Steel Scrap Processing: Sustainable Recycling as a Significant Contributor to the Transition to Green Steel

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The decarbonization process of the steel industry lies in the implementation of steel production methods based on the transformation of scrap (EAF/IF) rather than other technologies based on the use of iron ore and coal as raw materials (BF/BOF). Although ferrous scrap will be incorporated into future strategies for reducing greenhouse gas emissions, there are still limitations associated with the accessibility of high-quality scrap. The presence of tramp elements, such as non-ferrous metals, may restrict the use of ferrous scrap in the production of certain grades of steel. Therefore, scrap treatments, processing, and cleaning will be an opportunity associated with the recovery of non-ferrous fractions. Simultaneously, scrap processing will be the key process for maximizing the value of the lowest-grade scrap and reducing the operating costs of the melting processes. This paper is an integrated case study in which garbage, scrap, junk, and reused materials are employed from beginning to end by leveraging scientific knowledge, technological progress, and creativity to create value. Scholars can utilize a range of innovative and economically effective strategies to address environmental issues. This study gives an integration case study. Utilizing scientific knowledge, technological advancement, and ingenuity, waste, trash, junk, and recycled materials are utilized from start to finish to generate value.

Keywords: Scrap Processing, Shredder, Shearing, EAF Optimization, Green Steel, HMS,

1. Background

The global response to the threat of climate change took a step forward in 2015 when 190 nations adopted the Paris Agreement. In 2019, the United Nations announced that over 60 countries including the United Kingdom and the European Union had committed to carbon neutrality by 2050. Moreover, some nations have pledged to work toward earlier dates. Together, these agreements have led to growing pressure to pursue decarbonization across all industrial sectors.

Iron and steel production is therefore an energy and carbon dioxide (CO_2) intensive manufacturing process which can be substantially carried out into two main dominant different routes: Blast Furnace/Basic Oxygen Furnace (BF/BOF) and Electric Arc Furnace (EAF) production.

BF/BOF production uses iron ore to produce steel. The reduction of iron ore to iron in a BF is the most energy-intensive process within the steel industry. Due to that, the steel sector is currently the largest industrial consumer of coal, which provides around 75% of its energy demand. Coal is used to generate heat and to make coke, which is instrumental in the chemical reactions necessary to produce steel from iron ore in BF/BOF Route.

The alternative route is based on Electric Arc Furnace Technology where scrap is remelted to produce steel.

BF/BOF production is more energy intensive and emits more CO_2 than EAF production (Aichinger and Steffen 2006). In terms of environmental impact, the BF-BOF method is about 2.5 times more carbon intensive than the EAF method (Li et al., 2012).

Currently blast furnace-based production, using coal and iron ore, accounts for around 70% of steel production worldwide, with steel scrap-based EAF production accounting for around 30% and inching up thus, according to IEA (International Energy Agency - Iron and Steel Technology Roadmap) among heavy industries, the iron and steel sector ranks first when it comes to CO_2 emissions, and second when it comes energy consumption. The iron and steel sector directly accounts for 2.6 gigatonnes of carbon dioxide (Gt CO_2) emissions annually, 7% of the global total from the energy system and more than the emissions from all road freight.

Each production route, BF/BOF rather than Scrap/EAF, offers different mitigation options to move towards the CO2 emission challenges however, only those that can be entirely electrified has the potential to achieve full decarbonisation, i.e. the scrap-EAF route using clean power. The scrap-EAF route is fully commercialised and practiced extensively across the globe. Even so, it could be further improved by recycling more steel and enhancing its quality at sustainable cost.

2. Scrap based Electric Arc Furnace - Overview

The steel markets are highly competitive, and cost-efficiency is one of the top priorities for all the steelmakers and every meltshop must play with the opportunity offered by recycled steel scrap to increase their profitability in the market on the basis of all the possible benefits that a proficient scrap management program can provide. It has also to be considered that steel is usually considered as a commodity complying with common global standards. Therefore, analogous steel products of different companies are almost perfect substitutes even if produced by different raw materials.

The optimization, in term of Operating Cost of an EAF, is an extremely complex evaluation dependent on the Mass Balance as well as the Energy Balance. Many studies investigated into the possibility of modelling the entire transformation process (T. Hay, V.Visuri, M. Aula et al., 2020). In the following figures are enumerated all the different inputs and output necessaries to evaluate EAF performances and, consequently, the relevant Operating Expenditure.

