Optimization of Fe Feedstocks for EAF Steelmaking

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ABSTRACT

Much attention is being paid to EAF technology as a means of achieving lower carbon footprint steelmaking. The single largest cost in EAF steelmaking is steel scrap. At the same time, scrap has the largest impact on Scope 2 and Scope 3 CO2 emissions. CIX has been exploring the impact of scrap quality for several years utilizing a value-in-use model and has previously published data on the impact of scrap dirt levels on CO2 footprint and EAF operating costs. As some countries put pressure on the steel industry to recycle more scrap, it becomes apparent that recycle is maximized when the cleanest recycle stream is made available.

Recently, CIX has collaborated with several industrial partners to quantify the benefits of upgrading scrap quality including impact on operating cost, steel plant productivity, CO2 footprint and steel quality. Through actual examples and analysis of scrap processing trials, this paper will show that scrap quality can be improved economically and that this is the natural evolution of scrap processing operations. Case studies will focus on upgrading shredded scrap and heavy melt scrap.

Keywords: Steel scrap, Scrap quality, Scrap optimization

INTRODUCTION

EAF technology has been identified 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. Many steelmakers are considering a process path consisting of direct reduction followed by the EAF. However, the availability of high-grade iron ore to support this transition is in question. 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 (OBM) 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. To utilize raw materials more effectively, the steelmaker needs to have a better understanding of the raw material properties. Fundamentally, the steelmaker wants Fe units, everything else other than alloys has no real benefit to the steelmaking operation. Ultimately, as will be shown in this paper, scrap quality is integral to controlling carbon footprint, improving circularity and providing a sustainable steel industry.

As we explore the availability of scrap and OBMs to feed the steel industry, it becomes apparent that OBM demand is directly tied to scrap quality. The ability to upgrade scrap quality has been explored in the past but the common consensus of the steel industry has been that this is uneconomical.

SCRAP QUALITY AND ITS' IMPACT ON STEELMAKING

Scrap Projections to 2050

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.

However, projections of scrap quality indicate that obsolete scrap may achieve an average copper level of 0.5 wt.% by 2050. Thus, while scrap availability is not likely to be an issue, scrap quality will be. Some of the challenges for steel scrap are summarized in figure 1. Those shown in green are issues which already have technical solutions available.

Figure 1: Challenges to EAF operations regarding scrap

Steel residuals refer to elements such as Cu, Ni, Sn and Mo (and to a lesser extent Cr) that cannot be refined (removed) from the steel. These elements become more concentrated as steel scrap is recycled. They 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 products limit the concentration of these residuals in the steel in order to meet the product requirements (see figure 2). Copper is usually the residual that is most closely tracked as an indicator of scrap quality.

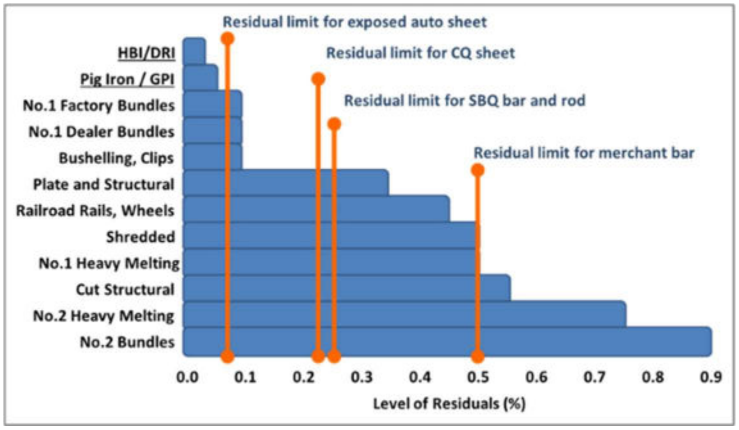


Figure 2: Residual levels by commodity and product requirement

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 - OBMs enable the circular economy for steel. Without OBMs in the scrap mix, a significant portion of steel scrap will become impossible to recycle and will be destined for land fill. It is very clear that as an industry, we must do a better job of segregating scrap based on its physical and chemical properties in order to achieve a circular economy for steel scrap while also minimizing utilization of virgin materials.

In the last 10 years, co-mingling of different scrap types has become more common and 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 is a form of “residual leakage” whereby residual levels in recycled scrap rise at an accelerated rate, reducing the scrap quality. This inherently drives the steel producer to greater use of OBMs to dilute residual levels to achieve the necessary steel product specifications. The industry needs better scrap definitions so that the steelmaker can make optimum use of the recycled material.

If on average obsolete scrap contains 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.

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. Shredders are a top offender with respect to the aforementioned comingling of end-of-life scrap streams. 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 have diminished utility because of the high degree of variability in the various scrap grades which is not captured in their reporting.

Circularity/Sustainability

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 (from electronics, wiring harness, battery, safety system, radio, computer, and within the starters and alternators) which needs to be removed in order to maintain the value of the recycled auto scrap. This free copper has an economic value and should 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. More free copper can be removed by repeated shredding and magnetic separation, and by enhanced equipment maintenance. Recently Nucor and SDI are producing shredded scrap with 0.16 wt. % Cu. 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.

Clearly greater effort must be made to separate free copper. The issue will be more critical with electric vehicles where copper content is 3 - 6 times that of a conventional automobile. Circularity is not achieved through recycle alone. Much more thought needs to go into designing steel products to ensure that copper and other bulk residuals can be removed easily prior to recycling of these products at their end of life. True circularity requires manufacturers to take responsibility for end of life for their products. Manufacturers need to design so that at end of life, the best possible segregation of recycle streams can be achieved. To maximize recycling rates, the material being recycled must minimize the content of extraneous materials. This would improve the value of recycled material while also reducing CO2 footprint and promoting sustainability. A recycled stream of lower copper scrap would decrease the need for OBMs, though it is clear that for steel grades requiring very low levels of residuals, the most practical solution currently is to dilute residuals through addition of OBMs. OBMs enable the recycle of scrap that otherwise might not have a commercially viable use.

Figure 3: EAF Operations must coordinate many tasks

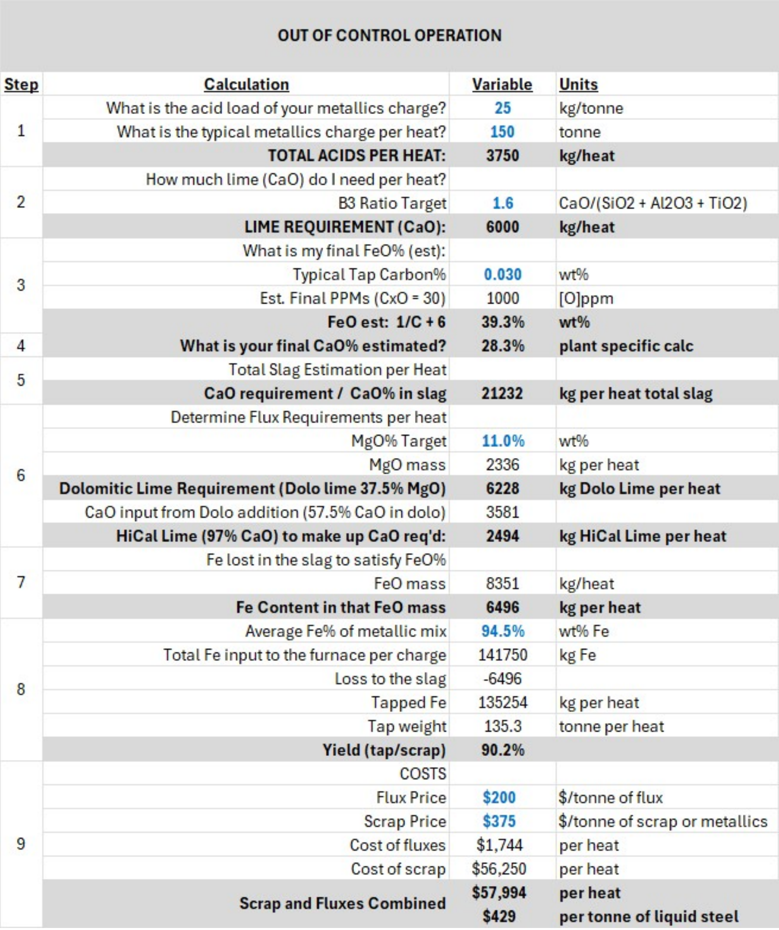
Scrap quality is integral to controlling both the carbon footprint and efficiency of steelmaking operations and every effort needs to be made to prevent "residual leakage" leading to lower quality scrap and inefficient utilization of the inherent value-in-use (VIU) of various scrap commodity streams.

