Ferrous and non-ferrous recycling: Challenges and potential technology solutions

Leslie Brooks, Gabrielle Gaustad, Adam Gesing, Teija Mortvedt, Felipe Freire

Rochester Institute of Technology, 190 Lomb Memorial Drive, Rochester, NY, United States
Gesing Consultants, Windsor, Ontario, Canada

Abstract

Metals recycling is one of the oldest industries in the United States that now employs over 530,000 individuals. It has always played a significant role in the economy, supplied extensive goods and services, and the costs and benefits directly and/or indirectly extend worldwide. Improved efficiency in metals recycling is crucial to achieving a more circular economy; to enable this requires understanding how the industry operates and the challenges it must overcome. Increasing metal product diversity and design complexity combined with increased feed volumes has introduced recent additional challenges. This review explores the current status and state of the industry and examines potential technology solutions that address inbound inspection and material identification challenges.

Keywords:
Recycling
Secondary production
Positive material identification
Steel
Aluminum

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Acronyms & Abbreviations:
ASR, automotive shredder residue; CCD, charged couple device; C&D, construction and demolition debris; DE-XRT, dual energy X-ray transmission; EAF, electric arc furnace; ECR, eddy current rotor; EDXRF, energy dispersive XRF; ELV, end-of-life vehicle scrap; HVAC, heating, ventilation and air conditioning; IR, infrared; LIDAR, light detection and ranging; LOD, limit of detection; MRF, materials recovery facility; MSW, municipal solid waste; NF, non-ferrous; NIR, near infrared; OES, optical emission spectroscopy; PGNA, prompt gamma neutron activation analysis; PMI, positive material identification; RDF, refuse derived fuels; RoHs, restriction of hazardous substances; SDD, silicon drift detector; SG, specific gravity; Si-PIN, silicon drift diode intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region; SS, stainless steel; ToF, time of flight; WEEE, waste electrical and electronic equipment; WDXRF, wavelength dispersive XRF; WtE, waste-to-energy; XRF, X-ray fluorescence.

Corresponding author.
E-mail address: gabrielle.gaustad@rit.edu (G. Gaustad).

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1. Introduction

The way we manage and view 'waste' directly impacts our ability to achieve a more circular economy and fundamentally shapes the future of our planet. Step one is working to replace the throw-away mentality with a reduce and reuse one. In instances where that is not an option, recycling offers an alternative. Recycling diverts end-of-life products from landfills to be re-processed into usable products, ultimately reducing extraction of primary materials and thus, conserving energy and resources. The Environmental Protection Agency (EPA) estimates that 75% of the US’s waste is recyclable and currently we recycle about 30% (epa.gov); a multitude of factors play a role in low overall recycling rates. However, as complex as the recycling industry is it is important to recognize that there are three key aspects to improving recycling: technology, consumer participation, and operational efficiency. It is essential to recognize and highlight the challenges of ferrous and non-ferrous recycling to inform efforts required to manage current consumption rates. Understanding what technologies are available and their potential for operational improvements will serve to counter the challenges the industry is currently facing as described below.

2. State of the industry

There are many factors that have a direct impact on the industry as a whole and on individual yards; many are out of a firm's control, but they must find ways to manage them effectively regardless. Constraints range from environmental, health and safety regulations, commodity markets, and technology, to competition, logistics, and varying motivations. Economic opportunity and an effective, efficient operation stems from recyclers being knowledgeable of and understanding these industry constraints.

2.1. Stringent environmental, health, and safety regulations

Environmental, health, and safety regulations are imperative but challenging for recycling operations. Operating in this line of work means regularly coming into contact with large, sharp materials, hazardous materials, and heavy machinery. According to the Institute for Scrap Recycling Industries (ISRI), the industry currently provides jobs [directly and indirectly] to 534,506 workers (ISRI.org). The scrap industry ranks above the national average when it comes to injuries and illness per year (Rosengren, 2016). Employees are not the only ones at risk; people in areas surrounding yards, truck drivers, and customers/peddlers also incur risk. The range of people that can be impacted by recycling operations is considerable, which is why compliance plays a significant role and regulations exist on a local, state, and federal levels. The decision to accept a wider range of materials will directly correlate with additional regulations and compliance ranging from handling, to shipping and packaging. As a result, yards are monitored and controlled by environmental regulations under several laws: The Clean Air Act (CAA), Clean Water Act (CWA), Resource Conservation and Recovery Act (RCRA), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and The Toxic Substance Control Act (TSCA), all apply to scrap yards (Wagger, 2013). Additionally, these stringent regulations impact nearly every aspect of the business, from being permitted to operate and location, to how materials are handled and accepted, and possibly requiring large upfront mitigation costs. Enforcement of these regulations comes with a zero forgiveness policy and fines for non-compliance start as high as $37,500/day (Wagger, 2013); this doesn’t include the potential costs of mitigating the negative public relations that can accompany violations.

2.2. Markets

Commodity markets can be extremely volatile. They can fluctuate unexpectedly and not necessarily in response to typical supply and demand expectations. China, being the largest net importer of scrap materials from the US, for example, has a significant impact on the US recycling industry particularly when it comes to pricing, types of scrap commodities, and transportation logistics (Salidjanova et al., 2017). The current administration’s trade issues with China may cause the nation to redirect over 700,000 metric tons of material (by 2019) (Rosengren, 2018). Much of what the U.S. exports to developing countries is the most challenging scrap types: highly co-mingled, unsorted, and often with high levels of cross-contamination. In response to exports decreasing, the National Recycling Coalition (NRC) and others in the industry are working on a nationwide effort to reform the recycling process—essentially doing away with municipal solid waste and scrap comingling and urging “cleaner” streams (“National Recycling Coalition comments on “China Crisis”,” 2018). Inconsistent domestic buyers and sellers can also cause the movement of material to become stagnant or excessively fluid regardless of price. In some cases, this leads to yards having to sit on material or when feasible, sell at an alternative price to a different end user; this may also result in an altered product of potentially less quality. Because of this, working on very small profit margins and determining how to process material is a delicate process.

