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Modeling the Profitability and Environmental Impact of Alloy Scrap Sorting & Specialized
Scrap Melting

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ABSTRACT

The ferroalloys used in the melting of steel to give it its desired elemental alloy composition make up a significant portion of the steel's cost and greenhouse gas emissions. These ferroalloy additions require intensive mining and refinement. Just like the melting of scrap steel, the costs and emissions of ferroalloy can fluctuate widely depending on the location of the mine and refinery, as well as the element and purity of the ore mined. When melting steel scrap with an intensive melting process a significant portion of these crucial alloying elements already contained within the scrap are lost to the melt slag and need to be replaced with ferroalloy additions. Typically, with low-quality mixed scrap, this intensive melting process helps remove impurities and dirt which could negatively impact the microstructure and properties of the steel. However, this is a considerable problem with high alloy scrap, as the elements lost to the slag can make up a significant portion of the steel's melting cost. To effectively utilize this value, scrap should be sorted based on its elemental composition and melted with a method that preserves the alloying elements within the steel melting. Using data on furnace elemental loss coefficients and CO₂ emissions factors for transportation/refining, a blend of scrap steel can be optimized to minimize ferroalloy additions, reducing material costs and greenhouse gas emissions.

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Chapter 1

Introduction and Background

With the impending effects of climate change leading to decarbonization efforts across many industries and increasing demand for raw materials, the prospect of remelting quality scrap steel has become increasingly important. It is estimated steel production makes up roughly an estimated 7 to 9 percent of global greenhouse gas emissions [1] with annual steel production surpassing 1950 million tons in 2021[2]. Through utilizing scrap steel melted in an electric furnace steel steelmakers can reduce CO₂ emissions from 1990kg of CO₂/Metric ton of steel made with virgin ore to 270kg of CO₂/Metric ton of steel made with scrap in an Electric Arc Furnace, as well as reducing costs by 439 USD /Mt Ton down to 365 USD /Mt Ton. [3] Typically this scrap steel is melted in electric furnaces which are usually induction or arc-based. The use of an electric furnace compared to a blast furnace shifts greenhouse emissions from fuel burned at the facility to the local electricity input from the power grid which will vary significantly depending on the source of power and percentage of renewable energy on the grid.

Furthermore, the ferroalloys used in the melting of the steel to give the steel its desired elemental alloy composition make up a significant portion of the steel's cost and greenhouse gas emissions. Ferroalloy additions require intensive mining and refinement. Just like the melting of scrap steel, the costs and emissions of ferroalloy can fluctuate widely depending on the location of the mine and refinery, as well as the element and purity of the ore mined [4]. When melting steel scrap with an intensive melting process a significant portion of these crucial alloying elements already contained within the scrap are lost to the melt slag and need to be replaced with

ferroalloy additions. Typically, with low-quality mixed scrap, this intensive melting process helps remove impurities and dirt which could negatively impact the microstructure and properties of the steel [5]. However, with high alloy scrap, this is a considerable problem, as the elements lost to the slag can make up a significant portion of the steel's melting cost. To effectively utilize this value, scrap should be sorted based on its elemental composition and melted with a method that preserves the alloying elements within the steel melting. By utilizing data on furnace elemental loss coefficients and CO₂ emissions factors for transportation/refining, a blend of scrap steel can be optimized to minimize ferroalloy additions, saving on costs, while reducing Greenhouse gas emissions.

Sub-Chapter 1.1 Background on Scrap Steel Remelting

Unlike polymers, ceramics, and most organic materials, metals can be recycled infinitely by melting them into liquid form. The main difficulty in this recycling loop is maintaining the desired composition of this metal during the melting process. Gaseous elements such as hydrogen, oxygen, and nitrogen can dissolve in the molten steel leading to issues in mechanical properties such as embrittlement [6]. Unwanted metals such as tin, lead, and copper often end up in a scrap melt and have detrimental effects on the ductility, strength, and thermal properties of the steel as well as its ability to form a desirable microstructure [7]. To tackle the issue of reaching and maintaining a desired melt chemistry, various refining practices are employed to remove these elements such as blowing in a mix of oxygen and argon as well as melting the steel in a vacuum to allow these impurities to end up in the slag or to leave the molten metal, separating back into the atmosphere.

If a recycling process could ensure a pure input of clean steel the risk of these contaminants would be reduced drastically, and a less intensive melting technique could be used which would reduce the oxidation and reduction of elements in the melt. In methods such as induction melting the steel is heated through rapid changes in magnetic fields and when melting is carried out at a lower frequency a uniform heating of the steel preserves the alloy content of the melt.

Sub-Chapter 1.2 Background on Scrap Steel Collection

In dealing with the recycling of steel scrap the first question in determining its use is its source, manufacturing/process/home scrap, or end-of-life/post-consumer scrap. Manufacturing scrap is produced in machine shops or fabrication has a known chemistry and verified cleanliness. Typically, this scrap is remelted in the facility where it was produced in a melt with a similar chemistry. In select instances, this scrap may not be immediately recycled due to it being produced at a separate facility or the steelmaking process being centered around virgin material versus remelted steel scrap. End-of-life scrap makes up most of the scrap sold in the market and is procured from discarded consumer goods, demolition sights, and salvage operations.

This type of scrap can have significant levels of impurities when using unprocessed general blend scrap. Through various methods of magnetic processing, ferrous scrap can be separated from nonferrous metal. From there on, the scrap can be sorted based on its form. Light iron is made up of thin, easily bent iron/steel that can be easily shredded and processed. This type of scrap is typically coated with either paint or another metal. Pre-heating the scrap should

be able to burn away this coating. Heavy iron scrap is made up of thicker ferrous parts that can't be bent. The preparation of this scrap for melting is made up of cutting it down into smaller pieces. This scrap is comprised mostly of castings and structural steel parts. Specific common cast parts such as rotors, brake pads, recognizable stainless parts, and engine components are typically made with high-temperature processes and have high levels of alloy additions [8].

Most civilians and businesses will only ever interact with local scrap or junk yards which take in scrap metal in the form of discarded equipment, broken parts, and construction/salvage scrap metal. These scrap yards typically sort the scrap as it is received from their customers. These yards usually sell this scrap to larger processors who act as suppliers to foundries and steel mills. These processors typically have specialized equipment to further purify the scrap by removing coatings, oxides, grime, and other metals possessing different magnetic or density properties see Figure 1 for representation of supply chain.

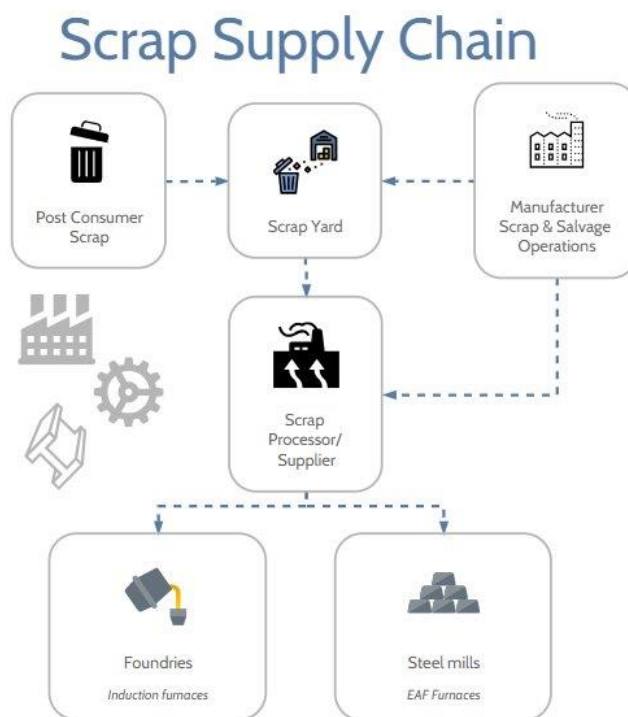


Figure 1: Basic outline of Steel Supply Chain

Chapter 2

Quantifying CO₂ Emissions

To begin to quantify the potential cost and emissions savings of scrap steel remelting, the current steel supply chain and production process must be broken down into various processes. Shipping methods and power sources also need to be considered. For the United States, CO₂ emissions can be calculated from the electricity/fuel burned in the process. CO₂ coefficients have been released by the Energy Information Administration and the Environmental Protection Agency in the United States. Utilizing emissions or power/fuel consumption estimations from previous industry reports or figures provided by industry partners within the supply chain the emissions from transportation can be calculated. Weighing the effect transportation plays will be useful in determining the potential emissions savings from sourcing locally and quantifying the diminishing rate of return for scrap sourcing from sources further away.

Sub-Chapter 2.1 Transportation Emissions

The first set of relevant emission factors comes in the form of transportation figures which give a standard rate of CO₂ per ton-mile transported based on whether truck, rail, or barge is used in shipping. Due to transportation making up most global CO₂ emissions, the fuel efficiency of various methods of transportation has been widely studied and accurate data is widely available, making transportation one of the most accurate and precise parts of estimating the environmental impact of steel. As part of this model, the 3 major factors in determining transportation emissions are the weight of the material transported, the distance transported, and the mode of transportation. For a general estimate where multiple prospective locations are being

evaluated for impact, the distance transported can be quickly estimated by inputting the initial zip code and a list of prospective zip codes, using a simple script that converts the zip code into latitude and longitude coordinates. The script then calculates the distances between the coordinates using Haversines formula (distance between two points on a sphere). This same script can also sort the data to conduct a sensitivity analysis for a given location's access to potential suppliers. For two known locations in a preexisting supply chain, the distance can be found by entering the two addresses into any online mapping program or from the quotes given by the shipping company they have contracts with. Using these distances and the weight transported with a preset freight emissions factor the carbon emissions per trip can be calculated. According to the preliminary research from the Congressional Budget Office, the preset freight carbon emissions factors are .18 kg, .022 kg, and .063 kg per ton mile for trucks, trains, and barges respectively [9]. Perhaps the most efficient way of calculating transportation emissions would be collecting data on the volume of fuel used per trip, and multiplying the value by the given fuel sources efficiently factor. For gasoline, diesel, coal, and train electricity the fuel source factors are 8.88kg of CO₂ per gallon [10], 10.18kg of CO₂ per gallon [10], 2.86 kg of CO₂ per kg burned [11], and 13.57 kWh per mile traveled [12]. Please see the following chapter for the energy grid emissions calculation. For transportation costs, standard freight rates are available online and can be readily quoted for companies. For these models, a rate of .156 USD ton-miles for trucks, .051 USD ton-miles for rail [13], and .0675 USD ton-miles for barge are used (value estimated as total domestic shipping revenue in US/total freight ton-miles) [14]. Please note: these factors can vary depending on the region and current fuel and labor costs.

Sub-Chapter 2.2 Ferroalloy Emissions

During the creation of alloy steel, the ferroalloys used to give the steel its desired chemistry make up a significant portion of the costs and environmental impact of the steel. These ferroalloys are refined multiple times through various processes. The raw ores used in the creation of these alloy additives are mined in various locations around the world and often require significant energy to extract the metal from the ore slurry mined from the ground. The most common ferroalloys used in steel production are ferronickel, ferrochromium, ferromanganese, and ferrosilicon. Other elements such as cobalt, molybdenum, phosphorus, vanadium, copper, and titanium are added in trace amounts to improve various properties of the steel. These are often in the form of wire, pellets, or ingots that get added to the steel melt to bring it up to the desired chemistry.

Ferroalloys are produced through virgin materials found only in select regions spread across the world and have an energy-intensive production process, featuring many different production steps each with various gaseous emissions and power grid electricity uses. The first step in this production process is typically crushing and batching of the ore. This is carried out to produce a mix suitable for smelting. The next step of processing this ore is typically drying, especially, in cases where this ore mix is a wet slurry or in a humid environment steam from moisture could cause issues during further steps in the production process. In certain cases, the dry mix is then further ground into a powder. Following the crushing and drying of this ore, the resulting mix is subsequently milled to separate the mineral from the rock rubble. The mix of separated metal is then made into usable solid nodules through pelletizing or sintering. These nodules are then preheated and smelted to produce a melt of the ferroalloy. This liquid metal is then poured into ingots or granulated into small nodules. Some of the alloying elements lost to

the slag can be recovered through crushing/milling, roasting, and magnetic methods. Typically, after smelting, the metal is then refined using a separate remelting method to get impurities out of the ferroalloy or to tweak the purity of the mix. This refining is usually done with electrical remelting methods such as submerged arc furnaces which specialize in melting electrically resistant materials refer to Figure 2 [15]. The production and environmental impact of ferroalloy production varies significantly depending on the purity/composition of the ore, melting temperature of the metal, and the distance traveled/power grid drawn from.