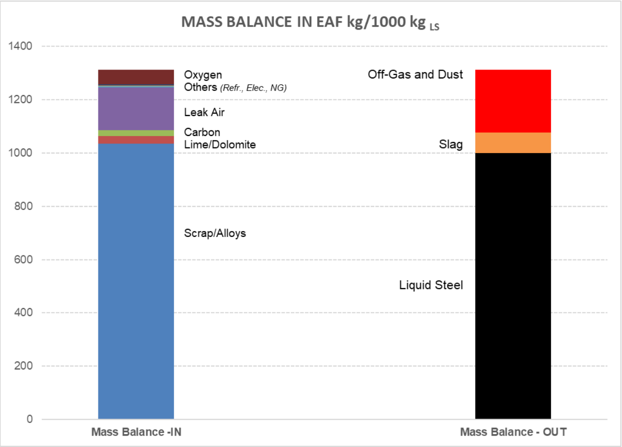


Figure 1- EAF Mass Balance

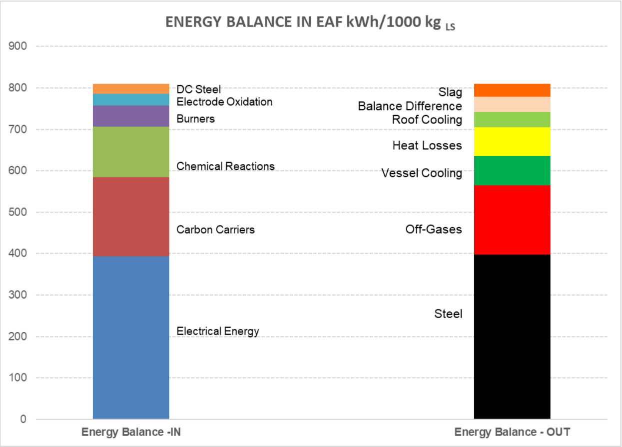
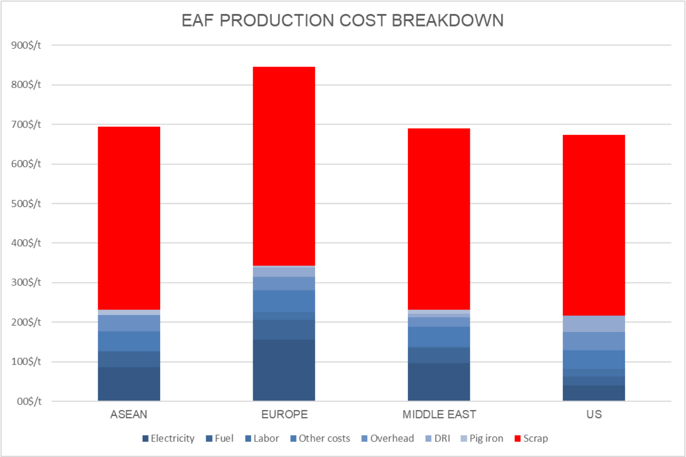


Figure 2- EAF Energy Balance

The Electric Arc Furnace real Operating Expenditure is defined by a matrix where all the parameters defined in the mass and energy balance are coupled with relevant Cost and Prices. It shall anyhow be considered that a reduction in any of the cost parameters doesn't imply automatically a reduction of the whole Opearating Cost.



Such a matrix has been realized by data collected by TransitionZero and Global Efficiency Intelligence (2022) and in Figure 3 is visible the impact of the different contribution in the construction of the EAF Production Cost.

Steel Scrap, which is the highest Cost in the Breakdown reported, could be sourced at different proces, depending of its Phisical and Chemical Characteristics: feeding EAF with cheaper scrap doesn't necessarly imply a saving in the melting process. It could generates lower yields, higher consumption of Energy and Time or generates breakages to the electrodes mitigating the savings achived by purchasing cheaper infeed materials. Under some circumstances (unavailbaility of processed scrap) the entire melting process might result nor sutaibanble under the economical point of view.

3. Scrap Type and Characteristics

Steel Scrap shall not be considered as a unique and unambiguous product and its characteristics in term of size, density, purity, affect not only its price but also its yield in the Furnace and the Operating Cost of the whole melting process.

Many entities such as ISRI (Institute of Scrap Recycling Industries) and EFR (European Ferrous Recovery & Recycling Branch) define the steel scrap characteristics as a function of the chemical and physical characteristics and it is not uncommon that the steelmaker itself defines its own scrap specifications.

Universal knowns categories of scrap that are HMS1 and HMS2 (Heavy Melting Steel – ISRI Code 200-206), shredded scrap (ISRI Code 210-212), bundles divided into No.1 and No2. (ISRI Code 208, 209) are widely used.

