

OBMS & CARBON NEUTRAL STEELMAKING
Whitepaper 2: Future Challenges for the EAF Process

OBM's & CARBON NEUTRAL STEELMAKING

Paper 2 Future Challenges for the EAF Process

An assessment of future challenges for the EAF process resulting from efforts to reduce the carbon footprint

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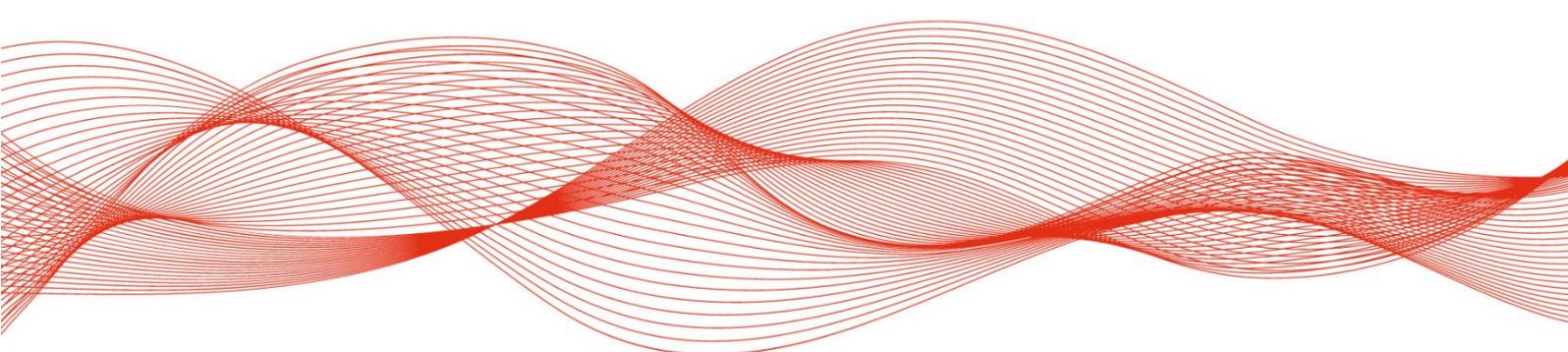
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Foreword

Overview

With the recent acceleration in interest, strategic thinking, and commitment towards decarbonisation, we as a key component of the steelmaking value chain need to play our part in this endeavour. To be effective in tackling the challenges and opportunities we face, the merchant ore-based metallurgy sector has begun exploring its role in the pathway to creation of a carbon-neutral steelmaking industry. The current findings are contained in the first edition of a series of whitepapers on this topic.

Introduction to the Whitepapers

The whitepapers aim to foster discussion and ignite collaboration with stakeholders in the merchant ore-based metallurgy value chain including academia and public policy makers. We believe that the foundation to successful decarbonization is knowledge sharing and awareness raising on the challenges and opportunities inherent in this process, garnering deeper understanding and fostering potential solutions but most importantly ensuring sustainable outcomes.

Many companies in our value chain from iron ore miners to steelmakers have already published their thinking and strategy for decarbonization and there will be more to come. The purpose of our whitepaper is to examine these, identify common elements and issues and to catalyse thinking and advocacy for action. We recognise this is an evolving space and therefore plan to continually monitor and regularly update the whitepaper as a living document.

IIMA OBM & Carbon Neutral Steelmaking Whitepapers

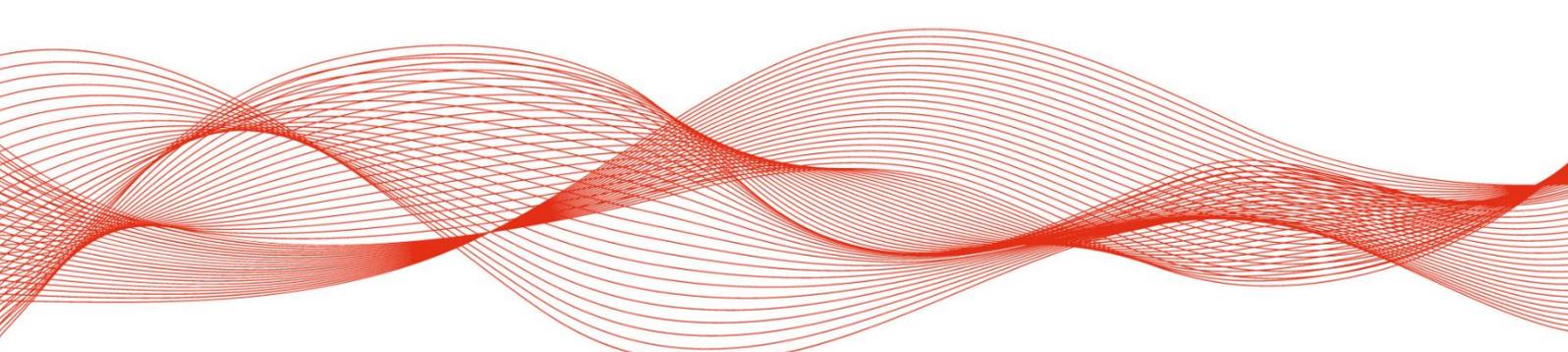
- **Whitepaper 1** - Ferrous Metallurgy for Steelmaking
- **Whitepaper 2** - An Assessment of Future Challenges for Electric Arc Furnace Steelmaking
- **Whitepaper 3** - Future DRI Production & Iron Ore Supply
- **Whitepaper 4** - Blast Furnace/Basic Oxygen Furnace Steelmaking and Alternative Iron Smelting Technologies

Abstract

Much attention is being placed on EAF technology as a means of transitioning to lower carbon footprint steelmaking. However, as one begins to evaluate the opportunities that the EAF brings to this endeavor, one quickly realizes that the future of EAF technology is closely entwined with the selection of raw materials that we utilize to make the steel. In fact, it is impossible to separate the two topics when one is attempting to develop low carbon solutions for steelmaking.

The iron and steel industry is about to hit a crisis, due to increasing residual levels in scrap and declining generation rates for high quality prompt scrap. Ore based metallics (OBMs) play a critical role in diluting scrap residual levels and enabling the recycle of steel scrap. Ferrous feedstocks impact directly on EAF productivity, yield and efficiency. As a result, both topics have been addressed in this paper.

The following discussion attempts to lay these issues bare for the reader to evaluate and begin to determine the questions that we should be asking as we embark on the journey to a carbon neutral 2050. The discussion is not intended to provide definitive solutions at this point in time but rather to promote the thought and discussion necessary to develop sound technological solutions for the future.



1 Introduction

To meet the carbon reduction targets of 2050, EAF technology is under heavy focus



The global steel industry has embarked on a foray into the evaluation of new technologies aimed at meeting CO₂ reduction targets by 2050, currently direct CO₂ emissions from the sector are around 2 Gt CO₂, or around 25% of industrial CO₂ emissions. Several approaches and technologies are under evaluation around the world and at times it is difficult to clearly identify the targets.

The Electric Arc Furnace (EAF) is currently the technology with the lowest carbon footprint. Typically, 500 - 800 kg of CO₂ are generated for each tonne of steel produced. In addition to 100 % scrap-based EAF steelmaking, the EAF production route has shown that it can produce the same higher value products as the integrated (CO/BF/BOF) route if up to 40 % of the metallic charge consists of ore-based metalics (OBMs) (pig iron, direct reduced iron (DRI) or hot briquetted iron (HBI)). It is also clear that a circular economy for steel scrap is contingent on residual dilution from OBMs in order to meet product requirements. This will be the case until we develop technology capable of economically removing residuals from steel scrap.

Future steelmaking assumes that electricity from renewable sources will form the basis for energy input into the process. The bulk of the CO₂ emissions from 100 % scrap-based steel production is a function of power generation, in the future, the carbon footprint of the EAF will shrink considerably with renewable power generation.

It is clear that the EAF has been identified as a preferred technology for steelmaking in the long term. It is also clear that OBM utilization is required to make this happen. What is not clear at this point is whether the goal is to "eliminate" carbon in the EAF or to minimize its' use. The purpose of this paper is to identify the challenges for EAF steelmaking for the next 30 years so that sound technical solutions can be evaluated prior to their implementation in the long-term strategy for steelmaking.

