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Decarbonisation challenges for steelmaking and scrap recycling role

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Проблеми декарбонізації металургії та роль переробки металобрухту

Abstract. *This article discusses the challenges the steelmaking industry faces in striving to achieve competitive alternatives and potential solutions in response to the imperatives of decarbonization and zero-waste manufacturing. Expanding scrap recycling is a logical practical solution that the steel industry must pursue to effectively reduce its carbon emissions amidst its current structure. One of the steps towards achieving this is by utilizing alternative scrap sources to enhance iron recovery. The Recovery Slagged Scrap (RSS) from steelmaking includes metal pieces covered by low-conductive slag, which changes its melting behaviour. Analysis of trials results has shown that adding RSS to BOF iron-bearing charge mix can speed up the formation of primary slag and at proper consumption does not pose technological difficulties. Utilizing RSS as a coolant or slag-forming addition may improve the melting process and provide cost reduction of a charge mix for a steelmaking facility.*

Key words: *decarbonization, steelmaking, scrap recycling, iron recovery.*

Анотація. *В статті обговорюються виклики, з якими стикається металургійна промисловість у прагненні досягти конкурентоспроможних альтернатив та потенційних рішень у відповідь на імперативи декарбонізації та безвідходного виробництва. Розширення переробки металобрухту є логічним практичним рішенням, до якого має прагнути сталеливарна промисловість для ефективного зменшення викидів вуглецю в умовах її нинішньої структури. Одним із кроків до досягнення цього є використання альтернативних джерел брухту для підвищення відновлення заліза. Відновлений шлаковий брухт (RSS) зі сталеливарного виробництва включає металеві шматки, покриті низькопровідним шлаком, що змінює його поведінку при плавленні. Аналіз результатів випробувань показав, що додавання RSS до залізовмісної шихти кисневого конвертера може прискорити утворення первинного шлаку і при належній витраті не створює технологічних труднощів. Використання RSS як охолоджувача або шлакоутворюючої добавки може покращити процес плавлення та забезпечити зниження собівартості шихти для сталеливарного підприємства.*

Ключові слова: *декарбонізація, виробництво сталі, переробка металобрухту, відновлення заліза.*

Introduction: state-of-the art of CO2 emission in today's steelmaking routes

Steelmaking is one of the energy- and CO_2-intensive branches of the modern industry [1,2]. Every average ton of crude steel (1,882.6 bln ton production in 2024) is accompanied by around 1.85 tons of CO_2, summarising 7-8% of global emissions.

Throughout all stages of metals’ raw excavating, preparation, and processing, there are both direct and indirect emissions of greenhouse gases, including CO_2. Direct emissions include methane at coal mining, coke gas at coke burning, and exhaust gases from the reduction and burning of carbon-bearing components (at sintering and pellets roasting, blast furnace (BF) or direct reduction iron (DRI) gas- and coal-fed units, and steel melting in oxygen converters (BOF) and electric arc furnaces (EAF)) and CO_2 at limestone and magnesite calcination. Indirect emissions come from energy used for all these and downstream technological processes and transportation. Not less problem for further sustainable growth of steelmaking is the considerable amount of raw materials needed annually: iron ore – 2.4 bln ton [1, 2]; coal – 1.1 billion tons; lime (dolime) 140-160 mln t [3]; and magnesite – 18 - 27 mln t (for refractory lining and mixtures [4]).

The focus of steelmaking over the past decade has shifted towards the development of low-carbon and carbon-free technologies. The leading steel manufacturers form Global Low-Carbon Metallurgical Innovation Alliance [5] making strides towards a low-carbon future [6] and have taken up the challenge to achieve carbon neutrality in 2050 to meet the Paris Agreement on climate change targets. Ferrous metallurgy’s CO_2 emissions are expected to fall 30% by 2050 compared to 2021 levels [7] and the main challenge is efficiently remove carbon from iron reduction processes.

