

Article

Explorative Multiple-Case Research on the Scrap-Based Steel Slag Value Chain: Opportunities for Circular Economy

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Abstract: This paper analyses the scrap-based steel slag from the electric arc furnace and secondary metallurgy and proposes a framework for valorising its value chain. Toward this aim, the role of slag features, technological advancements for the treatment of slag, applications, legislation, and their value chain in the circular economy and industrial symbiosis opportunities are discussed within the proposed framework. By interviewing a group of Italian steelmakers, accounting for around 30% of Italian scrap-based steel volume, we analyse various value chain key factors, namely, technology, legislation, production volume, and economic aspects. Consequently, we assess the as-is situation of the sector and elaborate on the challenges and expectations for the future in terms of collaboration frameworks. The results show how vertical (by internal treatment) and horizontal integrations (by collaborating with other potential industries) support decisions on material flow and facilitate circularity in sharing this kind of material. The most influential enabler in a vertical integration is the economic aspect, while in the horizontal integration the enablers are the market and technology. We also address the importance of raw-material self-sufficiency through analysing closed-loop supply chains and collaborative supply-chain networks.

Keywords: scrap-based steel slag; circular economy; multiple-case study research



Citation: Falsafi, M.; Fornasiero, R. Explorative Multiple-Case Research on the Scrap-Based Steel Slag Value Chain: Opportunities for Circular Economy. *Sustainability* **2022**, *14*, 2284. <https://doi.org/10.3390/su14042284>

Academic Editors:

Augusto Bianchini and Jessica Rossi

Received: 31 December 2021

Accepted: 11 February 2022

Published: 17 February 2022

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1. Introduction

Around 26% of the worldwide total of crude steel is produced in electric furnaces [1]. Among the electric furnace production methods, the scrap-based route has attracted significant attention in recent years as the most sustainable route. The principal reason for this attention is the high fossil fuel consumption when coal is used in iron-based steel production. Coal consumption causes high levels of CO₂ emissions, accounting for 10 times as much as scrap-based production. Scrap-based production, compared to iron-based, consumes less energy (74%) and water (40%), while at the same time producing less pollution (76%) and environmental emissions (86%) [2]. A doubling of the scrap availability by 2050, derived primarily from obsolete scrap, is another reason for the attention being focused on this production route [3].

Therefore, more research into the scrap-based steel value chain from the inbound and outbound flows is a necessity. Many steelmakers (SMs) will have to recalibrate iron-based steel production as a strategic decision (e.g., [4]). These decisions are part of the carbon direct avoidance of the EU steel industry's technological pathways [5].

Around 42% of the crude steel produced within the EU-28 is electric-based [1], with Italy's share, 29%, placing it first in the EU. Almost 85% of crude steel in Italy is produced via the electric furnace route. Therefore, a scrap-based steel value chain analysis is fundamental for the European electric SMs to facilitate the transition towards a 'recycling society'. Italy's efforts to reduce the environmental impact of steel production have resulted in 30% less

CO₂ emissions (compared to 1990), 24% less energy consumption (compared to 1990), and 30% less water consumption (compared to 2015) [6].

Around 15% of the weight of the steel produced by the electric furnace (10%) and secondary metallurgy (5%) is slag, which is the highest proportion among other steel co-products. Even though slag landfilling causes serious environmental problems, the proportion of slag landfilled worldwide is not negligible.

As a consequence of the recent increase in scrap availability and the expected increase in the scrap-based production route, a higher amount of slag deriving from the electric arc furnace (EAF) will be available. This trend calls for a circular economy (CE) approach by using the synergies of sharing resources among different industries in an industrial symbiosis (IS) environment. An advanced IS improves the economic status of an SM by increasing profit and cutting costs, facilitating the movement towards a zero-waste industry and a lean production perspective. Such a strong value chain decreases environmental impacts through the effect of IS in technological pathways of CO₂ mitigation [7], smart carbon usage, and carbon direct avoidance, increasing energy efficiency [8,9] and promoting a CE for slag as the primary steel co-product.

In the EU, slag can be treated and utilised as either by-product or end-of-waste. It is considered a by-product if, among others, its further use is certain and can be used directly after normal industrial practices (e.g., granulation, pelletisation, cooling, milling, and weathering) within the activities of steel plant [10,11]. If the slag value chain cannot be aligned with the by-product definition, it is considered waste for the steel plant where it is produced and can be further treated; it is compliant with the end-of-waste definition if, among others, it undergoes recovery, including recycling and operation activities [12]. Nevertheless, these definitions cannot be interpreted as limiting factors to treat and apply slag and should be equally supported, regardless of their legal status.

This paper aims to explore the opportunities for slag valorisation in Italy through multiple-case research. Through the benchmark among SMs, the best practices are elaborated and their advantages for the SMs in Lombardy region are discovered. Consequently, the current status of electric arc furnace slag (EAFS; black slag) and secondary metallurgy slag (SMS, white slag) are addressed, and their ideal value chains are proposed.

2. Literature Overview

Instead of prioritising an open-ended conception of the value-added chain, CE enables cyclical thinking, looking for closed loops, or minimising virgin materials and energy consumption through economic and environmental strategies [13]. IS is one of the core models for the transition to CE [14], considering the exchange and valorising of residues within certain industries usually grouped by proximity. While IS analysis focuses primarily on the symbiotic exchanges and their environmental impacts, CE focuses on the economic and business aspects [15]. Thus, the integration of IS and CE is a strong enabler for analysing the eco-industrial clusters.

Accordingly, the EU's approach to CE in the steel sector has resulted in many initiatives for the secondary raw material market, quality, innovative consumption, and economic instruments [16]. However, valorisation of the goods tradable within the EU, environmental regulations, and labour costs are notable challenges for the EU in its goal to achieve 'zero waste' [17,18]. As an industrial approach and considering the weak link between the IS for analysing the business models in CE and Italy's paramount role in CE practices [13], this paper fills this gap by analysing the slag value chain through a CE model to valorise the application opportunities.

Table 1 shows the literature that analyses the steel slag value chain, and its application in different industrial fields, considering different production routes. The 'Evaluation approach' column in Table 1 represents the core aspects of the analysis in each paper. In most of the studies, slag processing and use are analysed in terms of IS. Some studies focus just on the slag application [19–24], while many of them analyse the slag value chain in a broader value chain of various industries in an IS [7–9,25–31]. Most of the papers analyse

the environmental advantages of the flows in IS, and some of them have explored economic, chemical, and regulatory points of view. Almost half of the papers study real cases, while others analyse slag application based on lab experiments or theoretical concepts, which may potentially be high-value-added applications in practice [32].