One way of classifying scrap according to its source is to distinguish scrap from steel plants and rolling mills, scrap from the steel processing (new scrap), and scrap from products after their use (old scrap). New scrap is generated during the initial manufacturing processes and its composition is well known and it does not need any pre-treatment process before it is re-melted, although densification might be necessary. Old scrap, which is the most available material on the market, is collected after a use cycle and it is extremely variable in terms of physics and chemical characteristics depending on the source (Infrastructure and Building Demolition, End-Life-Vehicles, House Appliances etc.) and it can be provided either separately or mixed, often contaminated to a certain degree, depending highly on its origin and the collection systems used.

Scrap is a scarce resource, given that steel products have an average life cycle of about 40 years. Scarcity of uncontaminated good quality scrap is exacerbated by the exports of scrap materials – especially HMS1 and HMS2 towards High-Demanding countries (Turkey, South Korea, where scrap is widely used in Steel Production).

A large amount of scrap is available in South East Asia. This local scrap is typically a low-cost material characterized by an extremely low density (0,15-0,20 t/m^3), high level of impurities such as concrete, dust and soil, plastic, glass, and other impurities.

4. Scrap Use and implication in EAF Steelmaking

To define the characteristics of the ideal raw material for electric steelmaking it is necessary to identify the basic working principles and how the real standard operations differ to the ideal ones in electric based furnaces.

The actual energy used in the EAFs depends on the quality and conditions of the charged materials (scrap, DRI etc.), the amount of slag, the total time of the heat, the configuration and geometry of the EAF, the refining processes to produce the kind of steel desired.

The practical minimum total energy needed in the EAF estimated by Fruehan et al. is 438 kWh/ton of liquid steel even if the prediction of the final results is hardly predictable even by the plant designers which observed and compared the performances of a set of reasonably similar EAFs around the world and noticed a wide variability in terms of performances based upon the charged materials and the equipment availability.

All these facts underline that worldwide there is wide margin of improvement in the EAF resource efficiency field.

a) Reducing Number of Bucket Charge (for Bucket Charging)

In a batch EAF process, the scrap density affects the number of charges required to produce a heat but also impacts the electrical and chemical energy profiles. Dense scrap can slower the melting process and if aggressive burners and the oxygen lancing profiles are employed, the dense scrap may deflect the jet back onto the furnace walls causing a damage. If large quantities of dense scrap are charged, it may be necessary to operate at lower arc voltage and higher current during refining in order to ensure that the dense material is fully melted before the tapping.

The furnace charging is typically done by a clam-shell designed buckets which are moved on the top of the furnace itself when the roof and the electrodes are raised and swung to the side of the furnace. After charging the first bucket, the roof and the electrodes move back into place on the furnace so that the first melting cycle can start. For every additional charging bucket the roof is opened again and this implies the thermal losses related to off-gas and the radiation without considering that in the dead time power is off and the plant is not actively melting.

The thermal losses related to the charging phase represent a combination of the off-gas losses and radiation losses and are of the order of about 12–20 kWh/m^2·min referred to the surface area of the melt and the time between the roof being lifted and being closed again. The simplest way to reduce them is to reduce the number of the bucket charges. For each charging procedure at least 23kWh/t are usually lost.

By processing “local”, low price scrap, bulk density will drastically increase and, considering that the charging bucket volume is unchangeable due to the geometrical characteristics of furnace, it means that a lower number of buckets are necessary to charge the same amount of scrap into the furnace.

b) Promote Scrap Pre-Heating (for Consteel® or Shaft Furnace Type)

The best preheating results are achieved through a scrap characterized by a high surface to volume ratio. In the preheating phase the heat is mainly transfer to convection of the hot combustion gases. The efficiency of the heat transfer process is influenced by the residence time of the gas and by the temperature gradient (cold scrap = high heat transfer). The radiation intensity and the residence time of the gas (or the temperature gradient between the gas and scrap), is the intensity of the heat exchange, which depends mainly on the surface area of the scrap pieces. Not only the heat exchange is strongly dependent on the geometry of the scrap, but the geometry also has a strong influence on the heat conduction within the scrap piece itself.

c) Increase Yield Liquid Steel/Scrap

By cleaning the densified scrap, most of the free impurities are removed and are easily separated from scrap by common equipment such as magnetic drums. It has been reported that a rough amount of 6-12% impurities including soil, polymers and non-ferrous metals have been removed by the scrap mix of an EAF by an effective scrap shredding & sorting plant. By eliminating such impurities from the scrap, the metallic yield of the EAF charge increased and halved the amount of slag generated.