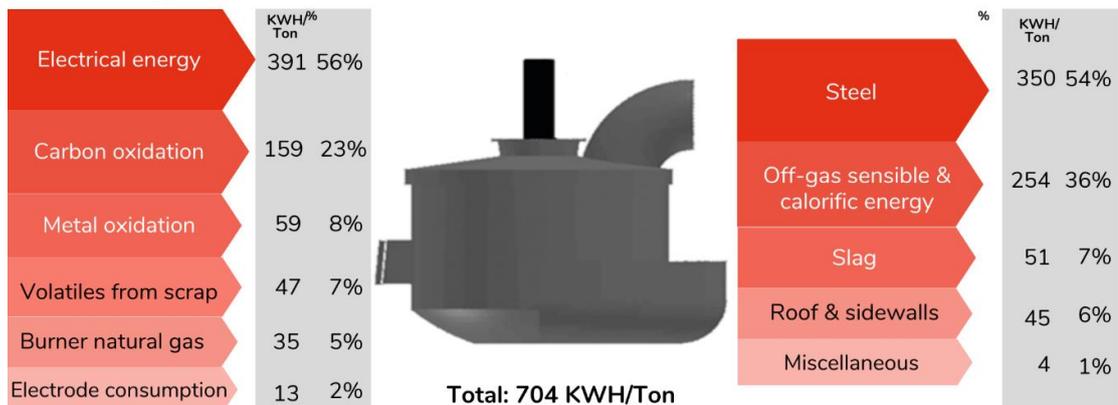
1.1 Background

Inherently, it is difficult to envisage "zero" carbon steelmaking as steel is defined as an alloy of Fe and carbon. As such, zero carbon steelmaking is a misnomer - what is actually intended is a low carbon or carbon-neutral steel industry. Currently the aim is to identify how much the carbon footprint of EAF steelmaking can be reduced without seriously impacting the fundamentals of the process itself.

1.1 Typical EAF energy balance

FIGURE 1: STATIC ENERGY BALANCE FOR THE EAF

Furnace energy balance



Static energy balances for the EAF have been presented previously by Jones. A typical example is presented in Figure 1 above.

1.2 Sources of carbon in the EAF

Currently CO₂ emissions are classified as follows:

- **Scope 1** - covers direct emissions from owned or controlled sources.
- **Scope 2** - covers indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed by the reporting company.
- **Scope 3** - includes all other indirect emissions that occur in a company's value chain.

Currently most steelmaking operations are focused on Scope 1 and to a lesser extent Scope 2 emissions. As will be demonstrated further on in this paper, the steelmaker must be aware of potentially large Scope 3 emissions associated with raw materials. For the steelmaker, fluxes, Fe metalics and even logistics can contribute significantly to Scope 3 emissions, and these may significantly impact the process technologies utilized in the future.

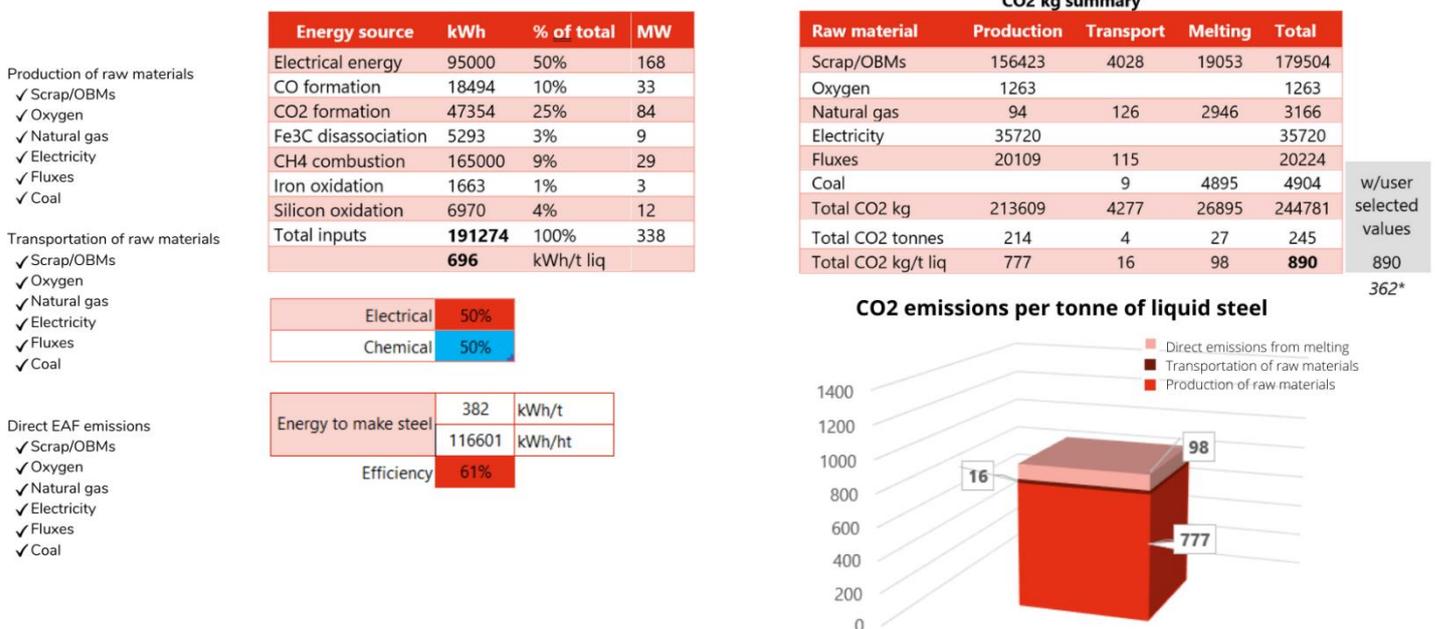
The first step in reducing the carbon footprint of the EAF is to identify the various sources of carbon coming into the process.

The key primary sources of CO₂ emissions from the EAF:

- Generation of electricity
- Natural gas - used as a fuel
- Oxygen reaction with carbon in the steel bath
- Combustion of oil, grease and other combustible materials associated with the scrap charge
- Carbon contained in the various scrap materials
- Carbon contained in ore-based metallics (OBMs) - pig iron, direct reduced iron (DRI), hot briquetted iron (HBI)
- Consumption of graphite electrodes
- Refractory consumption - e.g., MgO-C brick
- Reaction of charge C in the EAF
- Reaction of injection carbon in the EAF
- CO₂ Evolution from calcination of lime

Figure 2 shows the amount of CO₂ that each of these sources contributes to the overall carbon footprint of the EAF Process. As we attempt to eliminate these sources of CO₂ emissions from the EAF, we must keep in mind why they were implemented in the process in the first place and the functionality that they provide.

FIGURE 2: CONTRIBUTION OF CO₂ TO EAF PROCESS BY SOURCE



2 EAF Raw Materials

The future of EAF technology is closely entwined with the selection of raw materials used to make the steel



2.1 Scrap supply and the importance of residual metallic impurities

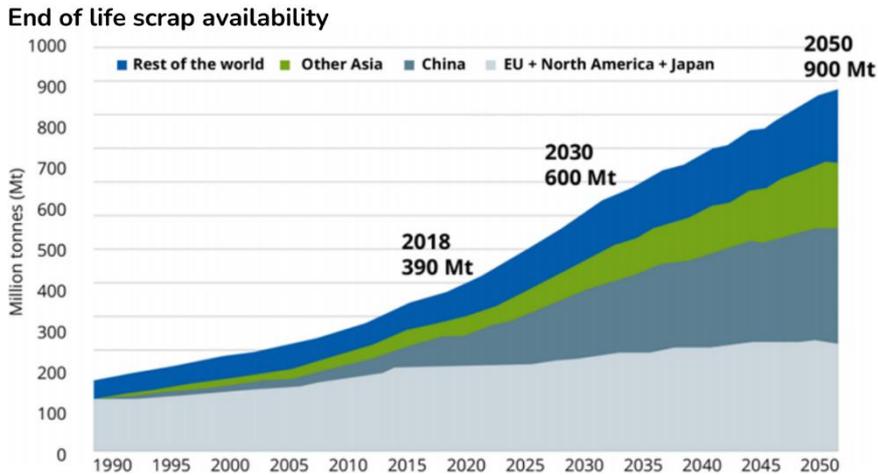
Steel residuals refer to elements such as Cu, Ni, Sn and Mo that cannot be refined (removed) from the steel. These elements can impact the formability of the steel as they tend to segregate to grain boundaries and deform at a rate different from the bulk steel matrix. As a result, various steel applications limit the amount of these residuals in the steel in order to meet the product physical requirements and the ability to form the desired products. Copper is usually the residual that is most closely tracked of the various residuals.