2.3. Technology

Recycling of metals once knew a simpler time when standard tools and equipment could effectively help you sort, identify, process, and move materials. However, increasing complexity of product design combined with the growing volume of materials entering recycling facilities has introduced challenges which now require innovative, strategic technological assistance. Technology development for this industry can be challenging due to a multitude of types, sizes, shapes, and forms of materials, and not only are metals typically mixed but non-metals are often comingled as well. When loads arrive at processing facilities, aside from peddler scrap, they are often in truck-load quantities ranging from a few thousand pounds to 40 k lbs. After the vehicle’s gross weight is scaled in, the yard is expected to dump, identify, sort, move the material, record an empty vehicle weight, weigh sorted commodities on a separate scale (when applicable), make deductions/upgrades, and pay out all within minutes time of arrival time. This is happening one load after another, continuously all day. As a
result, the types of technologies needed for improvements are wide ranging. There are the apparent inbound inspection needs outlined in Section 3 but there is additional processing that is often required for the yard to sell or move the material to a smelter or a mill (i.e. size reduction, size and shape separation, material liberation, lifting, transporting, and confirmed positive material identification). For technologies to be successful and penetrate the market they must be affordable and deliver a quick return on investment (ROI). Plus, yards are not only seeking technologies that are able to perform several functions but ones that fit within the current flow of their operation. Additions to equipment are typically preferred over the high costs to install entirely new equipment. Other considerations for new technology includes additional safety measures and operation training for employees.

2.4. Scrap industry structure and competition

According to the U.S. Census Bureau, there are over 8,000 facilities operating in the U.S. (as of 2017). This number includes processors and brokers, who either directly collect or facilitate the collection and purchase of scrap from industrial and/or commercial accounts and/or from individuals, typically referred to in the industry as “peddlers.” With the exception of brokers, these facilities are responsible for separating scrap into various types or “commodities” and preparing loads of scrap that are segregated according to the ISRI-specified scrap categories for sale to export markets, or domestically in the U.S. Depending on the material that is accumulated at a particular facility, the material will be shipped to a steel mill, steel shredding plant, aluminum/non-ferrous secondary smelter, and/or another type of secondary metal scrap processor such as a wire chopping plant. It is also significant to note that several yards are considered “feeder yards;” yards that are still responsible for separating material but accumulate much smaller volumes. These yards will typically send mixed loads (multiple commodities separated but on a single truck) to higher volume yards where the material is then combined and sent to the types of facilities previously stated.

Competition among scrap yard facilities comes in many forms and has been on the rise for quite some time. Although it is common for new start-ups to emerge, unless new business owners are well versed in an understanding of the industry and the market conditions are optimal, they will be less likely to thrive. Often, start-ups come in with aggressive purchasing prices that they cannot necessarily match with adequate sale prices. These upicks in purchasing prices are a nuisance to preexisting yards’ business, either forcing them to pay more for plant feed (even if not economical) to keep their customers, or risk losing feed suppliers. There are also instances where new competition discovers niche markets for common commodities and can support aggressive buying.

In earlier years, the business of metals recycling was mostly a family business whose customer base developed from relationships grounded in exceptional customer service, loyalty, honesty, and fairness. There has been a recent shift toward metal producers, usually larger corporations, owning their own feed yards. Both types of yards, due to ever-thinning margins, have been forced to prioritize things like easy in-and-out business, fast payment terms, best price despite weight, and places that can act as a one-stop shop.

2.5. Logistics

Freight has several different forms to which it can be transported (i.e. baled, boxed, loose), all dependent on whether it is transported by rail, ship, truck, or some combination. The mode(s) by which it is transported (often decided by the purchaser) dictates how the load is packaged and handled, how much of the material can be loaded, and finally, how it will be priced. Seventy percent of freight is presently moved by trucking (Bartheld, 2018); tractor-trailer trucking comes in a number of forms: flatbed, van-trailer, roll-off/open top container, export container, etc. Some of these are more difficult to load than others and all have varying weight limits. Having the correct equipment for loading and unloading is essential because trucks are expected to be weighed in, emptied, and weighed out relatively quickly. Often, scrap companies do not have their own fleet of trucks and transportation must be outsourced. Truckers get paid by mileage not by the hour, and if a yard does not have an efficient process, requiring that some trucks wait extended periods of time to be loaded /unloaded, the company might refuse to work with them (Sandoval, 2001). Not having the right equipment can also lead to damaged trucks and trailers (which may be owned by a third party) when loading and unloading. Furthermore, yards must be diligent about having a clear/clean pathway for trucks as to avoid flats, which can be especially difficult when the majority of material moving through a yard is capable of causing damage. If any of these become common occurrences, not only are repairs costly but business may be lost. Aside from the magnitude of obstacles to overcome once a truck is on site, it is important to point out that the act of scheduling trucks can be particularly challenging as well, for availability can be limited. Although there are hundreds of thousands of trucking firms, that doesn't mean they have large fleets and that all trucks in their fleet are operational (due to repairs or a shortage in drivers) (Sandoval, 2001). Other logistic considerations include route optimization considering weight and height limits.

2.6. Incentives

An underlying impact on the system that can be influenced but not controlled, is motivation (i.e. what drives individuals to participate). It can influence a company’s reputation/image or be the difference between choosing to sort different commodities vs. comingling everything and having contamination. Some facilities are committed to being environmentally conscious, while some are not or do not have that luxury due to constraints. Some are committed to the recycling business because of an environmental commitment. Some prioritize profits, while some will accept less to reduce inventory. Differing incentives are a component of sustainability that is most often the hardest to address – the social component. A scrap yard cannot control individual motivation per se, but they, along with other environmental stewards, can educate individuals as to how the system operates and compensating them based on the intrinsic value of their recyclables, availability of information and ease of acquiring also play a role in an individual’s involvement thus, it is important that the industry addresses education.

3. Inbound inspection and material identification challenges

Industry constraints listed above limit economic opportunity for recyclers, but the challenges presented in this next section are areas where facilities may have more influence. Having an operation that is effective and efficient, takes advantage of cost and time saving technology, and is proactive on environmental compliance regulations, has the ability to thrive in this business and be a leader in innovation, strategy and operations. The focus areas of this work include: inbound material identification (IMI), quantification of contamination, sorting/processing, load form, safety, and communication. Scrap recyclers work on low margins which means small errors can have big impacts. This includes everything from improper purchases to yard fires. Purchasing material as one thing for instance, copper clad steel as copper,
has a price difference upwards of $3/lb. Although other examples may be a price difference of a few cents when you are purchasing thousands to hundreds of thousands of pounds of material, those pennies add up quickly and diminish profits. Yard fires are a very serious problem as well; in 2017, an estimated 1,500+ fires took place at processing facilities in the U.S. and there are cases of prior year’s experiencing more than double that (Fogelman, 2018). Yard fires produce serious consequences costing not only millions of dollars in clean-up, downtime, and repairs but it can also cost lives (Fogelman, 2018). Metal scrap is hard to burn, what typically ignites is the organic contaminants including oils, paper, cardboard, rags, plastic and wood. Quantification, proper handling and disposal of contaminants and proper deductions for their presence in the inbound feed is key to safety, environmental compliance and the economic bottom line of any scrap yard. Facilities can do their best to be clear to their staff and meticulous with their suppliers about what they will and will not accept at their facility and in what form things need to be delivered, but unwanted materials inevitably slip through. Reducing the frequency and likelihood of these occurrences will be a significant stride forward for the industry.