Why we need to Improve Scrap Quality?

A major impediment to improving scrap quality is that very few steelmakers fully understand the impact of the extraneous materials in the scrap. In many cases, the EAF act primarily as a process for producing liquid steel from Ferrous feedstocks but the secondary function is one of an incinerator where plastics, oils, lubricants, wood and other combustible materials are burned. It is the combustion of these materials which places a much greater burden on the meltshop environmental systems.

Inclusion of non-ferrous metallics and stainless-steel lead to a rise in the residual content of the melted steel, resulting in a loss in value.

The production of steel results in three basic output streams: gas, slag and steel. The proportions of these products depend on the input materials chosen. The production of anything but steel is at the expense of the steelmaker. Carbon and moisture result in gas formation (including oil, wood, paint, plastic and other hydrocarbons). Silicon and aluminum oxidize and form what are referred to as the acid slag components Al2O3 and SiO2. Literal dirt contains mostly SiO2 and Al2O3. Ash from coal also contributes to the acid load of the raw materials input. Steelmakers must balance their slag basicity by adding a specific amount of lime for every specific mass of "dirt" or acids. This combination of dirt and lime will also contain a percentage of FeO that is in balance with the final carbon content of the steel bath that is required for that grade of steel being produced. The iron oxide in the final slag will be higher for lower carbon steel and lower for higher carbon steel. That iron oxide comes from either rust or oxides in your scrap or it is formed by reactions with injected oxygen, lowering the steelmaker's yield. Designing a slag is a relatively straightforward process, seen in figure 4:

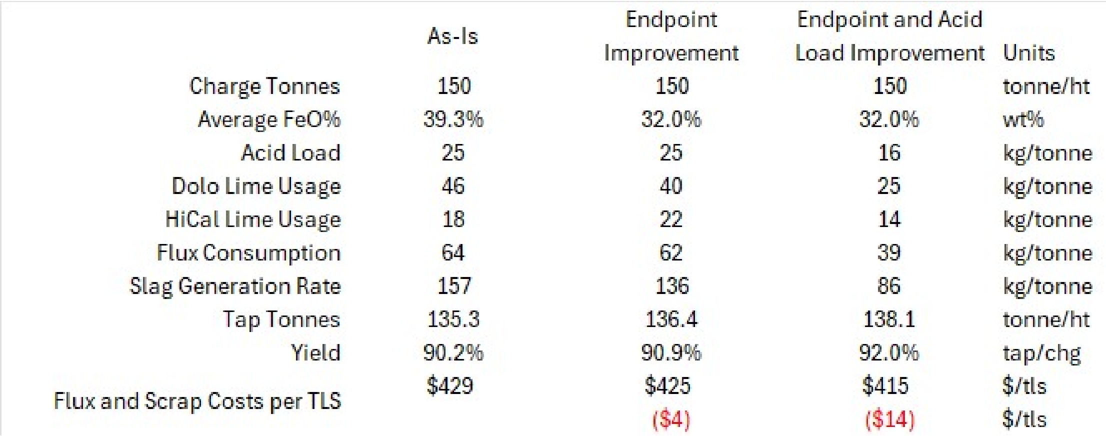


OUT OF CONTROL OPERATION

Step	Calculation	Variable	Units
1	What is the acid load of your metallics charge?	25	kg/tonne
	What is the typical metallics charge per heat?	150	tonne
	TOTAL ACIDS PER HEAT:	**3750**	**kg/heat**
2	How much lime (CaO) do I need per heat?		
	B3 Ratio Target	1.6	CaO/(SiO2 + Al2O3 + TiO2)
	LIME REQUIREMENT (CaO):	**6000**	**kg/heat**
3	What is my final FeO% (est):		
	Typical Tap Carbon%	0.030	wt%
	Est. Final PPMs (CxO = 30)	1000	[O]ppm
	FeO est: 1/C + 6	**39.3%**	**wt%**
4	**What is your final CaO% estimated?**	**28.3%**	**plant specific calc**
5	Total Slag Estimation per Heat		
	CaO requirement / CaO% in slag	**21232**	**kg per heat total slag**
6	Determine Flux Requirements per heat		
	MgO% Target	11.0%	wt%
	MgO mass	2336	kg per heat
	Dolomitic Lime Requirement (Dolo lime 37.5% MgO)	**6228**	**kg Dolo Lime per heat**
	CaO input from Dolo addition (57.5% CaO in dolo)	3581	
	HiCal Lime (97% CaO) to make up CaO req'd:	**2494**	**kg HiCal Lime per heat**
7	Fe lost in the slag to satisfy FeO%		
	FeO mass	8351	kg/heat
	Fe Content in that FeO mass	**6496**	**kg per heat**
8	Average Fe% of metallic mix	94.5%	wt% Fe
	Total Fe input to the furnace per charge	141750	kg Fe
	Loss to the slag	-6496	
	Tapped Fe	135254	kg per heat
	Tap weight	135.3	tonne per heat
	Yield (tap/scrap)	**90.2%**	
9	COSTS		
	Flux Price	$200	$/tonne of flux
	Scrap Price	$375	$/tonne of scrap or metallics
	Cost of fluxes	$1,744	per heat
	Cost of scrap	$56,250	per heat
	Scrap and Fluxes Combined	**$57,994** **$429**	**per heat** **per tonne of liquid steel**

Figure 4: estimated yield and flux impacts of melting endpoint carbon and scrap acid load

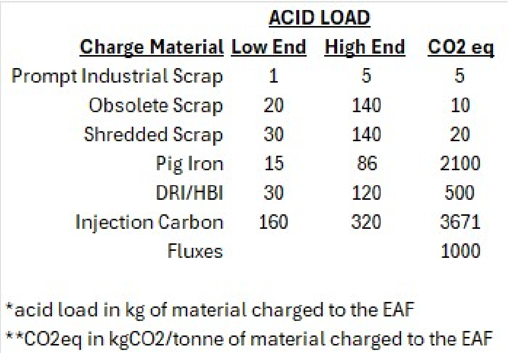
Using that crude, but effective, technique, one can demonstrate the effects of operations gaining control of their final bath condition (aka "endpoint control") and the powerful effect of operations and purchasing gaining control of the scrap acid content. The impact is staggering. Using the above operation, the effect of improving endpoint control and bringing FeO to about 32% would impact the operation to the tune of almost $4 per tonne of liquid steel. By further improving the acid load (reducing it from 25kg/tonne to 16kg/tonne), the operations would improve its cost by approximately $14/tonne of liquid steel! The cost impacts are enormous and are summarized in figure 5.