Allowable copper content for various grades of steel are (It can be seen that the range varies considerably for the various steel products):

- Rebar 0.2 - 0.4 wt. % Cu, can be as high as 0.8 wt. %
- Bearing quality - max 0.3 wt. % Cu
- Carbon steel wire rod - max 0.3 wt. % Cu
- Rope steel wire rod - max 0.15 wt. % Cu
- Spring steel wire rod - max 0.2 wt. % Cu
- Tool steels max 0.25 wt.% Cu
- Structural steel 0.2 - 0.5 wt. % Cu, average 0.2 - 0.3 wt. %
- Steel plate (A36) 0.2 wt.% Cu
- Tubular goods 0.08 - 0.20 wt. % Cu
- Steel sheet 0.04 - 0.10 wt. % Cu

Projections of scrap availability between now and 2050 indicate that the quantity of scrap available for recycle will grow considerably. This is good news for the EAF steelmaker as scrap makes up the majority of the metallic charge to the furnace. Figure 3 below from worldsteel shows projections out to 2050 by geographical region.

FIGURE 3: WORLDSTEEL SCRAP AVAILABILITY PROJECTION TO 2050



From 2020 onwards there is a small amount of growth in EU/NAFTA/Japan. The largest growth is in China and the rest of the world. Of course, the amount of scrap is only one part of the story. The scrap quality is also of key interest for the EAF steelmaker. The quality of the scrap is dependent on the product group that the scrap is sourced from. Referring back to the earlier list, if the steel scrap comes from structural works, the copper level is probably about 0.3 wt. %. If the steel scrap comes from products made with sheet steel, the copper content could be from 0.04 - 0.1 wt. %. If the steel scrap is sourced from tubular products, the copper content is likely 0.12 - 0.15 wt.% Cu. Special bar products will provide scrap with a copper content of 0.15 - 0.3 wt. %. Recycled rebar will contain 0.3 - 0.8 wt. % copper.

In addition, the age of the steel and the region where it is sourced will also likely impact on copper content. It is well known that the life cycle of steel varies greatly by geographical region.

In the last 10 years, co-mingling of different scrap types has become more common and scrap blends such as 80/20 #1/#2 heavy melt can have copper content in the range of 0.5 - 0.6 wt. %. As a result, the nomenclature utilized to describe various scrap types has become less meaningful. To add to the confusion, the nomenclature also varies by geographical region. The worldsteel EAF experts group addressed this issue several years ago by generating a matrix of scrap nomenclature equivalencies. However, in the last few years the situation has become worse, and, in many cases, higher quality scrap is being contaminated with lower grade scrap. This inherently drives the steel producer to greater use of OBMs to dilute residual levels to achieve the necessary steel product specifications.

Prompt scrap is defined as material that is generated in the manufacturing process. The chemistry of this material is generally well known. An example

would be bushellings. Obsolete scrap is defined as material that is reclaimed when a steel product reaches its' end of life. Examples would be shredded automobiles, white goods or rebar. It is important to recognize that many different grades of scrap exist within these two broad classifications and that these various scrap grades contain different levels of residuals, inert content and other components. Home scrap is defined as scrap that is generated within the steelmaking facility in the process of producing steel. Examples would include ladle and tundish skulls, steel recovered from slag pots and trim losses that occur in the rolling/finishing processes.

Figure 4 below shows worldsteel projections for the amounts of prompt, obsolete and home scrap that will be available out to 2050 (x axis is year, y axis is Mt). It can be seen that home scrap is expected to grow a little post 2020 as more steelmaking capacity comes online. Prompt scrap supply is also expected to grow post 2020, but most of this will be in the developing economies. In the developed economies (Europe and NAFTA), the supply of prompt scrap is on the decline as manufacturing generates smaller and smaller quantities of waste through increased efficiency. Obsolete scrap supply will grow enormously post 2020 as buildings and infrastructure reach the end of their useful life in the developed countries and are replaced.

FIGURE 4: WORLDSTEEL PROJECTION OF SCRAP AVAILABILITY BY TYPE

Global scrap availability

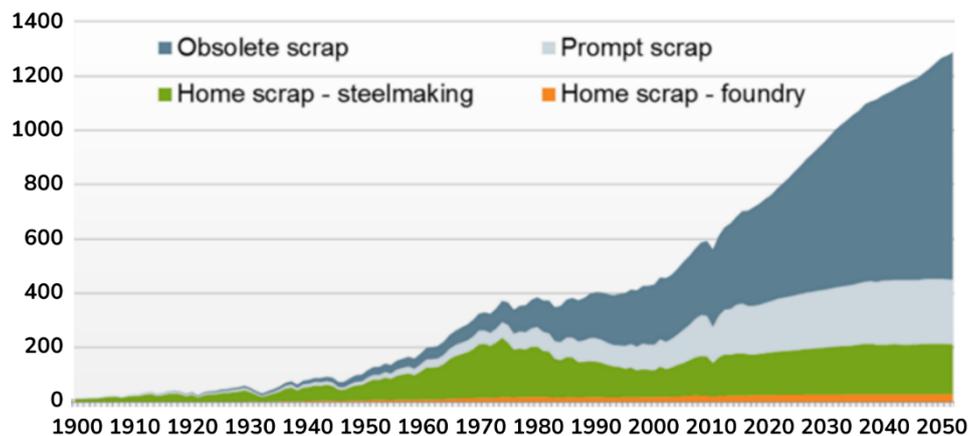


FIGURE 5: PROJECTION OF SCRAP AVAILABILITY BY REGION

Global scrap availability

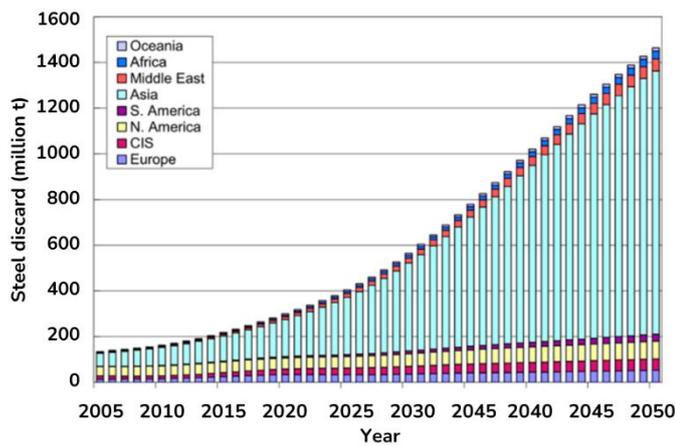


Figure 5¹ shows a detailed breakout of projected scrap generation by geographical region out to 2050. Again, this graph confirms the large growth in scrap availability in Asia and only minimal growth in NAFTA and Europe. However, the figures depicted in this graph do appear to under-estimate current scrap generation levels in these regions.

FIGURE 6: GROWTH IN OBSOLETE SCRAP BY SOURCE SECTOR

Global scrap availability

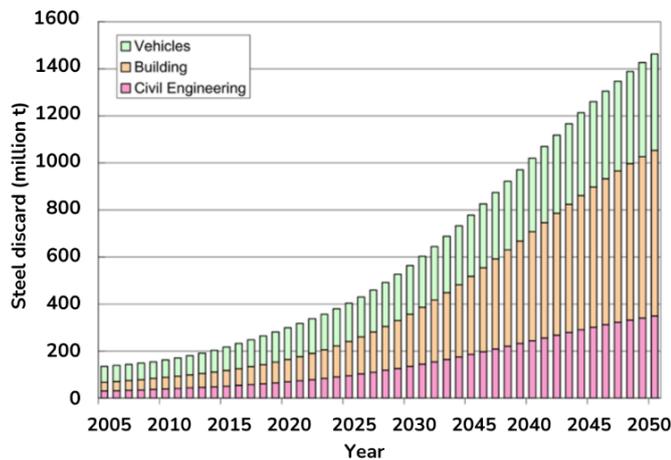


Figure 6² also indicates that the bulk of growth in steel scrap will be obsolete scrap (from building and civil engineering) with an average copper content of 0.3 wt. % copper or higher.

¹ Hatayama, H.; Daigo, I.; Matsuno, Y.; Adachi, Y. Outlook of the world steel cycle based on the stock and flow dynamics. *Environmental Science and Technology*. 2010, 44 (16), 6457-6463. DOI 10.1021/es100044n. H. 3

² Ibid.