The main source of CO_2 emissions is ironmaking dates back to prehistoric times, when mainly only carbon and flame were available for iron reduction from metal-bearing ores. To someone without knowledge of the features of the optimal conditions for the realisation of variety of physicochemical processes of reduction and refining in steel production, the procedures may seem paradoxical and illogical. In the traditional blast furnace-oxygen converter tandem, a large amount of carbon is first used to produce pig iron and its content in the metal is increased to almost 4%, and then it is

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removed using oxygen, which was removed from the ore on the first stage. Nevertheless, the blast furnace (BF) is still the most efficient unit of carbothermic reduction of iron. Furthermore, the downstream Basic Oxygen Furnace (BOF) process converting an iron into steel is also very attractive, being energy efficient due to the exothermic oxidation of carbon, silicon, and iron during oxygen blowing, eliminating the need for external heat sources.

It should be mentioned that the GHG emission from today's steelmaking routes (t CO_2/t steel) is sufficiently different [8,9]: BF followed by BOF produces 2.33; natural gas-based DRI followed by EAF – 1.37; and EAF with 100% scrap – 0.68 (based on 2022 calculation), that defines last option to be the mainstream vector. To cut CO_2 emissions, the ironmaking route must be fundamentally transformed (by eliminating carbon as reductant) or added by installations capturing CO_2 from exhaust gases.

Specific strategies and technologies employed by steel manufacturers may vary depending on factors such as energy consumption conditions and developing technological improvements [10] market constraints and regional regulations.

We do not discuss in detail the most ambitious scenario of the global transfer to electrolytic hydrogen as reducer and fuel, which, like the direct electrolysis of iron, can provide genuinely carbon-free metallurgy since there is yet to be enough energy capacity for such transition worldwide. Nevertheless, the concept of green hydrogen electrolysis is promising for its potential as a clean and renewable energy carrier and power grid stability balancing in spite that its large-scale production remaining economically challenging [11-13].

Currently, most hydrogen production is achieved through steam methane reforming, which utilizes natural gas. This method gives "blue" hydrogen that is cheaper but results in carbon dioxide emissions that should be accounted for steel making it "grey" (not fully "green"). The challenges include the need for extensive infrastructure for hydrogen production, transportation, and storage, and the overall economics of the process.

Small-scale pilot projects and demonstration plant have successfully produced molten iron by iron oxide electrolysis (MOE) [14-16] using renewable energy, but these projects face constraints when it comes to scaling up production to meet significant volumes of demand and the high cost of renewable energy technologies. As renewable energy technologies become more cost-effective and efficient, the economic viability of large-scale projects is expected to improve and open pathways for implementing technological advancements for traditional and future industrial routes.

The nowadays challenges of basic oxygen steelmaking industry

A significant share of today's steelmaking ecosystem consists of the energy-efficient but carbon-intensive BF/BOF route, which changing for any other facilities would have far-reaching effects on steel customers. For example, In the EU in 2020, more than half of the steel produced (56%) was made via the primary BF/BOF route and the other 44% through the recycling route using EAF [17]. In China, which produces half of all world steel, abandoning the BF/BOF route favouring EAF is most challenging because BOF steel share is almost nine times higher than that produced in EAF (10.9%).

Besides, only scrap recycling is not enough source to meet the growing steel demand. Global consumption of ferrous scrap in 2022 was 610 million tons, nearly 32%wt of raw materials, for 1.95 billion tons of total crude steel production (Figure 1).

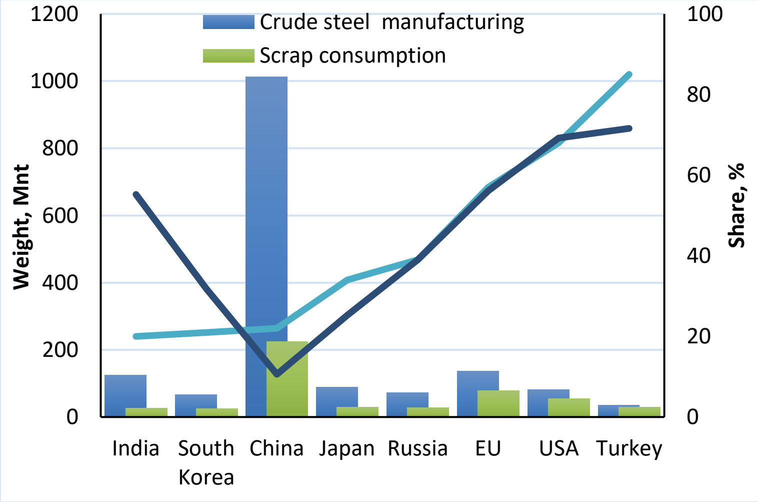


Figure 1. Scrap share and main performances of steelmaking by countries (2022).