	As-Is	Endpoint Improvement	Endpoint and Acid Load Improvement	Units
Charge Tonnes	150	150	150	tonne/ht
Average FeO%	39.3%	32.0%	32.0%	wt%
Acid Load	25	25	16	kg/tonne
Dolo Lime Usage	46	40	25	kg/tonne
HiCal Lime Usage	18	22	14	kg/tonne
Flux Consumption	64	62	39	kg/tonne
Slag Generation Rate	157	136	86	kg/tonne
Tap Tonnes	135.3	136.4	138.1	tonne/ht
Yield	90.2%	90.9%	92.0%	tap/chg
Flux and Scrap Costs per TLS	$429	$425	$415	$/tls
		($4)	($14)	$/tls

Figure 5: Summary of a hypothetical operation improving endpoint control and scrap acid load

Reduction in acid load is paramount to achieving the potential savings. To reduce acid load, one must first track it and understand the sources. This seemingly simple statement is sadly not often done. Scrap inspection, lime-based mass balances of slag results, specification development with suppliers and periodic rejections and checks of actual delivered results are mandatory, but not always performed. Consider figure 6, which shows some potential impacts of generic charge materials:



	ACID LOAD		
Charge Material	**Low End**	**High End**	**CO2 eq**
Prompt Industrial Scrap	1	5	5
Obsolete Scrap	20	140	10
Shredded Scrap	30	140	20
Pig Iron	15	86	2100
DRI/HBI	30	120	500
Injection Carbon	160	320	3671
Fluxes			1000

*acid load in kg of material charged to the EAF

**CO2eq in kgCO2/tonne of material charged to the EAF

Figure 6: range of acid load contribution by commodity

The future will demand that acid contents of all raw materials are understood, controlled and even more importantly – beneficiated. Processes that can measure and or improve the acid load, prior to charging those materials into the EAF will become essential and valuable. Adding in the effect on a plant's CO2 footprint, with respect to calcined lime consumption can only stress this importance more. Limestone ($CaCO_3$) is calcined prior to EAF consumption. The basic definition of calcination involves driving CO_2 off of $CaCO_3$ to make CaO. The heat necessary to calcine lime is normally provided by methane combustion, or in some cases coal combustion. The mining and transportation of these energy sources only adds to the CO_2 equivalent passed on to the steelmaker. When, by definition, the steelmaker must add 1.6 tons of calcined lime to every ton of acids, the effects are common sense.

TECHNOLOGIES FOR SCRAP UPGRADING

CIX has worked with two different suppliers of scrap processing equipment. SICON GmbH supplies a wide range of scrap processing equipment. Gammatech provides technology to track the copper content of scrap as it is being processed. The methodology of the two companies differ, but the main consideration is that both companies are understand the concept of scrap upgrading and recognize the importance for steel sustainability.

SICON GmbH, offer a range of innovative and modular tools referred to as "Refining" and focus on grades E40 (Shredded Scrap), E46 (Shredded Scrap from incineration plants) and E1 (HMS 1/2). The range includes ScrapTuning®, EcoScan® Online, and HMS Cleaning Advanced.

The necessity for implementing such procedures in raw material preparation varies depending on the plant, location, and production program as described before mentioned. In general, the scrap mix is based upon subjective specifications and not objective, measured properties. AI-based predictive models for scrap quality work well if the steel scrap has no attached materials, copper wires, aluminum castings or weight reducing plastics. The limitations are obvious and the creativity of the scrap industry amazing. AI solutions can be used to support analysis coupled to a steel scrap blending facility.

The ScrapTuning® and HMS Cleaning Advanced tools pursue three main objectives:

a) Concentrating the metallic Fe.
b) Complete decontamination from inert materials, non-ferrous metals, non-metallic components, and composite materials,
c) Isolation and separation of steel scrap particles with high inherent residual content (Cu, Ni and Cr)

Sicon HMS Cleaning Advanced (figure 7), has proven effective in numerous steel plants to decontaminate sheared scrap. In its standard configuration, HMS Cleaning Advanced includes uniform dosing, screening, and iron separation. The cascading screening ensures that the shearing scrap is tumbled, enhancing decontamination. The isolated contaminants contain high-value non-ferrous metals, easily sold to recover operating costs.

Figure 7: HMS Cleaning Advanced, by Sicon

Current facilities with focus on magnetic separation are inefficient and require stronger magnetic fields with enough space to support effective separation of the magnetic from non-magnetic materials along with an efficient screening and material movement as well as acceleration. This approach increases efficiency to 99%.

The scrap sector often uses pressing operations to compact loose light gauge scrap into dense bundles. This increase in density reduces transport costs for the supplier and better basket density for the steelmaker. The downside is that contaminants cannot be removed, and the bundle's chemistry is unmeasurable. To resolve this issue, a newer configuration of HMS Cleaning Advanced includes a slow-running pre-shredder. The EcoRip® Neo, is part of the Sicon portfolio and specifically designed to address the challenges of scrap bundles. Delivering steel scrap at the desired densities, complete decontamination and the ability to analyse 100% of the raw material.

Pre-treatment with the EcoRip® Neo (figure 8) homogenizes shearing scrap and further improves cleaning efficiency. This process sequence increases the liquid steel yield in steel plants. An additional step is available for flat-steel producers, which is based upon an AI-based optical inspection, automatically sorting undesirable components. The AI and sorting algorithm are trained and optimized depending on production needs.

An essential and integral part of HMS Cleaning Advanced is the continuous mass balancing of material flow. This enables rapid supplier assessment, and a measurable control of quality. Precise data and traceability are preferable to visual inspection during unloading. Steel plants importing by sea can accurately process and measure scrap quality at a rate of 300 tph, allowing for complete deliveries to be cleaned and assessed during vessel discharge.

Figure 8: EcoRip®Neo for HMS Preprocessing

As previously noted, the copper content in scrap presents an increasing problem. **ScrapTuning®** for Shredded Scrap is designed to turn fluctuating supplier quality into a quality controlled raw material without the need for an in-house shredder. Shredded scrap is cleaned in multiple stages. Only magnetic separation stage using polishing magnets, is generally insufficient. Sicon have designed a magnetic cascade with innovative underflow separation, requiring an advanced magnetic design (MagSpin). This process is supported by an additional air separation stage, to isolate and recover the final light non-magnetic contaminants. Resulting in a melt Cu content of 0.12-0.16% in a standard case.

The leading German processor TSR GmbH has optimized its Ferrous Downstream further resulting in even better results which are shown below. TSR is marketing this quality as TSR 40 and is replacing significant portion of DRI / HBI by this certified quality. Their achievements are shown in figure 9.