Table 1. Characteristics of literature analysing slag value chains.

Reference	Slag Type	Application	Evaluation Approach					Country
			Reg	IS/SC	Chem	Econ	Env	
[33]	BOFS, BFS	1,2	✓	✓		✓	✓	China, Japan
[20]	EAFS	3			✓		✓	Spain
[28]	EAFS, BOFS, BFS	4	✓	✓			✓	China
[21]	SMS	1		✓	✓		✓	Belgium
[25]	SMS	5,6,7,8	✓	✓				Finland
[9]	BFS	1		✓		✓	✓	China
[23]	EAFS	9		✓		✓		Mauritius island
[19]	BOFS, BFS	1,2		✓			✓	China
[27]	Iron and steel	—	✓	✓			✓	Brazil
[8]	BFS	2,10	✓	✓		✓	✓	China
[30]	Iron and steel	1		✓			✓	China
[22]	BOFS, BFS	1,2,3,9,10,11		✓			✓	Italy
[7]	BFS, BOFS	2		✓		✓	✓	China
[29]	All	1,2,10	✓	✓				France
[24]	All	—		✓			✓	Europe
[26]	BOFS	1,2,3,9	✓	✓			✓	Taiwan
[31]	BFS/ BOFS	1		✓			✓	Italy

Notes: Application: cement (1), construction (2), road (3), recycled as EAF feedstock (4), soil amendment (5), amelioration pellet (6), low competence concrete formulation (7), mine filler (8), concrete (9), agriculture (10), and glass (11); evaluation approach: Reg: regulation and policies, Chem: chemical, Econ: economic, Env: environmental, and SC: supply chain.

The majority of the studies focus on the blast and basic oxygen furnaces (BFS and BOFS) slag value chain, while there is less attention paid to EAFS and SMS. In addition, most of the papers analysing the real cases do not focus on slag as the central theme of the study. Almost all the papers focus on single, or up to three, case studies (e.g., [33]) and draw conclusions based on the observations in the specific case. Among all the studies, Pinto and Diemer [24] analyse the supply chain of slag based on the integration strategies. Through life cycle assessment, material flow analysis, and a focus on the iron recovery by slag treatment, they show that both vertically integrated and vertically hedged supply chains reduce iron ore consumption.

3. Materials and Methods

3.1. Research Design

The research method followed in this paper is based on the explorative approach, derived from in-depth and longitudinal research [34]. A procedure for the two-stage research is depicted in Figure 1. Through a comprehensive literature review, the objective was reviewed and validated, and, consequently, a set of questions was defined for the interviews (phase 1 in Figure 1). The organisations were then selected and contacted for appointment settings. The interviews were conducted in two stages. In the first stage, 15 organisations, including 5 SMs, 2 technology providers, 4 steel associations, and 3 scientific experts from different steelmaking countries, were contacted and interviewed.

This stage aimed to gain practical knowledge in the field by acquiring various perspectives regarding worldwide and Italian steelmaking. This stage led us to define the research objective, which was then followed by the second stage.

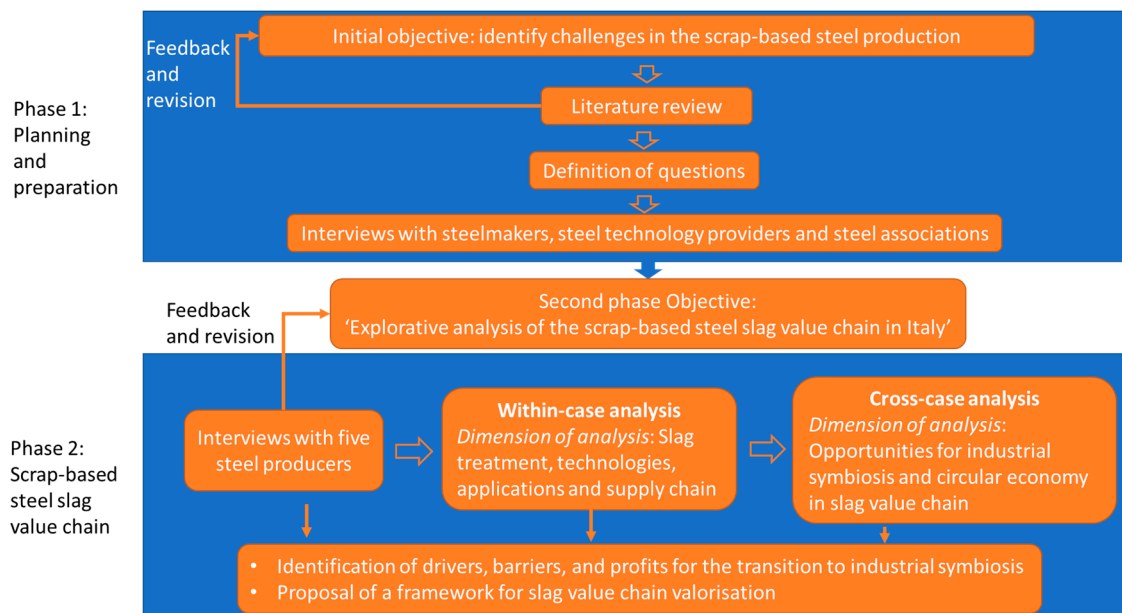


Figure 1. Research methodology.

Regarding the interview design in this stage, we identified a set of macro issues, namely, open challenges in the steel and slag industry, economic and technological overviews, slag applications, treatment, and supply chain. Consequently, interview questions were derived from these macro issues. The interviews were conducted both in person and online based on the geographical position of the interviewees. Depending on the expertise and the degree of focus, the discussions took from 30 to 120 min.

In the second stage, after studying multiple cases through interviews [35], we collected the data and analysed them based on the existing relevant theories in the literature and databases. Consequently, through the elaboration of each case (within-case analysis) and comparison and validation with the other cases (cross-case analysis), we built up new frameworks in the scrap-based steel slag value chain [36].

Toward this aim, five SMs were interviewed as the core part of the study, involving managers from the production, supply chain, R&D, and environmental sectors. The SMs were selected to assure the sufficient heterogeneity among them [37] regarding their size, revenue, and geographical position. Additionally, heterogeneous characteristics in their value chains of EAFS and SMS were considered, such as landfilling approaches, destination of as-received slag, treatment technologies, markets of treated slag, and the maturity of these value chains. For each SM, we conducted from one to three interviews, with a length of more than two hours each. The data from the companies were then gathered, organised, and analysed based on their coherency with the literature and the knowledge gained in the first stage of the research.