A further effect of the removal of such impurities (soil to be considered as 75-85% SiO_2 & Al_2O_3) is the decreased amount of limestone for correcting the slag basicity parameter.

Even in a very basic scrap management system the cash back on the scrap purchased depends on the amount of inert and non-ferrous detected and segregated to optimize the raw material purchasing strategies and the related costs.

d) Optimization of Power On and TTT Time

The use of the shredded low-grade scrap compared to heavy HMS/bundles allows also to optimize the melting time in EAF: the late or non-uniform melting of the scrap is a significant problem for operating the EAF. When melting large and compacted scrap pieces, such as bundles, crop-ends, ingots, ladle or tundish skulls etc, extended superheating times are needed but they are directly pointed out by higher energy consumption due to the losses in the water-cooled panels as well as in a reduction of the productivity. The problem of the non-uniform scrap melting decreases as the superheat of liquid bath increases and it can also be reduced by increasing the efficiency of the scrap preheating and of the proper set-up of the available melting tools.

A further advantage of the use of shredded low-grade scrap is represented by the absence of the large heavy scrap that can cause a blow-back of the flame onto the water cooled panels at the burner doors.

e) Reducing Electrical Energy Consumption

The decrease of the electrical energy consumption can be obtained by the charge of small size that allows to decrease the tap to tap time. The decrease of the whole tap to tap cycle the specific consumption in terms of kWh/t_{LS} decrease for a single heat. Furthermore, a more efficient use of the electric energy will take place since the amount of energy used to melt impurities such as soil and non-ferrous decreased after the removal of the non-metallic residues.

It has been estimated in 20 years’ experience on the field that a typical saving of 7-9 kWh/t is achieved by increasing the metallurgical yield of 1%.

f) Increase the Lifetime of Dust Suppression Plant

By removing dust and soil in the bucket charge the amount of the dust carried over by off gas is drastically removed enhancing the life time of the dust suppression system (Bag House) in the fume treatment plant.

g) Saving in Electrode Consumption

Industrial experience demonstrates that also scrap movement in the Furnace affects the EAF operations. After the scrap bucket is positioned over the furnace, the electrodes “bore” into the scrap melting the pieces near the electrodes as they are lowered. In the case of low grade scrap processed by low speed shredder, it gradually slides towards the arc area and the electric power supply can be maintained at a high level, without interruption or drastic electrode adjustment.

If the charge moves down unevenly, i.e. in large surges, usually called cave-ins, the electrodes must be drastically raised and power supply frequently is interrupted implying a high level of harmonics induced in the power network, deteriorating the quality of the electricity supplied to other users.

It is not infrequent that a movement of a big scrap piece or bundle cave-in causes the electrode breakages during the melting period, further resulting in downtime (the furnace power-off) for replacement.

5. SCRAP PROCESSING: TECHNOGIES IN USE

A wide range of equipment is used to decrease the size of bulky scrap into pieces small enough to enable combination, delivery, and subsequent feeding into furnaces.

The recyclable steel scrap may be prepared for charging in different ways;

- by cutting through the oxygen or by Diamond Wire Saw
- by pressing, forming bales
- by shearing (Excavators’ Attachments or Guillotine Shear or Blue Devil Rotary Shear)
- by fragmentation in an Hammer Mill

Size Reduction by Guillotine Shear (Source Zato)

Size Reduction by Hammer Mill (Source Zato)

In Europe, US, South Korea and Japan these equipment are usually managed by Scrap processors who handle and process the scrap and sell it to steel mills.

a) Shear:

The hydraulic guillotine shear slices heavy pieces of steel including I-beams, columns and railroad car sides. Shears vary in size and cutting force from 300 tons to more than 2000 tons of head force. It can be equipped with a compression chamber which might allow creation of Bales. Since the size of the cutting pieces can be varied, the capacity of such a machine is not fixed and decreases with the decreasing of the output material size. It can be equipped with a compression system which allows the generation of bales (or bundles) of scrap which are used for long ways transportation. Itis optimized for high scrap thicknesses thanks to the cutting force.