The most developed and commercially proven pathway to decarbonization is the EAF route involving alternative iron-bearing charge materials and efficiency-increasing techniques - scrap preheating, waste heat recycling and clean materials using. The possibility for the near future is to use proven steelmaking routes [18-20] together with existing infrastructure and technologies (Figure 2) combined with Carbon Capture Utilisation and Storage (CCUS) [20-22].

In our opinion, renewable electricity, minimized carbon and maximized hydrogen involvement as fuel wherever possible, and Carbon Capture Utilisation and Storage (CCUS) technologies are effective pathways to low-CO_2 and fossil-free steelmaking, which will be implemented in the nearest future. CCUS-equipped production is already a reality [21,22], which should be but not jet scale-up to big industrial capacities.

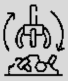
	Main raw material	Iron reduction	Hot metal	Steelmaking unit	Secondary metallurgy	CO_2 emission	Future improvements
Actual	Iron ore Coke Scrap (up	BF 	Pre-treatment  De-S /De-P	BOF 	LF  VD/VOD 	2,33	Circular carbon Biomass reductants Hydrogen injection Carbon capture and usage
	SOLID CHARGE -Scrap up to 100%  (+pig iron+DRI)			EAF 		0,68	Clean electricity
Future	High-grade iron ore Methane/Hydrogen Scrap Clean electricity	DRI – CH_4  DRI unit - H_2		EAF 		1,37 Near Zero	Clean electricity Hydrogen to iron ore reduction
	Low-grade iron ore Hydrogen reduction Clean electricity	DRI unit – CH_4  DRI unit- H_2	Smelting in SAF-type smelter 	BOF 		Sufficient reduction	Circular carbon Carbon capture and usage

Figure 2. Flow diagrams of main eventual routes of steelmaking

Integrated steel mills with BF-BOF are now elaborating strategies to change existing flow charts with more sustainable options. Despite the enormous investments needed, some producers have already decided to replace BF with DRI facilities. The direct reduced iron manufacture is now considered crucial to near-zero emission steel, and DRI involvement is foreseen for both BOF and EAF finals. However, the BOF process is inefficient with only solid iron-bearing charge mix and, therefore, an intermediary smelter became necessary to melt DRI and feed BOF by hot metal. Thus, well-developed and widely used in the ferroalloys industry, submerged arc furnaces (SAF) are good candidates for liquid metal supply to BOF.

Nevertheless, the tandem of DRI and EAF units is today's most recognized alternative to the traditional BF-BOF route, which rather not survive without equipping by CCUS.

Another common concern is the raw materials quality worsening: recirculated steel scrap accumulates tramp elements, and high-grade ores availability and iron content in DRI concentrates are shrinking, increasing the range of harmful and ballast components as well. DRI's residual gangues (having a high content of silica oxide) will increase lime and flux consumption.

Besides, replacing both graphite electrodes and magnesium-carbon lining in EAF with other materials will fundamentally change existing practices.

Modern EAFs use a single-slag process with scrap melting intensification by oxygen blowing and bath mixing by neutral gas purging for ordinary semi-finished product manufacturing for further secondary metallurgy processing. High-performance electric arc furnaces are equipped with powerful transformers (0.7 - 1.5 MVA/t), wall gas-oxygen burners system and door manipulators with oxygen lance. Slag foaming by injection of carbonaceous powders (10-15 kg/t) with the simultaneous blowing of oxygen (30-60 nm^3/t) accompanies by CO_2 emission but gives substantial gains: exothermic reaction heat (chemical energy), arcs shielding to better energy transfer to metal bath and additional power from CO afterburning reducing overall energy consumption on 10-30 kWh/t despite of more slag-forming additives; fewer metal losses due to part of iron oxides reduction from slag; nitrogen absorption decreases by 10-20 ppm (to a level of about 30 ppm for conventional semi-product).

The best available practice of high-performance 100-120 t EAF demonstrates specific electricity consumption of 310-360 kWh/ton due to up to 45% of the total heat input from chemical energy sources and mixing a bath, the heat duration - tap-to-tap time (TTT) reaches 34-45 minutes [last record 2023 was at Badishe stahl werke [23], which is approaching but less than the indicators for oxygen converters, which besides have larger volumes. Increasing the metal bath diameter reduces the efficiency of wall burners that lowering productivity. That means more EAFs will be necessary to balance the productivity of replacing BOFs.