3.2. Industrial Context

With around 85% and 69% of their production based on the electric furnace, Italy and Spain are two advanced countries in the research and application of slag. In Italy, around 88% of steelmaking plants (considering number of employees) and 85% (considering revenue) are located in four regions, namely, Lombardy, Umbria, Veneto, and Friuli Venezia Giulia [38,39]. Moreover, more than 70% of the scrap-based SMs are located in the north of Italy (producing almost 19,300,000 tons). The Lombardy region accounts for nearly 56%

of Italian production, amounting for almost 10,800,000 tons. Federacciai is the principal Italian reference for statistical data in the steel industry [40].

The Lombardy region, with an area of 23,863 km² and a population of 10,027,602, is located in the north of Italy [41]. It is the first most populated Italian region and the third most populated region in Europe. The gross domestic product (GDP) per capita is €36,600, ranking fifth in Europe [42].

Out of 37 Italian producers, 14 are located in Lombardy (Figure 2), corresponding to 98% of the crude steel production in this region. They are primarily located in the provinces of Bergamo, Brescia, Cremona, and Varese [39]. The core area is the Brescia province, with nine steelmaking plants. With a production volume of almost 6,100,000 tons, Brescia province's share accounts for 56% of the Lombardy region and 32% of Italy's EAF steel production.

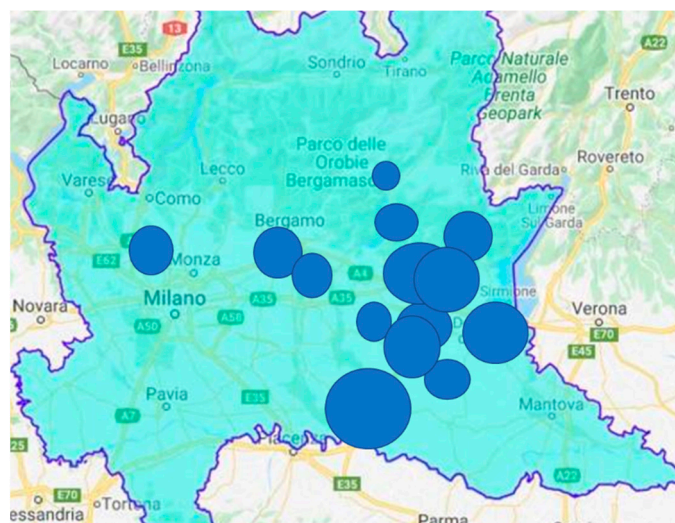


Figure 2. Steelmaking plants in the Lombardy region.

According to 2017 data (Table 2), out of 1.8 million tons of EAFS produced in Italy, Lombardy EAF producers were responsible for around 1.5 million tons, with a 35% share of landfilling as waste. The remaining 65% is used in industrial sectors either as by-product (48%) or end-of-waste (17%) (Figure 3). SMS produced in Lombardy in 2017 was around 454,000 tons. Out of this amount, 10% was recovered as end-of-waste, and the remaining 90% was disposed of (Figure 3). The highest proportion belonged to Brescia, with around 275,000 tons production volume of SMS, accounting for almost 60% of the total region's production volume.

Table 2. Production volume in Lombardy (Ton).

Year	Crude Steel	EAFS	SMS
2015	9,621,208	1,353,839	360,426
2016	9,952,653	1,177,315	398,696
2017	10,847,735	1,472,369	454,030

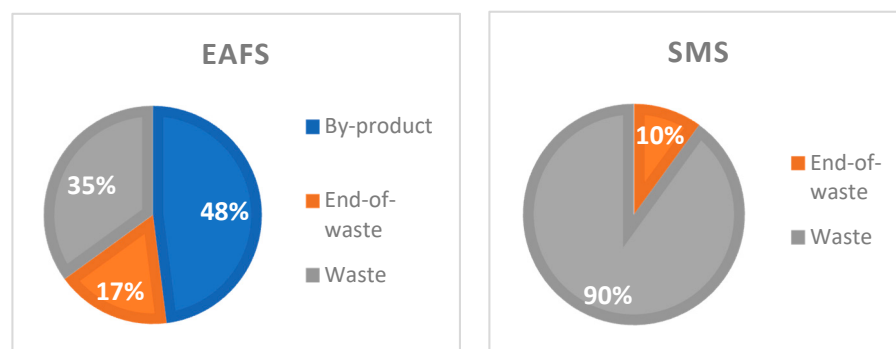


Figure 3. The slag status in Lombardy (2017).

Out of the treated volume, the highest proportion of the EAFS use are related to road construction (64%), cement industry (34%) and environmental recovery (2%) [43,44]. In Lombardy, the common applications of EAFS are divided into four categories [45], namely, unbound road embankments and foundations; draining layers of landfill cover (“capping”); load-bearing layers in the cemented mix; and aggregates for concrete, bituminous mixtures, and surface treatments for roads, airports, and similar surfaces subject to traffic. Among the low proportion of used SMS, the common applications are in the cement industry (42%), followed by internal use (30%), road construction (25%), and environmental recovery (3%) [43,44].

3.3. Description of the Cases

Five Italian producers with different sizes, steel grades, and slag value chains have been selected, representing 30% of the Italian total EAF production of steel, amounting to more than six million tons annually (Table 3). They range from large SMs, with almost half of the production volume among the five SMs and around 15% of the total Italian crude steel production, to small ones, located in the two regions in the north of Italy.

Table 3. Interviewed SMs’ steel production share and revenue.

Company	Production Share among Interviewed Companies	Production Share in Italy	Number of Employees	Revenue (million €)
SM1	12%	3.5%	>400	<400
SM2	16%	4.7%	>2000	<800
SM3	22%	6.6%	>1000	<700
SM4	49%	15%	>500	>800
SM5	2%	0.5%	<200	<100
Total	100%	30.3%		

SM1 is a medium-sized producer of high-quality steel with an EAF and two ladle furnaces. The primary customers are from the automotive sector. The company is aligning its production with the Industry 4.0 paradigm through a national project. Toward this aim, it is establishing the application of artificial intelligence to improve traditional production control for supporting operators in their decisional capabilities. Several approaches are available in the literature to demonstrate the efficacy of the digitalisation shift [46], both at operational [47–49] and strategic [50,51] levels. SM2 produces seamless steel tubes for applications in the energy, automotive, and mechanical industries. It has six production sites and one steelmaking plant in Italy, specialising in steel pipe operations. The company, committed to sustainable steel production, publishes environmental product declarations based on product lifecycle assessment methodology. One of its sustainable activities is

the use of recycled water for slag cooling through a circulation system, where only the evaporated proportion of water is wasted.