Figure 3. Head of the shear equipped with the blade

b) Hammer Mill Shredding

Hammer mill operating principle is straightforward. It is basically a closed chamber containing a horizontal rotating shaft on which hammers are mounted. The hammers are free to swing on the ends of the cross. The rotor is spun at a high speed inside the chamber while material is fed into a feeding hopper. The material is impacted by the hammers and is thereby shredded and expelled through screens grids and it is soon i comminuted into a size smaller than the grid mesh. Since it requires some time to reach the desired dimension(the so called resident time) the hammers hit several time each piece into the chamber allowing an effective removing effect of the material having different nature. A typical sketch of an hammer mill body is shown in Figure 4. Usually, they also include a dedusting system for extracting and treating dust generated during the process.

After being processed into an hammer mill shredder, depending on the design, the whole stream might pass through an aeraulic separation unit (the so called Z-Box) for removing light material such as light polymers, organic foams etc. “Shredder fluff” is the term given to the light materials, which are collected during the shredding process by cyclone air separation. Heavy part of the shredded stream is then addressed to a magnetic drum where an effective sorting of ferrous fraction (Magnetic) takes place. The material not recovered by the magnet (the so-called heavy shredder residue) might be processed by a further equipment to separate non-ferrous metals, copper wires, heavy polymers which can be sold as by-products.

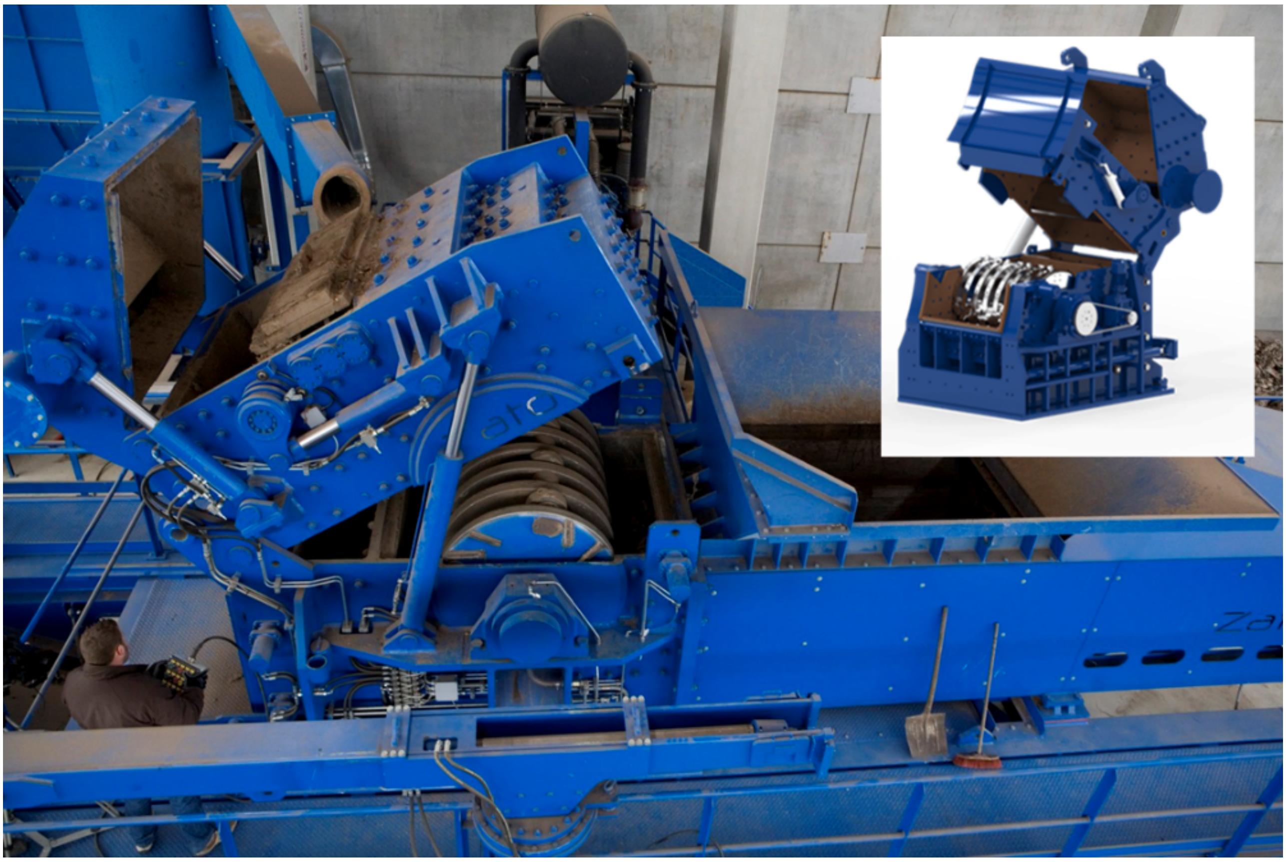


Figure 4 Hammer Mill Shredding Chamber with Rotor inside (Source Zato)