Thus, there are several challenges connected with BOF replacement by EAF. Increasing EAF operational tap weight to 200-350 tons requires installing transformers of colossal capacity. If we take norms of 0.7 – 1.5 MVA/t nowadays, their power will reach 150-600 MVA. The problem is that units will introduce significant disturbance and imbalance in the electrical distribution grids.

The entire range of existent iron-bearing charge involvement and phasing out carbon in EAF require drastic changes in the already well-optimized technology. Today electric arc furnaces can use various types of initial charge mix: scrap metal - up to 100%, liquid iron - up to 40%, and direct reduced iron - up to 100%, providing the most ecology and cost-efficient steelmaking process emitting much less CO_2 than the BF/BOF route. Steel scrap is the original raw material to melt in EAFs, and operation with other charge components both the DRI and or iron is less efficient because requires changes in technology and, in the ideal case, in the EAF design:

- both DRI and iron usage accompanied by bigger volumes of forming slags because of high silicon in their composition, which should be removed from metal and bound with lime additives;
- blowing of high carbon and silica iron melt accompanied by the temperature increase requires coolants (scrap, DRI, lime) that also leads to the same problem with slag handling. Moreover, molten iron usage does not align with decarbonization (as discussed above).

Another essential task is prioritizing the circularity of basic oxygen steelmaking (both from BOF and EAF) by-products, such as basic oxygen steelmaking slag (further BOS), through iron recycling. For every ton of crude steel produced is accompanied in average with 150-250 kg of slag. The composition of BOF/EAF slag typically consists of 85-90% mineral components, which are complex oxides of calcium, silicon, aluminium, manganese, iron, and calcium and manganese sulfides, and 10-15% metallic phase, made up of droplets and beads of various sizes and shapes. While BF slags are fully utilised in cement production and road construction good for other applications the steelmaking slags (both from BOF and EAF) is more challenging to reuse in the same fields due to the high content of metal oxides (iron, manganese, chromium and others (depending on the particular shop), metallic particles of various size and undissolved lime [24-29].

The extraction of metal pieces and particles of various fractions (usually to less than 1 mm) is the primary stage of today's way of solid steelmaking slag reuse that involves mineral processing technologies. Recovery slagged Scrap (RSS) gained from cooled steelmaking slags are specific materials with metal and slag parts. The annual formation of RSS worldwide can be estimated at 29 - 43 mln tons that cannot be neglected, and this resource can be effectively used in steelmaking, reducing demands for primary raw. For these reasons, this article gives a mathematical simulation of RSS melting and the results of its use in BOF shop.

Some results and consideration on Recovery Slagged Scrap (RSS) involving in steelmaking

In this study, the results of industrial batches of Recovery Slagged Scrap (RSS) is presented as the prospective way of CO_2 emission reduction and approach to zero-waste manufacturing. RSS (fraction 20-200 mm) was obtained from a specialized crushing and screening complex that processes slags from Ukrainian steelmaking plant (BOF producing semi-product of low-alloy steel grades). Cooled slags discharged from slag pots were crushed by a falling load with collecting of largest parts of Recovery Slagged Scrap (RSS). The rests were crashed further and classifying with undergoing de-slagging on a tumbling drum with further beneficiation (gravity, size, and magnetic separation) and further classification into batches. The metal part has the same composition as that of averaged semi-product of the shop, and the slag part chemistry is the same as a final refining slag in the steelmaking unit. The slag shares on the surface of RSS depended on its pieces' size and shape and made about 5% in weight (12-15 %vol) on average for fractions 20-200 mm from the slag of the BOF shop. The slag-free metal surface of scrap pieces is covered by a 1-2 mm thick iron oxides layer (Figure 3).

Figure 3. The appearance of bulk RSS in fraction 20-200 mm (a) and separate piece (b) - 85 mm in length.