SM3 has the capacity of producing a wide range of engineering special steel types, including hot-rolled and continuous casting products. The company has recently established intelligent production process control technologies through machine learning and predictive analytics. It also conducts activities for the management of internal and external logistics systems. SM4 produces high-quality steel for applications in the building and mechanical engineering sectors. The company, a leading SM, recognised in Italy and Europe, has investigated CE practices for its waste valorisation during the last years. SM4, through several projects, has successfully implemented efficient use of resources, wastes, and by-products such as scale and water. SM5 produces ingots, stainless-steel-forged bars, carbon- and alloy-forged bars for oil and gas, power generation, petrochemicals, and aerospace applications.

4. Results

Table 4 represents a summary of the status of EAFS and SMS for the five producers in terms of slag value chain. The main difference between the companies is guided by the legislation for slag use of the region where they are located: while SMs 3 and 4 are located in a region where legislation allows for the use of slag in some sectors (such as road construction), the regional legislation for SMs 1, 2, and 5 are stricter.

Table 4. Status of slag management in the interviewed SMs.

Company	SMS	EAFS
SM1	- Currently landfilled	- Treated by two third-party recyclers
	- The SM is in the development phase of a patent to treat the SMS for mechanical application	
SM2	- 90% is treated as end-of-waste by a third-party recycler	- Treated and sold to three main industries: road construction (such as bituminous asphalt), concrete, and civil engineering.
	- 10% is landfilled	
SM3	The treatment is carried out in the plant and is applied in cement production and road construction	
SM4	- Treated inside the plant	- Treated and used in the road construction
	- Lime and metal scrap are re-used	
SM5	- The treatment is carried out by the company	- The treatment is carried out by the company
	Landfilled	
		Landfilled

SM1 does not deal with the EAFS treatment since slag is transported to an external company. However, SM1 is studying possible applications for SMS to reduce landfilling and relevant costs. The company collaborates with national and regional legislators for new regulations to promote and enhance the applicability of slag. While SM2 treats both slag types, a small proportion of SMS (around 10%) is still stockpiled. The company uses the infrastructure in its premises to treat EAFS, while SMS is transferred to a third-party recycler. Since the company pays for this transaction and, therefore, it is a costly activity, SM2 is investigating the new treatment technologies for SMS commercialisation to benefit from economic advantages and to minimise the landfilling volume. In particular, it is evaluating the SMS treatment for soil stabilisation (e.g., asphalt filler).

SM3 treats the produced slag in the facilities located inside its premises. Its customers are the cement and road construction industries. SM4 is the most advanced in SMS treatment, which is carried out totally by the company. It also benefits from using recycled lime and metal scraps from slag as the feedstock for EAF production, reducing the cost of transportation and raw material provision. SM4 has registered a patent for its product made from EAFS, used in road construction as a replacement for basalt. The advantage

of the patented product, compared to basalt, is primarily applicable to rainy roads and highways. In this case, SM4's product facilitates water absorption by the road surface, and it is sold to major road construction companies. Given the small dimensions of the company, SM5 does not have facilities for slag treatment. They consider that studying the possibilities of shared facilities with the other SMs can be a feasible opportunity.

After interviewing the experts, it was confirmed that slag stockpiling incurs a high environmental impact; to prevent stockpiling, the importance of two strategies (Str) was noted:

Str1: Closing the material loop by the treatment and internal reuse of slag;

Str2: Treatment and application of slag in other industrial sectors.

For what concerns Str1, SM4 uses opportunities for implementing closed-loop strategies by establishing an SMS treatment unit (TU) for internal use of its EAF. In this case, the company benefits not only from the SMS reuse but also the opportunity to reuse the separated metals in EAF as home scrap.

For what concerns Str2, most interviewed SMs own the TU for EAFS in their premises. That is principally because of the high proportion of EAFS and the maturity of the technologies for its treatment. However, they need to exert more effort to prevent landfilling. The applications are focused primarily on road construction, followed by civil engineering and concrete production.

As shown in Figure 4, EAFS is mainly treated as a by-product; the landfilling proportion is not significant. Unlike EAFS, a higher percentage of SMS is landfilled, and among the used rate, the applications are not focused on a set of specific sectors. The main hurdles for the development of SMS treatment and application are legislative and technological aspects.

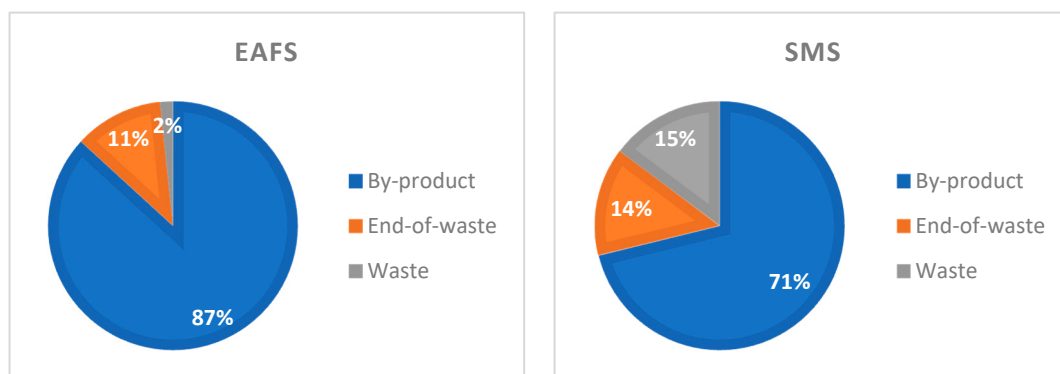


Figure 4. Slag status for the interviewed SMs.

