladle furnace (LFS), expressed in million tonnes (Mt). Out of the total slag produced in the province of Brescia, about 80% is EAF slag and the remaining 20% is LFS slag; this ratio remains almost constant for all years, due to the percentage of slag production per tonne of steel produced or refined [2]

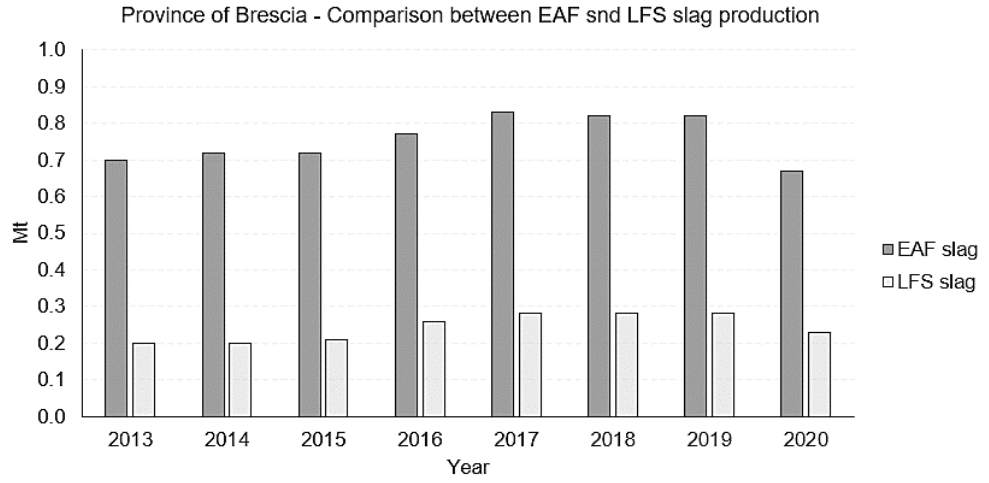

Fig. 6 Comparison between electric arc furnace slag (EAF) and ladle furnace slag (LFS) production in the province of Brescia, for the period 2013 – 2020. Values are expressed in million tonnes

The following figures show, respectively, a summary of Tables 1 and 2. In Figure 7, there is a comparison between the amount of EAF slag classified with the status of "by-product" and that classified with the status of "waste", expressed in million tonnes (Mt). For the latter category, a further subdivision was made according to whether the slag was destined for recovery or disposal. The same processing was carried out for LFS slag and the results are shown in Figure 8.

Comparing the two graphs in Figures 7 and 8, a huge difference can be seen with regard to the classification, and consequently the management, of the two types of slag: EAF slag was classified as a "by-product" in percentages ranging from 10 to 50%, depending on the year, while the percentages of LFS slag classified as a "by-product" were 0. With regard to the classification as "waste" destined for recovery, the percentages of EAF slag ranged from 15 to 55%, depending on the year, while those of LFS slag never exceeded 1%. Finally, a considerable difference can be noted with regard to the part of slag classified as "waste" and destined for disposal: while the percentages of EAF slag classified in this way have ranged from 27 to 53%, depending on the year, those of LFS slag have always reached 99%, denoting a reduced, if not null, demand for the material on the market and further highlighting the difficulties of the management, treatment and reuse of this type of slag.

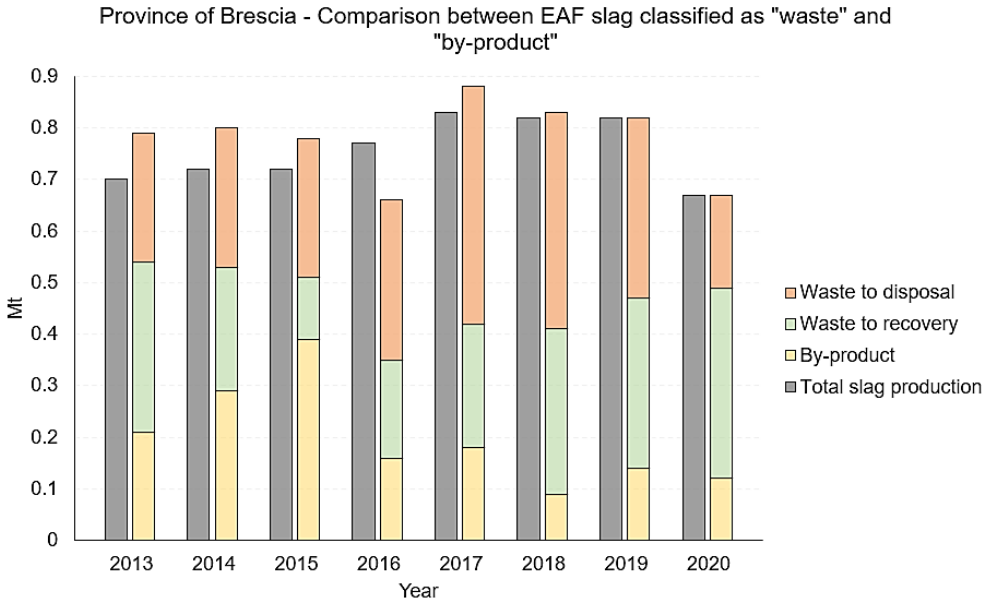

Fig. 7 Comparison between the quantities of EAF slag classified as “by-product” and as “waste”, distinguishing between waste destined for recovery and for disposal, expressed in million tonnes, for the period 2013 - 2020