3.1. Inbound material identification

Inbound material identification (IMI) is a persistent challenge in the metals secondary industry; incorrect inbound inspection costs scrap processors money and time. An experienced scrap inspector can combine their knowledge of the metal’s application, observe its density (heft) and the visual appearance of the surface, and utilize a few standard tools to help them group the metal scrap into Al + Mg alloys, ferrous steel, cast iron, stainless steel, Zn alloys, brasses, and bronzes. In the past, an inspector equipped with a magnet, file/knife, various acids, and a grinding wheel would be enough to sort scrap effectively and efficiently. However, the increasing complexity of alloy design and usage coupled with growing volumes makes these tools no longer adequate. Fig. 1 demonstrates the multitude of steps that must be taken to identify the major alloying element (in the absence of characterization and sensing technologies). The red boxes are the extent of IMI that can be achieved given the standard tests denoted by the blue boxes. The starred yellow boxes following the red boxes are opportunities for further verification using acids. Acid testing is far less common, but it is a means that yards have been able to use to assist in some level of identification. Another method that is commonly used but not identified in the diagram is observing the density of the material in question (how heavy the material feels). This is especially apparent when distinguishing Pb from other metals or Zn alloys from Al. To determine the trace elements that are present requires a more extensive analysis with specific acids but even once detected (if at all), you will not be able to determine the percentage of the elemental composition it possesses. Certainty of specific alloys cannot be determined with this method – it is only with knowledge of the metal’s application that one would be able to deduce the likeliest alloy. Elemental analyzers based on x-ray fluorescence (XRF) and laser induced breakdown spectroscopy (LIBS) may have potential for mitigating this issue and are discussed in more detail in the technology assessment (Section 4).

3.2. Contamination and deductions

Contamination comes in many forms and it can occur before it reaches the yard or within the yard itself. It can be as simple as non-metals: dirt, moisture, oils, concrete, paper, wood and plastics to more serious things like radioactive contaminants. What is considered contamination depends on the specification of the category of inbound scrap. In a load of source-segregated scrap of specific alloy, any other alloy or material is a contaminant. In a mixed metal load there are nonmetallic contaminants, and a load of a shredder residue might have a specification of minimum metal content in the non-metal residue. Depending on the type of load the scrap yard is preparing to receive, different inspection procedures are required.

Fig. 1. Above is a simple flowchart demonstrating what capabilities standard tools (that lack advanced technology) can provide.
In any case, contamination in excess of allowed specification means deductions must take place and making accurate quantification of proportion of contaminants is extremely difficult to do just by looking at a load. How do you know what is actually representative of what you are receiving when you cannot see what is in the middle or the bottom of the pile? Unless you sort piece by piece, you can never be sure. However, due to fast, frenetic operations, visual estimates of contamination are usually made prior to combining the inbound load with similar feed material from other sources. Sometimes the load is sampled and the sample is sorted to estimate the proportion of contaminants. Attempting to quantify and handle contamination is a costly endeavor: directly by finding a large quantity of lesser material mixed in and having paid for a higher value commodity, or by the time it takes to sort or process the contamination out, or by the weight you lose in form of moisture, dirt, foreign material or attachments. Managing and handling contamination is a vital part of operations for quality control but also for safety, economic, and environmental reasons.

Some of the larger scrap metal sorting plants that have suppliers with established supply records will pre-process each specific type of scrap from the given supplier separately through what is known as a “wash plant.” It is designed as part of a process to remove most of the non-metallic contaminants from a load, then proceed to sample and hand-sort the wash plant output. This allows the purchaser to get a good estimate of both the metallic recovery and also the contamination out, or by the weight you lose in form of moisture, dirt, foreign material or attachments. Managing and handling contamination is a vital part of operations for quality control but also for safety, economic, and environmental reasons.

Preparation of output loads to ISRI scrap specifications involves size reduction to below the maximum permitted piece size, removal of foreign attachments, removal of contaminants, and sorting. Processing and sorting have the potential to upgrade inbound scrap and, in many cases, generate a financial margin that can be beneficial to the yard. Due to threats such as furnace explosions, equipment failure, and the accumulation of impurities, material must always be thoroughly inspected, and contamination must be reduced to below the specification level. Depending on how material comes in and in what volume, the process can be simple or quite involved. Loads can come across the scale: loose, mixed, stacked on pallets, in gaylord boxes, baled, supersacks, shrink wrapped, etc. Material that comes in already boxed should be dumped, bales need to be broken (unless inspected prior to baling) and dumped loads from roll-offs need to be inspected and separated. Unless packing terms are established prior to shipments, yards have to be prepared for any number of possibilities.

Additionally, to upgrade material and/or avoid potential downgrades, material can be processed. Processing or cleaning material refers to the act of removing contamination and/or appropriate grouping. For instance, a load of steel is spread on the dumping floor then collected with a lifting magnet leaving behind liquids, non-metals, and non-ferrous metal pieces. The remaining non-ferrous could be grouped “as is” but if market conditions are favorable and time and equipment are available, there is potential for a #2 copper for instance, to be processed and become a #1 copper by shearing off a soldered joint, or “iron/dirty aluminum extrusions” can be transformed into a clean or painted 6063 alloy by removing a weather-strip and a couple screws. There are many difficulties presented in processing and upgrading scrap especially when you factor in time as a variable and needing appropriate tools to accomplish said tasks. Equally challenging is being able to actively and accurately track these undertakings. The action of manual processing inherently requires material being handled multiple times and often by multiple people. Furthermore, if the market is volatile, pricing and processing can make sense when the material is delivered but may possibly not be economically feasible tomorrow and, in some instances, drastic changes can happen within the same day.