Throughout the interviews, it emerged that there are some challenges that are predominant, and each SM has a different overview based on the characteristics of its slag value chain. We can summarise these challenges as the following factors:

1. Economic feasibility: consisting of upfront costs of the treatment facilities for each slag type due to investment in the infrastructure and technologies. Additionally, it concerns the revenues and operative costs of treatment.
2. Slag volume: the slag amount to be processed by TU should be sufficiently high to satisfy the minimum production capacity.
3. Legislation: consisting of the regional and national legislation for slag treatment and use. Additionally, it concerns the willingness of the industries to buy slag in accordance with the legislation or replace natural raw material.
4. Technology: some technologies are common among all SMs, and therefore, to establish a TU, there is no concern. However, some technologies are unique to a TU, where they register a patent. This case may derive from a particular treatment for a unique application or a requirement of a group of potential or existing customers.
5. Market: it is necessary to identify innovative markets for each slag type produced with a certain treatment procedure and technology. The lack of a specific industrial

segment or the unwillingness of such a segment can discourage new technologies from being adopted in a particular region.

6. Supply chain: collaboration among the supply chain tiers should be interconnected harmoniously so that the internal and external logistics can be smoothly managed.

Considering the revenue of SM2, SM3, and SM4, they face less of an economic challenge than SM1 and SM5. SM4 and SM5 have the least and most challenges in this regard to satisfy the production capacity of their TU. Therefore, even with sufficient funding opportunities for SM5, it may still not be an effective choice. Although all the SMs believe that convincing the potential users to buy the as-received or treated slag is a big challenge, SM3 and SM4 have higher chances in this direction. They can benefit from the legislation in their region and the industries that are already using the slag in their value chain. The SMs located in the regions with strict legislation for the slag application (e.g., SMs 1, 2 and 5), encounter more challenges compared to the SMs with less strict local legislation (e.g., SM 3, 4). Consequently, the latter SMs are considered benchmarks, and the best practices are evaluated for Lombardy.

In Lombardy, the areas with a high density of SMs can positively impact the market acceptability due to the fact that the industries in these areas are more involved in the steelmaking processes. Some industries may already have symbiotic exchanges of materials with the SMs, which can facilitate negotiations for potential slag exchange. While the slag production amount of SM1 and SM2 is sufficiently high for establishing the treatment facilities, strict legislation in their region prevents them from easily finding a market of application. Nevertheless, SM4 has a high level of production, and since legislation facilitates slag use, the chances of finding customers are high.

As most interviewees pointed out, the need for a strategy emerged to establish multi-lateral collaborations with the other industries so that slag can be efficiently used and transacted. This collaboration facilitates cross-sectoral application of technologies, in addition to savings in processing systems and energy consumption, results in lower transportation costs. All SMs believe that the logistics and transport for SMS is more challenging than EAFS. Comparing the experts' opinion on the aforementioned challenges and regarding the general trend for both slag types, it emerged that the technology aspect is the most challenging issue for SMS, followed by the low market demand. Regarding the EAFS, the most challenging issue for these companies is the high upfront costs for establishing treatment facilities in terms of some important dimensions such as machines, personnel training, and processes changes. There is a trade-off between the current costs of landfilling the slag and these investments, counterbalanced by selling the treated slag to the market.

5. Proposed Framework

Based on the analysis of the case studies and by evaluating the best practices in two Italian regions, in this section, we propose new collaborative frameworks to help companies to reduce slag landfilling. In order to define new collaborative frameworks in slag value chain, we consider the following dimensions as defined in Camarinha-Matos et al., [51] and Pinto and Diemer [24]:

1. Vertical integration: where capital, ownership, and management of slag value chain from its formation in steel plants to final use after treatment is centralised by the SM. This integration results in autonomous SMs facilitating decision-making and agility.
2. Horizontal integration: where capital, ownership, and management of slag value chain from its formation in the steel plants to its final use after treatment is decentralised. This integration results in seamless cooperation between the stakeholders in the supply chain, which derives from sharing technology and information systems.

These two dimensions need to be conceived to facilitate the implementation of CE and a more sustainable slag value chain, where economic and market aspects are among the impacting factors for choosing an optimum strategy [52,53]. Figure 5 represents the current and proposed value chains for EAFS. Market segments (e.g., road construction, civil engineering, and cement production) for EAFS in Italy are well-established and stable,

like in many other countries, such as the US, Canada, Australia, Japan, the UK, Germany, and France. Therefore, to increase the valorisation opportunities of EAFS, research should be directed at more specific applications within these market segments.