The whole equipment installed downstream the hammermill are generally identified as “Downstream Plant” and might be installed online with the Shredder Unit or Off-Line impacting on the operating cost, flexibility and recovery parameter of the whole installation. The main downstream equipment are eddy current separators for the sorting of the non-ferrous metals (ZORBA), the induction sensor sorting machines for the separation of stainless steel (ZURIK) and insulated copper wires (ICW), X-Ray and colour sorters for the separation of different metals based on chemical or physical characteristics.

Figure 5: Hammer Mill equipped with Ferrous Recovery System – courtesy of Tata Steel UK

Figure 6 Downstream Plant of an Hammer Mill incl. Sieving and NonFerrous Metal Recovery – (Source Zato)

6. SUATINABILITY OF SCRAP PROCESSING

A proper scrap treatment is necessarily different for every steel melsthop (production capacity) and for every geographical area (availability of raw materials and logistics). It is therefore necessary to guarantee smooth performances and decrease the furnace operating costs.

All the benefit in steelmaking listed at the point above can be easily achieved by frag material, i.e. processed by hammer mill shredder but this implies a higher cost for the material purchasing or, in case of direct installation in the steel melsthop, an high operating cost which affect its sustainability.

On the other hand, the guillotine shear is perfectly suitable for thick scrap but it does not add a significant value to light scrap due to the inability to remove the entrapped non-metallic material. Furthermore, its capacity with such a low grade material is limited, since thicknesses are often low and the density increase is not so effective.

The size, shape, density and composition of shredded ferrous scrap brings cost benefits to steelmakers and foundries owing to savings in time and in resource and energy use, and through a reduction in CO_2 emissions as compared to the sheared or baled scrap.

An important limitation in the use of the hammer mill shredder is the preparation of the scrap which shall be deprived of any combustible item (dust, gas or vapour) or pressurized tank and any thick material which deteriorate easily the movable parts of the main body. Several severe accidents had been reported worldwide due to inappropriate depollution of hazardous materials in the hammer mill.

In some countries and organization installation of hammer mill shredder have been limited by environmental regulation permits (since stack emission to atmosphere are always involved), space requirements, civil works related to its installation.

7. THAILAND CASE STUDY – TITAN METAL

An important amount of local scrap is typically a low-cost material characterized by an average low density (0,2 t/m^3), low thickness, high level of impurities such as concrete, dust and soil, glass and other impurities (Figure 7). This low-grade scrap might be directly fed into EAF but enormous benefits will rise from a basic treatment into the twin shaft shredder.

Figure 7: Light Scrap after Densification – courtesy of TITAN METALS - Thailand

The twin shaft shredder technology has been developed, in the latest nineties, as an alternative technology able to comminute low grade scrap into smaller pieces removing the entrapped non-ferrous materials.

This type of machine might be called as *Low Speed Shredder* or *Rotating Shear* and merges most of the advantages of the hammer mill and the guillotine shear in an unique piece of equipment. It basically consists in two shafts equipped with cutting blades enclosed into a robust casing. The hydraulic motors guarantee a torque able to continuously cut the material on the blade side.

A typical installation is shown below in Figure 8.

Figure 8 Example of Low Speed Shredder at Titan Metal - Thailand

From the cost point of view the guillotine shear can be considered a low operation-expenditure machine, while the hammer mill requires a lot of energy to produce a well fragmentized product.

The twin shaft shredder operating costs, as well as capital expenditure, are comparable to the guillotine shear but it is considerably lower than a hammer mill shredder.

The performances of the twin shaft shredder ensure a good removal effect which is particularly evident when the baled material (bundles) are processed: a large amount of unexpected non-ferrous material visibly flow out from the machine.

The twin shaft shredder might be equipped with a scrap cleaning line able to segregate the non-ferrous impurities (such as dust and soil) as shown in Figure 9 as well as further equipment for recovery of non-ferrous metals (Aluminium, Brass, Zamak, etc).

Figure 9: Impurities Segregated by Scrap Cleaning Line

8. CONCLUSION

In order to take advantage of the availability of low cost, low grade local scrap, several equipment have been considered.

It is the market economy that imposes the criterion of the production optimisation and in most cases, it can be the variable cost of the manufactured products. Striving to solve such optimisation tasks, as e.g. attaining the maximum yield of crude steel from metal scrap on minimum steel scrap costs, it is reasonable to find a compromising solution.