3.4. Inspector training and communication with suppliers

Training for operating equipment is very matter of fact, detailed and well-defined. However, those working in the yard inspecting or sorting and those managing sales and purchases have to think fast and on their feet. There are common, core items that flow through yards but on any given day, materials that flow through a yard can be sporadic and unfamiliar and there is no surefire way to train for this. In scrap yards, learning is very hands on and repetition based. This makes the job physically and mentally challenging and difficult for employers to find skilled workers. It can take months to begin to recognize what a given metal is without help and with cognitive certainty. However, as mentioned in the discussion on IMI, commodities are becoming more complex and thereby cognitive recognition will become more challenging. Technology, in the hands of someone who is trained how to use it, can diminish the amount of time it takes to learn how to visually identify materials moving through a plant. It is also important to consider that the time it takes to train someone costs money and there is no guarantee that workers will not take their skills elsewhere once they have acquired them.

Good communication between the supplier and the purchaser is crucial in this line of work but it is a constant struggle to achieve. Misinformation can lead to mistrust between buyer and seller. Suppliers can claim to have a particular item and it not be what they thought; this can be a genuine mistake or an intentional act in attempt to receive better pricing. Another contributor to this communication barrier is that the industry has inconsistent terminology. There can be multiple names used to describe the same thing or one of those names could mean something very different to a particular buyer/seller. For instance, “dirty aluminum” to some means aluminum with iron attachments and maybe even a specific (max/min) percentage of iron is expected but to others it might mean that it has plastic or excessive oil/grease. This dilemma stems from a widely varying supplier base and requires that material be confirmed as claimed/interpreted. The aforementioned ISRI Scrap Specifications Circular, provides guidelines for buying and selling a variety of processed scrap commodities, including ferrous and nonferrous scrap; other countries have similar standards. It is a good start at managing this problem for the scrap yard products, but many scrap yards purchase a proportion of their scrap from peddlers unfamiliar with ISRI and its specifications.

4. Technology assessments

This technology assessment covers material characterization and sensing techniques, in addition to separating and sorting technologies that are or have been utilized in the industry thus far. The technologies described below include a description of the technology, the materials it can be applied to, pros and limitations of its application, as well as representative vendors.

4.1. Material identification and separation

The following presents an overview of several common techniques for metals analysis that contribute to/aid in IMI either by
way of an x-ray-based instrument, through the formation of a plasma, or by neutron activation. Many of these techniques have been incorporated into sensing technology and sorting systems which will be presented in the following sections.

4.1.1. X-ray based
4.1.1.1. Radiation/X-ray detectors. A radiation detection system can detect and locate nuclear or radioactive materials. Radiation detectors passively monitor ionizing radiation in the form of gamma rays, or x-rays in a Geiger counter type ionization chamber, or in scintillator crystals. In more sophisticated systems, measurement of gamma or X-ray energy provides information of the nuclear event that generated the detected photon. These systems are capable of scanning more than 150 vehicles per hour in the typical flow of checkpoint traffic (Liu et al., 2008). Additionally, they have sensitive radiation detection with a very low false alarm rate and quick data integration and display. When installing the detectors, it is important to keep in mind variations in truck sizes as to avoid a case in which the truck is too large to pass through. Example vendors include: Leidos, Inc., Rapiscan Systems, RadComm.

4.1.1.2. Dual energy X-ray transmission (DE-XRT). DE-XRT sensors are universally used for airport luggage inspection and medical applications, the main difference being the data processing and image analysis software. A DE-XRT sensor provides an image of the materials, and the color and intensity give a relationship between the atomic number and the inspected material. The high density or high atomic number metals (atomic number 26 and higher) which have a high transmission damping show up darker in the image compared to the low-density metals (atomic number 13 and lower). The material shape and size can also be determined from the image. Metal recyclers can use DE-XRT sensors in belt type particle sorters to separate light metal scrap particles (Al and Mg) from dense nonferrous metals (Zn, Cu, Brass) as well as being able to sort out the non-metals from things like automotive shredder residue (ASR). DE-XRT technology is unique in that it is not interrupted or highly affected by surface contamination however, current commercial sensors do not have sufficient resolution to distinguish between the dense metals or their alloys, or between the light metals and their alloys. Tomra and Steinert are some well-known vendors of DE-XRT sensors.

4.1.1.3. X-ray fluorescence (XRF). X-ray fluorescence spectrometry is a two-step process that begins with the removal of an inner shell electron of an atom and the resulting vacancy is filled by a valence electron. The second step is the transition from the outer shell electron orbital to an inner shell electron orbital. This transition is accompanied by the emission of a fluorescent photon which holds characteristics of the element and is equal to the energy difference between the two electron energy levels. Thus, the energy of the fluorescent photon provides qualitative information concerning the elements’ identity. The number or intensity of fluorescent photons is characteristic of the amount or concentration of the elements present. The energetic X-ray spectrum can penetrate through a considerable depth of material, and that depth increases with the X-ray photon energy. This is used in X-ray transmission imaging.

X-ray fluorescence instruments are either energy dispersive x-ray fluorescence (EDXRF) or wavelength dispersive (WDXRF) spectrometers. X-rays are short wavelength electromagnetic radiation. A conventional X-ray spectrometer generally utilizes the region of about 0.1–11 nm. In a WDXRF instrument an X-ray monochromator is used prior to the X-rays impinging on the sample. An EDXRF instrument does not possess a monochromator. These multichannel instruments measure all the emitted X-rays simultaneously, thus EDXRF has the Fellgett (signal-averaging) advantage. The analytical information an XRF spectrometer provides can be both qualitative and quantitative in nature. One of the most important uses of XRF is its capability to provide rapid, real-time qualitative elemental analysis on many types of samples. EDXRF is an excellent qualitative tool. All elements are detected simultaneously, and a complete spectrum can be obtained in a minute or less. Many analytical problems can be solved solely on the basis of qualitative information. Quantitative information can also be obtained using X-ray fluorescence. These determinations are usually based on a linear relationship between the emitted X-ray intensity and concentration of known standards (Blitz, 2016). Calibration free algorithms are also available, adequate, and often used in EDXRF analysis.