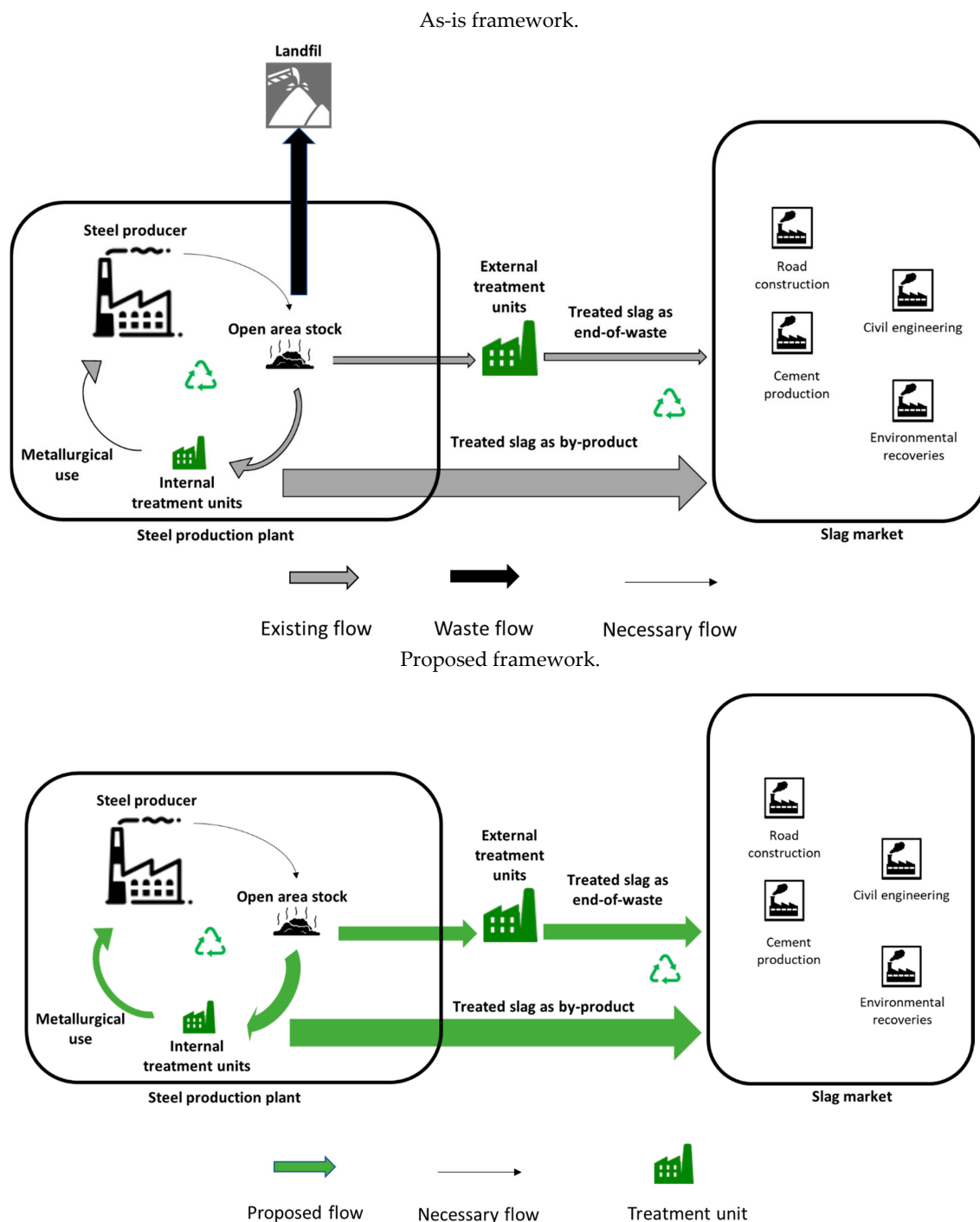


Figure 5. EAFS as-is value chain in Lombardy and proposed framework.

In Lombardy, some innovations have recently emerged. According to the interviewed experts, application in polymeric matrices is currently being tested and evaluated. Generally, sulphur is an element that facilitates cross-linking of polymers. The positioning of this material (generally sulphur-containing materials) in polymer matrices may therefore be appropriate. The other applications under study are the use of treated slag-based mixture

in 3D-printing as a cementless material based on MgO activation [54] or as composite material [55], basalt-like fibres [56,57], and wastewater treatment for removing phosphor [58,59].

SMs can benefit the most from horizontal integration by establishing TUs to sell the treated slag to customers and use some proportion (such as metal particles obtained from magnetic separation) back in their production processes. The most impacting factor for the decision between establishing a TU and transporting slag to an external TU is the economic affordability of the SM for investments.

Figure 6 represents the current and proposed value chain frameworks for SMS. Although there is a market for SMS, which attracts a low proportion of treated SMS, it is not mature enough to use as a raw material. The reasons are the instability of SMS' chemical composition and the proportion of SMS used in the production process compared to natural raw materials. In some applications (such as cement production), the raw material volume is so high that the SMS content can satisfy only a small proportion of the demand. Therefore, the companies may not perceive added value for applying SMS in their production processes.

One major challenge is the presence of free-CaO in SMS. The treatment technology depends on the trade-off between the silica and alumina content in the as-received slag since a high silica content contains lower content of free CaO. In addition, an alkaline can activate the cementitious property of SMS. Thus, direct slag treatment results in strength problems, appearing as cracks in the final product. To solve these challenges, possible solutions are one or a combination of the following pre-treatment processes before the main treatment on SMS:

1. Physical pre-treatment: such as grinding, sieving, and combining with the other materials (e.g., [60–62]).
2. Chemical pre-treatment: such as hydration and carbonation (e.g., [62,63]).
3. Temperature variations: such as cooling and heating (e.g., [61,63,64]).

Considering the similarities between the chemical characteristics of SMS, limestone, and lime products, one possible opportunity is to evaluate SMS use in the lime value chain [65]. Our analysis of the role of CaO within the lime production process shows that lime reactivity, impurity contents, and the proportion of free-CaO are key enablers. Therefore, for SMS use within the lime value chain, high proportion of free-CaO should be reduced through a pre-treatment process.

This analysis confirms that new industrial sectors should be investigated to horizontally integrate with the treatment process. These new industrial sectors can be explored through third-party recyclers as 'intermediary industries' between SMs and the final user industries. These intermediary industries facilitate SMS treatment and use by applying new technologies within their main production processes. SMS can be used inside their production process and, therefore, substitute a natural resource (e.g., limestone in the lime production plant) and reduce production costs. It can also be integrated with the existing infrastructure of the intermediary industries to produce a new product. This new product can help the company increase its product mix and thus achieve both higher profits and competitive advantage.

Due to the SMS challenges that prevents its direct use within the production process in the intermediary industry, a decision should be made for a pre-treatment process. While this decision depends highly on the type of intermediary industry, SMs usually prefer the process to be carried out inside the steelmaking plant to maintain a more vertical integration within the SM by preventing adverse environmental impacts and reducing transportation costs.