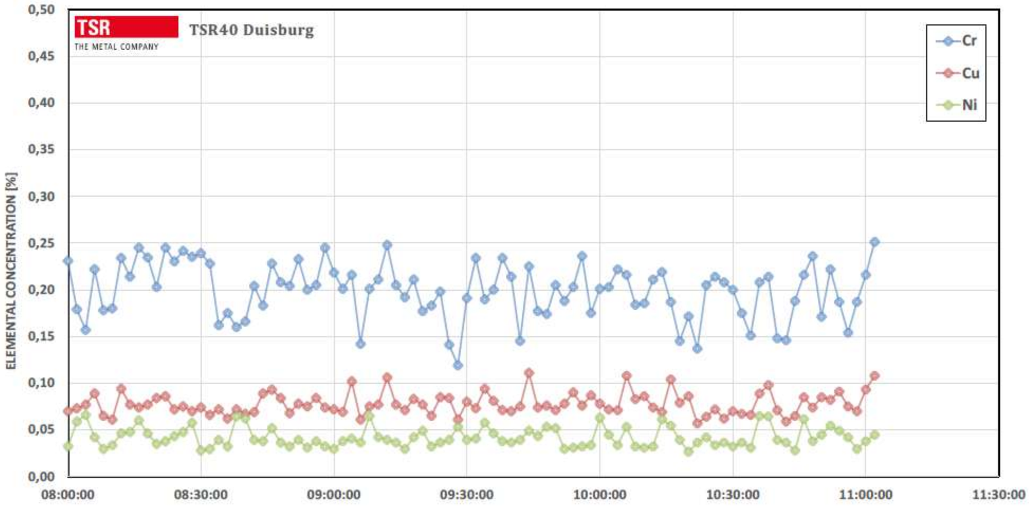
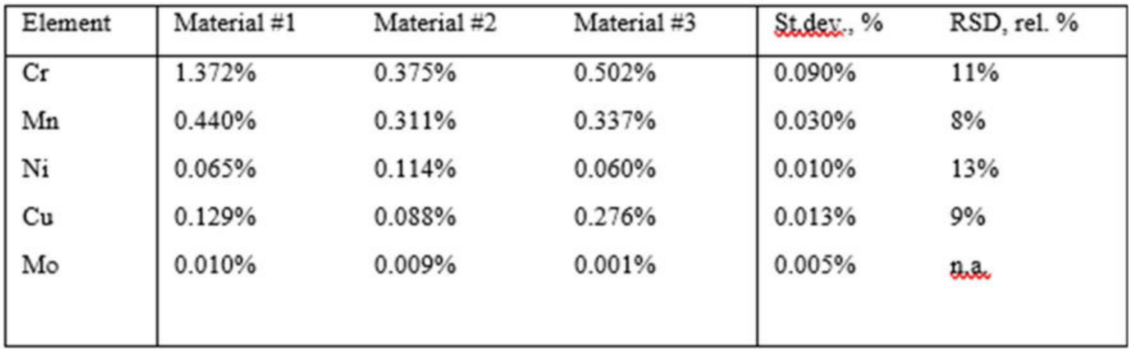


Figure 9: Exemplary copper levels att a TSR Facility, monitored by the EcoScan Online

The XRF (X-ray fluorescence) unit EcoScan® Online builds upon more than 20-year experience in online XRF analysis for various application types. EcoScan is designed with many application-special considerations in mind and is extremely reliable. The instrument may be operated in harsh environmental conditions and maintains its outstanding performance in a wide temperature range from -25 °C to +50 °C. The operating costs include only electricity and minor expendables.

The XRF unit irradiates the analyzed material and collects the composition-sensitive X-ray response. The data is then processed on a built-in computer and the analysis results are sent to the IoT system.

A typical application for steel scrap analysis produces elemental concentrations of Cu, Ni, Cr, Mn and Mo with relative accuracy of about 10% (see figure 10 for the actual results of the tests). Even though XRF is a surface analysis, validation tests on various installations have proven reliable determination of the scrap chemical composition.



Element	Material #1	Material #2	Material #3	St.dev., %	RSD, rel. %
Cr	1.372%	0.375%	0.502%	0.090%	11%
Mn	0.440%	0.311%	0.337%	0.030%	8%
Ni	0.065%	0.114%	0.060%	0.010%	13%
Cu	0.129%	0.088%	0.276%	0.013%	9%
Mo	0.010%	0.009%	0.001%	0.005%	n.a.

Figure 10: Three materials used to validate EcoScan performance

Capabilities at the Shredder:

Over the past 20 years more than 20M tons of shredded have been run through CrossBelt Recycled Metal (CB-RM) analyzers (see figure 11) and the results (figure 12) have shown shredded chemistries from a low of 0.15 Cu to a high of 0.56 Cu (see Figure 2). The CB-RM analyzer uses prompt gamma neutron activation analysis (PGNAA). PGNAA is a full-stream composite analysis technology that is distinctly different from sampling techniques used by XRF based systems

Figure 11: cross belt recycled metal analyzer (CB-RM)

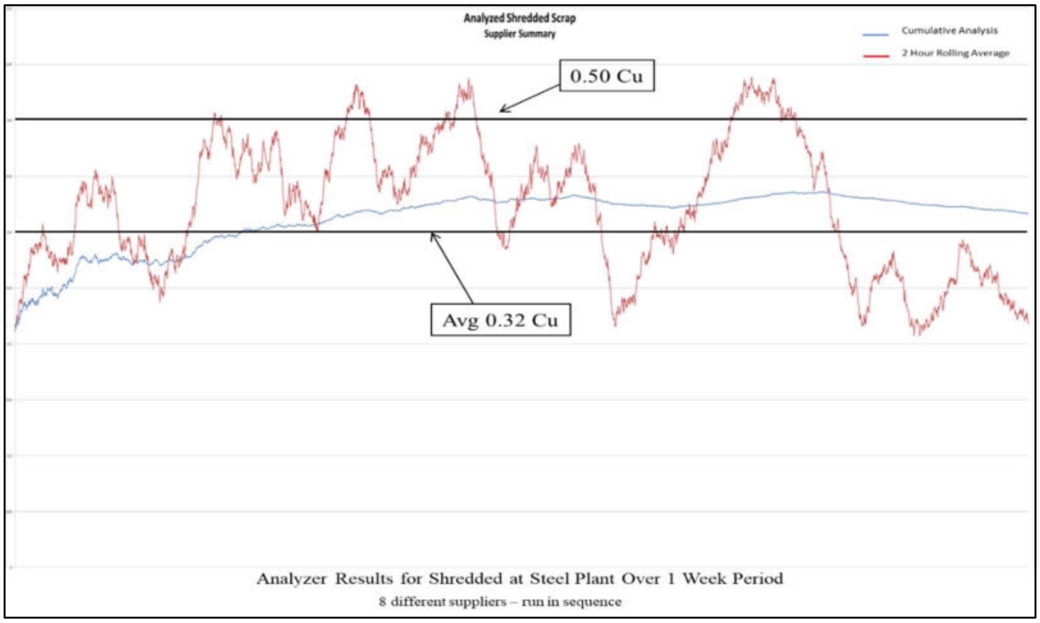


Figure 12: CB-RM Results

This high degree of variability in the ferrous shredded product is the result of many factors. While the authors of this paper are by no means shredder experts, it has been observed that factors such as feedstock, shredder mill grate and hammer patterns and wear characteristics, maintenance and replacement programs for these wear parts, drum magnet types and settings, and, to a lesser degree, the level of manual picking of copper contamination, all have significant influence on the final shredded quality and chemistry. Shredded density, which offers the opportunity for optimized magnet settings to remove the highest level on nonferrous metals has been seen as a key factor.

Without a real-time means to measure the chemistry of the product the variability exists in the finished product, the old adage of "you can't control what you don't measure" absolutely applies to the shredding process. Using the CB-RM analyzer in conjunction with a proprietary on-line density meter an operator can monitor and control the chemistry of the product they produce. The example in figure 13 shows what a shredder can achieve when moving from an unknow and out of control process to one of a well-controlled process. It has also been shown that when shredded with a density in excess of 85 lbs/cuft and a copper level below 0.25 % Cu is produced, the level of nonmetallic and nonferrous is also reduced by 3-7% which contributes to a higher yield and lower slag generation during melting at a steel mill.