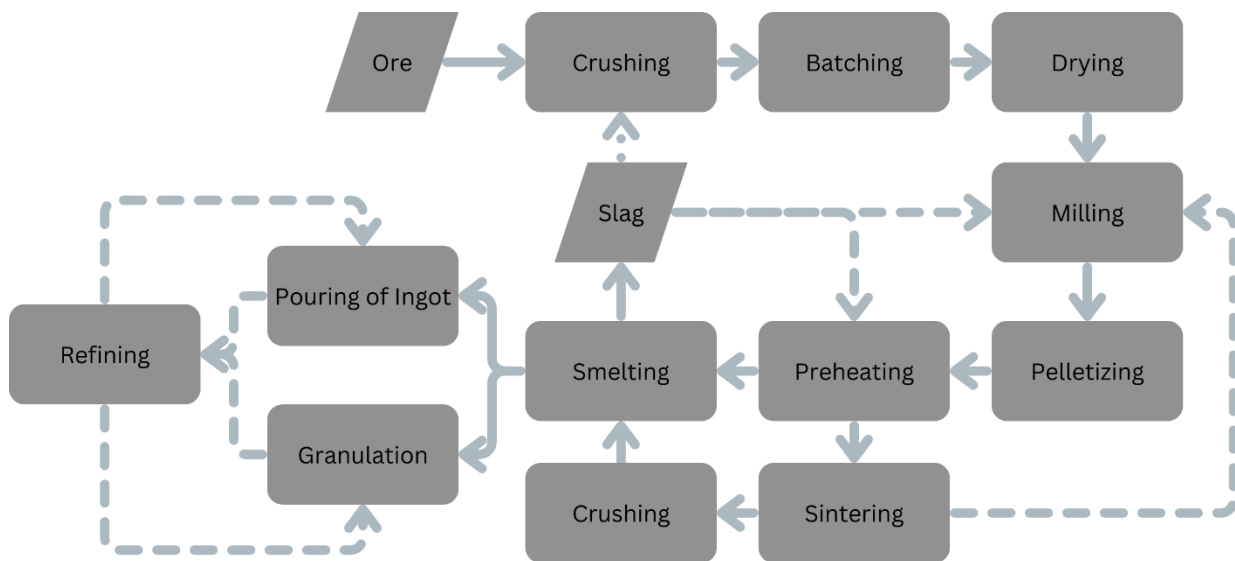


Figure 2: Outline of Ferroalloy Production Process

The following tables provide estimates of CO₂ emissions per unit of ferroalloy produced. To estimate the CO₂ impact of an alloy, the chemistry can be divided by the ferroalloy purity and offset by the expected losses to the slag to be converted into a percent ferroalloy composition value. These ferroalloy compositions can be added up to find the sum of emissions per chemistry for whatever melt size is planned (Table 1). As more countries migrate to renewable energy sources and adopt less intensive manufacturing techniques, the CO₂ impact for pure ferroalloys

will decrease. Smelting and refining tend to be the most energy-intensive part of the production process [16]. In addition to the ferroalloys, pure metals can be added to the melt mix to alloy the chemistry up, due to a higher rate of oxidation during intensive melts as these concentrations are not always ideal. Table 2 provides a general estimate of the CO₂ impact for the pure ingot form of commonly used metals. Even though not all of them are commonly used elements in steel alloying, it is still important to consider the pure metal emissions as valuable elements such as aluminum and copper should be separated from the scrap and remelted separately.

Ferroalloy	Percentage of element	kg of CO ₂ per kg produced	Source
Ferrochromium	65% Cr	6.625	World steel (Sphera) [17]
Ferromanganese	77% Mn	5.903	World steel (Sphera) [17]
Ferro molybdenum	67% Mo	8.091	World steel (Sphera) [17]
Ferro vanadium	80% V	82.426	World steel (Sphera) [17]
Ferronickel	29% Ni	9.438	World steel (Sphera) [17]
Nickel metal	100% Ni	14	MDPI [18]
Nickel oxide	76 % Ni	30	MDPI [18]
Ferronickel	35% Ni	6	MDPI [18]
Nickel Pig Iron	10% Ni	7	MDPI [18]
Ferrosilicon	45% Si	2.5	US EPA [19]
Ferrosilicon	65% Si	3.6	US EPA [19]
Ferrosilicon	75% Si	4.0	US EPA [19]
Ferrosilicon	90% Si	4.8	US EPA [19]

Table 1: Ferroalloy Emissions Estimates [17, 18, 19]

Metal Mix	kg of CO ₂ per kg of pure metal produced	Exporting Countries
Silicon	4.587	-
Nickel	10.826	South Africa, Canada, Norway, Australia, Russia
Manganese	14.857	South Africa, Australia
Magnesium	33.594	-
Aluminum	16.595	-
Tin	5.688	-
Lead	1.759	-
Copper	3.977	-
Zinc	2.612	-

Table 2: Pure Metal production Co2 estimate mix [17]

Sub-Chapter 2.3 Electricity Power Grid Emissions

The final and perhaps most substantial source of greenhouse gas emissions in the scrap remelting process is electricity (energy) usage. Throughout all steps of the process, electricity is used in moving the scrap around in the facility, shredding the scrap metal, measuring the chemistry content of the scrap metal, and finally powering the electric furnace used to melt the scrap steel. The emissions from this electricity used vary significantly by the method used in power generation with CO₂ intensive methods such as coal producing .74-1.689 kg of CO₂ per kWh produced, petroleum-based power generation methods producing .51-1.17 kg of CO₂ per kWh, and natural gas producing .29-.93 kg of CO₂ per kWh [20]. Renewable power generation methods such as solar, nuclear, wind, and hydropower still have slight CO₂ emissions due to energy use in the construction and maintenance of the infrastructure spread across the lifetime of power generation. For solar this is .041 kg- CO₂/kWh, .012 kg- CO₂/kWh for nuclear, .011 kg- CO₂/kWh for wind, and .004 kg- CO₂/kWh for hydropower [20].

Like many industrialized nations, countries such as the United States have varied power grids made up of many sections each relying on a multitude of different utility companies each with various facilities utilizing different fuel sources for power generation. Due to this variability, there are a few different approaches to take for CO₂ emission calculations: grid-based, company-based, and local power generation. If only the location is known, the zip code could be used to match the location to the section of the power grid where the electricity was generated. The US Department of Energy has documented the breakdown of power generation and their respective emissions for each of these power grid sections (see Figure 3 and Table 3) [21]. Depending on the electricity supplier, the breakdown of the power source can be provided. Using this report the average kg- CO₂/kWh can be estimated (in some cases an emissions factor

will be directly provided). Additionally, some companies can offer a premium rate to have the power designated as coming from their capacity at a renewable-based generation facility. In certain locations, facilities have invested in their power generation or have a contract with a nearby power plant for energy supply. In these scenarios, the estimated average daily power generation capacity of the local power generation would need to be compared to the fuel use (in the case of biomass or fossil fuels) to estimate a kg- CO₂ per kWh rate. If this power source was insufficient to cover the power use the previously mentioned methods would be used to cover the excess.

Subregion Name	Subregion Acronym for Map	Pounds of CO ₂ per MWh
ASCC Alaska Grid	AKGD	1,067.680
ASCC Alaska Grid	AKGD	1,067.680
ASCC Miscellaneous	AKMS	485.186
WECC Southwest	AZNM	819.656
WECC California	CAMX	531.678
ERCOT All	ERCT	813.552
FRCC All	FRCC	832.924
HICC Miscellaneous	HIMS	1,134.391
HICC Oahu	HIOA	1,633.097
MRO East	MROE	1,582.135
MRO West	MROW	995.790
NPCC New England	NEWE	539.367
WECC Northwest	NWPP	634.599
NPCC NYC/Westchester	NYCW	816.756
NPCC Long Island	NYLI	1,210.940
NPCC Upstate NY	NYUP	233.081
Puerto Rico Miscellaneous	PRMS	1,558.024
RFC East	RFCE	672.787
RFC Michigan	RFCM	1,214.061
RFC West	RFCW	1,046.132
WECC Rockies	RMPA	1,158.860
SPP North	SPNO	991.729
SPP South	SPSO	1,031.601
SERC Mississippi Valley	SRMV	772.737
SERC Midwest	SRMW	1,543.034
SERC South	SRSO	891.907
SERC Tennessee Valley	SRTV	931.586
SERC Virginia/Carolina	SRVC	639.665

Table 3: Table of eGRID Subregions Emissions [21]

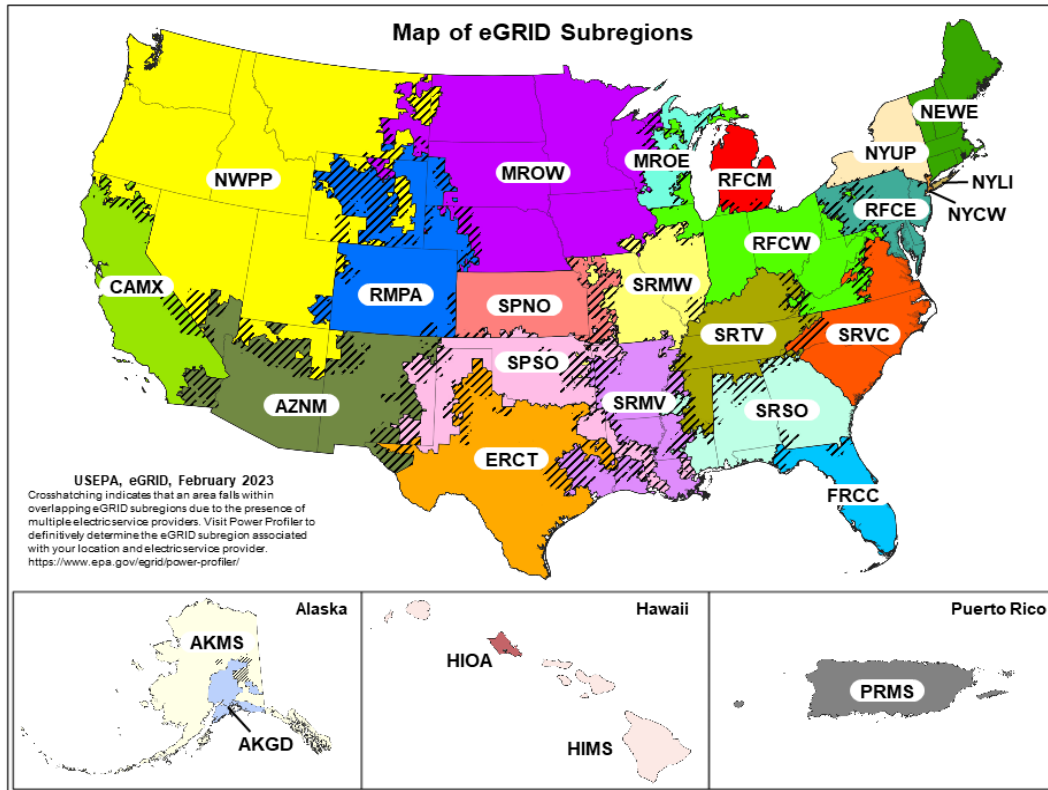


Figure 3: Map of eGrid subregions [21]

When estimating the rate of electricity used in producing each ton of steel it will vary significantly depending on the method used in melting. In the following chapter (Chapter 3) a more detailed explanation of the estimated kWh used to melt each ton of steel is discussed. In addition to steel melting, there are additional facility energy expenditures in the form of crane/cart transportation of metal within the facility, shredding of scrap steel in the scrap processing facilities, the purification of the scrap through magnetic and other sorting methods, and lastly the chemistry analysis of the scrap steel. These additional energy expenditures will be elaborated on in Chapter 4. As a rule for estimating the kWh per ton of steel produced, electricity meters can be checked, and utility statements can be looked at to find the exact electricity expenditures for the given period when the order of steel was produced. When dividing this

expenditure by the tons of steel produced a standard rate of electricity per ton of steel is found which can then be used in cost and CO₂ emissions calculation. In the case this information is not available a list of coefficients of melting/shredding steel per ton was found from the literature and can be used as a placeholder in this model for estimating cost and impact (see Table 4).

Process	kWh per MT of steel
Electric Arc Furnace	440 kWh [24]
Induction Furnace melt	660 kWh [27]
Scrap shredding	35 kWh [31]

Table 4: Estimates of Steel Processing Electricity Requirements

Chapter 3

Melting Parameters and Furnace Coefficients

Modeling the alloying elements lost to slag is extremely complicated and prone to significant variability due to the exact portion of elements and their electron affinities along with melting temperatures in conjunction with the rate/volatility of furnace heating playing a massive role in what elemental composition is lost to the slag. Up until recently the alloying content of scrap steel was mostly overlooked and intensive melting methods were utilized to separate any alloy chemistry into the slag to ensure impurity-free steel. Now that more accurate technology to measure scrap chemistry faster is more widely available and with the rising cost of ferroalloys, it is likely more research will be carried out to determine optimal melting methods and reasonable estimates for chemistry losses during melting.

Since the 20th century, steel has been made typically with a form of oxygen-blowing in which a mix of melted iron/pig iron has its impurities removed through oxidation. This method is effective for producing large quantities of steel with a low alloy content. In general, this method would best be suitable for reusing scrap with relatively high levels of contamination and dirt as well as a low concentration of valuable alloying elements [22]. For the context of valuing the alloy content of steel and focusing on reducing CO₂ emissions, electricity-based steelmaking is used for the creation of alloy-based scrap mixing. Electric Arc and Induction are the two most widely used methods of electric steelmaking and are becoming more widely used as the focus on renewable energy and emissions reductions becomes more of a priority for the steel industry.