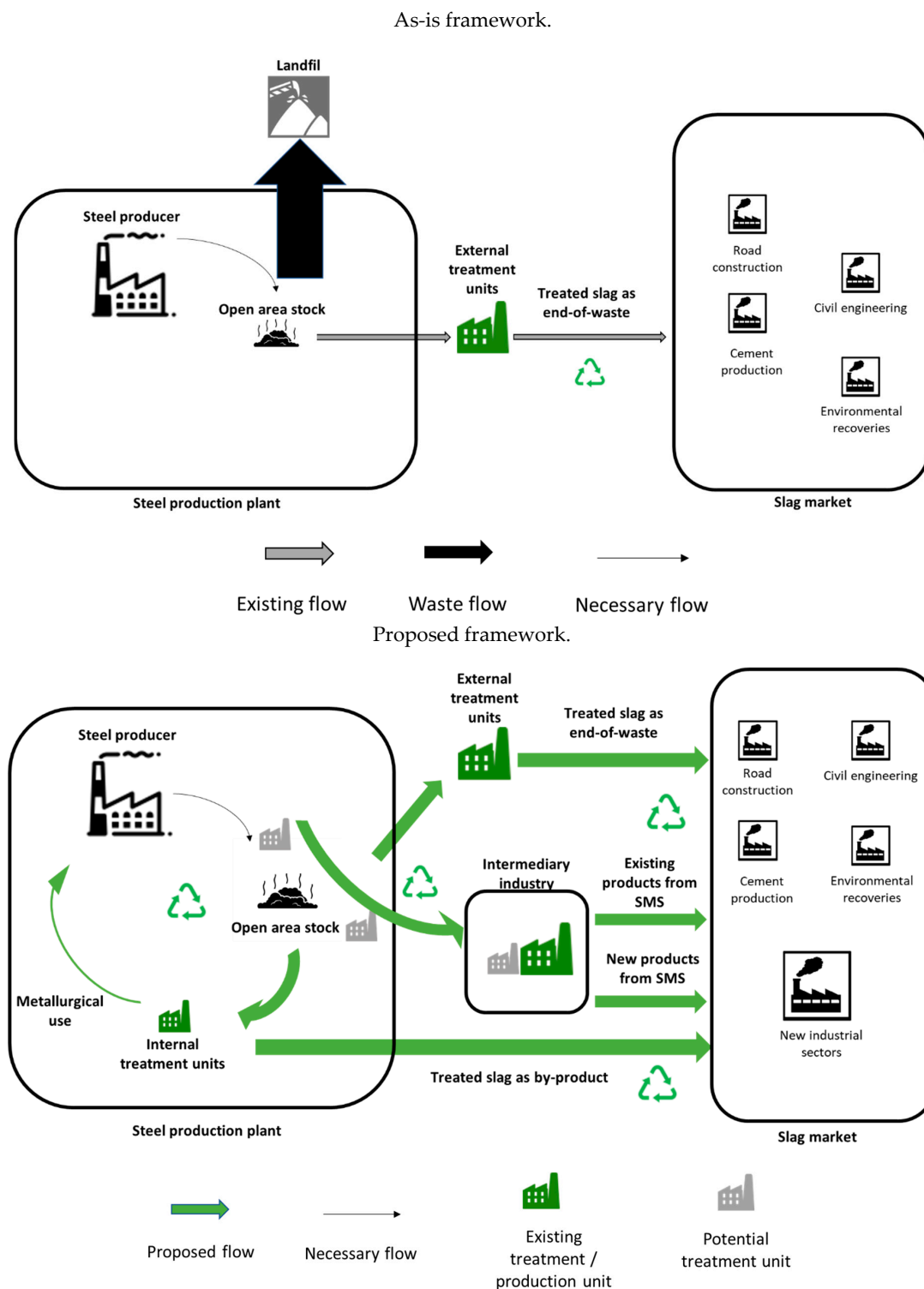


Figure 6. SMS as-is value chain in Lombardy and proposed framework.

As a result of the difficulties in the slag handling and the challenge for its transportation in the as-received form, supply chain costs increase, making slag's internal use a better choice compared to the external use. However, this decision depends on the chemical characteristics of SMS based on the steel type and production process. In particular, sulphur content plays an important role. If the sulphur proportion is high, the SM must carry out additional treatments to reduce it and prepare the slag for internal use [66,67]. However, since the cost of such treatments is high, this investment is usually not applied. Therefore,

the decision regarding the treated slag application, either keeping it for internal use or selling it, is a trade-off between the technological possibility of different SMS types for internal use and the economic balance with its use in other applications.

These integration strategies emphasise the role of slag (EAFS and SMS) within a collaborative network of stakeholders in IS. Steel plants are usually considered anchor tenants in an industrial cluster, where most material interactions happen within them. Slag can play a vital role in material exchange. According to the analysed value chain frameworks and the interviews' results with experts, we can define the following three configurations for SMs exchanging slag in an IS:

1. Single TU established by an SM, where the SM treats its slag and sells the treated slag to the user industries. This case has the minimum material exchange (i.e., exchanging treated slag) between the SM and user industries compared to the other configurations.
2. Collaboration of some SMs in the proximity and establishing a central treatment facility. The decision-making is decentralised, and the material exchange is among the collaborating SMs (i.e., exchanging as-received slag) and user industries (i.e., exchanging treated slag). An example is the collaboration of some SMs in the Brescia region to share some treatment activities (i.e., crushing and sieving) for EAFS.
3. From a regional perspective, a third-party to manage the entire network of companies in a geographical area. Treatment is carried out by one company attracting the slag from other SMs. The decision-making in this configuration is centralised, and the slag treatment company can be one of the SMs or the intermediary industry.

The integration strategies can drastically affect the decisions on the above configurations according to the production volume and size of an SM. Small SMs (e.g., SM5) can benefit from horizontal and vertical integration strategies by following the second and third configurations. They can either establish a TU, attracting the slag from other SMs, or collaborate with the other SMs, establishing a shared TU.

6. Drivers for the Implementation of the Proposed Framework

In order to analyse the drivers, benefits, barriers, and solutions for the application of a winning CE approach for the slag value chain, it is important to consider the main stakeholders and their role in slag management. For the purpose of this study, the main stakeholders are legislators, SMs, user industries, and potential intermediary industries.

As addressed, the crucial drivers towards implementing the proposed framework in the slag value chain are the market, the SM's size in terms of production volume, economic and financial affordability, treatment technology, and legislation. Furthermore, all the stakeholders must be aware of such drivers, which can influence their operational and policy-making decisions.

However, some barriers prevent the successful application of a complete CE model for the slag. One barrier is market acceptability, addressing the potential customers that may not be aware of the economic and technological advantages of integrating with such a value chain. Therefore, they might evaluate the investments as expensive and, thus, be unwilling to collaborate. Additionally, SMs may not be aware of the advantages and, therefore, evaluate the treatment technologies and challenges in the slag logistics as a non-value-added activity, which distracts their attention from their core business. One technological challenge is the leaching test. The applicability of the slag in the market depends on the leaching tests' results (e.g., according to the Italian standard EN12457-2). The necessity of a pre-treatment phase, particularly for SMS, is another technological challenge that can discourage the potential recycler from another industrial sector from entering this business.

From the legislative point of view, different regional legislation prevents the innovative value chains and technologies from putting them into practice in some areas of a country like Italy. Further efforts are required to improve and homogenise legislation throughout the national level to help the sector's development avoid using primary raw materials. More broadly, the inhomogeneous legislative frame in the EU and future threats for by-products and wastes are more vital constraints to developing common approaches [68]

and benchmarking practices. Regarding the slag pollutant emissions and relevant legislation, the Industrial Emission Directives take into account an integrated approach, paying particular attention to wastes [12]. For slag landfilling, limited space of landfilling and its relevant costs (e.g., taxes) are the primary limiting factors.