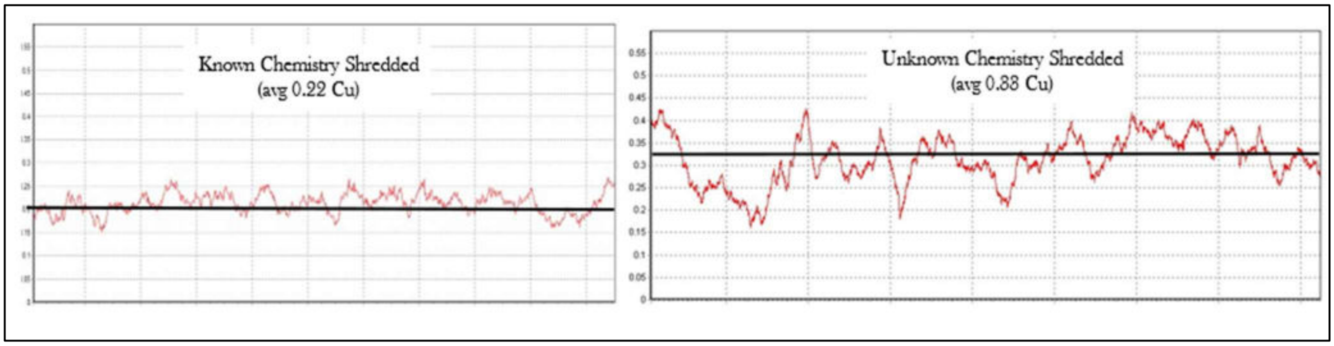


Figure 13: consistency tracked in known copper shredded vs unknown

HISTORICAL SCRAP UPGRADING RESULTS

We have previously shown the benefit of dirt removal from scrap. In fact CIX has been working with clients to remove dirt and copper from scrap for over 15 years. The following examples demonstrate the effectiveness of this approach.

Colakoglu

Colakoglu began working with one of the authors around 2010. After extensive analysis of the EAF operations and performance of a slag balance, it became very apparent that a lot of dirt was coming in with the scrap, especially imported scrap. The issue was exacerbated by the method of flux addition – flux was added in the scrap bucket and it was not possible to add sufficient basic flux to achieve good slag foaming. The EAF at Colakoglu is capable of reaching an active power of 220 MW when the arc is stable. It was decided that an effort would be made to reduce the dirt levels in the scrap. A slag based mass balance determined that the dirt levels averaged 3 to 4 % and occasionally reached levels as high as 7 %. Colakoglu implemented a series of vibrating conveyors and belts and managed to reduce the dirt level coming into the EAF to between 1 and 2 %. The payback on the equipment was less than 6 months.

Colakoglu also evaluated the free copper content in the imported scrap. Initially, Colakoglu employed pickers to walk the scrap yard and pick out visible pieces of copper bearing material. It was recognized that removal of copper reduced their dependence on local high quality scrap and the profit from selling the removed copper covered all costs of the pickers. Ultimately, Colakoglu implemented an automated system which showed very positive results.

Nucor/SDI results

Following the outbreak of the war between the Ukraine and Russia, the supply of pig iron int North America was significantly impacted. Both Nucor and Steel Dynamics embarked on programs aimed at improving the quality of shredded scrap to their steel mills. Both companies are fortunate in that they have vertically integrated scrap operations (Nucor – DJJ, SDI – OmniSource). Both companies have been able to produce shredded scrap with a copper content in the range of 0.16 – 0.17 wt.%. This has enabled both companies to significantly reduce their dependence on imported pig iron.

Arvedi results

Arvedi was another client of CIX which embarked on a program to optimize raw material inputs to the EAFs. Over a period of approximately 7 years, CIX worked with Arvedi's plant operations team to optimize EAF operations. A significant effort was placed on slag analysis and optimization of slag foaming. Arvedi operates the most productive ConSteel furnace in the world and an optimum slag practice was critical to achieving this. CIX worked with Arvedi to reduce dirt input to the EAF. In 2022, Arvedi started up one of the largest on-site shredder operations. At the same time, pickers were implemented to separate free copper from the processed material. Official results have not been published though it is rumored that Arvedi plans to install a second shredder at site.

Sicon is a supplier of scrap processing equipment. As part of their R&D program, they ran several trials aimed at upgrading heavy melt scrap. The results of these trials were analyzed in conjunction with CIX. The materials that were removed included wood, rocks, plastic, non-ferrous metals. If these materials had been charged to the EAF, the CO2 emissions would have been increased by ~ 200 kg/ton of scrap. The analysis showed that:

- Cu content was reduced by 0.15 wt. %
- Ni contents was reduced by 0.04 wt. %
- Cr content was reduced by 0.06 wt. %
- Pb was reduced by 0.03 wt. %
- P was reduced by 0.02 wt. %.

In addition, energy savings were projected at ~ 200 kWh/tonne of scrap. Clearly there is a significant opportunity to upgrade scrap quality and the costs of processing are greatly outweighed by the benefits.

Scrap upgrading at the steel plant

One of the emerging trends is for steelmakers to perform upgrading scrap at the steel plant. Historically, the pioneers in this approach were Colakoglu and Arvedi. However, more steel plant operations are now evaluating this approach, and it is a trend that is expected to grow in the future.

ECONOMICS OF SCRAP UPGRADING

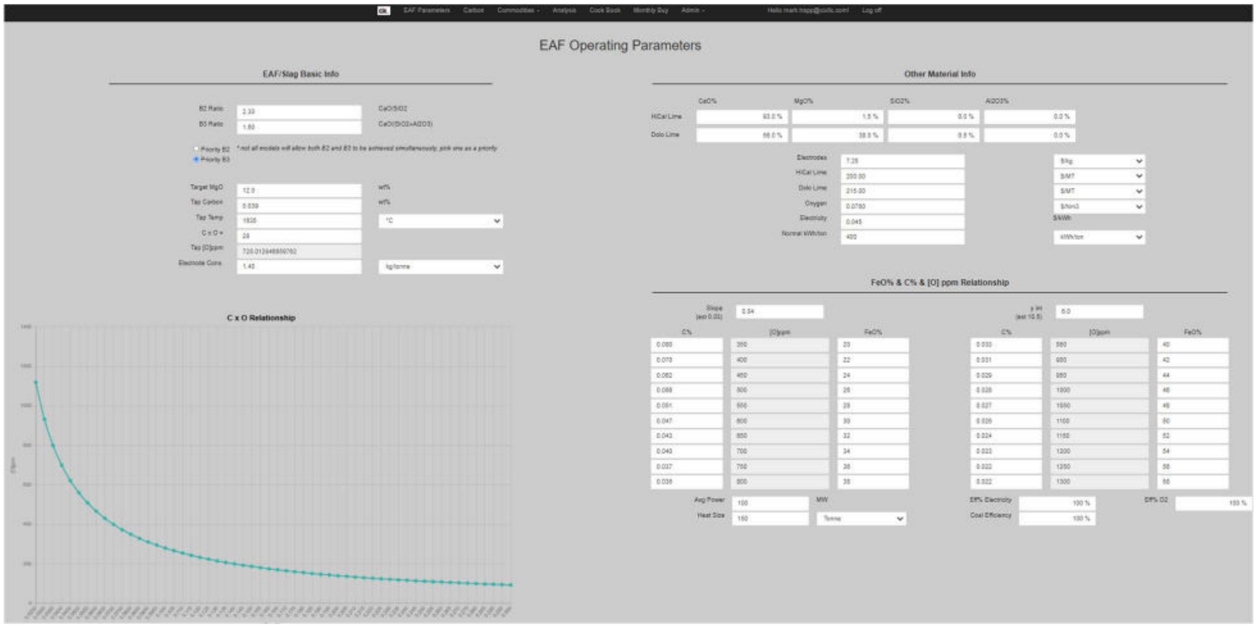
One of the major obstacles to upgrading scrap quality is the argument that the costs will outweigh the benefits. CIX has resolved this conundrum through the development of a value-in-use model that allows for detailed evaluation of EAF feedstocks to track the benefits of higher quality raw materials. Coupled with equipment and operating costs supplied by equipment manufacturers, it is a relatively simple exercise to determine the cost benefits.