FIGURE 7: METALLIC FEED RESIDUAL LEVELS FOR VARIOUS STEEL PRODUCTS

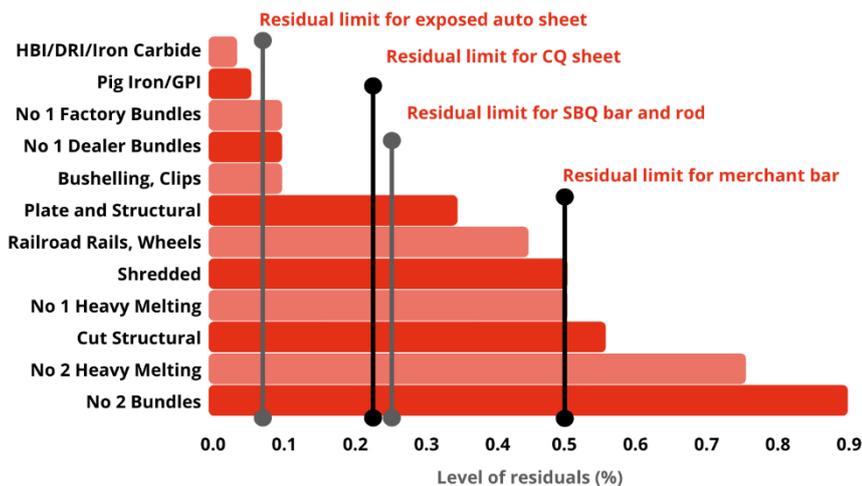


Figure 7 above shows residual levels in various metallic feeds for the EAF along with limits for various steel products. It is clear that most obsolete scrap that will be available in the future will be suitable only for the production of some structural grades, re-bar and merchant bar and can only be used to produce products with lower residual requirements if OBMs are used to lower the melt-in residuals to acceptable levels.

In order to produce sheet grades, pipe grades and many SBQ grades, it will be necessary to dilute the residuals in the obsolete scrap by adding OBMs which, being made from iron ore, have minimal traces of residual metallic impurities. Until an effective and economically viable means is discovered that allows for residuals to be removed from the steel scrap, the solution is dilution. It also becomes very clear that as an industry, we must do a better job of segregating scrap based on its physical and chemical properties. Regardless, it is clear that OBMs are required in order to enable the circular economy for steel. Without OBMs in the metallic feed mix, a significant portion of steel scrap will become impossible to recycle and will be destined for land fill.

Better design of products such as automobiles and appliances must be focused on easy dismantling at end of life so that free copper and other residuals can be more easily removed and thus not lead to down-grading of the steel scrap. For example, the contained copper in auto bodies may be 0.1 - 0.12 wt.% but most shredded scrap currently contains from 0.15 - 0.35 wt. % copper. This additional copper is "free" copper which needs to be removed in order to maintain the value of the auto scrap. This free copper has an economic value and can be recycled. Methods now exist for the removal of at least a portion of the free copper but until the steelmaker recognizes that each point of copper in the scrap brings with it a cost, most steelmakers will not pay the added cost to carry out this additional separation. However, some steel plant operations are now carrying out this

additional processing at the steel plant site. In some cases, the payback on the capital outlay for the equipment is less than 3 months.

The greater issue is that within a given scrap grade, the residual levels can vary enormously. For example, historically, shredded scrap was derived from shredded automotive and white goods and the copper content varied from 0.15 to 0.20 wt. %. Recently, shredded scrap in some regions has contained 0.35 wt.% Cu and in an extreme case 0.52 wt. % Cu. It is clear that shredded scrap is now produced with whatever will fit into the shredder itself and has little relation to the source of the scrap. Even the scrap pricing indices reported by many steel market intelligence groups are diminished in their utility because of the high degree of variability in the various scrap grades which is not captured in their reporting.

If the obsolete scrap contains an average of 0.3 wt. % copper, then to produce flat products with a maximum copper content of 0.08 wt.%, the metallics blend would need to contain approximately 3 parts of OBM with 1-part obsolete scrap. Even a pipe grade with a maximum copper specification of 0.15 wt.% would require a metallic feed blend with 1-part OBM to 1-part obsolete scrap. These examples demonstrate how important the role of OBMs is to the future of EAF steelmaking.

As the average copper content in recycled scrap increases, more and more OBMs are required to dilute the residuals in the scrap in order to produce certain steel products. Currently, the average copper content of all scrap recycled in North America is about 0.25 - 0.3 wt.%. Even at this level, it can be seen that in order to make a product with an 0.08 wt. % Cu max, it is necessary to blend around 70% OBM to achieve this target specification. Table 1 below shows the necessary OBM content of the charge mix based on the average scrap Cu content and the desired product Cu content. The yellow bands in the table depict the current situation in North America. It is expected that by about 2050, that the average copper content in obsolete scrap could reach 0.50 wt.%. This scenario is depicted by the red band in the table.

TABLE 1: NECESSARY OBM CONTENT OF CHARGE MIX TO ACHIEVE TARGET CU % IN STEEL PRODUCT

Scrap Cu wt %	% OBM required in the charge to make various steel products									
0.08	0.0%	N/A								
0.10	20.4%	0.0%	N/A							
0.15	47.3%	33.8%	0.0%	N/A						
0.20	60.6%	50.5%	25.3%	0.0%	N/A	N/A	N/A	N/A	N/A	N/A
0.25	68.5%	60.5%	40.3%	20.2%	0.0%	N/A	N/A	N/A	N/A	N/A
0.30	73.8%	67.1%	50.3%	33.6%	16.8%	0.0%	N/A	N/A	N/A	N/A
0.35	77.6%	71.8%	57.5%	43.1%	28.7%	14.4%	0.0%	N/A	N/A	N/A
0.40	80.4%	75.4%	62.8%	50.3%	37.7%	25.1%	12.6%	0.0%	N/A	N/A
0.45	82.6%	78.1%	67.0%	55.8%	44.6%	33.5%	22.3%	11.2%	0.0%	N/A
0.50	84.3%	80.3%	70.3%	60.2%	50.2%	40.2%	30.1%	20.1%	10.0%	0.0%
0.55	85.8%	82.1%	73.0%	63.9%	54.7%	45.6%	36.5%	27.4%	18.2%	9.1%
0.60	87.0%	83.6%	75.3%	66.9%	58.5%	50.2%	41.8%	33.4%	25.1%	16.7%
	0.08	0.10	0.15	0.20	0.35	0.30	0.35	0.40	0.45	0.50
	Product Max Cu Wt %									

Based on this table, the importance of separating scrap based on source and residual content becomes clear. This might not be economically viable right now. Scrap moves to the larger processors via smaller dealers who consolidate scrap from many sources. These smaller dealers won't tend to separate scrap based on source unless incentivized. Another obstacle is that there are many different sources of scrap and the sheer number of sources might make tracking by source unmanageable even if it was something we would like to do. In the near term, sorting based on copper content appears the most viable option. Given that the supply of steel scrap with a Cu residual content below 0.20 wt. % is already limited, it is critical that this material not be contaminated by co-mingling with scrap containing higher Cu content. The need to direct steel scrap into products with residual content similar to the scrap is also clear. As the supply of prime grade scrap shrinks, this becomes increasingly imperative. It can be seen that in the future, if steel scrap residual levels continue to climb, a significant portion of OBMs is required in the charge mix. It can be seen that even certain long products that have traditionally never required OBMs as part of the scrap mix, will indeed require OBMs in the future.

Several years ago, IIMA commissioned a study to derive the intrinsic value (cost) of a point of copper in the scrap. The study utilized 10 years of market pricing of various grades of scrap from the USA. The time period covered periods of very high scrap prices as well as periods of low market pricing. It is not surprising that the copper values derived from these data varied depending on the product type

(long versus flat). Overall, the cost penalty for the 10-year period ranged from \$1 - \$3 per point of copper. Regardless, it has been shown that a cost can be associated with copper and other residuals in the scrap and that in the future, this cost could be part of the decision-making process for scrap purchase and indeed some steelmakers are already applying a financial penalty based on the scrap copper content. Steelmakers should be willing to pay more for lower residual scrap and should expect lower pricing on material with higher residual levels.

An important part of limiting the impact of rising scrap residual levels is to start to take action now. In the first instance, an economic incentive is most likely to focus the industry's attention: the sooner a benchmarking system is put in place that puts a price premium on low residual scrap and incentivizes both steel end users and steel scrap processors to take the necessary actions to recognize and retain the value of low residual scrap, the greater the possibility to prevent the accelerated degradation of the scrap reservoir.

A system of tracking each scrap commodity type and relating the pricing to a baseline copper content based on value in use and a set of premiums or penalties based on deviations from the baseline appears to be a manageable, equitable solution to this issue.

2.2 Other scrap quality considerations

A major component of ensuring the supply of Fe metallics for the steel industry of the future is for the scrap industry to recognize that there are many physical and chemical properties of the scrap that contribute to the overall value-in-use for steelmaking.

