ARTICLE IN PRESS

ELSEVIER

Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

ENERGY POLICY

www.elsevier.com/locate/enpol

The energy benefit of stainless steel recycling

Jeremiah Johnson[a,b,*], B.K. Reck[b], T. Wang[b], T.E. Graedel[b]

[a]Program in Environmental Engineering, Yale University, New Haven, CT, USA
[b]Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, 205 Prospect Street, New Haven, CT 02140, USA

Received 5 December 2006; accepted 21 August 2007

Abstract

The energy used to produce austenitic stainless steel was quantified throughout its entire life cycle for three scenarios: (1) current global operations, (2) 100% recycling, and (3) use of only virgin materials. Data are representative of global average operations in the early 2000s. The primary energy requirements to produce 1 metric ton of austenitic stainless steel (with assumed metals concentrations of 18% Cr, 8% Ni, and 74% Fe) is (1) 53 GJ, (2) 26 GJ, and (3) 79 GJ for each scenario, with CO_2 releases totaling (1) 3.6 metric tons CO_2, (2) 1.6 metric tons CO_2, and (3) 5.3 metric tons CO_2. Thus, the production of 17 million metric tons of austenitic stainless steel in 2004 used approximately 9.0×10^{17} J of primary energy and released 61 million metric tons of CO_2. Current recycling operations reduce energy use by 33% (4.4×10^{17} J) and CO_2 emissions by 32% (29 million tons). If austenitic stainless steel were to be produced solely from scrap, which is currently not possible on a global level due to limited availability, energy use would be 67% less than virgin-based production and CO_2 emissions would be cut by 70%. The calculation of the total energy is most sensitive to the amount and type of scrap fed into the electric arc furnace, the unit energy of the electric arc furnace, the unit energy of ferrochromium production, and the form of primary nickel.

Keywords: Stainless steel; Energy intensity; Recycling

1. Introduction

Stainless steel, which contains iron, chromium, and often nickel, molybdenum, and other elements, is an alloy with applications ranging from household cutlery to reactor tanks for the chemical industry. Its anti-corrosion properties are among the main driving forces for the 25 million metric tons of production in 2004 (International Chromium Development Association, 2006). Ferroalloy production and the fabrication of stainless steel in electric arc furnaces are energy-intensive processes. By examining the energy requirements to produce stainless steel throughout the entire life cycle, and isolating the effect of scrap recycling on energy use, one can understand the true energy needs and opportunities for conservation. The World Commission on Environment and Development (1987) found that a "low energy path is the best way toward a sustainable future". Determining the energy intensities of materials (i.e., the energy required per unit mass) under different scenarios aides in understanding and identifying this low-energy path.

The goals of this study are to quantify the use of energy in the production of 1 ton of austenitic (i.e., nickel-containing) stainless-steel slab under three scenarios: (1) the base case scenario, "Current Operations," examines the global average operations of the stainless steel and ferroalloy industries in the early 2000s, (2) the "Maximum Recycling" scenario calculates the energy used if demand is completely met from recycled material, and (3) the "Virgin Production" scenario examines stainless-steel production in the absence of scrap. A systems approach will be employed; the entire life cycle of the material (and the associated energy demands of its transformations) from mining and/or scrap recycling through production will be examined. By comparing the results of these scenarios, one can quantify the energy that is saved by current recycling practices and the energy that could be saved

*Corresponding author. 20 Mead Street, Cambridge, MA 02140, USA. Tel.: +1 44 203 506 9439; fax: +1 44 203 413 6362.
E-mail address: jeremiah.johnson@aya.yale.edu (J. Johnson).

0301-4215/$ - see front matter
doi:10.1016/j.enpol.2007.08.028

if ample scrap were available and recycling rates reached 100%. The unit energy demands are also linked to CO_2 emission factors, which provide a carbon intensity per unit of stainless steel produced.

Energy analyses can track use from numerous points of reference, such as a facility, a process, or a substance. The utility of energy analyses that focus on substances (such as this study) includes gaining knowledge of a material's comprehensive energy requirements, the releases of pollutants associated with such energy use, and the energy-related consequences of altering material use patterns. Norgate (2004) reviews the effect of metal recycling on life-cycle performance for a suite of metals and pays particular attention to energy requirements. He finds the gross energy requirements for the production of stainless steel from primary sources to be 75 GJ/ton (note: $1\,GJ = 10^9\,J$) when ferronickel is used as the primary nickel feed source and 49 GJ/ton when nickel metal is used, with ferronickel using 59% of the total energy in the former case (Norgate et al., 2004). This latter study also isolated the effects of different fuel sources for electricity generation.