EDXRF sensors utilize X-rays to generate X-ray fluorescence (XRF) from the unknown sample in order to obtain an identification of the particular alloy under consideration. They have been commercialized in both handheld elemental analyzers (HHs) and in belt type particle sorters. As HH analyzers’ capabilities continue to improve and their prices decrease, they are becoming more widely used in scrap yards for manual alloy identification. EDXRF sensor particle sorters have been commercialized to find copper meatball contaminants in the ferrous shred product of steel shredder plants. They have the potential to replace manual picking from the main product stream or from the reject stream of the ballistic magnetic separator. Although XRF is a beneficial tool for elemental analysis and alloy identification it does have some limitations. Technology is continuously being developed to improve XRF’s lower precision for and difficulty in detecting light elements as well as improving read times to obtain quicker PMI. There are also extra safety precautions that must be taken when dealing with such instruments for they do emit radiation. Manufactures for handholds include, but are not limited to, Olympus, Oxford Instruments, Bruker, SciApS, etc. Tomra and Spectramet are known vendors for EDXRF sensor particle sorters.

4.1.2. Spectroscopy based
4.1.2.1. Optical emission spectroscopy (OES). Optical emission spectroscopy is a non-intrusive and non-disturbing plasma characterization technique. It relies on the detection of photons which are emitted during the de-excitation of the energetic particles in the plasma. Since the length of time associated with de-excitation energy transitions are very short, it is possible to obtain time-resolved measurements down to the nanosecond when using equipment with a sufficiently high sensitivity. OES can be utilized in various forms. For example, a plasma can be generated by microwave excitation as in induced coupled plasma (ICP) OES where the sample dissolved in acid is injected into the plasma generator. ICP-OES is among the most precise and accurate primary quantitative elemental analytical methods. In the case of arc spark-OES, an electric arc is used to melt, vaporize, and ionize a small sample of the metal alloy. The plasma emission is then analyzed by OES. Arc spark-OES is the standard industrial analytical method for elemental analysis of metal alloys. Another form of OES that is becoming more and more popular is incorporating a pulsed, focused laser beam that can also vaporize and ionize metal alloys. The light produced from the resulting plasma spark is analyzed by OES in laser induced breakdown spectroscopy also referred to as LIBS.

The data obtained by optical emission spectroscopy contains a large amount of information. Every optical transition is precisely characterized by electronic transitions to which are also added to the vibration energies of polyatomic particles. The position of each spectrum line therefore gives important information on the chemical composition of the plasma whereas their relative intensity informs us on the energy distribution between the various species in the plasma (Martinu, 2016).
4.1.2.2. Laser induced breakdown spectroscopy (LIBS). The LIBS technique relies on the use of a pulsed laser source to generate a high-temperature plasma that vaporizes a small amount of material, then the emitted spectra of the plasma is translated to material identification (Musazzi and Perini, 2014). A portion of the light emitted by the excited atomic and ionic species in the plasma is then collected and spectrally analyzed to determine the sample elemental composition. Quantitative LIBS analysis can also be performed when the assumptions of local thermal equilibrium (LTE) and optically thick plasma are satisfied (Anabitarte, 2012).

This technique has features like the absence of sample preparation, the ability to perform real-time, and in-situ analysis as well as a quasi-non-destructive and micro-analysis characterization of the laser beam sampling. Small laser focus makes the analysis sensitive to surface contamination and microstructural inhomogeneity. LIBS is considered a surface technique because unlike the varying penetration depth of XRF, pulse lasers can only penetrate a very small distance into the surface of a metal. Unless laser ablation pre-cleaning is incorporated in the analyzer, which adds additional time to the analysis, scrap that is not free of water, lubricants, paint, and other coatings will report inaccurate and/or less precise measurements. LIBS technology is said to have the potential to measure all elements of the periodic table although, it does struggle with Pb alloys, and refractory metals (i.e. W, Cr, Ti). LIBS sensor has been industrially implemented by Huron Valley Steel on a steel type particle sorter for Al alloy batching from scrap Al, and a commercial version has been under development by Tomra for some time. However, there has yet to be a full-scale particle sorter system commercially available in the general marketplace. LIBS based HH elemental analyzers have been recently commercialized by several manufacturers such as Rigaku, SciAps, and TSI Inc.

4.1.2.3. IR & NIR spectroscopy. Near-infrared (NIR) and infrared (IR) spectroscopy are absorption methods involving wavelength regions of 1–10 μm and 10–100 μm respectively, that extends the region of visible light to longer wavelengths and smaller frequencies/energies. Infrared radiation excites vibrational and rotational motions in molecules. Except for the differences in the energy transfer from the radiation to the molecule, the principles of IR spectroscopy are the same as those of UV–Vis spectroscopy or other spectroscopic techniques. The absorption of infrared light is characterized by the Bouger-Lambert-Beer Law. (Kleinschmidt, 2000). Desktop IR spectrometers identify plastics in 5 s. Accuracy depends on quality and completeness of the reference spectra library. The accuracy of identification on the American Plastics 37 Council 30-piece reference set was 90–100%. Most errors tend to be between closely similar polymers (acrylonitrile butadiene styrene [ABS] vs. styrene acrylonitrile [SAN]; polyamide 6 [PA6], also known as nylon 6, vs. polyamide 6/6 [PA66], also known as nylon 66; and polyethylene terephthalate [PET] vs. polybutylene terephthalate [PBT]).

4.1.2.4. Prompt gamma neutron activation analysis (PGNAA). In the Prompt Gamma Neutron Activation Analysis (PGNAA) technique, the elemental concentration of the sample is determined from the intensity of the prompt gamma-rays emitted by the sample due to its irradiation with neutrons (Lindstrom, 1993). The nuclei of some elements of a sample placed in a field of neutrons absorb neutrons and are transformed to an isotope of a higher mass number. Conventional neutron activation analysis employs the radiations emitted during the decay of radioactive products for elemental analysis. Some elements do not produce radioactive capture products but do emit prompt gamma rays at the time of neutron capture. If the sample is placed in an external neutron beam from a reactor and viewed by a high-resolution gamma-ray spectrometer, these gamma rays allow qualitative identification and quantitative analysis of the neutron-capturing elements present in the sample. The neutrons do not interact with electron shells and the probability of their capture by the nuclei is small; they can penetrate through a large depth of metal scrap. The energetic MeV characteristic gamma rays can escape from the full depth of the scrap layer conveyed on the belt. This permits an 100% analysis of all material in the stream, eliminating the representative sampling issues. While the neutron capture and the gamma ray emission probabilities vary from element to element, in principle quantifiable signal can be detected from every element, Hydrogen included.