Sub-Chapter 3.1 Electric Arc Furnace Melting

Electric arc furnaces operate by passing massive amounts of electricity through the metal melted to massive electrodes, utilizing the heat generated through the electrical resistance of the metal in the melt. This process rapidly melts the metal leading to the burning/oxidation of the elements in the melt. Especially close to the electrodes used in the melt, the rapid remelting of the steel and oxygen blowing leads to high rates of oxidation and reduction of alloying elements in the steel melt. Electric arc remelting is an efficient method for making low-alloy steel or steel from contaminated steel scrap with excess coating and grime that would need to be burned off [23]. Electric arc furnaces typically have massive melt capacities and thus possess a more efficient per-ton energy use with an average estimate of 440 kWh per ton melted [24]. Depending on the power applied, the chemistry of the melt, and the rate of oxygen blown the percentage of the alloying elements retained in the melt will vary. Based on the current literature the percent of alloying elements left in the melt are estimated in Table 5 [25].

Element	Percent retained in liquid melt
Chromium	30~95%
Nickel	98-99%
Manganese	16~80%
Silicon	N/A
Molybdenum	90~95%
Tungsten	97~99%
Vanadium	7~58%
Copper	90~95%
Cobalt	98~99%

Table 5: Percentage of chemistry retained during EAF melting literature review [25]

Sub-Chapter 3.2 Induction Furnace Melting

Induction heating utilizes an alternating electric field inside the crucible to heat the metal in the melt by reversing the magnetic field with an alternating eddy current. As the magnetic fields penetrating the charge metal are rapidly reversed, the scrap is heated evenly and at a relatively controlled pace, and the amount of alloying element oxidized can be controlled by the exposure to the atmosphere or any air introduced to the melt.

Due to inefficiencies in the eddy current heating system and the relatively small melt capacities typically ranging from half a ton up to 5 tons with certain large-scale furnaces having 50-ton capacities [26], the average power use of an induction furnace has been estimated as 660 kWh per ton of steel melted [27]. Although this power use is on average more than that of Electric Arc Furnaces, the savings on alloy content lost to the slag for steels with considerable elemental more than make up for it in terms of cost and emissions (see Table 6). The exact break-even point in these savings depends on the power grid the electricity is drawn from, how much energy was used in the processing and measuring of the scrap content, and if there was any extra distance needed to transport the steel.

Element	Percent retained medium frequency
Chromium	94.62 [28]
Nickel	97.63 [28]
Manganese	63~83 [29]
Silicon	62~89 [29]
Molybdenum	95.09 [28]
Tungsten	97.36 [28]
Vanadium	89.49 [28]

Table 6: Percentage of chemistry retained during EAF melting literature review [28, 29]

Chapter 4

Scrap Sorting and Integration of Novel Technology

To ensure a clean blend of scrap steel, various methods are employed to separate tramp metals, coatings, and dirt mixed in with scrap metal. Scrap yards purchase the metal in a variety of forms with different levels of cleanliness, and it is generally sent off to scrap processors for further processing. End-of-life post-consumer scrap typically doesn't contain much notable alloy content and is mostly in the form of structural steel and automobile steel. For this scrap, sorting methods such as magnetic or eddy current separation should be applied to ensure the purest iron blend of scrap steel before melting. When utilizing a general blend of sorted/shredded end-of-life scrap the chemical makeup should be verified with a method such as spectrometry or gamma-neutron analysis to ensure the level of tramp elements (copper and tin) falls within the acceptable range of alloy chemistry specifications [7]. This scrap is best used for melting processes with high levels of oxidation, as relatively little alloy is lost and the risk of being over-alloyed is less. Depending on the overall cleanliness of this blend it could still be used as feedstock to dilute high-value alloy scrap in a less intensive melt.

Generally, the most effective method for keeping scrap with considerable alloy content out of the basic scrap blend is to separate the scrap as it comes in or is salvaged from decommissioned equipment/structures. This can take the form of using an X-ray fluorescence Spectrometer (XRF) analyzing tool on large pieces of scrap, consulting a part serial number to find its content, or having a documented salvage plan created by the designers as part of a circular economy life-cycle effort.

Sub-Chapter 4.1 Sorting and Separation Methods

As previously stated in this paper the main risk and barrier to the use of end-of-life scrap in alloy melts is the risk of contamination from unwanted tramp elements. The sorting of this scrap is often done through multiple electromagnetic techniques, traditionally a strong magnet is either suspended over the scrap stream or inside a rotating drum that cycles over the scrap stream. Another method is using an alternating electromagnetic field to slow down scrap particles as they are shot out at high speeds through a conveyor based on their density and magnetism [30]. These methods are best suited for scrap shreds that have been ground up into small chunks ideally weighing a couple of grams each as they have a predictable mass and will flow more uniformly on a conveyor belt. In these scrap processing facilities, an estimated 18-35 kWh of energy per ton needs to be expended for shredding. The exact energy value will depend on the density of the scrap and the desired shred size [31]. For ballistic/electrodynamic sorting of scrap, the desired density of each stream can be tweaked by placing the stream separator at a set distance. This set distance is calculated by estimating the calculated force applied to the moving scrap stream by the electromagnetic field, the velocity of the scrap, and the point where it falls below a certain threshold. These estimates can be accurately predicted through magnetic field modeling [32]. This method of separating by magnetic field and density has already been implemented in scrap processing facilities and has been proven to sort out steel shreds with copper contents below 0.20% which is an acceptable level for most alloy steel applications [33]. Permanent magnet sorting, although typically requiring less power, is not as adjustable as electromagnetic eddy current sorting and is prone to picking up other magnetic metals with nickel and chromium as well as scrap containing neodymium magnets and should not be used as

the final step in the scrap sorting process. For ferrous metals that have been picked up, a second round of magnetic sorting should be applied to separate them from low alloy plain iron scrap. Subsequently, this mixture should undergo a chemistry measurement method to get a reading of the scrap bin's alloy content, which then can be diluted with pure light iron scrap to achieve an optimal level of alloy content (such as Chromium or Nickel) in the scrap mix.

To keep easily recognizable high-quality scrap separate from the general blend where it would undergo unnecessary processing and potentially risk its alloy content either being wasted or contaminating the rest of the mix, scrapped parts should be sorted out before shredding. In the past and in junk yards, this had been done by hand where workers would identify parts of equipment with high alloy content or a clean appearance and set them aside. With the onset of AI deep learning and image classification, this process can be automated. Through training, an AI model has been developed to scan countless images of different scrap types and identify scrap types with success rates of 90% for all scrap types [34]. These models can flag individual scrap chunks for removal by human pickers or with automated robotic arms. Additionally, they can classify an entire truck/bin load as a certain quality or composition to decide what processing the scrap should undergo. Small, light scrap can be shredded and then magnetically sorted. Relatively dirty, oxidized, or coated scrap can be sent to be roasted to reach a level of cleanliness before undergoing additional sorting. In instances where there is a high level of uncertainty or an unpredictable blend of scrap, the scrap can be downgraded and used for iron processes with less stringent chemistry requirements such as rebar, or used in an oxidation-intensive melting process. For scrap loads where stainless steel or clean parts were detected, the load can be sent to have its chemistry measured and sizeable individual high-value parts can be picked out of the mix to be further cleaned and used in an alloy-preserving induction melt.

Sub-Chapter 4.2 Chemistry Measurement Methods

To ensure the chemistry of scrap steel blends a multitude of studied and established techniques, all these techniques involve exposing the scrap to various forms of energy (thermal, laser, plasma, gamma, x-ray, etc.) and using sensors to measure the wavelength and intensity of the energy given off [34]. These methods are best suited for detecting different elements and have different levels of accuracy and operating costs.

X-ray technology is used in existing scrap processing facilities and is typically in the form of handheld alloy guns or as machinery that scans the scrap as it flows over a conveyor belt. These methods are commonly used for differentiating different grades of stainless steel by identifying differences in nickel, chromium, molybdenum, and magnesium compositions in the scrap mix [35]. Through experimental testing of different scrap metals with a set chemistry the frequency of energy emitted for each element can be better detected. Utilizing the percentage of the emitted radiation the alloy composition can be accurately predicted. These X-rays typically use 1-5 kW of energy in their normal operation [36].

Another commonly used method of measuring the alloy content through spectrometry uses lasers to create plasma in the steel. The light emitted by the plasma is then measured similarly to how the X-ray light is measured. Due to its prevalence in the steel industry, this form of spectrometry is commonly used in melt shops to verify the chemistry of the metal poured and gives accurate readings for all the elements commonly found in alloy steel [37]. To best ensure this method is effective the scrap needs to have a clean surface for identification. In the future, an automated method of sorting scrap pieces using a robotic arm with an attachment for surface

cleaning and then laser measurement could prove effective for sorting scrap pieces marked as potentially high value through magnetic or image classification.

When using infrared radiation as a method of measuring scrap chemistry, the amount of energy absorbed into the metal is measured and the reflection is recorded. Through machine learning and regression analysis the light reflected off the steel can be used to classify its alloy content. Like other spectrometry methods, this will require a clean surface to get an accurate reading of the light output [38]. This method operates much faster and with less power use than other methods of spectrometry with higher frequency radiation or power input.

Prompt gamma-ray neutron activation analysis is a flexible method of measuring the chemistry of a material with little impact on the material itself. This method is used across a multitude of applications ranging from security, archaeology, and mining/manufacturing. This method works by bombarding the material scanned with a beam of neutrons and then using sensors to measure the gamma rays emitted by the interaction [39]. This method can be applied to scrap certification and research has been done to determine the minimum detectable concentrations (in ppm) of most elements in the periodic table that are used in industry and what wavelength of radiation they emit [40]. Applications of this technology have been commercially implemented in the recycling industry and work is being done to optimize them for scrap metal chemistry detection [41].

Chapter 5

Optimizing Scrap Melts to Minimize Value Lost

When considering alloy scrap mixing for remelting there are a couple of different approaches to take when measuring the value for pricing the scrap or making the decision to change up a melt process and the inputs. One possible approach to this scrap melting is prospecting scrap loads based on their ferroalloy equivalent given the melting method utilized at the facility and using scrap with a set chemistry. This method would be helpful for scrap dealers looking to market the scrap on hand or justify investing in technology to produce and certify more valuable scrap. Another possible method is savings. In this method, the current supply chain is broken down in terms of cost and emissions, and the availability of different alloy scrap is then considered to estimate the savings in ferroalloys needed when using the alloy scrap. This method is helpful for mills or customers of steel mills looking to reduce costs and minimize their CO₂ impact. This method focuses on the end chemistry of the steel produced and can weigh all available scrap to determine an optimal mix for minimizing both costs and CO₂ emissions over the entire process.

What both methods share is an adjustment of the elemental requirements by the melting method elemental coefficients to determine the blend of scrap used or ferroalloy additions needed to bring the melt up to chemistry. To find cost-optimal blends of scrap and ferroalloy, linear programming can be used to find ratios of melt ingredients that result in the desired alloy chemistry and cleanliness.

Sub-Chapter 5.1 Estimating Ferroalloy Equivalencies

From the perspective of scrap dealers looking for a way to value their scrap and from the perspective of melters looking to reduce ferroalloy usage, calculating the post-melt ferroalloy equivalencies of different scrap types can significantly increase the value of the scrap. This will be especially true as ferroalloy prices and supply become more uncertain. Out of the three approaches in this chapter, this method is the most straightforward. It involves offsetting the measured/specified scrap blend chemistry by oxidation/reduction chemistry coefficients of the melting method. The loss rate at which these elements react with the melt and are either vaporized or lost to the slag depends on the melt parameters and individual furnaces used in the melt. With these rates there is expected to be considerable variability until a set process and defined chemical relationship is established for the melting process. Until this melting process-specific data is collected, Tables 5 & 6 can be used as approximate theoretical adjustment factors for these ferroalloy equivalency calculations. To be conservative in the calculation, to avoid the risk of overvaluing the scrap the lower end of the range should be used when converting it to ferroalloy equivalencies.