The hammer mill is undoubtedly the best machine to separate at the maximum extent scrap and the obtained final bulk density is not achievable by other machines which unfortunately requires high operational expenditures and investment costs. Moreover, such a technology requires a pre-treated scrap in order to avoid explosions and fires and to avoid un-shreddable objects are fed into the machine.

The twin shaft shredder is the most reliable equipment which enable to reduce significantly the volume of low grade scrap as well as standard and lightweight scrap, but also cars, sheets and pantographs. It can process most of the material available at a competitive transformation cost increasing its density to generate a more desirable purchase for the steelworks, due to the significant economic advantage in terms of the furnace charging (decrease in the number of basket loads with the consequent reduced energy consumption) and reduced volume of scrap stored in the scrap yard.

The coupling with a simple magnetic separation system dedicated enables any Scrap Processor to clean the processed scrap more thoroughly, further increasing its value and enabling to recover the considerable quantities of non-ferrous metals found within the processable scrap.

The machine works at slow speeds and with very high torque, to create a cutting force capable of processing the large amounts and different types of light scrap in complete safety.

The added value of this kind of machine grants huge benefits in electrical arc furnaces as well as induction furnaces plant, but it’s also applied in BOF, to act as an effective and convenient coolant scrap.

References

An, R., Yu, B., Li, R., & Wei, Y. M. (2018). Potential of energy savings and CO2 emission reduction in China’s iron and steel industry. *Applied energy*, *226*, 862-880.

Bhaskar, A., Assadi, M., & Nikpey Somehsaraei, H. (2020). Decarbonization of the iron and steel industry with direct reduction of iron ore with green hydrogen. *Energies*, *13*(3), 758.

Fan, Z., & Friedmann, S. J. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule*, *5*(4), 829-862.

Gao, Z. (2021). *Sorting and Impurity Removal to Improve the Recycling of Steel Scrap from Auto Shredder* (Doctoral dissertation, Colorado School of Mines).

Gao, Z., Sridhar, S., Erik Spiller, D., & Taylor, P. R. (2021). REVIEW OF IMPURITY REMOVAL METHODS IN STEEL SCRAP RECYCLING. *Journal of Solid Waste Technology & Management*, *47*(4).

Gielen, D., Saygin, D., Taibi, E., & Birat, J. P. (2020). Renewables‐based decarbonization and relocation of iron and steel making: a case study. *Journal of Industrial Ecology*, *24*(5), 1113-1125.

Gul, E., Riva, L., Nielsen, H. K., Yang, H., Zhou, H., Yang, Q., ... & Fantozzi, F. (2021). Substitution of coke with pelletized biocarbon in the European and Chinese steel industries: An LCA analysis. *Applied Energy*, *304*, 117644.

Gür, T. M. (2022). Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. *Progress in Energy and Combustion Science*, *89*, 100965.

He, H., Guan, H., Zhu, X., & Lee, H. (2017). Assessment on the energy flow and carbon emissions of integrated steelmaking plants. *Energy Reports*, *3*, 29-36.

He, K., & Wang, L. (2017). A review of energy use and energy-efficient technologies for the iron and steel industry. *Renewable and Sustainable Energy Reviews*, *70*, 1022-1039.

Lincicome, S. (2021). Manufactured Crisis:'Deindustrialization,'Free Markets, and National Security. *Cato Institute, Policy Analysis*, (907).

Liu, H., & Song, L. (2016). 14. Issues and Prospects for the Restructuring of China’s Steel Industry. *China’s new sources of economic growth*, 337.

Loibl, A., & Espinoza, L. A. T. (2021). Current challenges in copper recycling: aligning insights from material flow analysis with technological research developments and industry issues in Europe and North America. *Resources, Conservation and Recycling*, *169*, 105462.

Mandova, H., Leduc, S., Wang, C., Wetterlund, E., Patrizio, P., Gale, W., & Kraxner, F. (2018). Possibilities for CO2 emission reduction using biomass in European integrated steel plants. *Biomass and Bioenergy*, *115*, 231-243.

Mayer, J., Bachner, G., & Steininger, K. W. (2019). Macroeconomic implications of switching to process-emission-free iron and steel production in Europe. *Journal of Cleaner Production*, *210*, 1517-1533.

Mehrpouya, M., Dehghanghadikolaei, A., Fotovvati, B., Vosooghnia, A., Emamian, S. S., & Gisario, A. (2019). The potential of additive manufacturing in the smart factory industrial 4.0: A review. *Applied Sciences*, *9*(18), 3865.