PGNAA sensor systems are well established in the mining industry and are designed to handle high volume flows of material. Real time, full stream, accurate measurement of conveyed material average elemental composition irrespective of particle size and belt speed are possible. When a material stream is determined to be off-spec / contaminated, diversion of these segments of the material stream is possible. This would make it quite easy to stage mill feed material by composition/purity. This process could be utilized to improve melt quality and decrease cost by preemptively diverting off-spec loads. Gamma Tech has done significant work on the application of PGNAA cross belt analyzers for scrap metal, both ferrous and nonferrous. The first generation of PGNAA cross-belt analyzers were developed with radioisotope neutron sources like Californium, which continuously decays to produce a slowly decreasing flux of neutrons. Newly developed Deuterium-tritium fusion neutron sources are now beginning to be deployed in PGNAA sensors for cross-belt analyzers. Their neutron flux is electrically controlled and can be turned off when analyzer is not in-use. They are priced to be cost competitive with Californium radioisotopes and have a potential for future price reductions. Vendors that continue to work on incorporating PGNAA technology into applications for scrap processing and identification include Thermo Scientific, Gamma Tech, Sodern, PAN Analytical, and Gradel Fustion.

4.2. Diversion, separation, and sorting technologies

Diversion, separation and sorting technologies primarily involve the ‘piece and particle stream’ once material has been purchased into a metals processing facility. These techniques are capable of sorting/separating strictly by the metal type (ferrous, nonferrous, and/or color but not by alloy), by alloy, and have the ability to sort out nonmetal (i.e. plastic, foam, etc.) from metal.

In contrast with identification techniques, piece/particle sorting technologies are not just one component, they are a combination of moving particle line singulation or monolayer presentation system, sensor(s) measuring the particle property(ies), and a diversion system. Systems that utilize a combination of different sensors can achieve impressive selectivity and property resolution.

4.2.1. Physical diversion

4.2.1.1. Conveyors and diversion. A stacking conveyor pivots about its tail pulley allowing its head pulley to deliver the output to a selected storage bin. Combined with a PGNAA cross belt analyzer, this would enable scrap composition-based batching in an electric arc furnace (EAF) steel mill. In this application, the maximum piece length is ~1.2 m. A flip chute does not target individual particles, rather it diverts a defined portion of a stream that contains unwanted impurities or directs a stream of a particular composition or other characteristics to a selected output stream. This is a suitable solution to use with PGNAA cross belt analyzers, which do not have sufficient resolution to target individual scrap pieces but do provide accurate average stream elemental composition results. In this application the maximum piece length is ~300 mm.
Electromagnetically or pneumatically activated 'sweeps' push selected particles out of a singular line of particles which does not make it optimal for large throughput. Typically, this method is used for large particle, low volume applications and for laboratory proof-of-concept systems. Electromagnetically or pneumatically activated paddles rotate into the in-flight particle monolayer, diverting selected particles out of the particle stream. Paddle diverters compete with blow bars in belt particle sorters for handling of larger particles ~7–30 cm, however is not suited to handle particles >1 kg. Eriez is a manufacturer known to produce paddle diverters.

An excavator arm mounted grapple is essentially a pick and place device under the control of a skilled operator. It can handle loads of several tonnes and maximum piece sizes of 2–3 m. Mounting of appropriate sensors on the excavator arm could significantly improve the sorting capability of the grapple. For example, a color CCTV camera and a suitable flood lighting system could be used to improve operator's view of the scrap piece(s) being handled. Providing this system with artificial intelligence (AI) recognition software could allow it to tell the operator in real-time what it is that's being handled and where to put it.

4.2.2. Air separation & blow bars. Air flow can separate materials by density, size and shape. Some different means in which air separation can be utilized include air circulation through a hammer mill which has the ability to carry out a significant portion of light fluff: foams, textiles, paper, foils, etc. Additionally, conveyor belt systems use suction nozzles to pull off lightweight fluff from the hammer mill output. Vertical air separation systems feed scrap through a zig-zag column with air pushing upwards; heavier materials are collected at the bottom and other materials are pushed through feeds further up. A cyclone separator uses centrifugal force of a spinning air vortex to separate entrained lightweight particles from the air-fluff stream. Blow bars consist of a row of closely spaced high pressure air nozzles that are activated just at the right time, blowing selected pieces out of an in-flight particle stream. Typically blow bars are located near the head pulley of a sorting belt or near the end of a sorting chute. Each blow bar is coupled to a single output chute. Up to three blow bars have been assembled on a single particle sorter allowing separation of the input stream into upwards of four output streams, blowing out one particle at a time. These systems can be very fast allowing sorting of ~30% area-loaded <2 m wide sorting belts at speeds of ~3 m/s. Blow bar individual particle diverters are popular for color sorters, ECC metal detector sorters, DEXRT sorters, and XRF sorters. Blow bars are nearly universally used in industries for diversion for either belt or chute type sensor-based particle sorters. In general, air separation techniques are considered to be mature industrial, low-cost technology solutions.

4.2.2. Field/force based diversion
4.2.2.1. Electrostatic separators. Electrostatic separators are used to separate conductive products from non-conductive ones. The metal mixture to be separated is introduced via a vibrating conveyor to a rotating earthed metal drum and transported to the area of a corona electrode. The material is electrostatically charged there with up to 35,000 V. Conductive materials (metals) give up their charge very quickly to the drum and are ejected by the rotating movement. The non-conductive materials however lose their charge only very slowly, remain adhered to the surface of the metal drum and are finally brushed off. The material is therefore separated into a conductive and a non-conductive fraction. The material stream to be separated should be a conductive/non-conductive mixture of fines, between 1 mm and 8 mm, dry (surface moisture <0.2%), completely liberated mono-material particles and be predominantly dust-free for adequate separation. Electrostatic separators are an efficient way to regain valuable metals by pulling out nonmetals or to rid nonmetals from metal parts before further processing. It is a dry separation process capable of delivering high metal purities and optimal for fine metal particles in mixtures of metal and non-conductive materials with high metal content. Typical applications include cable and electronic waste, granulated printed circuit boards, and metal grinding dust. Steel shredder fines and granulated light fractions are predominantly nonmetal and are typically very wet. Dry feed material is required to operate which can often cause the drying cost to exceed the value of the metal recovered, thus, a shredder plant is not a preferred installation for electrostatic separation. Hamas is a known vendor of electrostatic separators.