For the example used to demonstrate this concept three common grades of steel are used: 304 stainless steel, 4340 steel, and 8620 steel. 304 stainless steel is a widely used stainless steel commonly used in consumer and industry goods due to its exceptional corrosion resistance making it ideal for any application that would expose it to oxidation [42]. 304 stainless steel is widely available in most scrap trading sites. 4340 steel is a commonly used low alloy steel known for its toughness, strength, and workability making it ideal for intensive industrial machinery and structural components [43]. 8620 steel is another commonly used low alloy steel

known for its flexible uses when hardening to a desired strength making it ideal for components with specified medium strength applications [44]. All three of these steels are widely known in industry and process scrap or salvage scrap would be relatively easy to procure, making them ideal candidates for scrap melting experiments to determine the losses when remelting with different furnace and oxygen blowing settings. Assuming the scrap is purely an unoxidized/uncoated batch or sourced directly from a specific manufacturer, the chemistry of the scrap would match the chemistry required of the steel listed in Table 7. The melting of the steel would then alter this chemistry and the percentage chemistry of the scrap would then be multiplied by an offset factor to get a liquid steel equivalent value. With this post-melt value, the chemistry can then be divided by the purity of the ferroalloy (i.e. 65% Cr ferro chrome would be represented as .65) to get the percent ferroalloy saved. Mathematically this can be represented by a row matrix of the scrap steel chemistry being multiplied by a column matrix of the furnace coefficients, and then multiplied by a column matrix containing the inverse composition of the ferroalloy (i.e. 65% Cr ferro chrome written as 1/.65 or 1.54) (Equations 1 & 2).

$$(\%FeNi \ \%FeCr \ \%FeMn \ \%FeSi \ \%FeMo) = (\%Ni \ \%Cr \ \%Mn \ \%Si \ \%Mo) * \begin{pmatrix} \%Ni \text{ retained} \\ \%Cr \text{ retained} \\ \%Mn \text{ retained} \\ \%Si \text{ retained} \\ \%Mo \text{ retained} \end{pmatrix} * \begin{pmatrix} 1/\%FeNi \\ 1/\%FeCr \\ 1/\%FeMn \\ 1/\%FeSi \\ 1/\%FeMo \end{pmatrix}$$

Equation 1: Ferroalloy Equivalency matrix calculation

Alloy	C	Ni	Cr	Mn	Si	Mo	S	P
304 Stainless	0.07	8.00 - 10.50	17.50 - 19.50	2.0	1.0	0	< .03	< .05
4340	0.40	1.65 - 2.00	0.70 - 0.90	0.60 - 0.80	0.15 - 0.30	0.20 - 0.30	< .04	< .035
8620	.20	0.40 - 0.70	0.400 - 0.600	0.70 - 0.90	0.15 - 0.35	0.15 - 0.25	< .04	< .035

Table 7: Elemental Chemistry Composition percentage of Commonly used Steel Grades

$$(\%27.14 \ \%26.92 \ \%2.46 \ \% .97 \ \%0) = (\% 9.25 \ \%18.50 \ \%2.0 \ \%1.0 \ \%0) * \begin{pmatrix} .976 \\ .946 \\ .63 \\ .62 \\ .951 \end{pmatrix} * \begin{pmatrix} 1/.35 \\ 1/.65 \\ 1/.77 \\ 1/.65 \\ 1/.67 \end{pmatrix}$$

Equation 2: Ferroalloy Equivalency of Pure 304 stainless melted in medium frequency induction furnace*Assume mean chemistry & poor elemental retainment during melting (Table 6)

Using these ferroalloy equivalencies both the cost and emissions savings can be calculated based on the mass of the scrap used in the melt. For example, if 1 Mt of 304 stainless steel was remelted in an induction furnace 271.4 kg less of 35% Ni-ferroalloy would be needed in the melt resulting in a savings of 1.628 Mt of CO₂ from the nickel content alone. Tables 8 and 9 show the chemistry of steel after scrap melting. These values can then be converted into ferroalloy equivalencies for the desired purity of ferroalloy that is typically supplied to the melting facility. As the price of these ferroalloys increase these scrap grades will likely become a more attractive alternative, and more investment will be put into sorting out these high-value metals and the chemical composition of these steel scrap loads to ensure the chemical composition is correct and free of contaminants (especially tramp elements). Another potential use of these equivalency calculations can be to evaluate certain pieces of steel scrap as investments if no steel producer is willing to buy the scrap at a rate comparable to its alloy content. The firm would then be wise to store the scrap until its market value reached that of its alloy content or use this value to justify running the heat of the metal creating a clean high-value ingot from the scrap.

Alloy	Ni	Cr	Mn	Si	Mo	S	P
304 Stainless	9.50	5.55	.96	0	0	0	0
4340	1.80	.24	.33	0	.23	0	0
8620	.55	.15	.38	0	.25	0	0

Table 8: Elemental Retainment for Pure Steel Scrap Remelted in Electric Arc Furnace* Assume Mean Chemistry

Alloy	Ni	Cr	Mn	Si	Mo	S	P
304 Stainless	9.50	17.50	1.90	.63	0	< .03	< .05
4340	1.80	.76	.66	.15	.24	< .04	< .035
8620	.55	.47	.76	.17	.27	< .04	< .035

Table 9: Elemental Retainment for Pure Steels Remelted in Induction Furnace* Assume Mean Chemistry

Sub-Chapter 5.2 Finding Alternative Steel Melting Processes for a Given Alloy

When considering how a sorted scrap steel solution could reduce cost and emissions the first step is calculating the costs and emissions of the current process to estimate what potential savings could be realized from changing the process. On the monetary side, the cost should be known as any facility with a functional accounting department would have a breakdown of shipping costs for each order, a utility statement, worker wages, and the raw material cost for all the melted ingredients. Equation 3 provides a rudimentary formula for calculating the cost per ton of melting a certain alloy. For environmental impact, the calculations are a bit more cumbersome to estimate. The main inputs for this method are the mass of each ferroalloy used in the melt, the ratio of scrap to virgin material used in the melt, the energy use of the equipment used in the melt and in the processing of the scrap, and the distance and mode of transportation used to transport the material to the melt see Equation 4. Figure 4 outlines the inputs & outputs for this type of model.

$$\frac{Cost}{ton} = \frac{ShippingCosts}{tons\ in\ order} + \frac{Kwh\ used\ in\ melt}{Tons\ in\ melt} (price/Kwh) + \sum_1^{Elem.} \frac{(tons\ of\ ferro\ alloy\ used)}{Tons\ in\ melt} (price/ton\ of\ alloy) + \frac{operating\ cost}{tons\ used\ in\ melt}$$

Equation 3: Rudimentary Cost Estimation per Ton Melted based on Alloy Chemistry

$$\frac{Emmissions}{ton} = (Distance * \frac{Freight\ Coef.}{TonMile}) + \frac{Kwh\ used\ in\ process}{Tons\ in\ melt} (Co2/Kwh) + \sum_1^{Elem.} \frac{(tons\ of\ ferro\ alloy)}{Tons\ in\ melt} (CO2 /ton\ of\ alloy) + \frac{operating\ emmissions}{tons\ used\ in\ melt}$$

Equation 4: Emissions per Ton Melted based on Alloy Chemistry

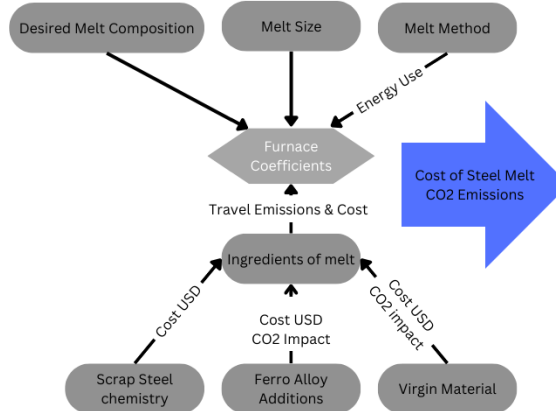


Figure 4: Inputs for Steel Cost and Emissions Melt Optimization Model

To demonstrate how this model would work for exploring alloy scrap blends as a substitute for the traditional low alloy scrap brought up to chemistry by ferroalloy additives, a melt chemistry of 4340 will be used. When setting up the current supply chain system some key inputs will need to be considered; location/PowerGrid drawn from a per kWh-emission factor, the distance traveled and shipping method for the raw materials used, the melt method used how many kWh used per ton, the type of ferroalloys used/ferroalloy emission factors, and the oxidation/reduction rates of the furnace used. In this demonstration, it is assumed the general blend of iron/steel scrap traveled 300 miles by truck to the melting facility located in the RFC West eGrid subregion where steel is produced with an electric arc furnace. Due to the frequent price fluctuations research should be done when entering price estimates for scrap, ferroalloys, and shipping rates. The available steel scrap grades are 304 stainless at \$900 per ton (200 miles), 4340 steel at \$700 per ton (400 miles), 8620 steel at \$500 per ton (150 miles), and general light iron at \$200 per ton (300 miles away). In terms of ferroalloys 35% FeNi is estimated to cost \$4,000 per ton, 65% FeCr is estimated to cost \$3,000 per ton, 77% FeMn is estimated to cost \$1,200 per ton, 65% FeSi is estimated to cost \$1,100 per ton, and FeMo is estimated to cost \$23,000 per ton. The truck shipping rate is \$ 0.24 per ton-mile and the energy price per kWh is \$0.16. The weight of the melt is assumed to be 1 ton. Please see Equations 5 & 6 for cost and emissions calculations. To find the ferroalloy required, divide the required chemistry by the ferroalloy purity. The grid factor is converted to kg./kWh by dividing the lbs./MWh by 2205.

$$\frac{Cost}{ton} = \frac{300 m * \$.24}{1 T} + \frac{475 kWh}{1 T} (\$.16/Kwh) + \sum_1^5 \frac{(.0514)}{1} (\$4,000/Ni) + \frac{(.0123)}{1} (\$3,000/Cr) + \frac{(.0091)}{1} (\$1,200/Mn) + \frac{(.0033)}{1} (\$1,100/Si) + \frac{(.0037)}{1} (\$23,000/Mo) + \frac{\$200}{1}$$

Equation 5: Rudimentary Cost Estimation per Ton Melted based on 4340 in EAF

$$\frac{Kg CO2}{ton} = \frac{300 m * .18kg}{1 T} + \frac{475 kWh}{1 T} (.474kg/Kwh) + \sum_1^5 \frac{(.0514)}{1} (5,454/Ni) + \frac{(.0123)}{1} (6,023/Cr) + \frac{(.0091)}{1} (5,366/Mn) + \frac{(.0033)}{1} (3636/Si) + \frac{(.0037)}{1} (7355/Mo) + \frac{N/A}{1}$$

Equation 6: Rudimentary Emissions Estimation per Ton Melted based on 4340 in EAF

Using these methods the expected cost per ton of steel was \$690.15 (\$760.75 per MT) and an estimated CO₂ emission of 721.61 kg (795.44 per MT) for the current process. With this preliminary estimate for cost and emissions, a standard is set for the changes that can be made to the supply chain process to reduce costs and emissions. To develop possible mixes of scrap blends that will meet the different alloy chemistries a series of linear equations were written with each elemental percentage being used as a constraint and cost/emissions being minimized as the function. Each scrap input will be assigned a variable X_n to represent the percentage used in the melt. The scrap input percentage (X_n) values are then multiplied by the furnace coefficient value $F_{element}$ to represent the alloy percentage lost to oxidation during melting. In the case the mix of scrap cannot hit a desired alloy content, a ferroalloy variable is utilized in each constraint ($X_{element}$) to make up any chemistry not met from the scrap remelt. To complete the mix, a portion of iron will be blended into the mix (X_i). This constraint is to ensure the total percentage of each scrap used totals 100% or each decimal adds up to 1. The objective function will be a minimization function summing all the inputs together, taking into account the electricity, distance traveled, costs of the scrap, costs/emissions, and any miscellaneous factors related to facility overhead or consumables used in the melt. The first set of these factors in the equation are the electricity values, E_m represents the electricity used in melting the steel, E_p represents the electricity used in processing the steel in the melting facility (shredding and scanning), E_F represents the facility overhead electricity (this should be calculated by dividing the total electricity usage by the tons poured in the given period), and E_O represents the onsite power generation at the facility (the costs and emissions from this will be accounted for under miscellaneous). Finally, all of these values will be multiplied by the cost/emissions per kWh (R).