CIX VIU Model

CIX has been running a web-based value-in-use model (VIU) for several years now. The model has several user interfaces:

- An EAF characteristics page (figure 14), where the user can input their custom EAF parameters

    - Average power
    - Current electrode consumption
    - Utilities costs and flux composition and cost
    - Typical final bath carbon and temperature
    - Aim slag chemistry
- A carbon composition page (for charge carbon and injection carbon)
- A database of scrap types and ore based metallics
- A page allowing head-to-head comparisons of multiple commodities against each other on a per liquid ton cost basis (residuals not included in analysis) (figure 15)
- A “cookbook” page where the user can enter multiple recipes and calculate the liquid steel cost considering raw materials and utilities
    - If desired, the user can optimize the charge and find the least cost recipe within user defined boundaries
    - The optimized recipe can find the least cost charge mix that meets both copper level maximums and power on time maximums
- A monthly buy page where the user can enter the number of heats to be made using the customized, named recipes and calculate inventory levels needed and the required purchase volumes
- At an extra cost, with needed VPN access and integration costs, the user can run live regression analysis, by pile ID, on residuals based on real melt chemistry data and recipe data. (figure 16)



EAF Operating Parameters

EAF/Slag Basic Info

B2 Ratio 2.33 CaO/SiO2
B3 Ratio 1.60 CaO/(SiO2+Al2O3)

○ Priority B2
● Priority B3

*not all models will allow both B2 and B3 to be achieved simultaneously, pick one as a priority

Target MgO 12.0 wt%
Tap Carbon 0.039 wt%
Tap Temp 1635 °C
C x O = 28
Tap [O]ppm 720.0128488590762
Electrode Cons 1.40 kg/tonne

C x O Relationship

Other Material Info

	CaO%	MgO%	SiO2%	Al2O3%
HiCal Lime	93.0 %	1.5 %	0.0 %	0.0 %
Dolo Lime	58.0 %	38.0 %	0.0 %	0.0 %

Electrodes 7.28 $/kg
HiCal Lime 200.00 $/MT
Dolo Lime 215.00 $/MT
Oxygen 0.0780 $/Nm3
Electricity 0.045 $/kWh
Normal kWh/ton 400 kWh/ton

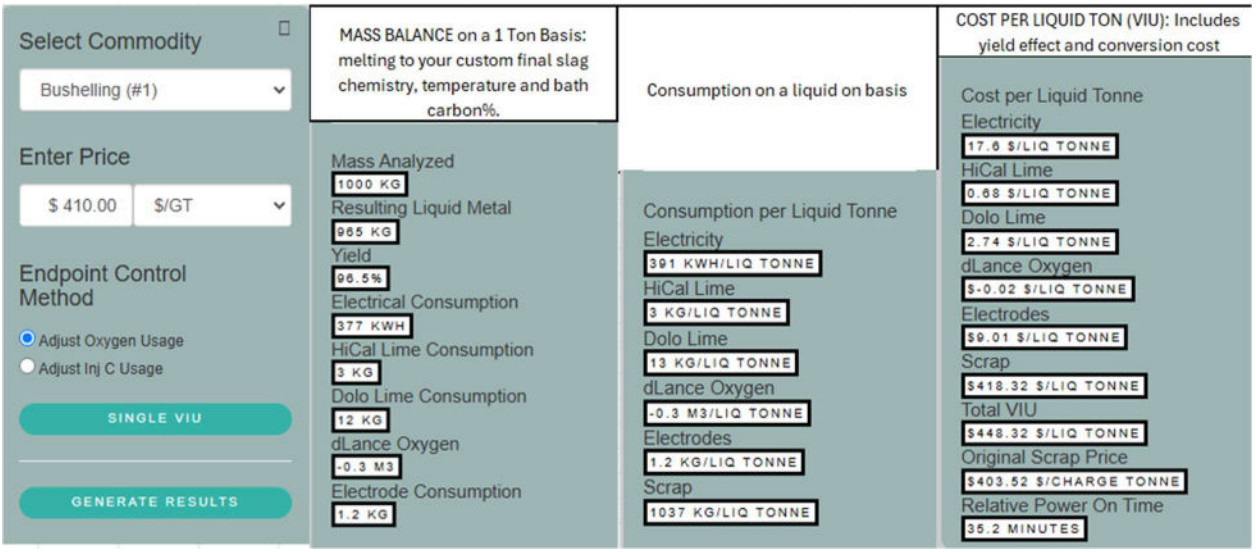
FeO% & C% & [O] ppm Relationship

Slope (est 0.03) 0.04
y int (est 13.5) 6.0

C%	[O]ppm	FeO%	C%	[O]ppm	FeO%
0.080	350	20	0.033	860	40
0.070	400	22	0.031	900	42
0.062	450	24	0.029	950	44
0.056	500	26	0.028	1000	46
0.051	550	28	0.027	1050	48
0.047	600	30	0.025	1100	50
0.043	650	32	0.024	1150	52
0.040	700	34	0.023	1200	54
0.037	750	36	0.022	1250	56
0.035	800	38	0.022	1300	58

Avg Power 100 MW
Heat Size 150 Tonne
Eff% Electricity 100 %
Coal Efficiency 100 %
Eff% O2 100 %

Figure 14: User customizable EAF parameters page: allows customizable slag chemistry, endpoint and pricing of utilities



Select Commodity: Bushelling (#1)

Enter Price: $ 410.00 $/GT

Endpoint Control Method

● Adjust Oxygen Usage
○ Adjust Inj C Usage

MASS BALANCE on a 1 Ton Basis: melting to your custom final slag chemistry, temperature and bath carbon%.

Mass Analyzed: 1000 KG
Resulting Liquid Metal: 965 KG
Yield: 96.5%
Electrical Consumption: 377 KWH
HiCal Lime Consumption: 3 KG
Dolo Lime Consumption: 12 KG
dLance Oxygen: -0.3 M3
Electrode Consumption: 1.2 KG

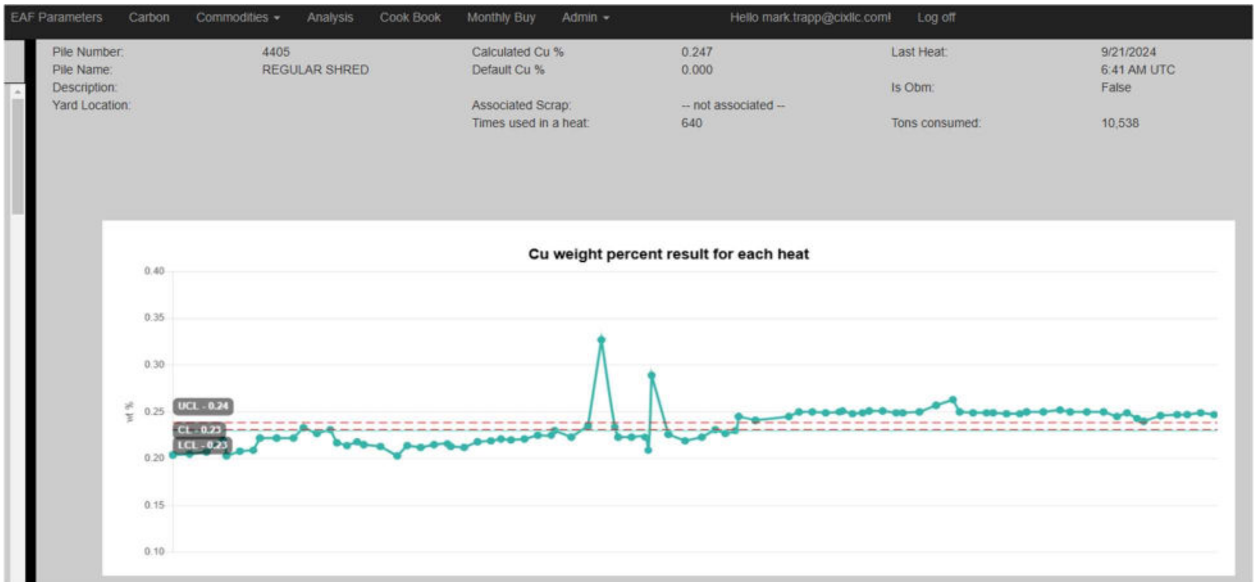
Consumption on a liquid on basis

Consumption per Liquid Tonne
Electricity: 391 KWH/LIQ TONNE
HiCal Lime: 3 KG/LIQ TONNE
Dolo Lime: 13 KG/LIQ TONNE
dLance Oxygen: -0.3 M3/LIQ TONNE
Electrodes: 1.2 KG/LIQ TONNE
Scrap: 1037 KG/LIQ TONNE