4.2.2.2. Eddy current-based metal detectors, sensors, & separators. The utilization of the eddy current is nothing new to those in waste management and recycling but there are additions that can be made to these systems. One example of this is an eddy current coil metal detector. These metal detectors typically consist of two coils, an emission coil that generates an alternating or pulse magnetic field and a detection coil that detects them. Any metal that is in the magnetic field changes the magnetic circuit impedance and generates an output signal proportional to metal particle size and conductivity. Metal detectors can be installed on residue conveyor belts to monitor and quantify the amount of metal lost to the landfill, and to signify need for process corrections required to eliminate these losses. Furthermore, an array of small eddy current coil metal detectors can be used as a sensor for a metal sorter, separating residual metal from the eddy current rotor (ECR) sorter residue stream to create zurik, a nonferrous scrap package with a high percentage by volume of stainless steel (SS). Some of these sensors can locate the metal pieces on the sorting belt and distinguish between diamagnetic (i.e. Al, Cu, brass and Zn) and paramagnetic (i.e. SS) metal pieces by analyzing the phase shift between the emitted and received alternating magnetic field signal. With diamagnetic metals, the received signal leads, but for paramagnetic metals, the received signal lags. In this group of technologies, differences in scrap particle properties generates a difference in the force on the particle that automatically directs the particle either over or under the splitter. Typically, these are binary separations, but in some cases a split into three streams is practiced.

Although such technology has high throughput capability and typically low cost, a major limitation of the current metal detectors that exist on the market is that they simply count the number of metal pieces above the threshold size. There is however a potential for developing detectors that estimate the quantity of metal lost by taking into the account the size of the individual signal pulses, and differentiating between diamagnetic nonferrous, paramagnetic stainless steel and ferromagnetic steel. Vendors of eddy current coil-based metal detectors and particle sorters include: Eriez, Tomra, Steinert, and S + S.

4.2.2.3. Eddy current rotor separators (ECRs). When an efficient force separation method is available, typically it is more cost effective than the same separation line with a particle sorter. A strong eddy current force is generated in an electrically conducting particle when it is exposed to a fast alternating magnetic field. By Lenz's law, eddy current force repels the particle from the source magnetic field. This principle is utilized in eddy current rotor separators (ECRs) which use a fast spinning roll surfaced with alternating N and S rows of permanent super-magnets to generate the local alternating magnetic field. ECRs utilize an alternating magnetic field that generates eddy currents and electrically conductive particles get repelled from the rotor field ejecting conductive non-ferromagnetic particles. Ferromagnetic attraction
dominates the eddy current repulsion and ferrous particles are strongly attracted to the rotor and are spun by the high frequency pole changes, drilling holes in the belt and the rotor shell. Thorough magnetic separation of ferrous particles from the ECR feed is a must.

ECR repulsion is highly dependent on particle size and shape. Different ECR designs are necessary for large and small particles. Closely sized particle feed streams give better results. Some shapes (e.g., wires and foils) fail to be separated out by ECRs that are designed for large particles due to insufficient eddy current generation. Smaller particles need a higher frequency (HF) magnetic field to generate sufficient repulsion. Manufacturers are now marketing HF ECR’s specifically designed for metal separation from fines. This then enables additional metal recovery from grit and fines screened from 1 mm to 9 mm. The metal recovered from such grit and fines are mainly cast Al grit and small pieces of Cu wire.

An ECR’s splitter can be adjusted for either high product purity or high product recovery. Achievement of both requires ECR separators in series or multiple passes through an ECR separator. ECRs are sometimes operated with two splitters to obtain high purity and high recovery fractions in a single pass through the separator. In general, ECRs separate electrically conductive non-magnetic materials from nonconductive materials. Materials recovery facilities (MRFs), use ECRs to separate Al beverage cans from other nonmetallic containers. They are currently used in shredder plants for Zorba recovery, a nonferrous scrap package high in aluminum content. They are also used in nonferrous metal sorting plants to produce pure Twitch (Al scrap product). Stainless steel and lead fines, however, are poor electrical conductors and stay in the nonmetallic stream. They can be detected and separated by eddy current coil sensor-based particle sorters described above.

4.2.2.4. Magnetic separation. Magnets are one of the most valuable tools when it comes to sorting metals. They are you’re “go to” tool for extracting ferrous metals from waste streams by means of magnetic attraction. Although materials containing iron are most prevalent and of lower value, which is why it is essential to be able to extract them from higher value commodities easily, nickel and cobalt are also able to be identified using magnetic forces. Magnets are available in several different configurations. For instance, there are scrap lifting magnet attachments for excavator arms (often in combination with grapples), primary drum magnets separating ferrous shred from the shredder output, over-belt magnets pulling up residual ferrous from nonferrous stream conveyor belt, and magnetic head-pulleys pulling down residual ferrous from nonferrous stream conveyor belt head pulley. Additionally, there are secondary drum magnets diverting residual ferrous, pieces with ferrous attachments, and slightly magnetic particles from the nonferrous stream as well as a magnetic ballistic separator that uses momentum to throw ferrous particles with substantial nonferrous attachments over the splitter, while the magnetic head-pulley pulls the clean ferrous product down short of the splitter.

With a magnetic ballistic separator, residual nonferrous and other non-magnetic materials are not affected by the magnetic field and fly over the second splitter. A magnetic ballistic separator permits nearly automated production of clean ferrous shred product at the shredding plant. There can be significant improvements seen in the ferrous shred purity and nearly complete removal of shred pieces with substantial Cu/brass attachments (meatballs). It is a lower cost, higher throughput solution as compared to XRF sensor particle sorter and is usually suggested as a replacement for handpicking in this application. The downfall is that up to 20% of the ferrous in the feed reports to the Cu “meatball” output stream requiring recovery of clean ferrous from this stream, and of clean nonferrous from the residue stream.

Nearly all these magnetic separator configurations are available with either permanent magnets or electromagnets. In most cases, the permanent magnet units are less expensive to buy, operate and maintain. One can use magnetic separators in these configurations to design simple, low-cost circuits to separate the ferrous portion of most of the ferrous scrap types in scrap yards from the problem impurities such as sand, dirt, rocks, saw, ice, water and other fluids. Overall, magnets are efficient in separating ferrous from nonferrous content. Rare-earth (RE) magnet units can even separate slightly magnetic austenitic stainless steel.