Properties of scrap that contribute to value-in-use include:

- Chemistry and residual levels
- Bulk density
- Sizing
- Yield
- "Dead melt" energy consumption
- Si, C content
- FeO, SiO₂, Al₂O₃ content
- Oil, grease and coatings content
- Extraneous materials - plastic, fluff (zorba)
- Dirt content
- EAF baghouse dust generation potential
- Moisture content

While there has been greater scrutiny of the scrap chemistry and residual levels, many of these parameters and their impact on the steelmaking process have been ignored. Many of these have environmental ramifications and several directly impact the carbon footprint of steelmaking. For example, high moisture content robs the process of energy (used to evaporate the moisture) and results in inefficiency in the process. Any components which will ultimately report to the slag, increase the amount of slag generation. An increase of 1 kg dirt associated with the scrap will ultimately increase slag generation by more than 5 kg and will result in a yield loss of approximately 1.4 kg of Fe. Historically, dirt levels associated with obsolete scrap ranged from 1 to 2 %. In recent years, the dirt content has climbed to as high as 4 % and in some regions, dirt levels as high as 7 to 12 % have been observed in shipborne scrap. The good news is that steelmakers can easily track dirt levels in their scrap by taking regular slag samples and applying a slag model to evaluate these results. Mechanical equipment exists that can be used to quantify and remove the dirt levels in the scrap. The payback on such equipment is typically less than a year based only on chargebacks to the scrap supplier for exceeding the guaranteed maximum dirt level (typically 1 %).

Recently, there have been several studies to evaluate the outlook of steel scrap out to 2050 - 2070. These studies have been carried out predominantly in Japan and to a lesser extent in Europe. These studies tend to consider two broad categories of scrap - prompt scrap and obsolete scrap. These analyses have been very useful in evaluating the future challenges with respect to rising residual levels and placing emphasis on the need to develop scrap processing technologies for the reduction of contained and free copper associated with recycled scrap. What these studies have failed to point out however, is that there are steps that must be taken now, to help preserve the quality of scrap and to address the acceleration in rising residual levels in scrap. Most studies only consider generic prompt and obsolete scrap grades. The variety of scrap commodities must be recognized and incorporated into this analysis along with a clear understanding related to various scrap commodity properties. Real life is much more complicated, but the more detailed analysis is necessary to develop meaningful solutions.

The scrap industry must be made aware that co-mingling of high- and low-quality scrap is in fact leading to the rise in scrap residual levels which directly leads to increased demand for OBMs. The transition of the local scrap market to one that is global in nature is also a contributor. In order to better control the quality of scrap, the various subcategories within the general classification of obsolete scrap must be better defined. This requires that additional scrap categories are defined so that there will be low, medium and high copper classifications that will make it easier to keep the various categories segregated. The same can be said of

prompt scrap – turnings and borings are frequently contaminated with non-ferrous turnings that have been generated at the same machining operation. Bushelling on the other hand should be uniform in nature and will have a known chemistry.



Of course, there is a cost associated with segregation of various scrap types and qualities. That is why a system with penalties and premiums would be an effective means of promoting the desired actions on the part of scrap processors. In some scrap market conditions, the costs associated with better scrap processing and better segregation may appear prohibitive. In a down market, the price difference between bushelling and shredded scrap may be miniscule. There have been periods where the Chicago price for bushelling has dropped below that of shredded scrap. In an up market, the pricing of various scrap commodities tends to spread to a much larger degree. In the USA for 2021Q2, the spread between bushelling and shredded scrap reached approximately \$100. A better understanding of scrap value-in-use could be applied to drive more pro-active action on the part of the scrap processor without negatively impacting profitability over the long run.

As the supply of obsolete scrap increases, it becomes imperative to try to match scrap residuals levels to the products being made. For instance, we can recycle re-bar to produce more re-bar or merchant bar products based on the copper requirement of the product closely matching the copper content of the scrap. Failure to implement such a program will result in cross-contamination of the more valuable scrap commodities and will drive a greater need for OBMs to meet stringent product residual requirements.

2.3 Hydrogen-based DRI

Several steelmakers are evaluating the possibility of procuring DRI produced with hydrogen. If 100 % hydrogen is used, the product would contain zero carbon. If some natural gas is used in the cooling section of the DR module, a product with up to about 1 % carbon could be produced.

The hydrogen based DRI scenario presents some interesting challenges to EAF operations. At zero carbon content, there is a requirement to provide some other reductant source in the EAF to recover the Fe units tied up as FeO in the DRI. The analysis indicates that as pellet Total Fe goes up, there is more FeO remaining in the pellet for a given DRI metallization. This is somewhat counter-intuitive, but at the end of the day, this effect is offset by the lower feedstock demand per tonne of steel for DRI with high total Fe content. If, however, the objective is to reduce the amount of Fe recovery work done in the EAF, the best option is to produce DRI with a high degree of metallization rather than high Total Fe per se.

Other challenges for the EAF include the following:

- Zero C DRI may require a higher steel bath temperature in order to melt at the same rate as for C-bearing DRI. Conversely, the feed rate of zero C DRI may need to be reduced compared to the rates common for C-bearing DRI.
- Some studies have noted that the reaction of C and FeO in the DRI pellet helps to accelerate the breakdown of the pellet in the slag leading to faster dissolution rates. If this is confirmed, the feed rate of hydrogen based DRI may be impacted.
- C-bearing DRI tends to lead naturally to slag foaming, a process that is highly beneficial for both energy efficiency and recovery of injected materials in the EAF. Hydrogen based DRI will not provide this slag foaming benefit, and this may negatively impact EAF efficiency.

Understanding of the impact of zero C DRI on EAF operations will continue to grow and develop as various pilot trials are conducted by industry participants in the coming years.

Some research work indicates that hydrogen based DRI tends to produce a product with a finer pore structure which is more reactive (pyrophoric) than conventional natural gas based DRI. If this is the case, storage of hydrogen based DRI may pose some additional challenges.

A significant issue related to increased DRI production is the availability of DR grade pellets. Some operations have run trials with up to 25 % BF grade pellets substituted for DR grade pellets. This leads to increased slag generation due to the higher gangue content and associated increases in Fe Yield losses, increased

energy consumption and decreased productivity (similar to the discussion around scrap dirt levels above). In addition, higher gangue levels increase the requirement for fluxes to offset the acid gangue components. The carbon footprint to produce these fluxes carries through to impacting the net carbon footprint of steelmaking.

Another concern is that lower grade pellets may contain higher levels of phosphorus. This is a serious concern as higher levels of phosphorus in metallic feedstocks may necessitate EAF operation at higher slag basicity in order to achieve acceptable phosphorus levels in the steel. Operating at higher slag basicity only exacerbates the slag volume issue with even greater Fe yield losses and greater flux requirements.

It is unclear at this time what role pig iron will play in future EAF steelmaking operations. Typically, pig iron contains 4.5 % carbon. If all of this is removed in the EAF then for an operation utilizing pig iron as 50 % of the metallic charge, the contribution to CO₂ emissions would be 82.5 kg/tonne of liquid steel. At the same time, it is clear that OBMs are required to dilute the residual levels in recycled scrap and that the residual levels are rising, resulting in greater requirements for OBMs. In the near term, hydrogen based DRI is not the answer as there is a severe shortage of DR grade pellets to meet the IEA³ projected requirements (under its sustainable development scenario IEA projects >400 million tpy of DRI production required by 2050). The blast furnace is a highly efficient process which results in a product in which the metallic oxides are removed and thus do not negatively impact the EAF process. Currently, pig iron is the material of choice for most EAF operations wishing to dilute scrap residuals.

In addition, developments are under way to utilize hydrogen in the blast furnace and to implement the use of biomass to replace carbon. In Japan, waste plastics have been injected into the blast furnace to reduce the carbon footprint of ironmaking. Without doubt, blast furnace ironmaking will continue to evolve between now and 2050 and for the foreseeable future, pig iron will continue to play a pivotal role to enable steel scrap recycling.

It becomes clear that if chemical energy use in the EAF is minimized, the driving force to utilize OBMs in the EAF becomes purely as a source of "clean" iron units and not necessarily as a source of carbon. Some hybrid processes have been proposed where low grade pellets are reduced in a DR process followed by smelting to produce pig iron. As a result, some may investigate whether a pig

³ International Energy Agency

iron with lower carbon content could be viable in the future. Other research is looking to recover/provide clean iron units as a feedstock to the EAF.

Steel scrap typically has a carbon content ranging from 0.04 - 0.80 wt.% with an average of 0.2 - 0.35 wt. %. As a result, a circular economy with respect to steel pre-assumes that carbon cannot be entirely eliminated from the EAF. As a result, CO₂ emissions of 3.6-6.4 kg/tonne of liquid steel will continue to occur.