The distance value D_n represents the distance (miles) traveled. D_n is multiplied by the cost/emissions factor of the mode of travel (\$/CO₂ per ton-mile). This will be per load of scrap and can take into account multiple different scrap suppliers. The next section of the function is cost/emissions. In this section (C_n) which is a cost/emissions per ton factor is multiplied by the proportion of each scrap/ferroalloy used in the melt (X_n). This section takes each available scrap type into account as a summation function and takes into account each ferro alloy used in the mix ($X_{element}$) as well as the general iron used in the melt (X_i). The last section includes any miscellaneous costs or emissions due to furnace melting consumables (T) or additional labor needed to complete the melt (Lw). The following program considers the different scrap blends and includes static cost values not involved in the optimization to give a holistic value of the entire cost/emission (Program 1). To demonstrate this optimization these models focused on minimizing cost and emissions will be run as both EAF and Induction melting using the model inputs previously outlined in the chapter and assuming negligible: onsite power generation $E_O = 0$, facility electricity $E_f = 0$, and consumable/labor costs $T, Lw = 0$. The scrap inputs are $X_1 = 304, X_2 = 4340, X_3 = 8620$ (Programs 2a, 2b & 3a, 3b).

$$\text{Minimize: Cost} = (E_m + E_p + E_f - E_o)(R) + D_1X_1 + D_2X_2 + D_3X_3 + D_iX_i + C_1X_1 + C_2X_2 + C_3X_3 + C_{Ni}X_{Ni} \\ + C_{Cr}X_{Cr} + C_{Mn}X_{Mn} + C_{Si}X_{Si} + C_{Mo}X_{Mo} + C_iX_i + (T + Lw)$$

$$1 = X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo}$$

$$Ni \% \leq \%Ni_1X_1 * F_{Ni} + \%Ni_2X_2 * F_{Ni} + \%Ni_3X_3 * F_{Ni} + X_{Ni}$$

$$Ni \% \geq \%Ni_1X_1 * F_{Ni} + \%Ni_2X_2 * F_{Ni} + \%Ni_3X_3 * F_{Ni} + X_{Ni}$$

$$Cr \% \leq \%Cr_1X_1 * F_{Cr} + \%Cr_2X_2 * F_{Cr} + \%Cr_3X_3 * F_{Cr} + X_{Cr}$$

$$Cr \% \geq \%Cr_1X_1 * F_{Cr} + \%Cr_2X_2 * F_{Cr} + \%Cr_3X_3 * F_{Cr} + X_{Cr}$$

$$Mn \% \leq \%Mn_1X_1 * F_{Mn} + \%Mn_2X_2 * F_{Mn} + \%Ni_3X_3 * F_{Mn} + X_{Mn}$$

$$Mn \% \geq \%Mn_1X_1 * F_{Mn} + \%Mn_2X_2 * F_{Mn} + \%Ni_3X_3 * F_{Mn} + X_{Mn}$$

$$Si \% \leq \%Si_1X_1 * F_{Si} + \%Si_2X_2 * F_{Si} + \%Si_3X_3 * F_{Si} + X_{Si}$$

$$Si \% \geq \%Si_1X_1 * F_{Si} + \%Si_2X_2 * F_{Si} + \%Si_3X_3 * F_{Si} + X_{Si}$$

$$Mo \% \leq \%Mo_1X_1 * F_{Mo} + \%Mo_2X_2 * F_{Mo} + \%Mo_3X_3 * F_{Mo} + X_{Mo}$$

$$Mo \% \geq \%Mo_1X_1 * F_{Mo} + \%Mo_2X_2 * F_{Mo} + \%Mo_3X_3 * F_{Mo} + X_{Mo}$$

Mathematical Program 1: Outline of Linear Equation scrap blend Optimization model ($X_n \geq 0$)

$$\text{Minimize: Cost} = (440kwh + 35kwh)(.16) + (200 * .24)X_1 + (400 * .24)X_2 + (150 * .24)X_3 + (72)X_i + 900X_1 + 700X_2 + 500X_3 + 4,000X_{Ni} + 3,000X_{Cr} + 1200X_{Mn} + 1,100X_{Si} + 23,000X_{Mo} + 200X_i$$

$$1 = X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo}$$

$$.0165 \leq (.095X_1 + .0185X_2 + .0055X_3).98 + .35X_{Ni}$$

$$.02 \geq (.095X_1 + .0185X_2 + .0055X_3).98 + .35X_{Ni}$$

$$.007 \leq (.175X_1 + .0085X_2 + .005X_3).3 + .65X_{Cr}$$

$$.009 \geq (.175X_1 + .0085X_2 + .005X_3).3 + .65X_{Cr}$$

$$.006 \leq (.02X_1 + .007X_2 + .008X_3).16 + .77X_{Mn}$$

$$.008 \geq (.02X_1 + .007X_2 + .008X_3).16 + .77X_{Mn}$$

$$.0015 \leq (.01X_1 + .002X_2 + .0025X_3)0 + .65X_{Si}$$

$$.0030 \geq (.01X_1 + .002X_2 + .0025X_3)0 + .65X_{Si}$$

$$.0020 \leq (0X_1 + .0025X_2 + .002X_3).9 + .67X_{Mo}$$

$$.0030 \geq (0X_1 + .0025X_2 + .002X_3).9 + .67X_{Mo}$$

Mathematical Program 2A: Linear Equation scrap blend Optimization model EAF Costs

$$\text{Minimize: Emissions}(kg) = (440kwh + 35kwh)(.474) + (200 * .18)X_1 + (400 * .18)X_2 + (150 * .18)X_3 + (300 * .18)X_i + (6 * 907kg)X_{Ni} + (6.6 * 907kg)X_{Cr} + (5.9 * 907kg)X_{Mn} + (3.6 * 907kg)X_{Si} + (8 * 907k)X_{Mo}$$

$$1 = X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo}$$

$$.0165 \leq (.095X_1 + .0185X_2 + .0055X_3).98 + .35X_{Ni}$$

$$.02 \geq (.095X_1 + .0185X_2 + .0055X_3).98 + .35X_{Ni}$$

$$.007 \leq (.175X_1 + .0085X_2 + .005X_3).3 + .65X_{Cr}$$

$$.009 \geq (.175X_1 + .0085X_2 + .005X_3).3 + .65X_{Cr}$$

$$.006 \leq (.02X_1 + .007X_2 + .008X_3).16 + .77X_{Mn}$$

$$.008 \geq (.02X_1 + .007X_2 + .008X_3).16 + .77X_{Mn}$$

$$.0015 \leq (.01X_1 + .002X_2 + .0025X_3)0 + .65X_{Si}$$

$$.0030 \geq (.01X_1 + .002X_2 + .0025X_3)0 + .65X_{Si}$$

$$.0020 \leq (0X_1 + .0025X_2 + .002X_3).9 + .67X_{Mo}$$

$$.0030 \geq (0X_1 + .0025X_2 + .002X_3).9 + .67X_{Mo}$$

Mathematical Program 2B: Linear Equation scrap blend Optimization model EAF Emissions *Scrap Processing Assume 0 kg/CO2

When run through the linear programming software (using the Excel solver addon), the cost-optimal blend to produce 4340 with EAF melting was: 17.15% 304 scrap, 81.47% light iron,

0.15% FeNi, 0.70% FeMn, 0.23% FeSi, 0.30% FeMo (total cost \$546 per ton, total emissions 365 kg of CO₂). The optimal blend for emissions was found to be: 13.13% 304 scrap, 85.99% 8620 scrap, .58% FeMn, .23% FeSi, .07% FeMo (total emissions of 304 kg of CO₂, total cost of \$686 per ton).

$$\begin{aligned} \text{Minimize: Cost} &= (600\text{kwh} + 35\text{kwh})(.16) + (200 * .24)X_1 + (400 * .24)X_2 + (150 * .24)X_3 + \\ &(72)X_i + 900X_1 + 700X_2 + 500X_3 + 4,000X_{Ni} + 3,000X_{Cr} + 1200X_{Mn} + 1,100X_{Si} + 23,000X_{Mo} + 200X_i \\ 1 &= X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo} \\ .0165 &\leq (.095X_1 + .0185X_2 + .0055X_3).976 + .35X_{Ni} \\ .02 &\geq (.095X_1 + .0185X_2 + .0055X_3).976 + .35X_{Ni} \\ .007 &\leq (.175X_1 + .0085X_2 + .005X_3).946 + .65X_{Cr} \\ .009 &\geq (.175X_1 + .0085X_2 + .005X_3).946 + .65X_{Cr} \\ .006 &\leq (.02X_1 + .007X_2 + .008X_3).63 + .77X_{Mn} \\ .008 &\geq (.02X_1 + .007X_2 + .008X_3).63 + .77X_{Mn} \\ .0015 &\leq (.01X_1 + .002X_2 + .0025X_3).62 + .65X_{Si} \\ .0030 &\geq (.01X_1 + .002X_2 + .0025X_3).62 + .65X_{Si} \\ .0020 &\leq (.0X_1 + .0025X_2 + .002X_3).95 + .67X_{Mo} \\ .0030 &\geq (.0X_1 + .0025X_2 + .002X_3).95 + .67X_{Mo} \end{aligned}$$

Mathematical Program 3A: Linear Equation scrap blend Optimization model, Induction Costs

$$\begin{aligned} \text{Minimize: Emissions(kg)} &= (600\text{kwh} + 35\text{kwh})(.474) + (200 * .18)X_1 + (400 * .18)X_2 + \\ &(150 * .18)X_3 + (300 * .18)X_i + (6 * 907\text{kg})X_{Ni} + (6.6 * 907\text{kg})X_{Cr} + (5.9 * 907\text{kg})X_{Mn} + (3.6 * \\ &907\text{kg})X_{Si} + (8 * 907\text{k})X_{Mo} \\ 1 &= X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo} \\ .0165 &\leq (.095X_1 + .0185X_2 + .0055X_3).976 + .35X_{Ni} \\ .02 &\geq (.095X_1 + .0185X_2 + .0055X_3).976 + .35X_{Ni} \\ .007 &\leq (.175X_1 + .0085X_2 + .005X_3).946 + .65X_{Cr} \\ .009 &\geq (.175X_1 + .0085X_2 + .005X_3).946 + .65X_{Cr} \\ .006 &\leq (.02X_1 + .007X_2 + .008X_3).63 + .77X_{Mn} \\ .008 &\geq (.02X_1 + .007X_2 + .008X_3).63 + .77X_{Mn} \\ .0015 &\leq (.01X_1 + .002X_2 + .0025X_3).62 + .65X_{Si} \\ .0030 &\geq (.01X_1 + .002X_2 + .0025X_3).62 + .65X_{Si} \\ .0020 &\leq (.0X_1 + .0025X_2 + .002X_3).95 + .67X_{Mo} \\ .0030 &\geq (.0X_1 + .0025X_2 + .002X_3).95 + .67X_{Mo} \end{aligned}$$

Mathematical Program 3B: Linear Equation scrap-blend Optimization model, Induction Emissions *Scrap Processed Assume 0 kg/CO₂

When run through the linear programming software (using the Excel solver addon), the cost-optimal blend to produce 4340 with Induction melting was: 5.44% 304 scrap, 90.03% light iron, 3.27% FeNi, 0.69% FeMn, and 0.30% FeMo (total cost \$581 per ton, total emissions 603 kg of CO₂). The optimal blend for emissions was found to be: 2.43% 304 scrap, 81.31% 8620 scrap, 14.00% 4340 scrap 2.10% FeNi, .13% FeMn, .03% FeMo (total emissions of 465 kg of CO₂, total cost of \$736 per ton). Table 10 below illustrates the optimal steel blends when minimizing cost and/or emissions using an electric arc furnace (EAF) or induction melting to produce various alloy steels.

Steel Chemistry	Optimal Blend For Costs (EAF)	Cost (USD) (Kg-CO ₂)	Optimal Blend For Emissions (EAF)	Cost (USD) (Kg-CO ₂)	Optimal Blend For Costs (Induction)	Cost (USD) (Kg-CO ₂)	Optimal Blend For Emissions (Induction)	Cost (USD) (Kg-CO ₂)
304 Stainless	70.99% 304, 3.97% FeNi, 21.19% FeCr 2.30% FeMn, 1.54% FeSi,	\$1588.13 1915 kg	70.99% 304, 3.97% FeNi, 21.19% FeCr 2.30% FeMn, 1.54% FeMo,	\$1588.13 1915 kg	32.36% iron, 32.98% 304, 14.14% FeNi, 18.54% FeCr, 1.86% FeMn,	\$1622.63 2327 kg	30.36% 304, 32.98% 8620, 14.14% FeNi, 18.54% FeCr, 2.06% FeMn,	\$1704.95 2321 kg
4340	17.15% 304, 81.47% iron, 0.15% FeNi, 0.70% FeMn, 0.23% FeSi, 0.30% FeMo	\$546 365 kg	13.13% 304, 85.99% 8620, 0.58% FeMn, 0.23 % FeSi, 0.07% FeMo,	\$686 304 kg	5.44% 304, 90.03% iron, 3.27% FeNi, 0.69% FeMn, 0.03% FeMo,	\$581 603 kg	2.34% 304, 81.31% 8620, 14.00% 4340, 2.10% FeNi, 0.13% FeMn,	\$736 465 kg
8620	85.91% iron, 4.29% 304, 0.27% FeCr, 9.07% FeMn, 0.23% FeSi, 0.22% FeMo	\$521.36 812 kg	2.41% 304, 88.21% 8620, 0.22% FeCr, 8.93% FeMn 0.23% FeSi	\$687.91 754 kg	86.88% iron, 3.62% 304, 0.18% FeNi, 9.03% FeMn, 0.06% FeSi, 0.22% FeMo	\$514.52 785 kg	1.03% 304, 90.47% 8620, 8.48% FeMn	\$672.60 874 kg

Table 10: Optimal Steel Blends for Various Target Alloys calculated via Excel Solver addon

Utilizing the results of these models alternative melting blends for the alloy can be considered, the company can choose to pursue a more cost-effective approach where profits are the number one concern or an environmental strategy where emissions are the priority. A hybrid approach can be taken to balance both methods where CO₂ is assigned a dollar per kg value and the objective function is a combination of both cost and emissions. From the example model run

the results showed that keeping the melting method as EAF was superior to changing it to induction in terms of both emissions and cost, additionally relying on a mix of light iron and 304 stainless steel scrap as a source of alloying content could produce massive savings from replacing the ferrochrome and most of the ferronickel used in the melt. This method also produced massive reductions in emissions.