To overcome the aforementioned barriers, stakeholders and researchers should attract the attention of slag recyclers (SMs and intermediary industries) by demonstrating economic and environmental advantages. This awareness happens through scientific and industrial campaigns. Consortia among the SMs and potential stakeholders are other effective ways to directly negotiate the innovative value chains and technologies with the legislators. The engagement of potential intermediary industries should be emphasised and motivated within these consortia, and subsidies for upfront costs should be defined to establish new technologies and R&D activities and find new markets. These incentives, integrated with the current landfilling fees, maintain an economic motivation for all the SMs to prevent landfilling and can be integrated as part of the initiatives for IS applications.

An example is the observatory of the CE and energy transaction organised by the Lombardy region, which aims to improve the legislation for slag through the SMs in Lombardy with the policymakers. An initial outcome of this consortium is the comprehensive document for EAFS [45]. Another institutional initiative is a project between the trade union and the steel association aiming to disseminate and share knowledge, information, and experiences to bring opportunities associated with the CE [69]. The Symbiosis User Network initiative, with the collaboration of steel players, is another effort in Italy to build collaborations towards an IS [69].

EU commission promotes obligatory legislation for the market of wastes, known as “recycled content”. Deriving from this concept, slag as a recycled co-product can better match immature market segments than mature ones [70]. A harmonised legislation in the EU is required to valorise the use of slag as an ‘industrially cogenerated by-product’ through incentives and sustainable-based solutions [71]. In addition to the waste framework directives, which is the core for waste management, further links to other directives related to its value chain are advantageous (such as the waste shipment regulation [72]).

Another solution is to learn from the steelmaking hubs in other regions with successful experiences. This solution is applied in this paper by benchmarking two Italian regions and applying the learning from the successful value chains. While there exist multi-lateral collaborations in Lombardy, and therefore, there is a high potential of IS practices, legislative obstacles for SMs to eliminate negative environmental impacts are the main challenges. Besides, all the administrative procedures should be approved within a suitable time to be aligned with recent technological advancements.

An essential driver of the implementation of the proposed framework is performance. Using slag in different industries is beneficial for both SMs and user industries. Slag users reduce their raw material costs, and for the SMs, there is a solid commitment to boosting energy and resource efficiency, preventing slag stockpiling, reducing CO₂ emissions, reducing landfilling costs, and increasing profits by selling treated slag.

From the process point of view, the metal and lime re-use from slag in EAF reduces primary raw material, water, and energy (such as heat) consumption. It also promotes efficient transportation, localisation of waste management, and new business models to avoid waste streams with closed-loop flows. However, the choice of the best value chains also depends on the quantification of the benefits gained by the stakeholders.

7. Conclusions

The proposed frameworks for the EAFS and SMS show how an integrated downstream supply chain can be effectively and efficiently managed by stakeholders. It allows for the overcoming of some gaps in the literature by proposing a multiple case study based on five major steel companies in Italy and paying attention to the slag value chain from EAF and secondary metallurgy. The framework represents a new way to organise slag flows: by focusing on relationship types and the most critical factors (i.e., market, legislation, economic,

sustainability, technology, and supply chain). This framework allows one to define some scenarios as a preliminary work for an in-depth and quantitative evaluation model.

We demonstrate that CE can be applied through both vertical and horizontal integrations, enriching the CE models available in the literature. In particular, we address how the decisions in vertical (by internal treatment) and horizontal integration (by intermediary industries) in the material flow can facilitate circularity. The most influential enabler in vertical integration is the economic dimension since the proposed framework has the potential to increase profits from the transactions of treated slag and reduce logistics costs. It also reduces lead times and customer-related risks by centralising the treatment infrastructure. In addition, the internal use of slag not only causes a more efficient and sustainable supply chain but also increases raw material self-sufficiency. The horizontal integration, by decentralising decision-making through intermediary industries, positively impacts the market and technology by increasing expertise in the field, resulting in a highly valorised value chain through the exploration of new markets, products, and the use of impurities and alloying elements in slag.

Considering the research outlook in Europe from SPIRE2050 [73], this study contributes to the knowledge in the steel industry and a principal by-product, slag, by adopting the following aspects:

1. Reaching out to the main stakeholders in the Italian steel industry (i.e., SMs, technology providers, academic experts, and steel associations) through case-study surveys to gain comprehensive practical knowledge in the field.
2. Comprehensively analysing the methods, technologies, and strategies to avoid, valorise, and re-use scrap-based steel slag. In addition, the use of slag as an alternative and renewable feedstock for scrap-based steel slag was discussed.
3. Discussing the feasibility of the introduction of cross-sectorial applications with the other industries in the context of CE and IS.
4. Providing best practices in Europe since an increase in the electrification of steelmaking is expected.

Performing the above activities boosts R&D opportunities and enhances knowledge-sharing and learning from best practices for future steelmaking in Europe. Defining specific applications is still in its infancy because several technologies have been developed and tested at the laboratory level and need further development for full implementation. While process sustainability is demonstrated, there is also the problem of the long-term sustainability of the product (i.e., use of derivatives of slag for road and construction and the possibility to pollute land). In addition, there is still some reticence within companies to change materials and start using secondary raw materials such as derivatives of slag.

Further research should be directed at the viability analysis of new technologies and potential markets. Given the complexity of the decision variables involved in the definition of a CE model for slag value chain (i.e., technologies, the market, legislation, the economy, and the supply chain), it could be useful to develop a multi-criteria modelling approach for making decisions on each type of slag value chain identified in the proposed framework.

Author Contributions: Conceptualization: M.F., R.F.; research method: M.F., R.F.; investigation: M.F.; formal analysis, M.F., R.F.; writing—original draft preparation, M.F.; writing—review and editing, M.F., R.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: We declare that our study is under the category of non-interventional studies and the interviews have been held according to our organisation privacy rules. The respondents were informed about the aim of the study and no personal data have been collected. The information provided by the respondents have been studied only in aggregated way, with no reference to the specific interviewed person and the unit of analysis is anonymised companies.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express their gratitude to Enrico Malfa and Marta Guzzon from Tenova S.p.A for their continuous support throughout different phases of the research. The authors would also like to appreciate the collaboration of five Italian steel producers involved in this work through the interviews for the elaboration of case-research.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BFS: Blast furnace slag; BOFS: Basic oxygen furnace slag; CE: Circular economy; EAF: Electric arc furnace; EAFS: Electric arc furnace slag; IS: Industrial symbiosis; SC: Supply chain; SM: Steelmaker; SMS: Secondary metallurgy slag; TU: Treatment unit

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