Miranda, A. M., Assis, P. S., Brooks, G. A., Rhamdhani, M. A., Fontana, A., King, A., ... & da Costa Moreira, G. P. (2019). Monitoring of less-common residual elements in scrap feeds for EAF steelmaking. *Ironmaking & Steelmaking*, *46*(7), 598-608.

Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., & Tortorella, G. (2018). Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. *Journal of Manufacturing Technology Management*, *30*(3), 607-627.

Pamenter, S., & Myers, R. J. (2021). Decarbonizing the cementitious materials cycle: A whole‐systems review of measures to decarbonize the cement supply chain in the UK and European contexts. *Journal of Industrial Ecology*, *25*(2), 359-376.

Powell, B. R., Krajewski, P. E., & Luo, A. A. (2021). Magnesium alloys for lightweight powertrains and automotive structures. In *Materials, design and manufacturing for lightweight vehicles* (pp. 125-186). Woodhead Publishing.

Quader, M. A., Ahmed, S., Dawal, S. Z., & Nukman, Y. (2016). Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO2) Steelmaking (ULCOS) program. *Renewable and Sustainable Energy Reviews*, *55*, 537-549.

Saleh, T. A. (2022). Nanomaterials and hybrid nanocomposites for CO 2 capture and utilization: environmental and energy sustainability. *RSC advances*, *12*(37), 23869-23888.

Shirinbakhsh, M., & Harvey, L. D. (2021). Net-zero energy buildings: The influence of definition on greenhouse gas emissions. *Energy and Buildings*, *247*, 111118.

Stewart, D. J., & Barron, A. R. (2020). Pyrometallurgical removal of zinc from basic oxygen steelmaking dust–A review of best available technology. *Resources, Conservation and Recycling*, *157*, 104746.

Wang, R. Q., Jiang, L., Wang, Y. D., & Roskilly, A. P. (2020). Energy saving technologies and mass-thermal network optimization for decarbonized iron and steel industry: A review. *Journal of Cleaner Production*, *274*, 122997.

Wooders, P. (2012). Energy-Intensive Industries: Decision making for a low-carbon future. *The case of steel*.

Yemelyanov, O., Symak, A., Petrushka, T., Zahoretska, O., Kusiy, M., Lesyk, R., & Lesyk, L. (2019). Changes in energy consumption, economic growth and aspirations for energy independence: Sectoral analysis of uses of natural gas in Ukrainian economy. *Energies*, *12*(24), 4724.

Zhang, Q., Zhao, X., Lu, H., Ni, T., & Li, Y. (2017). Waste energy recovery and energy efficiency improvement in China's iron and steel industry. *Applied energy*, *191*, 502-520.

Zhao, J., Ji, G., Yue, Y., Lai, Z., Chen, Y., Yang, D., ... & Wang, Z. (2019). Spatio-temporal dynamics of urban residential CO2 emissions and their driving forces in China using the integrated two nighttime light datasets. *Applied Energy*, *235*, 612-624.

Y. Yetisken, U. Camdali, and I. Ekmekci COST AND EXERGY ANALYSIS FOR OPTIMIZATION OF CHARGING MATERIALS FOR STEELMAKING IN EAF AND LF AS A SYSTEM. Metallurgist, Vol. 57, Nos. 5–6, September, 2013

T.Lis OPTIMISATION OF METAL CHARGE MATERIAL FOR ELECTRIC ARC FURNACE. METALURGIJA 50 (2011) 4, 219-222

T. Hay, V. Visuri, M. Aula, and T. Echterhof - A Review of Mathematical Process Models for the Electric Arc Furnace Process Steel Research Int. 2020

G.Balamurugan, S.M. Prabhakaran, Future Optimization Solution for managing Scraps in medium & Large Manufacturing Industries, International Journal for Innovative Research in Science & Technology, 2018.

ISRI Scrap Specification Circular

EU-27 Steel Scrap Specification EuRIC

M. Piazza, F. Bianco, D. Patrizio, M. Ometto, EAF process optimization through a modular automation system and an adaptive control strategy

"AisT 2014 Electric Arc Furnace roundup", iron and steel Technology, January 2014

71st Electrical Furnaces' sectional Meeting

H. Trenkler, Energy-saving DC twin shell arc furnace for melting low-grade scrap, ABB Review 9/10 1996

A.S. Newell, Proceedings of Electric Steelmakers Guild AMG, 2017