The slag part of RSS was a hardened stone-like substance with 2.8-3.6 basicity ($\sum(CaO + MgO)/ \sum SiO_2$ and FeO content 17-22 wt%. The main components content was determined by X-ray fluorescence method according Ukrainian standard DSTU 3564-97. The slag part is similar to the composition of the high basicity refining slag at the end of BOF melt ($CaO/SiO_2>2.8$; CaO 45-60 wt%; SiO_2 13-18 wt%; FeO 15-25wt%; MgO 4-8 wt%;) that is consistent with many previous researches [24, 28-30]. The bulk density was defined as simple dividing a mass (4.5-5 tons) of RSS scrap (20-200 mm) on scrap pan volume (3 m^3) that gave the bulk density value in the range 1500-1600 kg/m^3.

Metal part chemical composition was determined by standard spectral analysis according to ASTM E415-21. Elements content it deviated from piece to piece, but average total alloying elements is less than 1 wt%, sulphur and phosphorus contents are in the limits for ordinary structural steels (no more than 0, 04% for both).

Because of sufficient oxide layer on the RSS surface (both slags or oxides), its melting mechanism is different from conventional scrap with a clean surface. At low melt flow velocity, RSS pieces melting time is close to ordinary scrap pieces. At higher rates that are typical for high-intensive steelmaking processes, the melting time of RSS pieces can increase. Faster melting of RSS occurs due to low melting points and low thermal conductivity of slag, reducing the period of frozen shell formation preceding the kinetic stage of melting. The importance of the period of frozen shell was formation shown by research [31], where it takes almost 50% of the total melting time of DRI, and the thickness of this shell increases by increasing the initial particle size. The discovered patterns also coincide with the conclusion made for scrap melting controlled by carbon mass transfer at 1573–1723 K that the relative contribution of parameters is the following: mixing power > bath temperature > specific surface area > carbon content [32].

This approach can enhance RSS technology in steelmaking units. Since RSS screens heat transfer to the lower layers of charge it is not recommended to put it above of another scrap grades that should be compelled at loading profile composing. To prevent sticking of RSS in big pieces it should be charged over the entire area of a steelmaking unit bath. Faster melting of the charge mix containing RSS and induction of primary slag due to the participation of scrap slag in slag formation, which made it possible to reduce the consumption of lime and fluorspar without deteriorating desulfurization conditions. However, in this case, it is necessary to take into account the specifics of the RSS composition and, probably, a change in the loading technology and intermediate slag removal be required to prevent an increase in the content of impurities but this reduces the productivity of the converter.

The early formation of slag via dissolving lime is a crucial factor for reducing iron burning losses, efficient melt refining and lining protection at oxygen blowing in both BOF and EAF [27, 33,34]. Due to relatively low melting point and high content of FeO the RSS's slag part contributes in early appearance of liquid slag and increasing its basicity (CaO/ SiO_2) supporting dephosphorization and desulphurization. The positive effect of BOF's slag reuse in various periods of melting is well known - slag can act as fluxing agent intensifying lime dissolution and slag formation, as BOF's bath cooler while and after blowing and as a thickener for the final slag before tapping to reduce its ingress into the ladle and for lining slagging. The RSS's slag cover performs the same functions increasing primary slag volume, basicity and speed-up lime dissolution [33-36].

Content of elements in RSS is close to a final product that is good for any processing unit. RSS extracted from BOF slag of steelmaking plant producing semi-product of low alloyed steels fully meets these requirements since deviations of semi-product composition are quite narrow, besides several heats' slags can be averaged in one batch.

In the BOF steelmaking process, two types of slags are formed: slags of the initial melting period - primary slags with a high (up to 50 wt%) iron content (represented by FeO and Fe_2O_3 oxides and metal beads) and low basicity. Such slags are discharges after the initial refining period completion and in principle can be stored and processed separately for utilisation for other purpose; -the final slags from the production of low-carbon steel contain a lower amount of iron (see above) but have higher basicity value (up to 4 units). A small part of the final slag enters the steel-pouring ladle together with the semi-product, and after casting, a conglomerate of the final slag and metal residues is formed, containing the maximum content of metallic iron.

In BOF the oxygen blowing of hot metal is accompanied by the release of a large amount of heat, which most often is absorbed by scrap having closest in composition to the semi-finished product produced from the unit in compare with other alternative iron coolers (hard iron, direct reduced iron, sinter or pellets, iron ore lumps), limestone or lime. Replacing scrap by any of these materials has its positive and negative aspects, affecting the chemical composition of semi-product, slag foaming, tap temperature and refractory wear [36].