Chapter 6

Summary, Conclusions, and Future Work

As steel and iron producers increasingly look for ways to secure alloy and scrap supplies while setting cost and CO₂ emissions reduction goals, this body of work presented in this thesis will become increasingly more important.

As part of this work, cost and emissions models have been developed to guide steel melting decisions on the makeup of the melting process and the melt charge.

Through utilizing a live/automated version of this model scrap blends can be created based on the current market prices or scrap availability. Additionally, CO₂ emissions and savings can be estimated in a quantifiable manner and the melting and raw material sourcing process can be accounted for in part of the manufacturing emissions calculations and savings goals. Additional research will need to be carried out on melting scrap blends to determine the behavior of alloying elements contained in scrap steel melts so a more accurate model of how these scrap blends oxidize can be created, drastically improving the reliability of these calculations while allowing for melters to develop more cost-effective and sustainable melting practices.

BIBLIOGRAPHY

- [1] “Climate change policy paper,” *worldsteel.org*, Sep. 23, 2022.
<https://worldsteel.org/publications/policy-papers/climate-change-policy-paper/> (accessed Feb. 11, 2024).
- [2] “World Steel in Figures 2022,” *worldsteel.org*, Jun. 2023. <https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/> (accessed Feb. 11, 2024).
- [3] G. Zang *et al.*, “Cost and life cycle analysis for deep CO₂ emissions reduction of steelmaking: Blast furnace-basic oxygen furnace and electric arc furnace technologies,” *International Journal of Greenhouse Gas Control*, vol. 128, pp. 103958–103958, Sep. 2023, doi:
<https://doi.org/10.1016/j.ijggc.2023.103958>.
- [4] L. Holappa, “Basics of Ferroalloys,” *Elsevier eBooks*, pp. 9–28, Jan. 2013, doi:
<https://doi.org/10.1016/b978-0-08-097753-9.00002-2>.
- [5] “Steelmaking in Electric Arc Furnace – IspatGuru,” *Ispatguru.com*, 2022.
<https://www.ispatguru.com/steelmaking-in-electric-arc-furnace/> (accessed Feb. 17, 2024).
- [6] J. Ancheta, “Effects of chemical elements to steel,” *Linkedin.com*, Oct. 26, 2023.
<https://www.linkedin.com/pulse/effects-chemical-elements-steel-joemar-ancheta-1pikc/> (accessed Mar. 02, 2024).
- [7] A. Ramadan, A. Shash, El Mahallawi, Iman, D. Senk, and T. Mattar, “Studying the effect of tramp elements in scrap on industrial recycled steel processing and quality,” Mar. 2014.
- [8] T. Buechel, “4 Common Types of Steel Scrap,” *iScrap App*, Feb. 16, 2024.
<https://iscrapapp.com/blog/4-common-types-of-steel-scrap/> (accessed Mar. 27, 2024).
- [9] Congressional Budget Office, “Emissions of Carbon Dioxide in the Transportation Sector,” 2022.
Available: <https://www.cbo.gov/system/files/2022-12/58566-co2-emissions-transportation.pdf>
- [10] “Greenhouse Gas Emissions from a Typical Passenger Vehicle | US EPA,” *US EPA*, Jan. 12, 2016. <https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger->

- [18] W. Wei, P. B. Samuelsson, A. Tilliander, R. Gyllenram, and Jönsson, Pär G, “Energy consumption and greenhouse gas emissions of nickel products,” *Energies*, vol. 13, Art. no. 21, 2020, doi: <https://doi.org/10.3390/en13215664>.
- [19] U.S. Environmental Protection Agency, “Technical Support Document for the Ferroalloy Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases,” 2009. Accessed: Mar. 28, 2024. [Online]. Available: https://www.epa.gov/sites/default/files/2015-02/documents/tsd_ferroalloys_epa_1-22-09.pdf
- [20] A. Berggren, “Comparing CO2 emissions from different energy sources,” *COWI*, Sep. 20, 2023. <https://www.cowi.com/about/news-and-press/comparing-co2-emissions-from-different-energy-sources#:~:text=Carbon%20dioxide%20equivalent%20is%20a,emissions%20of%20different%20greenhouse%20gases.&text=Coal%3A%20740%2D1689%20g%20CO2e%2FKWh>. (accessed Mar. 28, 2024).
- [21] United States Environmental Protection Agency, “eGRID Technical Guide | US EPA,” *US EPA*, Feb. 14, 2018. <https://www.epa.gov/egrid/egrid-technical-guide> (accessed Mar. 28, 2024).
- [22] D. Schaeffler, “A Brief History of Steelmaking,” *MetalForming Magazine*, Aug. 31, 2020. <https://www.metalformingmagazine.com/article/?/materials/mild-steel/a-brief-history-of-steelmaking-gu> (accessed Mar. 02, 2024).
- [23] H. Andrei, C. Cepisca, and S. Grigorescu, “Power Quality and Electrical Arc Furnaces,” *ResearchGate*, 2024, doi: <https://doi.org/10.5772/15996>.
- [24] H. Andrei, C. Cepisca, and S. Grigorescu, “Power Quality and Electrical Arc Furnaces,” *Power Quality Blog*, Jan. 19, 2022. <https://powerquality.blog/2022/01/19/power-quality-and-electrical-arc-furnaces/#:~:text=To%20produce%20a%20ton%20of%20steel%20in,being%20greatly%20improved%20at%20a%20fast%20pace>. (accessed Mar. 28, 2024).
- [25] L. Reijnders, “Conserving functionality of relatively rare metals associated with steel life cycles: a review,” *Journal of Cleaner Production*, vol. 131, pp. 76–96, Sep. 2016, doi: <https://doi.org/10.1016/j.jclepro.2016.05.073>.

- [26] “The largest steel plant in the world operating induction furnaces | Foundry Trade Journal,” *Foundrytradejournal.com*, 2016. <https://www.foundrytradejournal.com/features/the-largest-steel-plant-in-the-world-operating-induction-furnaces> (accessed Mar. 26, 2024).
- [27] “SH Arjunwadkar, MR Ransing and RS Ransing, ‘Seven Steps to Energy Efficiency for Foundries’. Technical Paper, Foundry Management and Technology, pp:24-29, vol 143, no. 3, March 2015.”
- [28] L. Wu, K. Liu, H. Mei, G. Bao, Y. Zhou, and H. Wang, “Thermodynamics Analysis and Pilot Study of Reusing Medium and High Alloy Steel Scrap Using Induction Melting and Electroslag Remelting Process,” *Metals*, vol. 12, no. 6, pp. 944–944, May 2022, doi: <https://doi.org/10.3390/met12060944>.
- [29] C. Sharma, J. Trivedi, and S. Chadhury, “On Increasing Mn Recovery During Production of Mn-Based Stainless Steel,” *Transactions of the Indian Institute of Metals*, Apr. 2017, doi: <https://doi.org/10.1007/s12666-017-1125-7>.
- [30] J. R. Nagel, D. Cohrs, J. Salgado, and R. K. Rajamani, “Electrodynamic Sorting of Industrial Scrap Metal,” *Kona Powder and Particle Journal*, vol. 37, no. 0, pp. 258–264, Jan. 2020, doi: <https://doi.org/10.14356/kona.2020015>.
- [31] S. Mueller, “Optimizing Shredder Operations,” *ISRI*, Dec. 10, 2019. <https://www.isri.org/scrap-articles/optimizing-shredder-operations> (accessed Mar. 27, 2024).
- [32] J. D. Ray, J. R. Nagel, D. Cohrs, and R. K. Rajamani, “Forces on Particles in Time-Varying Magnetic Fields,” *Kona Powder and Particle Journal*, vol. 35, no. 0, pp. 251–257, Jan. 2018, doi: <https://doi.org/10.14356/kona.2018016>.
- [33] “Eriez - Shred1 Ballistic Separator,” *Eriez.com*, 2024. <https://www.eriez.com/NA/EN/Products/Metals-Recycling/Ferrous-Recovery/Shred1-Ballistic-Separator.htm> (accessed Mar. 27, 2024).

- [34] W. Xu *et al.*, “Classification and rating of steel scrap using deep learning,” *Engineering Applications of Artificial Intelligence*, vol. 123, pp. 106241–106241, Aug. 2023, doi: <https://doi.org/10.1016/j.engappai.2023.106241>.
- [35] M. B. Mesina, T.P.R. de Jong, and W.L. Dalmijn, “Automatic sorting of scrap metals with a combined electromagnetic and dual energy X-ray transmission sensor,” *International Journal of Mineral Processing*, vol. 82, no. 4, pp. 222–232, Jun. 2007, doi: <https://doi.org/10.1016/j.minpro.2006.10.006>.
- [36] M. Weiss, “Resource Recycling in Waste Management with X-ray Fluorescence,” *Montanuniversität Leoben*, 2016. <https://pure.unileoben.ac.at/en/publications/resource-recycling-in-waste-management-with-x-ray-fluorescence> (accessed Mar. 27, 2024).
- [37] S. Van, Dillam Jossue Diaz-Romero, B. Engelen, I. Zaplana, and J. R. Peeters, “Assessing the efficiency of Laser-Induced Breakdown Spectroscopy (LIBS) based sorting of post-consumer aluminium scrap,” *Procedia CIRP*, vol. 105, pp. 278–283, Jan. 2022, doi: <https://doi.org/10.1016/j.procir.2022.02.046>.
- [38] M. Cesetti and P. Nicolosi, “Waste processing: new near infrared technologies for material identification and selection,” *Journal of Instrumentation*, vol. 11, Art. no. 09, 2016, doi: <https://doi.org/10.1088/1748-0221/11/09/C09002>.
- [39] Ghada AlMisned, Tariq Al-Abdullah, Fatai Liadi, and Adil Hawsawi, “Improving a PGNAA Technique to Detect Heavy Metals in Solid Samples,” *Applied sciences*, vol. 12, no. 8, pp. 3714–3714, Apr. 2022, doi: <https://doi.org/10.3390/app12083714>.
- [40] B. Maróti, T. Belgya, Z. Homonnay, L. Szentmiklósi, and A. Császár, “Non-destructive analysis of metals and alloys using prompt gamma activation analysis and complementary methods PhD dissertation.” Accessed: Mar. 27, 2024. [Online]. Available: https://edit.elte.hu/xmlui/bitstream/handle/10831/42101/MB_PhD_dissertation.pdf?sequence=2

- [41] H. Kurth and M. Kalicinski, “Real-Time On-Line Elemental Analysis of Scrap for Steelmaking,” in *AIST Iron & Steel Technology*, Jan. 2024, pp. 94–100. Accessed: Mar. 28, 2024. [Online]. Available: <https://imis.aist.org/store/detail.aspx?id=pr-pm0124-3>
- [42] AZoM, “Grade 304 Stainless Steel: Properties, Fabrication and Applications,” AZoM, May 18, 2005. Available: <https://www.azom.com/article.aspx?ArticleID=2867>. [Accessed: Mar. 29, 2024]
- [43] AZoM, “AISI 4340 Alloy Steel (UNS G43400),” AZoM, Sep. 07, 2012. Available: <https://www.azom.com/article.aspx?ArticleID=6772>. [Accessed: Mar. 29, 2024]
- [44] AZoM, “AISI 8620 Alloy Steel (UNS G86200),” AZoM, Sep. 06, 2012. Available: <https://www.azom.com/article.aspx?ArticleID=6754>. [Accessed: Mar. 29, 2024]

Appendix A

Tables and Equations

Ferroalloy	Percentage of element	kg of CO ₂ per kg produced	Source
Ferrosilicon	65% Cr	6.625	World steel (Sphera) [17]
Ferromanganese	77% Mn	5.903	World steel (Sphera) [17]
Ferro molybdenum	67% Mo	8.091	World steel (Sphera) [17]
Ferro vanadium	80% V	82.426	World steel (Sphera) [17]
Ferronickel	29% Ni	9.438	World steel (Sphera) [17]
Nickel metal	100% Ni	14	MDPI [18]
Nickel oxide	76 % Ni	30	MDPI [18]
Ferronickel	35% Ni	6	MDPI [18]
Nickel Pig Iron	10% Ni	7	MDPI [18]
Ferrosilicon	45% Si	2.5	US EPA [19]
Ferrosilicon	65% Si	3.6	US EPA [19]
Ferrosilicon	75% Si	4.0	US EPA [19]
Ferrosilicon	90% Si	4.8	US EPA [19]

Table 1: Ferroalloy Emissions Estimates [17, 18, 19]

Metal Mix	kg of CO ₂ per kg of pure metal produced	Exporting Countries
Silicon	4.587	-
Nickel	10.826	South Africa, Canada, Norway, Australia, Russia
Manganese	14.857	South Africa, Australia
Magnesium	33.594	-
Aluminum	16.595	-
Tin	5.688	-
Lead	1.759	-
Copper	3.977	-
Zinc	2.612	-

Table 2: Pure Metal production Co2 estimate mix [17]