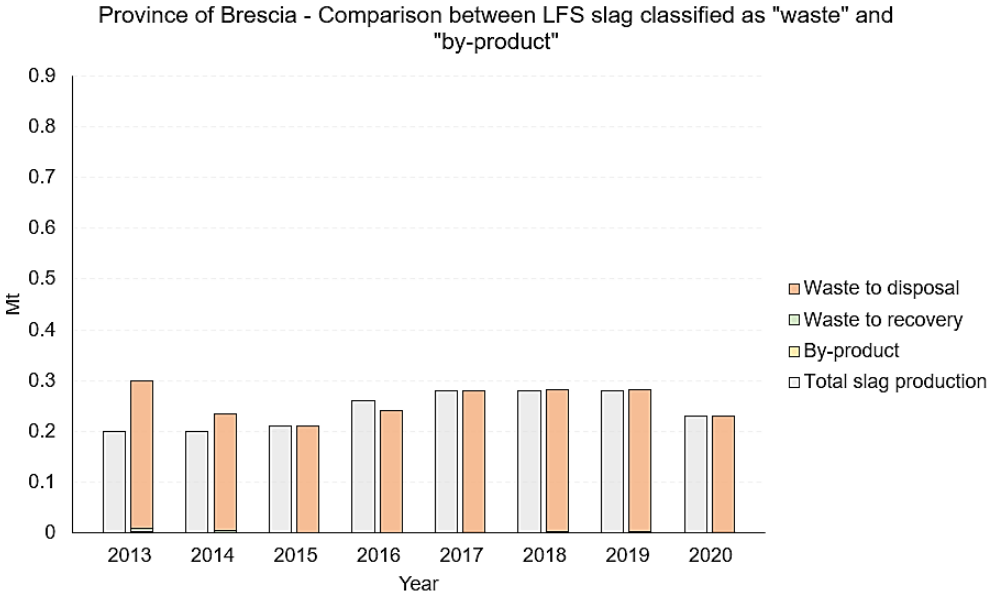

Fig. 8 Comparison between the quantities of LFS slag classified as “by-product” and as “waste”, distinguishing between waste destined for recovery and for disposal, expressed in million tonnes, for the period 2013 - 2020

Conclusions

The MUD database is undoubtedly a very effective tool for representing the state of the art in the production and management of steel slags in a given area. However, it has some weaknesses, which have made necessary the direct involvement of operators and consortia of the steel industry in the province.

In recent years (with the exception of the production of 2020, which was strongly influenced by the SARS-CoV-2 pandemic), the production trend of primary steel and, consequently, of steel slags, has showed a slight increase, making it essential to make a careful assessment to better frame the management and treatment systems of these materials.

With regard to slag deriving from steel production in electric arc furnace (EAF), there has been an increase in the quantities classified as waste and destined for recovery (in percentages that, depending on the year, vary between 15 and 55%). This material is reused in various applications and, concerning the province of Brescia,

some of the operators in the sector have declared that they reuse EAF slag mainly in cement mixes, road sub-bases, for the production of certified products (e.g. aggregates to be reused in concrete or bituminous conglomerates), landfill covering layers, filling, embankments, etc. Unfortunately, the percentages of EAF slag classified as waste and destined for landfill disposal are still very high (varying between 27 and 52% of the total production), highlighting once again the need to increase the reuse of this material, not only by simply increasing the quantities reused in already known applications, but also by investigating further possible reuses. Its increased reuse would bring benefits not only from the waste management point of view, but also in terms of land and raw material exploitation, greenhouse gasses emissions, reduction of areas to be dedicated to landfills, etc. Finally, it is worth noting that a lack of direct involvement of the operators in the sector would have led to an "error" in the assessment of the real quantities of slag actually produced since by-product are not considered in the MUD database.

Finally, regarding the production and management of LFS slag, a big difference with EAF slag can be seen in that all the slag produced is classified as waste and destined for landfill disposal (on average, about 275 thousand tons per year). The great heterogeneity of this material, together with the many difficulties in its reutilization due to its characteristics, make further and in-depth studies extremely necessary in order to find suitable applications for its safe reuse and to limit the quantities destined for disposal.

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