2.4 Scrap and the circular economy for steel: key take-aways

So, the question is “**what should we be doing now to ensure circularity of scrap recycling and provide sustainability to the steel industry?**”. The following are a few key take-aways:

- **Too much emphasis on scrap cost - not enough on scrap value.** A much more comprehensive understanding of scrap value-in-use (VIU) is required to justify more appropriate scrap pricing related to scrap utility.
- **Need better definition and tracking of scrap characteristics** and these can be used to better understand VIU and drive behavior conducive to better segregation of scrap based on these parameters.
- **Steelmakers must also work more closely with scrap processors to segregate lower-residual, high-value scrap** and to reduce the blending of lower-grade materials into the “cleaner” scrap. This will likely mean that the pricing structure of various scrap types will show greater separation related to residual content. Essentially steelmakers will have to pay more to maintain the availability of cleaner scrap grades. At the same time, though, there needs to be an economic incentive for scrap processors to do a better job of free copper removal and for vehicle manufacturers to design vehicles for easier free copper removal.
- **Technologies that can economically reduce the amount of free copper in scrap must be improved** and applied universally to slow the rise of copper (and other deleterious) residual levels in steel scrap.
- **Scrap and slag models can be highly effective for tracking scrap quality** and need to be applied to gain a better understanding of scrap properties.
- **Scrap processing at the steel plant site is a highly effective method to remove dirt** which will improve operating costs, improve Fe yield, reduce flux and energy consumption and reduce the carbon footprint of EAF steelmaking.
- **Better tracking of C, Si and Al levels in scrap** in order to understand the impact on acid slag components, the start of FeO generation and thus the start of slag foaming (i.e. the chronological timing of these processes in the EAF).
- **The availability of “prime” scrap is shrinking** in many of the mature economies as manufacturers become more efficient and generate lower quantities of scrap. In addition, as steel technology evolves (such as advanced

high-strength steels), **the quantity of steel being used in vehicles is also shrinking.**

- **Raw materials markets are very dynamic so solutions will not be a “one size fits all”.** Approach the various options with an open mind and position the correct tools in order to adjust feedstock strategy rapidly as conditions change.

3 EAF operations – past & present

An overview of the energy input to the EAF



3.1 Forms of fossil fuel energy in the EAF

Energy input to the EAF process takes two forms - electrical energy input and chemical energy input.

Chemical energy input is provided by the following unit operations:

- Natural gas combustion with oxygen (oxy-fuel burner).
- Oxygen bath reactions necessary to refine the steel - C, P, Si, Al - these are deliberate.
- Oxygen bath reactions that occur as a consequence of refining - Fe, Mn - these are a consequence of the thermodynamics associated with oxygen injection into the steel bath.
- Carbon reduction of FeO in the slag which is an endothermic reaction. This reaction contributes to slag "foaming" which helps to contain the electric arc and greatly enhances energy efficiency.
- Graphite electrode oxidation and tip sublimation.

It is important to recognize the historical evolution of EAF operations with respect to the use of fossil fuel energies. Initially a small amount of oxygen was injected to "refine" the steel once the heat had fully melted in (Flat bath). Refining allowed for impurity elements such as phosphorus, silicon, aluminum and manganese to be removed from the steel. The bulk of the oxygen addition, however, was used to adjust the carbon content of the steel prior to tapping the heat into a ladle.

Historically, the amount of oxygen used for refining was in the range of 5.8 to 8.7 Nm³/tonne liquid steel (200 - 300 scf/ton liquid steel). In the 1980s, transformer sizes were somewhat limited and in order to increase the input rate of energy to the EAF, some operations began to charge additional carbon and to generate chemical energy in the EAF by reacting the carbon with oxygen. Thus, it was possible to add both electrical and chemical energy to the process concurrently.

In the mid-1980s the concept of foamy slag evolved from the use of DRI in the EAF. It was recognized that under the proper conditions, CO evolution in the steel bath and at the bath slag interface would result in the slag foaming up to as much as 3 times the volume of un-foamed slag. It was observed that this phenomenon resulted in much better containment of the electrical arc leading to better arc stability and a large improvement in the efficiency of energy transfer to the steel bath. Slag foaming was a natural result of DRI use in the EAF because this material contains carbon and unreduced iron (FeO). As the material melts in the slag, CO gas bubbles are evolved, and the slag foams. A study of this mechanism led to greater levels of oxygen injection in the EAF coupled with the injection of carbon in order to artificially foam the slag and achieve the associated benefits.

As EAF operations continued to evolve and tap-to-tap times became shorter and shorter, it was recognized that there were “cold spots” in the EAF where scrap did not melt in as rapidly as other sectors of the EAF. As a result, even though the bulk of the material in the EAF was molten, the tap-to-tap time was extended in order to melt the scrap in these cold spots. This led to increased cycle times, reduction in productivity, over-heating of the bath and an overall reduction in energy efficiency. Oxy-fuel burners were implemented in the EAF to accelerate scrap melting in the cold spots. Even though the total energy used for this purpose was relatively small, the impact on high efficiency melting operations was huge.

Prior to these advancements in EAF technology, chemical energy provided approximately 15 - 20 % of the net energy input to the EAF. Following the implementation of injection of large quantities of oxygen in the EAF, the net contribution of chemical energy to the EAF grew to 40 % and in some extreme cases represented 50 - 60 %. As the generation of gases inside the EAF increased, EAF productivity also increased, but at the cost of energy efficiency because the energy lost to the off-gases also increased considerably. In modern, high productivity EAF operations, it is not uncommon for energy losses to the off-gas to be between 30 - 50 % of the total equivalent energy input to the EAF.

4 EAF operations – future challenges

Evaluation of the sources of CO₂ in EAF operations
and how to reduce them



The most logical approach to reduction of the EAF carbon footprint is to evaluate the various sources of CO₂ in EAF operations and then determine how fossil fuels associated with that function can be substituted or reduced without negatively impacting on the efficiency of the process.

4.1 Slag foaming - arc containment

Slag foaming has been shown to be one of the most important technological advancements in EAF steelmaking. While poor arc coverage can result in a heat transfer efficiency of 50 - 70 %, good arc containment can result in electrical efficiency as high as 93 % in the EAF. A completely submerged arc as experienced in some smelting operations achieves an efficiency close to 100%. Good arc containment is most important when the EAF is operating at flat bath conditions. During the initial stages of scrap melting, the arc tends to be contained by the scrap. For operations that operate at flat bath throughout the tap-to-tap cycle, arc containment is critical to efficient operation.

For most operations, slag foaming is the most effective way to increase the slag depth and contain the arc. However, it is important to note that this is not the only option. If the slag depth is sufficient to contain the electric arc, it may not be necessary to foam the slag. This requires that the EAF be designed to carry over a larger slag volume and brings with it some additional challenges.

Additional challenges from EAF's carrying over a larger slag volume include:

- It may prove more difficult to dephosphorize the steel
- The larger slag volume will require additional energy to heat it to steelmaking temperatures. The energy contained in a tonne of EAF slag is approximately 740 kWh/tonne. If the slag volume in an EAF is doubled, the energy requirement may increase by as much as 60 - 80 kWh/tonne liquid steel
- Greater slag volume may impact slag carry-over to the ladle during tapping
- Skull formation in the EAF may become an issue especially if there are "cold spots" in the EAF

If the gangue content in DRI/HBI increases due to a shortage of low gangue DR pellet feedstock (i.e. resulting in the use of lower grade iron ore pellets), the resulting increase in slag volume may actually be complementary to the modified EAF operation. However, if the pellets have high phosphorus levels, a significant problem arises as without sufficient FeO in the slag coupled with high slag basicity, it may not be possible to lower phosphorus levels in the steel to acceptable levels. If oxygen usage is limited, it may prove necessary to dose the slag with mill scale or iron ore fines in order to provide sufficient FeO to promote phosphorus removal.

One of the biggest challenges associated with greater slag volumes is the potential for Fe yield loss to the slag. If the EAF is designed to hold more carry-over slag, this is less of an issue. Some operations in the past have added mill scale to the slag in order to reduce Fe yield loss. To control Fe Yield loss, it is critical to maintain strict end-point control. If a heat is over-blown with oxygen and has a large slag volume, yield losses will be much greater. Of course, if oxygen use in the EAF is drastically reduced, Fe yield loss to the slag becomes less of an issue.

Slag foaming is also highly beneficial for efficient utilization of injected gases and solids in the EAF. Elimination of slag foaming might result in greater process inefficiencies and lower recoveries.



EAF operation with a very deep slag layer may also create problems with roof feeding of raw materials such as DRI, HBI, GPI⁴ and fluxes. In order to promote rapid melting and Fe recovery to the bath, it may prove necessary to operate at lower slag basicity and/or to modify the slag to reduce viscosity and promote Fe drainage to the bath. Once again, if materials contain high levels of phosphorus, high Fe yield losses are likely to occur and operation at low slag basicity may not be possible.