Subregion Name	Subregion Acronym for Map	Pounds of CO ₂ per MWh
ASCC Alaska Grid	AKGD	1,067.680
ASCC Alaska Grid	AKGD	1,067.680
ASCC Miscellaneous	AKMS	485.186
WECC Southwest	AZNM	819.656
WECC California	CAMX	531.678
ERCOT All	ERCT	813.552
FRCC All	FRCC	832.924
HICC Miscellaneous	HIMS	1,134.391
HICC Oahu	HIOA	1,633.097
MRO East	MROE	1,582.135
MRO West	MROW	995.790
NPCC New England	NEWE	539.367
WECC Northwest	NWPP	634.599
NPCC NYC/Westchester	NYCW	816.756

NPCC Long Island	NYLI	1,210.940
NPCC Upstate NY	NYUP	233.081
Puerto Rico Miscellaneous	PRMS	1,558.024
RFC East	RFCE	672.787
RFC Michigan	RFCM	1,214.061
RFC West	RFCW	1,046.132
WECC Rockies	RMPA	1,158.860
SPP North	SPNO	991.729
SPP South	SPSO	1,031.601
SERC Mississippi Valley	SRMV	772.737
SERC Midwest	SRMW	1,543.034
SERC South	SRSO	891.907
SERC Tennessee Valley	SRTV	931.586
SERC Virginia/Carolina	SRVC	639.665

Table 3: Table of eGRID Subregions Emissions [21]

Process	kWh per MT of steel
Electric Arc Furnace	440 kWh [24]
Induction Furnace melt	660 kWh [27]
Scrap shredding	35 kWh [31]

Table 4: Estimates of Steel Processing Electricity Requirements

Element	Percent retained in liquid melt
Chromium	30~95%
Nickel	98-99%
Manganese	16~80%
Silicon	N/A
Molybdenum	90~95%
Tungsten	97~99%
Vanadium	7~58%
Copper	90~95%
Cobalt	98~99%

Table 5: Percentage of chemistry retained during EAF melting literature review [25]

Element	Percent retained medium frequency
Chromium	94.62 [28]
Nickel	97.63 [28]

Manganese	63~83 [29]
Silicon	62~89 [29]
Molybdenum	95.09 [28]
Tungsten	97.36 [28]
Vanadium	89.49 [28]

Table 6: Percentage of chemistry retained during EAF melting literature review [28, 29]

Alloy	C	Ni	Cr	Mn	Si	Mo	S	P
304 Stainless	0.07	8.00 - 10.50	17.50 - 19.50	2.0	1.0	0	< .03	< .05
4340	0.40	1.65 - 2.00	0.70 - 0.90	0.60 - 0.80	0.15 - 0.30	0.20 - 0.30	< .04	< .035
8620	.20	0.40 - 0.70	0.400 - 0.600	0.70 - 0.90	0.15 - 0.35	0.15 - 0.25	< .04	< .035

Table 7: Elemental Chemistry Composition percentage of Commonly used Steel Grades

Alloy	Ni	Cr	Mn	Si	Mo	S	P
304 Stainless	9.50	5.55	.96	0	0	0	0
4340	1.80	.24	.33	0	.23	0	0
8620	.55	.15	.38	0	.25	0	0

Table 8: Elemental Retainment for Pure Steel Scrap Remelted in Electric Arc Furnace* Assume Mean Chemistry

Alloy	Ni	Cr	Mn	Si	Mo	S	P
304 Stainless	9.50	17.50	1.90	.63	0	< .03	< .05
4340	1.80	.76	.66	.15	.24	< .04	< .035
8620	.55	.47	.76	.17	.27	< .04	< .035

Table 9: Elemental Retainment for Pure Steels Remelted in Induction Furnace* Assume Mean Chemistry

Steel Chemistry	Optimal Blend For Costs (EAF)	Cost (USD) (Kg-CO ₂)	Optimal Blend For Emissions (EAF)	Cost (USD) (Kg-CO ₂)	Optimal Blend For Costs (Induction)	Cost (USD) (Kg-CO ₂)	Optimal Blend For Emissions (Induction)	Cost (USD) (Kg-CO ₂)
304 Stainless	70.99% 304, 3.97% FeNi, 21.19% FeCr 2.30% FeMn, 1.54% FeSi,	\$1588.13 1915 kg	70.99% 304, 3.97% FeNi, 21.19% FeCr 2.30% FeMn, 1.54% FeMo,	\$1588.13 1915 kg	32.36% iron, 32.98% 304, 14.14% FeNi, 18.54% FeCr, 1.86% FeMn,	\$1622.63 2327 kg	30.36% 304, 32.98% 8620, 14.14% FeNi, 18.54% FeCr, 2.06% FeMn,	\$1704.95 2321 kg
4340	17.15% 304, 81.47% iron, 0.15% FeNi, 0.70% FeMn, 0.23% FeSi, 0.30% FeMo	\$546 365 kg	13.13% 304, 85.99% 8620, 0.58% FeMn, 0.23 % FeSi, 0.07% FeMo,	\$686 304 kg	5.44% 304, 90.03% iron, 3.27% FeNi, 0.69% FeMn, 0.03% FeMo,	\$581 603 kg	2.34% 304, 81.31% 8620, 14.00% 4340, 2.10% FeNi, 0.13% FeMn,	\$736 465 kg
8620	85.91% iron, 4.29% 304,	\$521.36 812 kg	2.41% 304, 88.21% 8620, 0.22% FeCr, 8.93% FeMn	\$687.91 754 kg	86.88% iron, 3.62% 304,	\$514.52 785 kg	1.03% 304, 90.47% 8620, 8.48% FeMn	\$672.60 874 kg

	0.27% FeCr, 9.07% FeMn, 0.23% FeSi, 0.22% FeMo		0.23% FeSi		0.18% FeNi, 9.03% FeMn, 0.06% FeSi, 0.22% FeMo			
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Table 10: Optimal Steel blends for various target alloys

$$(\%FeNi \quad \%FeCr \quad \%FeMn \quad \%FeSi \quad \%FeMo) = (\%Ni \quad \%Cr \quad \%Mn \quad \%Si \quad \%Mo) * \begin{pmatrix} \%Ni \text{ retained} \\ \%Cr \text{ retained} \\ \%Mn \text{ retained} \\ \%Si \text{ retained} \\ \%Mo \text{ retained} \end{pmatrix} * \begin{pmatrix} 1/\%FeNi \\ 1/\%FeCr \\ 1/\%FeMn \\ 1/\%FeSi \\ 1/\%FeMo \end{pmatrix}$$

Equation 1: Ferroalloy Equivalency matrix calculation

$$(\%27.14 \quad \%26.92 \quad \%2.46 \quad \%0.97 \quad \%0) = (\%9.25 \quad \%18.50 \quad \%2.0 \quad \%1.0 \quad \%0) * \begin{pmatrix} .976 \\ .946 \\ .63 \\ .62 \\ .951 \end{pmatrix} * \begin{pmatrix} 1/.35 \\ 1/.65 \\ 1/.77 \\ 1/.65 \\ 1/.67 \end{pmatrix}$$

Equation 2: Ferroalloy Equivalency of Pure 304 stainless melted in medium frequency induction furnace*Assume mean chemistry & poor elemental retainment during melting (table 6)

$$\frac{Cost}{ton} = \frac{ShippingCosts}{tons \text{ in order}} + \frac{Kwh \text{ used in melt}}{Tons \text{ in melt}} (price/Kwh) + \sum_1^{Elem.} \frac{(tons \text{ of ferro alloy used})}{Tons \text{ in melt}} (price/ton \text{ of alloy}) + \frac{operating \text{ cost}}{tons \text{ used in melt}}$$

Equation 3: Rudimentary Cost Estimation per Ton Melted based on Alloy Chemistry

$$\frac{Emmissions}{ton} = (Distance * \frac{Freight \text{ Coef.}}{TonMile}) + \frac{Kwh \text{ used in process}}{Tons \text{ in melt}} (Co2/Kwh) + \sum_1^{Elem.} \frac{(tons \text{ of ferro alloy})}{Tons \text{ in melt}} (CO2 /ton \text{ of alloy}) + \frac{operating \text{ emmissions}}{tons \text{ used in melt}}$$

Equation 4: Emissions per Ton Melted based on Alloy Chemistry

$$\frac{Cost}{ton} = \frac{300 \text{ m} * \$24}{1T} + \frac{475 \text{ kwh}}{1T} (\$.16/Kwh) + \sum_1^5 \frac{(.0514)}{1} (\$4,000/Ni) + \frac{(.0123)}{1} (\$3,000/Cr) + \frac{(.0091)}{1} (\$1,200/Mn) + \frac{(.0033)}{1} (\$1,100/Si) + \frac{(.0037)}{1} (\$23,000/Mo) + \frac{\$200}{1}$$

Equation 5: Rudimentary Cost Estimation per Ton Melted based on 4340 in EAF

$$\frac{Kg \text{ CO2}}{ton} = \frac{300 \text{ m} * .18kg}{1T} + \frac{475 \text{ kwh}}{1T} (.474kg/Kwh) + \sum_1^5 \frac{(.0514)}{1} (5,454/Ni) + \frac{(.0123)}{1} (6,023/Cr) + \frac{(.0091)}{1} (5,366/Mn) + \frac{(.0033)}{1} (3636/Si) + \frac{(.0037)}{1} (7355/Mo) + \frac{N/A}{1}$$