COST PER LIQUID TON (VIU): Includes yield effect and conversion cost

Cost per Liquid Tonne
Electricity: 17.6 $/LIQ TONNE
HiCal Lime: 0.68 $/LIQ TONNE
Dolo Lime: 2.74 $/LIQ TONNE
dLance Oxygen: $-0.02 $/LIQ TONNE
Electrodes: $9.01 $/LIQ TONNE
Scrap: $418.32 $/LIQ TONNE
Total VIU: $448.32 $/LIQ TONNE
Original Scrap Price: $403.52 $/CHARGE TONNE
Relative Power On Time: 35.2 MINUTES

Figure 15: head-to-head VIU comparisons of all commodities in the database. Can be used for VIU difference calculations or breakeven analysis



Pile Number: 4405
Pile Name: REGULAR SHRED
Description:
Yard Location:
Calculated Cu %: 0.247
Default Cu %: 0.000
Associated Scrap: -- not associated --
Times used in a heat: 640
Last Heat: 9/21/2024 6:41 AM UTC
Is Obm: False
Tons consumed: 10,538

Figure 16: Add-on regression analysis package. Requires a high level of scrap yard organization on the user's part and VPN access. This is not part of the standard package and requires integration work.

The VIU Model is a great tool that allows the user to manage optimization at the purchasing level, which is the level that really matters. Buying low value materials and spreading them out through the month to low levels does not mitigate the impact on costs. If something is purchased, it will eventually be consumed and the costs are incurred. It is better to buy the highest valued materials to yield the lowest cost liquid steel. The model could even be used to see a "what-if", for example: what would my liquid steel cost be if I were to increase my tap carbon by 0.01%?

The model comes with some standard commodities, but for the best results, the user needs to modify things such as gangue content, etc. to match their local scrap market. This might require some regression analysis or dead melting to fine tune the scrap characteristics. Also, if the live regression analysis is used, there is no way to avoid the fact that the recipe tracking and pile management must be well organized to get good results. This is common sense, best-practice for managing the largest cost of steelmaking, but sadly is not often commonly practiced!

CIX CO2 Footprint Model

The VIU model output, on a single commodity basis, lends itself to linkage to a CO2 footprint model, which outputs the CO2 equivalent (in kgCO2eq/tonne). For now, this add-on is only in Excel, but future plans include adding it to the web-based model. The intent of this model is to estimate the effect of the scrap recipe on the CO_2 intensity (aka CO_2 Footprint) of the liquid steel produced. It is not intended to be used for reporting to official agencies and is intended to be qualitative in nature, meaning the intent is not to create a perfect EAF model. It is designed to show the relative effect of one scrap recipe on another with respect to the CO_2 intensity. In this document, scrap is used interchangeably with ore-based materials (OBM's) at times. Scrap is generically used in this case to mean metallics charged into the EAF.

The model looks at the effects of the following scrap qualities/characteristics on the EAF process (figure 17):

- Acid content of the scrap
- Yield of the scrap
- Electricity requirement for the scrap
- Carbon content of the scrap
- Distance the scrap must travel to be received by the steel plant and mode of transportation.
- The natural gas or electricity used in the production of a particular scrap.
- The carbon footprint of the material (example: Pig Iron)

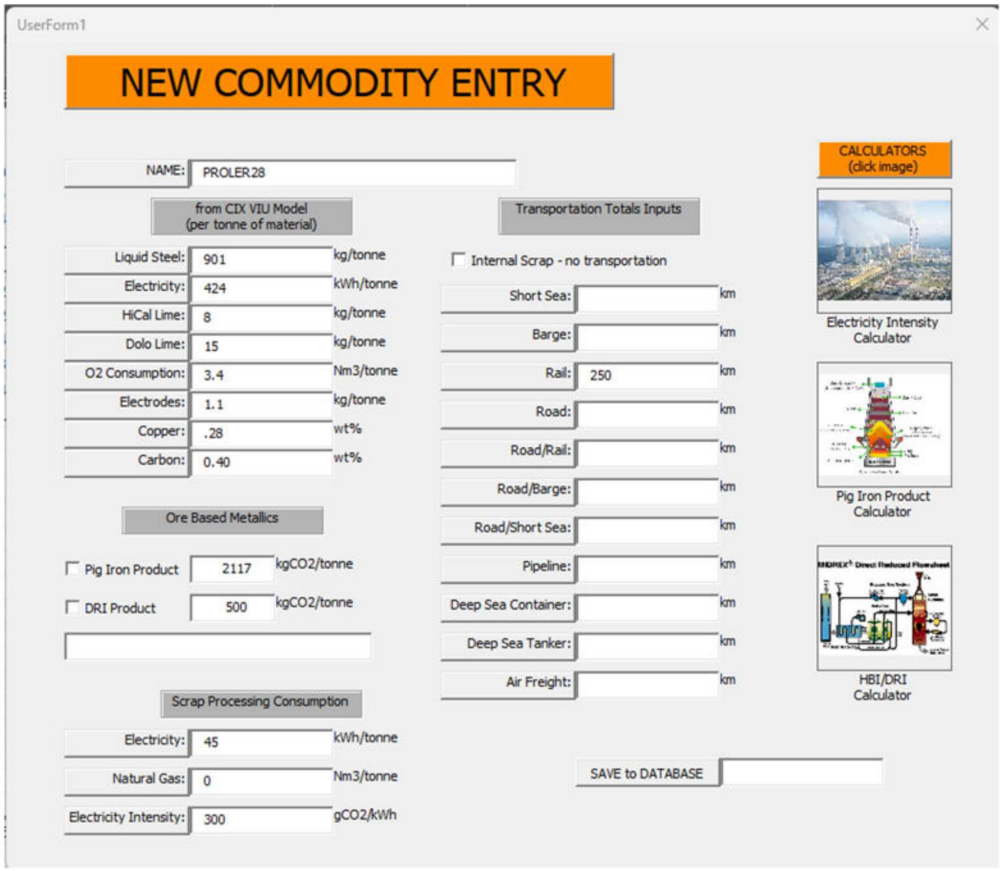
When calculating a CO_2 intensity, it becomes very important to use agreed-to intensity factors. The model keeps a page of references, which can be added to as needed. In the three years that CIX has been involved in doing CO_2 modelling, the biggest challenges are:

- A lack of an agreed-to, universal methodology that actually captures all aspects of CO2 intensity
- Changing intensity factors
- Unclear process boundaries
- A desire for companies to publish a very low intensity – leaving less room for true improvement
- When the method of accounting for CO2 changes, do you re-run previous years' data with the new calculations or simply explain large changes in CO2 intensity by explaining the changing calculation methods?