Many EAF operators disregard the impact of gangue and dirt on the carbon footprint of their EAF operations. The greater the amount of dirt/gangue associated with scrap/OBMs, the greater the amount of metallic feedstock that

⁴ Granulated Pig Iron

must be charged to the EAF to produce a given weight of liquid steel product. Of greater concern is the fact that greater dirt/gangue content requires greater additions of basic fluxes (lime, dolo-lime) to the EAF. Even though the lime/dolo-lime does not contribute to CO₂ emissions at the steel plant level, the production of lime/dolo-lime from limestone/dolomitic limestone is a major source of CO₂ emissions and must be addressed at some point, as such an issue outside the scope of this paper. The combined impact of higher dirt/gangue levels on Fe yield, flux requirements, energy consumption, etc. can have a considerable impact on the carbon footprint of steelmaking and must be addressed as soon as possible.

Currently, high productivity EAF operations use 10 - 20 kg/tonne liquid steel of injected carbon. This contributes 37 - 74 kg CO₂ per tonne of liquid steel.

Several options exist for substitution of the injection carbon. Recycled plastic has been demonstrated as a slag foaming agent in EAF operations worldwide. The main issues with this technology include proper segregation of waste plastics (based on content) to ensure that dangerous by-products (such as dioxins/furans) are not generated in the EAF and the fact that the plastics tend to break down very quickly when injected into the EAF. This creates a problem with the ability to generate a sustained release of CO gas bubbles to foam the slag. The rapid thermal breakdown of the plastics tends to result in a surge of CO evolution which is not beneficial for good slag foaming operations. As a result, recycled plastic is typically used to replace 20 - 35 % of the injection carbon.

Another possibility is to replace injection carbon with biomass. In order to be effective as a slag foaming agent, it is necessary that the biomass be converted to biochar. In the past, some EAF operations have utilized charcoal made from roasted coconut shells as an effective slag foaming agent. Other waste biomass sources may prove suitable. The key to good slag foaming operations will depend on achieving the correct sizing and density of these materials coupled with a rate of thermal breakdown that allows for sustained generation of CO gas to foam the slag.

In the case of recycled plastics and biochar, much work needs to be completed to determine optimum sizing and properties to provide high recovery rates and sustained slag foaming.

A major challenge for bio-carbon utilization in the EAF is the fact that bio-materials tend to have very high water content. Therefore, the moisture must be removed prior to utilization of such material in the EAF process. The cost of the energy required to remove the moisture may impact the economic viability of using such materials. In addition, some potential sources of bio-carbon may contain phosphorus, nitrogen or sulfur which would be detrimental to the

steelmaking process. It will be important to fully understand the various bio-material sources to find those best suited to produce bio-carbon. In order for bio-carbon to be truly carbon neutral, the rate of generation (plant growth) must match the rate of consumption. It remains to be seen whether this balance can be maintained.

Slag viscosity potentially poses an issue for feeding DRI/HBI through the furnace roof. A well foamed slag will allow penetration of the roof fed materials into the slag where melting can take place. If instead, more slag mass is used as the means of containing the arc, higher Fe losses may occur. In addition, if oxygen utilization is reduced, FeO levels in the slag may not be high enough to provide a fluid slag. Roof feed rates may be limited and DRI/HBI may build up on top of the slag leading to late melting of the material and potential yield losses to the off-gas system.

4.2 Need for auxiliary energy

In order to ensure even melting of the scrap in the EAF, it will be necessary to provide some form of energy input in the furnace cold spots. The simplest solution would be to substitute the natural gas currently used in the EAF. The possible "green" substitute fuels could include hydrogen, ammonia, biogas, syngas, coal gas or gas from municipal solid waste.

Ammonia would essentially be an option to use hydrogen as the fuel but with the benefits that ammonia is much safer and more stable than hydrogen gas and can be transported and stored more easily. However, the burner would need to be designed to minimize NO_x formation as high NO_x levels could eliminate the benefits of reduced CO₂ emissions.

Another option would be to utilize a non-transferred arc plasma torch to input energy to the cold spots. This technology has been implemented in the past to heat steel in the casting tundish. The cost of a plasma torch is typically much higher than that of a burner with the same thermal rating, but plasma technology has the advantage that it is electricity based.

4.3 The role of oxygen in low C steelmaking

Currently, oxygen performs several functions in the EAF - in the past 25 years, it has become a major source of energy to the EAF process. However, secondary functions include the promotion of slag foaming via reaction products and the refining of the steel which is a metallurgical function.

The metallurgical function of refining cannot be eliminated in the EAF. In the early days of EAF steelmaking, this function was shown to require 5.8 to 8.7 Nm³/tonne liquid steel (200 - 300 scf/ton liquid steel). Elements "refined" from the steel

would include phosphorus, silicon, aluminum, manganese and a small amount of carbon.

Another function of oxygen injection in the EAF is to promote mixing of the steel bath. This aids with respect to more uniform and rapid melting of the steel scrap and is especially important with respect to roof fed materials such as DRI, HBI and GPI. It has been found empirically that oxygen injection directed near the impact point of roof fed materials on the surface of the bath is critical to maintaining fast feed rates and melting of these materials. Alternatively, a form of bath stirring could be employed (either gas based or electromagnetic), but it is difficult to focus bath stirring on a specific location and it is not generally considered that bath stirring would provide a benefit similar to oxygen injection.

Another alternative would be to direct the roof fed material through multiple feed points so that the material is introduced at multiple points in the furnace leading to both an accelerated total feed rate and accelerated melting of the material.

Oxygen reaction with carbon in the steel bath also provides a means of removing dissolved nitrogen and hydrogen from the steel. If the amount of CO generation in the steel bath is limited, the result may be higher dissolved nitrogen levels in the tapped steel. This can be addressed through additional processing of the steel in a degasser downstream but for some grades requiring extremely low nitrogen levels (< 25 ppm), it may prove difficult to meet the required specification.

4.4 Low C scrap melting

Many of the projections for future carbon neutral steelmaking call for utilization of DRI/HBI produced via hydrogen reduction. There is no doubt that some form of OBM will be required in order to enable scrap recycling as more and more obsolete scrap is recovered. Fully hydrogen based DRI/HBI would have zero carbon content. If some natural gas was utilized in the reduction process, the material might contain up to 1 % carbon.

If the material contains zero carbon, the melting temperature will be higher than for C-bearing feedstock. This might result in greater power requirements for the EAF and extended power-on time.

In the past, zero carbon HBI was produced by Cleveland Cliffs in a facility based in Trinidad. Melting trials with this material showed that it melted quickly when layered with pig iron in the scrap bucket. The high level of carbon in the pig iron enabled faster and more complete melting of the zero-carbon material. However, in a low carbon EAF operation, this may pose an issue and it is likely that

continuous feeding rates through the roof for zero carbon HBI/DRI would be substantially lower than for C-bearing feedstock materials.

4.5 EAF design considerations

Based on some of the process changes identified in the previous sections of this paper, it can be seen that some changes to EAF design might also be required. One such change would be a deeper furnace bottom. This would be advantageous for greater slag carry-over from heat to heat and could also be beneficial if large quantities of DRI/HBI are fed through the roof. However, a means of mixing the roof fed material into the bath must be provided. This could be through gas/electromagnetic stirring or perhaps the injection of inert gas through a sidewall lance. Regardless, the EAF power consumption will increase.



As oxygen and fossil fuel utilization in the EAF is reduced, it may be possible to eliminate some water-cooled components, for example if the energy input is primarily electrical and is focused in the center of the furnace. However, this approach would have to balance concentration of energy in the center of the EAF with the formation of skulls and cold spots on the furnace circumference. It is possible that adjustments to the electrode pitch circle will be required to enable the correct balance.

If the primary form of energy input to the EAF is electricity, then several challenges arise. In the past, the utilization of chemical energy grew because it could be added to the EAF concurrent to the addition of electricity. This allowed shorter and shorter cycle times to be achieved. In the past, the limitation on electrical energy input was related to the possible size of the EAF transformer. In recent years, transformer sizes have increased considerably and are no longer the

bottleneck. However, if EAF operations in the future wish to retain tap-to-tap cycle times as low as 30 to 40 minutes, graphite electrodes must be capable of delivering power densities up to double the present requirements.

It seems likely that electrical power requirements will grow considerably in an EAF with low/no chemical energy use. The power requirement might grow to the range of 500 - 550 kWh/ton liquid steel. In order to maintain the same EAF cycle time, this would require that the power density in the EAF increase by 60 - 90 %. This will require stronger graphite electrodes and much bigger transformers. The physical properties of graphite electrodes may need to be adjusted. Grid requirements may limit the size of an EAF operation (a function of short circuit capacity (SCC) at the point of common coupling (PCC) and the amount of static Var compensation provided). This is of particular concern for current EAF operations. Many may already have maximized the size of their transformers based on the current SCC at the PCC. If this is the case, static Var compensation may be an option in the future or major upgrades to the grid may be required to allow for greater access to the active power (MW) required to maintain current productivity levels. The most advanced static Var compensation systems can provide correction on the quarter cycle. In the future, it may be necessary to provide correction on an even faster basis.