Equation 6: Rudimentary Emissions Estimation per Ton Melted based on 4340 in EAF

Appendix B

Figures and Mathematical Programs

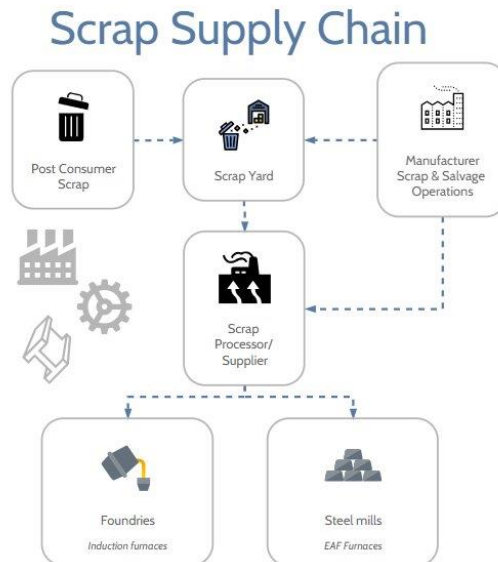


Figure 1: Basic outline of Scrap Supply Chain

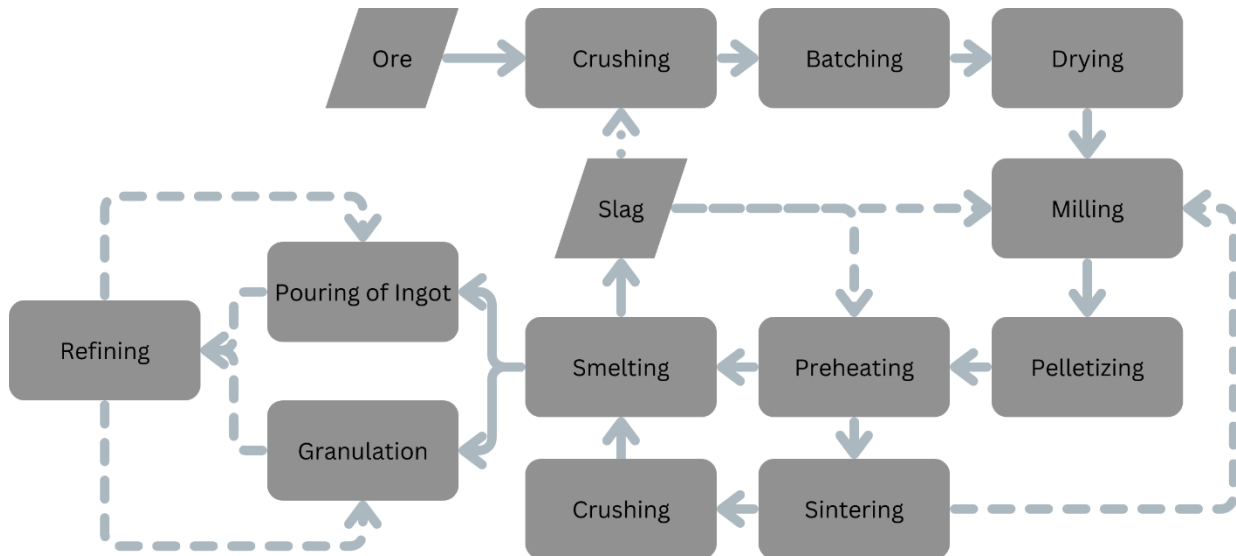


Figure 2: Outline of Ferroalloy Production Process

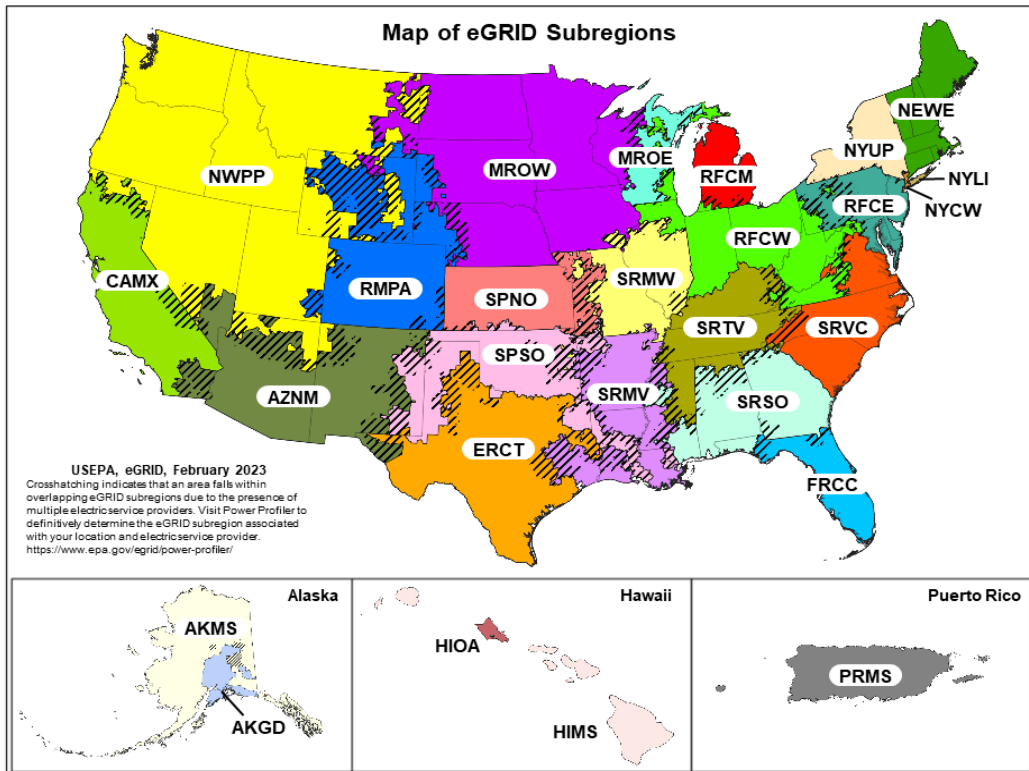


Figure 3: Map of eGrid subregions [21]

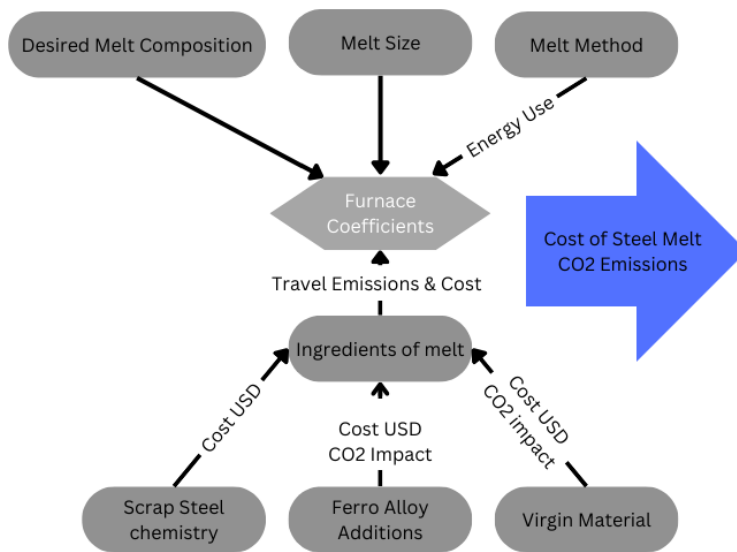


Figure 4: Inputs for Steel Cost and Emissions Melt Optimization Model

$$\text{Minimize: Cost} = (E_m + E_p + E_f - E_o)(R) + D_1X_1 + D_2X_2 + D_3X_3 + D_iX_i + C_1X_1 + C_2X_2 + C_3X_3 + C_{Ni}X_{Ni} + C_{Cr}X_{Cr} + C_{Mn}X_{Mn} + C_{Si}X_{Si} + C_{Mo}X_{Mo} + C_iX_i + (T + Lw)$$

$$1 = X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo}$$

$$Ni \% \leq \%Ni_1X_1 * F_{Ni} + \%Ni_2X_2 * F_{Ni} + \%Ni_3X_3 * F_{Ni} + X_{Ni}$$

$$Ni \% \geq \%Ni_1X_1 * F_{Ni} + \%Ni_2X_2 * F_{Ni} + \%Ni_3X_3 * F_{Ni} + X_{Ni}$$

$$Cr \% \leq \%Cr_1X_1 * F_{Cr} + \%Cr_2X_2 * F_{Cr} + \%Cr_3X_3 * F_{Cr} + X_{Cr}$$

$$Cr \% \geq \%Cr_1X_1 * F_{Cr} + \%Cr_2X_2 * F_{Cr} + \%Cr_3X_3 * F_{Cr} + X_{Cr}$$

$$Mn \% \leq \%Mn_1X_1 * F_{Mn} + \%Mn_2X_2 * F_{Mn} + \%Ni_3X_3 * F_{Mn} + X_{Mn}$$

$$Mn \% \geq \%Mn_1X_1 * F_{Mn} + \%Mn_2X_2 * F_{Mn} + \%Ni_3X_3 * F_{Mn} + X_{Mn}$$

$$Si \% \leq \%Si_1X_1 * F_{Si} + \%Si_2X_2 * F_{Si} + \%Si_3X_3 * F_{Si} + X_{Si}$$

$$Si \% \geq \%Si_1X_1 * F_{Si} + \%Si_2X_2 * F_{Si} + \%Si_3X_3 * F_{Si} + X_{Si}$$

$$Mo \% \leq \%Mo_1X_1 * F_{Mo} + \%Mo_2X_2 * F_{Mo} + \%Mo_3X_3 * F_{Mo} + X_{Mo}$$

$$Mo \% \geq \%Mo_1X_1 * F_{Mo} + \%Mo_2X_2 * F_{Mo} + \%Mo_3X_3 * F_{Mo} + X_{Mo}$$

Mathematical Program 1: Outline of Linear Equation scrap blend Optimization model ($X_n \geq 0$)

$$\text{Minimize: Cost} = (440kwh + 35kwh)(.16) + (200 * .24)X_1 + (400 * .24)X_2 + (150 * .24)X_3 + (72)X_i + 900X_1 + 700X_2 + 500X_3 + 4,000X_{Ni} + 3,000X_{Cr} + 1200X_{Mn} + 1,100X_{Si} + 23,000X_{Mo} + 200X_i$$

$$1 = X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo}$$

$$.0165 \leq (.095X_1 + .0185X_2 + .0055X_3).98 + .35X_{Ni}$$

$$.02 \geq (.095X_1 + .0185X_2 + .0055X_3).98 + .35X_{Ni}$$

$$.007 \leq (.175X_1 + .0085X_2 + .005X_3).3 + .65X_{Cr}$$

$$.009 \geq (.175X_1 + .0085X_2 + .005X_3).3 + .65X_{Cr}$$

$$.006 \leq (.02X_1 + .007X_2 + .008X_3).16 + .77X_{Mn}$$

$$.008 \geq (.02X_1 + .007X_2 + .008X_3).16 + .77X_{Mn}$$

$$.0015 \leq (.01X_1 + .002X_2 + .0025X_3)0 + .65X_{Si}$$

$$.0030 \geq (.01X_1 + .002X_2 + .0025X_3)0 + .65X_{Si}$$

$$.0020 \leq (0X_1 + .0025X_2 + .002X_3).9 + .67X_{Mo}$$

$$.0030 \geq (0X_1 + .0025X_2 + .002X_3).9 + .67X_{Mo}$$

Mathematical Program 2A: Linear Equation scrap blend Optimization model EAF Costs

$$\text{Minimize: Emissions (kg)} = (440kwh + 35kwh)(.474) + (200 * .18)X_1 + (400 * .18)X_2 + (150 * .18)X_3 + (300 * .18)X_i + (6 * 907kg)X_{Ni} + (6.6 * 907kg)X_{Cr} + (5.9 * 907kg)X_{Mn} + (3.6 * 907kg)X_{Si} + (8 * 907k)X_{Mo}$$

$$1 = X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo}$$

$$.0165 \leq (.095X_1 + .0185X_2 + .0055X_3).98 + .35X_{Ni}$$

$$.02 \geq (.095X_1 + .0185X_2 + .0055X_3).98 + .35X_{Ni}$$

$$.007 \leq (.175X_1 + .0085X_2 + .005X_3).3 + .65X_{Cr}$$

$$.009 \geq (.175X_1 + .0085X_2 + .005X_3).3 + .65X_{Cr}$$

$$\begin{aligned}
.006 &\leq (.02X_1 + .007X_2 + .008X_3).16 + .77X_{Mn} \\
.008 &\geq (.02X_1 + .007X_2 + .008X_3).16 + .77X_{Mn} \\
.0015 &\leq (.01X_1 + .002X_2 + .0025X_3)0 + .65X_{Si} \\
.0030 &\geq (.01X_1 + .002X_2 + .0025X_3)0 + .65X_{Si} \\
.0020 &\leq (0X_1 + .0025X_2 + .002X_3).9 + .67X_{Mo} \\
.0030 &\geq (0X_1 + .0025X_2 + .002X_3).9 + .67X_{Mo}
\end{aligned}$$

Mathematical Program 2B: Linear Equation scrap blend Optimization model EAF Emissions *Scrap Assume 0 kg/CO2

Minimize: Cost = $(600kwh + 35kwh)(.16) + (200 * .24)X_1 + (400 * .24)X_2 + (150 * .24)X_3 + (72)X_i + 900X_1 + 700X_2 + 500X_3 + 4,000X_{Ni} + 3,000X_{Cr} + 1200X_{Mn} + 1,100X_{Si} + 23,000X_{Mo} + 200X_i$

$$\begin{aligned}
1 &= X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo} \\
.0165 &\leq (.095X_1 + .0185X_2 + .0055X_3).976 + .35X_{Ni} \\
.02 &\geq (.095X_1 + .0185X_2 + .0055X_3).976 + .35X_{Ni} \\
.007 &\leq (.175X_1 + .0085X_2 + .005X_3).946 + .65X_{Cr} \\
.009 &\geq (.175X_1 + .0085X_2 + .005X_3).946 + .65X_{Cr} \\
.006 &\leq (.02X_1 + .007X_2 + .008X_3).63 + .77X_{Mn} \\
.008 &\geq (.02X_1 + .007X_2 + .008X_3).63 + .77X_{Mn} \\
.0015 &\leq (.01X_1 + .002X_2 + .0025X_3).62 + .65X_{Si} \\
.0030 &\geq (.01X_1 + .002X_2 + .0025X_3).62 + .65X_{Si} \\
.0020 &\leq (0X_1 + .0025X_2 + .002X_3).95 + .67X_{Mo} \\
.0030 &\geq (0X_1 + .0025X_2 + .002X_3).95 + .67X_{Mo}
\end{aligned}$$

Mathematical Program 3A: Linear Equation scrap blend Optimization model, Induction Costs

Minimize: Emissions (kg) = $(600kwh + 35kwh)(.474) + (200 * .18)X_1 + (400 * .18)X_2 + (150 * .18)X_3 + (300 * .18)X_i + (6 * 907kg)X_{Ni} + (6.6 * 907kg)X_{Cr} + (5.9 * 907kg)X_{Mn} + (3.6 * 907kg)X_{Si} + (8 * 907k)X_{Mo}$

$$\begin{aligned}
1 &= X_1 + X_2 + X_3 + X_i + X_{Ni} + X_{Cr} + X_{Mn} + X_{Si} + X_{Mo} \\
.0165 &\leq (.095X_1 + .0185X_2 + .0055X_3).976 + .35X_{Ni} \\
.02 &\geq (.095X_1 + .0185X_2 + .0055X_3).976 + .35X_{Ni} \\
.007 &\leq (.175X_1 + .0085X_2 + .005X_3).946 + .65X_{Cr} \\
.009 &\geq (.175X_1 + .0085X_2 + .005X_3).946 + .65X_{Cr} \\
.006 &\leq (.02X_1 + .007X_2 + .008X_3).63 + .77X_{Mn} \\
.008 &\geq (.02X_1 + .007X_2 + .008X_3).63 + .77X_{Mn} \\
.0015 &\leq (.01X_1 + .002X_2 + .0025X_3).62 + .65X_{Si} \\
.0030 &\geq (.01X_1 + .002X_2 + .0025X_3).62 + .65X_{Si} \\
.0020 &\leq (0X_1 + .0025X_2 + .002X_3).95 + .67X_{Mo} \\
.0030 &\geq (0X_1 + .0025X_2 + .002X_3).95 + .67X_{Mo}
\end{aligned}$$

Mathematical Program 3B: Linear Equation scrap-blend Optimization model, Induction Emissions *Scrap Assume 0 kg/CO2