The introduction of rare earth magnets was a major advancement in magnetic separation techniques because they have much higher magnetic strength than conventional ferrite or ceramic magnets (up to 25 times more pull), yet provide similar circuit stability and long service life. The magnetic strength of the RE magnet falls in the medium-intensity range – 4000 to 10000 gauss. Most widely used RE magnets contain an NdFeB intermetallic composition. Properly designed RE magnets also have high magnetic gradients and a greatly increased holding force. This means they can “reach out” and attract weakly magnetic or very fine iron contaminants and hold them so tightly that wash-off by-product flow is virtually eliminated. The RE magnet field strength and reach makes them well-suited for improving the recovery of:

1. Steel shred and other particles with attached steel on primary magnet drums.
2. Nonferrous particles with steel attachments.
3. Weakly magnetic contaminants, such as iron oxide or rust, which do not respond well to conventional ferrite magnets.
5. Conductive nonferrous metal particles by eddy current separators.

Although magnets are a powerful tool the following limitations exist. A circuit with a series combination of different magnetic separators is necessary to efficiently separate clean ferrous, from mildly magnetic iron oxides, from pieces with nonferrous attachments and from stainless steel. Magnetic separators alone cannot deal with multi-material assemblies such as cars, white goods and other mixed old scrap. These need to be shredded and mono-material pieces must be liberated before clean ferrous fraction is magnetically separated. Vendors that provide magnetic separation solutions include: Eriez, IFE Aufbereitungstechnik GmbH, IMRO, Steinert US, Bunting Magnetics Company, Ohio Magnetics, Recycling Equipment Manufacturing, SGM magnetics, U.S. Shredder & Castings, Walker Magnetics.

4.2.3. Fluid based diversion

4.2.3.1. Fluidized bed sink-float. An inclined vibrating air table fluidizes the low-density particles in the feed stream. These flow down the slope while the dense particles are not fluidized and are conveyed by vibrations up the table slope. This is effective for small, close in size particles and is used to separate plastic insulation from chopped copper wire. For fluidized sink-float, the bed of sand is fluidized by the forced airflow where the speed of the airflow controls the density of the sand. Al and Mg floats while Fe, Zn, Cu and brass sink. Products are separated from the sand by screening. However hollow shapes get filled with non-fluidized sand and sink regardless of density, reducing the recovery of light products and contaminating dense products.

4.2.3.2. Heavy media separation. Feed material mix that is sized to below ~150 mm and has ranging densities, are placed into a liquid bath of water with a specific gravity (SG) of 1, or water containing a fine suspension of magnetite with an SG of 2, or ferrosilicon with an SG of 4.5 in water. The quantity of magnetite or ferrosilicon in
suspension is adjusted so that the fluid is in between the specific density of the alloys that are to be sorted. Heavy media is one of the most effective high-volume methods for sorting plastics, wood and rubber from mixed aluminum, and from other heavier nonferrous metals recovered from automobile shredder nonferrous concentrates. However, this method is not effective when sorting higher-density alloys, since it is not practical to achieve fluid-specific densities in the range of 7.0 g/cc or above. Additionally, there is the issue of added contamination from any dense, hollow or boat-shaped components for they are likely to float. Furthermore, there is high cost of maintaining constant density slurries. Some known vendors for heavy media separation include FLSmith Minerals, ESR International, and AD REM.

5. Discussion and future work

The technology appropriate for a particular metal scrap recycling plant depends on the plant size and its location in the processing chain. The two items of technology that are common to all plants are the radiation detectors and weighbridge scales. In the case of the industrial scrap yard, current inbound inspection practice involves a visual confirmation of the scrap category in a video camera image of the top of the load by the scale operator. The unloaded pile in the scrap yard is visually assessed by an inspector to confirm the scrap category declared by the supplier, qualitatively estimate the proportion of contaminants in the load, and to assign the applicable deductions. As loads of new (prompt) scrap are typically compositionally homogenous, sampling a few pieces of each distinct shape, and testing them with a hand-held elemental analyzer gun is sufficient for some degree of positive alloy identification.

Such in-depth inspection for nominally ferrous scrap may consist of transferring the unloaded scrap load from the dumping floor to the storage location for this type of scrap with a load cell-equipped lifting magnet. The load-cell data would record ferrous scrap weight, leaving contaminant moisture, nonferrous and nonmetallics on the dumping floor. In some cases, the inbound trailer of nominally ferrous scrap may be unloaded with such a lifting magnet leaving the contaminants in the trailer to be returned to the supplier. For shredding plants, the feed is predominantly oversized ferrous steel scrap and multi-material assemblies inbound elemental or alloy identification is less of an issue. Minimill customers value low amounts of Cu, Ni and Cr in their ferrous scrap shredded feed. Getting a good value for the nonferrous metal concentrates is easier with consistent composition and metal content of each of the metal concentrates produced by the non-ferrous recovery circuit. Finally, metal content in the nonmetallic residue is both direct financial loss and an indication of lack of control in the metal recovery and sorting circuit.

The information provided in this document is only capable of evaluating the economic feasibility of the technologies listed to a certain degree. Economic assessments should ultimately analyze and calculate a business’s return on investment (ROI) for a given technology in the realm of their operation and that requires a very involved, specific and technical valuation that will be unique in every case. There are frameworks that can be and have been developed to estimate ROI pre and post the introduction of advanced technology. These frameworks involve quantitatively structuring material flows and understanding how incoming materials are transformed or upgraded into output grades to be transferred or sold in the scrap market. Other methodologies will need to be employed to clearly understand other aspects. For example, a life-cycle assessment could be applied to a specific yard-mill case and studied to understand the improvements in environmental performance metrics. Technological strategies may also enable enhanced operational strategies like blending algorithms and reverse logistics models.

The more work being done to understand the past, present, and future challenges of waste management and recycling, the quicker we can arrive at solutions to overcome them. Comingled streams are becoming more prevalent and at a faster rate than the industry has been able to keep up with. This has a lot to do with the fact that technologies being developed for IMI do not perform ‘in-field’ as well as they do in theory. Instruments and advancements in technology for the secondary metals industry must be specifically designed for these types of operations and the only way to do that is to understand how they in fact operate in-situ.

The metals recycling industry plays a critical role in the future of sustainable development. It is understood that improving secondary utilization rates will require much more than a simple technology solution, i.e. systematic improvements within material handling facilities. Beyond the secondary metal industry there will need to be improvements in alloy design, enhanced consumer participation, and extended producer responsibility. Reduction in primary extraction, conservation of materials and energy, preservation of land and resources, are just a few of the many reasons we need to prioritize addressing the challenges presented in this report. Fundamentally, if we are to seriously shift worldview to a circular economy approach, we genuinely require a system that can handle and support that shift.

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