The philosophy of CIX, Inc. with respect to CO_2 intensity accounting is:

- Count EVERYTHING – this allows even small improvement efforts to be captured in the future
- Downstream and upstream activities cannot be double counted. Downstream activities should be in the boundary of the downstream user.
- The next step of the process, whether an internal or external customer, would assume this intensity into their process.
  *Note: there is actually more involved in this calculation in the CARBON_VIU model. It also considers the flux consumption, the electrode consumption, the electricity, etc.

This output shows the theoretical mass/energy results from melting one ton of a particular commodity and making steel and slag to a prescribed target temperature and chemistry. The input form used in the CARBON_VIU model is shown in figure 17.



NAME: PROLER28

Liquid Steel: 901 kg/tonne
Electricity: 424 kWh/tonne
HiCal Lime: 8 kg/tonne
Dolo Lime: 15 kg/tonne
O2 Consumption: 3.4 Nm3/tonne
Electrodes: 1.1 kg/tonne
Copper: .28 wt%
Carbon: 0.40 wt%

☐ Pig Iron Product 2117 kgCO2/tonne
☐ DRI Product 500 kgCO2/tonne

Electricity: 45 kWh/tonne
Natural Gas: 0 Nm3/tonne
Electricity Intensity: 300 gCO2/kWh

☐ Internal Scrap - no transportation
Short Sea: km
Barge: km
Rail: 250 km
Road: km
Road/Rail: km
Road/Barge: km
Road/Short Sea: km
Pipeline: km
Deep Sea Container: km
Deep Sea Tanker: km
Air Freight: km

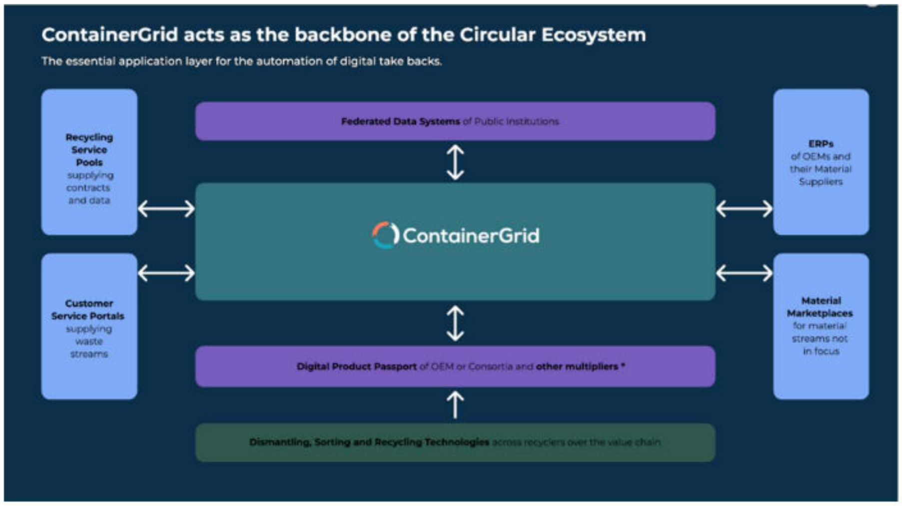
Figure 17: CARBON_VIU User Interface to Input Materials

CONTINUOUS IMPROVEMENT

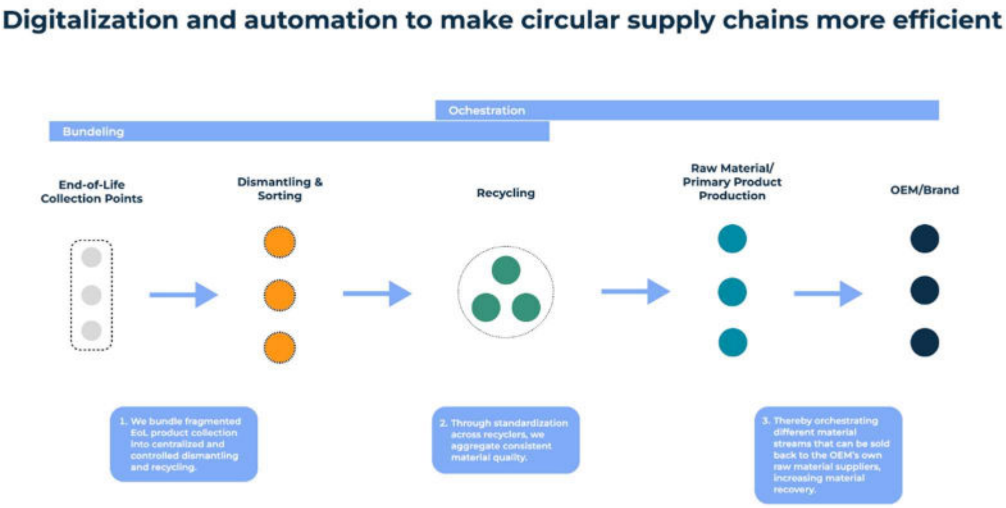
Without doubt, CIX' experience with scrap upgrading has shown that it is both cost effective and contributes to more efficient EAF operations. In addition, scrap upgrading can help to avoid significant CO2 emissions. In the EU, reduction in these CO2 emissions is likely to drive the interest in scrap quality improvement. In North America, the driver is likely to be more related to better EAF operations. Regardless, it is clear that upgrading scrap quality is the way of the future and is a solution to the issue of rising residual levels in the scrap reservoir. The balance of OBM requirements to supplement recycled scrap is heavily dependent on gaining better control over scrap quality.

In the EU, some start-up companies are proposing solutions to the EAF raw materials challenge in the future. One such company is ContainerGrid. They have proposed a model as shown in the figure 18. Their concept is to track scrap quality through the circular supply chain in order to certify the CO2 footprint of steel produced from this scrap and supplied to their ultimate customer, the fabricator.

Innovative business models such as this, will make scrap upgrading a necessity in the future.



The essential application layer for the automation of digital take backs.



1. We bundle fragmented EoL product collection into centralized and controlled dismantling and recycling.
2. Through standardization across recyclers, we aggregate consistent material quality.
3. Thereby orchestrating different material streams that can be sold back to the OEM's own raw material suppliers, increasing material recovery.

Figure 18: ContainerGrid and its process

IS GOVERNMENT POLICY REQUIRED?

It is unclear whether changes to the scrap industry will require government intervention. In regions such as Europe, government policy will likely speed up the transition. In North America, a free-market approach is preferred. However, CIX has shown that the benefits of upgrading scrap quality greatly outweigh the costs.

Manufacturers are beginning to accept that they must design more effectively for end-of-life dismantling. This will only continue to enable the scrap processor to provide a cleaner, higher value product for the steelmaker.

CONCLUSIONS

Hopefully, this paper has ignited an interest in the possibilities of upgrading scrap quality. When CIX first embarked on a review of scrap quality, our focus was to improve EAF operations by stabilizing operations, achieving consistency, improving yield and reducing energy consumption. As we dug into a deeper analysis, we encountered other suppliers with similar goals. CIX feels confident when it states that the single greatest opportunity for optimization of EAF operations lies in providing optimized raw materials to the process. In the past, steelmakers have argued that any attempt to improve scrap quality would not be cost effective. Based on our work spanning more than 15 years, CIX can confidently state that this is a false narrative. The future of EAF steelmaking will be a function of the amount of steel that can be recycled and its' quality. The raw material balance for future EAF operations will be a balance of scrap and ore based metallics. The rate at which we have to adopt greater quantities of ore based metallics can be controlled through our actions to maximize the quality of steel scrap.