Based on our analysis of BOF shop statistics, we found that using RSS resulted in copper, nickel, and chromium content in steel that was 1.6-2.0 times higher, while purchased steel scrap had content that was 3-4 times higher compared to metalized pellets. Thus, the composition of iron-bearing charge should be controlled to keep satisfactory level of impurities.

RSS using as a coolant does not entail changes in the BOF melt technology but has the same advantages as using of main materials of BOF charge - scrap and lime: slag part acts as a fluxing agent in helping to form refining slag early facilitating the removal of impurities and promoting better steel cleanliness and scrap is scrap – nothing to say more.

Performed analysis shown that there are no obstacles that are associated with technological difficulties and environmental safety since the scrap is used in the same unit. RSS is easily sorted into various fractions and has quite a stable chemical composition. For high-quality steel melting RSS can be mixed with DRI to reduce and keep a competitive product cost.

The RSS extracted from slags from EAF working on 100% scrap contents more tramp elements, which removal in the steelmaking processes is inefficient or impossible (non-ferrous metals Cu, Sn, Ni, Cr, Vo, W and As, Sb). This reason in an EAF the addition of own RSS should be limited by 10-20 % (preliminary). Another reason is that residual slag on the surface of RSS has low electric conductivity; thus, thick layers of charged RSS will deteriorate arcing in the EAF.As in the case of BOF, RCC should not be loaded on top of another scrap charge. The usage of RSS in EAF charge mix can accelerate slag forming that lowers energy consumption and refractory wear.

Very preliminary the RSS fraction for EAF should be reduced to 20- 100 mm (instead of upper size 200 mm for BOF) to prevent problem with arcing because of low conductivity of slag covered its surface. Nevertheless, it seems that the allowable amount of RSS in the low-alloy steelmaking is limited primarily by increase in total volume of slag. When the RSS originates from fresh slags of the BOF shop working with stable composition of semi-product the amount of phosphorus and sulphur in the slag part is not critical. On contrary, the high basicity BOF slags contain a certain amount of lime this is one more argument to RSS recycling in steelmaking units.

Another case is steelmaking shops producing of high alloy and stainless steel, where the slags composition varied from heat to heat and content of alloying elements in both RSS slag and metal parts can be sufficiently different depending of the ordered grade. RSS from such slags is even more valuable because of high content of alloying elements, and it is important to carefully classify slags on several grades and process them separately to assure stable chemical composition.

The following RSS classification from semi-product for low alloy steel manufacturing can be recommended basing on experimental trials and literature data [30,35,36] scrap of fraction 0-10 mm having a slag content of more than 10% wt. can be and usually is utilized in the sinter charge. Meanwhile, scrap measuring 10-120 mm and with a slag content of 5-10%wt is used in the blast furnace charge. Scrap measuring 20-200 mm with less than 5% slag content fit to using in steelmaking units. The optimal steps for RSS classification and use can differ from plant to plant, depending on processing facilities and the exploited steelmaking process but found peculiarities of RSS melting allow improve charging practice of basic oxygen steelmaking (both BOF and EAF) and resulting performances. Any case the widening of RSS reuse in steelmaking will increase iron recycling efficiency and became a small brick in a basement of carbon-neutral and zero-waste steel production.

Conclusion

Decarbonization is a challenge and a possibility for steelmaking simultaneously, being a chance to check new approaches and technologies and improve existing technological routes in between which EAF is the most prospective.

Technological scenario for different steelmaking shops can depend on iron-bearing charge conditions and availability of hydrogen and renewable reductants and fuels.

In our opinion, it is not rational to pursue zero-carbon steelmaking because carbon is the most effective and inexpensive hardener, reducing agent, fuel and integral part of refractories, electrodes, and casting mixtures. Today there are no practical solutions to completely exclude carbon from composition of both steel grades and essential metallurgical materials. Nevertheless, all possibilities where carbon can be efficiently replaced by another reductant or electricity should be widely implemented.

The alternative scrap involvement confirms lime consumption decreasing with the same value of desulphurization as it was predicted by improvements in slag formation and better dissolution of lime due to action of slag part of RSS.

RSS internal recycling in both BOF and EAF can contribute to the iron recovery ratio, lower costs of iron-bearing charge mix and is a step toward zero-waste steelmaking.

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