If greater slag retention is desired in future operations, the furnace bottom will need to be deeper to hold the slag and additional steel volume may also be required to provide slag free tapping. A deeper furnace bottom may also be beneficial to an operation where the bulk of the energy input to the process is electrical. However, as previously identified, some form of enhanced mixing would be required to keep the bath homogeneous.

As the EAF process evolves, there is a need for better process analysis tools coupled with advanced instrumentation to provide more complete and more timely information to control the process and rapidly identify the impact of process changes and equipment.

4.6 Impact on off-gas system

One of the big benefits of reducing the combustion of carbon in the EAF is that the amount of off-gas generation drops significantly. Depending on whether carbon is eliminated or substituted with biomass, the requirements for the off-gas system may change. Not only will the volume of off-gas be reduced but the energy content of the off-gas may also be much lower than conventional operations. In some cases, up to 50 % of the energy added to an EAF can be lost to the off-gas system as sensible and calorific heat. This has generated a lot of interest in energy recovery from the off-gas but this is a difficult task because the

energy content can vary by as much as 300 % through the entire tap-to-tap cycle. If off-gas generation and associated heat losses are reduced significantly in the EAF, off-gas heat recovery will not be necessary and will lead to higher overall EAF energy efficiency.

Lower gas velocity inside the EAF may make it easier to roof feed or inject finer materials without the risk of losses.

It is interesting to note that much of the current emphasis on de-carbonization of the steelmaking process is focused on process and equipment changes. Realistically, the carbon footprint of any EAF operation can be improved by about 20 % just through process optimization. A further 20 - 30 % improvement can be achieved through heat/energy recovery. Though both of these optimization opportunities have been explored in the past, they have never been adopted by the mainstream steel producers even though they offer potential payback periods of 2 to 5 years. They need to be re-visited to see what gains can be achieved in the near term.

5 Summary & conclusions

Summary points below are a catalyst for discussion, noting the importance of a structured approach to EAF evolution



This paper has been generated to provide a catalyst for discussion of future EAF operations. In some areas it has not been specific. This is because the basis to drive the EAF process is not well defined yet. It has been recognized that the EAF has a key role to play with regards to future “green steelmaking” activities, but most steelmakers are more focused on the “finish line” with respect to CO₂ emission reductions than they are on the steps that can be taken along the way to achieving these reductions. This paper has attempted to fill part of the knowledge gap and identify some of the questions that we should be asking sooner rather than later. Additional questions are sure to arise as we study the technical challenges and requirements. The paper is not intended to provide all of the answers at this point – rather it is intended to promote meaningful discussion aimed at providing robust solutions for the sustainability of steel production.

Summary:

- **Carbon can never be completely eliminated from steelmaking because steel is by definition an alloy of Fe and carbon.**
- **If chemical energy use in the EAF is minimized, the electrical power requirement will naturally increase.** Based on historic operating figures, it is expected that the requirement will be 500 – 550 kWh/ton. This would actually represent an efficiency improvement of about 10 – 15 % over current operations. However, based on some of the process options under consideration, the figure could end up closer to 600 kWh/ton.
- **The availability and specification of ferrous raw materials will be key to lowering the carbon footprint of the EAF.** As noted in a previous section, we must do a better job of segregating obsolete scrap and directing it back to the appropriate steelmaking facility to match the scrap residual content (e.g. routing recycled rebar back into rebar producing operations). It is hoped that some technologies will be developed to provide residual removal from scrap, but until this is possible, OBMs will be required to dilute residuals to the required product specifications. Better sorting and processing of scrap is also needed to remove free copper and retain the value of the scrap of higher quality scrap. The blending of various scrap types should only occur at the steel plant as necessary to meet product specifications.
- **In the future it is expected that most power generation will be renewable** and thus the largest source of CO₂ emission related to EAF operations will be eliminated. As a result, an increase in electrical power requirements becomes more about the electrical network configuration and whether the short circuit capacity at the point of common coupling can support the supply of the required amount of energy. The CO₂ footprint of power generation will no longer be an issue, and the challenges will be technical. For many existing EAF

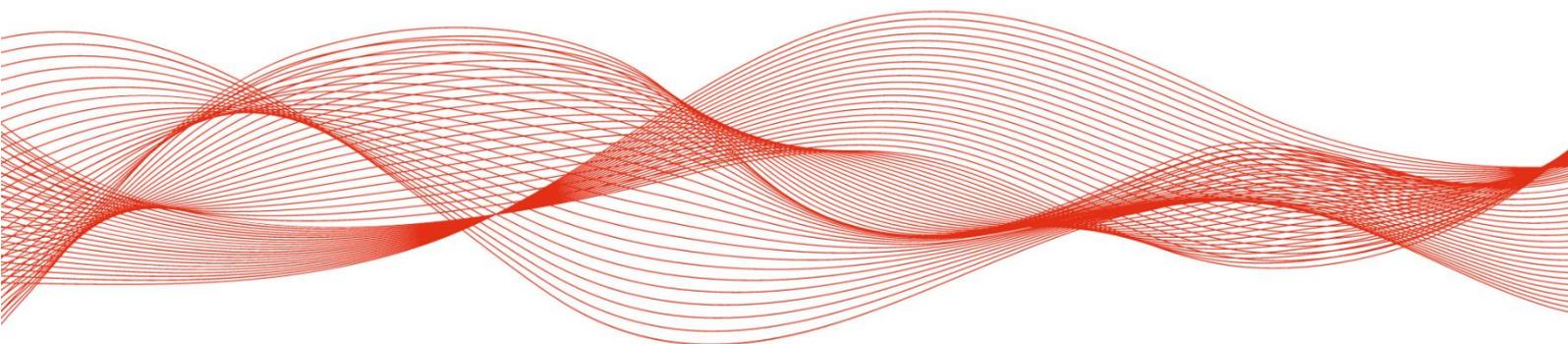
plants, this may require major upgrades to the electrical grid to meet process objectives.

- **Substitution for carbon with waste materials** (e.g., plastics) and biomass (bio-char, other plant waste) **may be feasible but does not actually reduce the carbon footprint of the EAF process unless the utilization rate in the EAF matches the generation rate.** In the case of most biomass, this is not the case. In the case of waste materials, it is better for society that these materials be consumed, though the resulting carbon footprint is real and perhaps this CO₂ could be classified under a different grouping (e.g., CO₂ emissions that provide a societal benefit - elimination of waste). Moisture removal from biomass prior to utilization as bio-carbon may result in a significant energy sink and contribute to process inefficiency.
- **Significant opportunities to reduce the carbon footprint of EAF steelmaking can be achieved in the near term through process optimization and the application of heat/energy recovery technologies in the steel plant.** The development and application of the appropriate process tools can greatly accelerate these improvements.
- **Optimum utilization of raw materials is imperative to reduce the carbon footprint of EAF steelmaking.** Fe yield is critical to this discussion. The evolution of the EAF cannot be considered in isolation to the raw material supply.
- **Several proactive steps must be taken in the short term to preserve the reservoir of higher quality scrap.** Failure to do so will impact negatively on any attempts to reduce the carbon footprint of EAF steelmaking.
- **Significant changes in power delivery to the EAF will likely be required in the near term as EAF operations transition to mostly electrical power input.** This may require upgrades to the electrical grid, the switchyard, the EAF transformer and even to graphite electrodes.
- Currently most steelmaking operations are focused on Scope 1 and to a lesser extent Scope 2 emissions. **The steelmaker must be aware of potentially large Scope 3 emissions associated with raw materials.** For the steelmaker, fluxes, Fe metallics and even logistics can contribute significantly to Scope 3 emissions, and these may significantly impact the process technologies utilized in the future.

Without a doubt, there are many possible innovations that will occur to the EAF process. **It is important that we follow a structured approach to the evolution of the EAF process:**

1. The first step is to understand material inputs to the process and their associated CO₂ emissions.

2. Step 2 involves material substitutions implemented in a manner that does not impact EAF efficiency and productivity.
3. Evaluate the need for physical changes to the EAF and associated auxiliary equipment to accommodate the desired process changes
4. Continue to strive for better efficiency through process evaluation and optimization. Identify opportunities for optimization and for energy recovery.
5. Improve instrumentation and data collection to improve understanding of the process. There is a great need to further embrace digitization and develop new instrumentation accordingly.
6. Develop better process feedback tools to identify the impact of changes more rapidly and completely.
7. Keep an open mind and evaluate opportunities based on their merits (or demerits as the case may be).



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