In an extensive information circular entitled ''Energy Use Patterns for Metal Recycling'' released in 1978, Kusik and Kenahan at the US Bureau of Mines, collected data on the energy requirements for recycling a variety of metals, including aluminum, copper, iron and steel, lead, nickel, stainless steel, tin, titanium, and zinc. Worrell et al. (2001) examined historical trends in iron and steel energy use, and quantified the energy and carbon dioxide benefit of implementing 47 energy-efficient technologies to the US energy sector.

In 2000, Michaelis and Jackson (2000a, b) detailed the energy flows associated with the iron and steel industries in the United Kingdom. Mining, iron and steel production, steel good manufacture, steel good use, trade, recycling and scrap, and transportation were considered. Much like the study presented here, their study was grounded in a material flow analysis approach that determined the mass flows of their target substances.

The International Institute for Applied Systems Analysis (IIASA) has created a model called CO2DB, based on energy chain analysis, which is comparable to life-cycle assessment (Strubegger, 2003). This model contains data for over 3000 technologies in order to enable the user to link and assess their technical, economic, and environmental characteristics.

Other related research projects include energy requirements of the Indian steel industry (Bhaktavatsalam and Choudhury, 1995) and its ability for energy conservation (Choudhury and Bhaktavatsalam, 1997), and the energy requirements and carbon dioxide emissions of the Indian aluminum industry (Das and Kandpal, 2000). On a broader scale, a report for the United Nations Division for Sustainable Development examined the potential for improved energy and material efficiencies for several sectors, and identified barriers to implementation and potential policy instruments (Worrell et al., 1996).

2. Methodology

A simplified system boundary diagram, which guides and bounds this study, was created for the stainless-steel cycle and is shown in Fig. 1a. It includes the major processes associated with the production of primary chromium, nickel, and iron, the preparation of scrap, the smelting of stainless steel, and the transportation of nine intermediate products. Within each of these major processes, there are numerous unit operations that utilize energy in various forms. Fig. 1b illustrates an example of energy use for one of these processes: ferrochromium production. This figure is representative of Outokumpu processes and differs from the traditional, Premus, and DC arc technologies, which are also included in this study. As shown in Fig. 1b, the primary energy requirements of electricity generation and the energy used to produce primary fuels (e.g., coal, petroleum, and natural gas) are included in this study's scope. The functional unit used herein is the production of 1 metric ton of 304 grade austenitic stainless steel, assumed to contain 74% iron, 18% chromium, and 8% nickel.

To quantify the energy requirements of the entire life cycle in stainless-steel production, one must thoroughly understand material flows and losses. This project relies on the findings on three material flow analysis projects, conducted by the Yale Stocks and Flows research staff, for iron (Wang et al., 2007), chromium (Johnson et al., 2006), and nickel (Reck et al., 2007), in which all anthropogenic flows for each element were quantified for approximately 60 countries. The global elemental loss rates associated with each production process are given in Table 1. Material flow data are representative of the year 2000 and unit energy use data are those that are most recently available, generally from the early 2000s.

Three scenarios were examined: (1) ''Current Operations'' assumes a weighted global average of scrap recycling rates; (2) ''Maximum Recycling'' assumes that all metal used in stainless-steel production comes from scrap; and (3) ''Virgin Production'' assumes that all metal used in stainless-steel production comes from virgin sources. These scenarios differ only in the proportions of primary and secondary metals used; unit energy for such things as transportation and mining, as well as material loss rates, are held constant and varied only by the amount of mass that passes through each subprocess. Because of limited scrap availability, Maximum Recycling could not be achieved on a global level. Virgin Production is also unlikely, due to the preponderance of scrap use in the stainless-steel industry. These two scenarios are intended to show the outer bounds of material and energy use, serving as a basis for comparing current global performance.

For the Current Operations scenario, the average share of secondary material (i.e., scrap) added to the stainless-steel melt was 42% for chromium, 43% for nickel, and 67% for iron. The Maximum Recycling scenario assumes total recycling (a hypothetical situation on a global level,

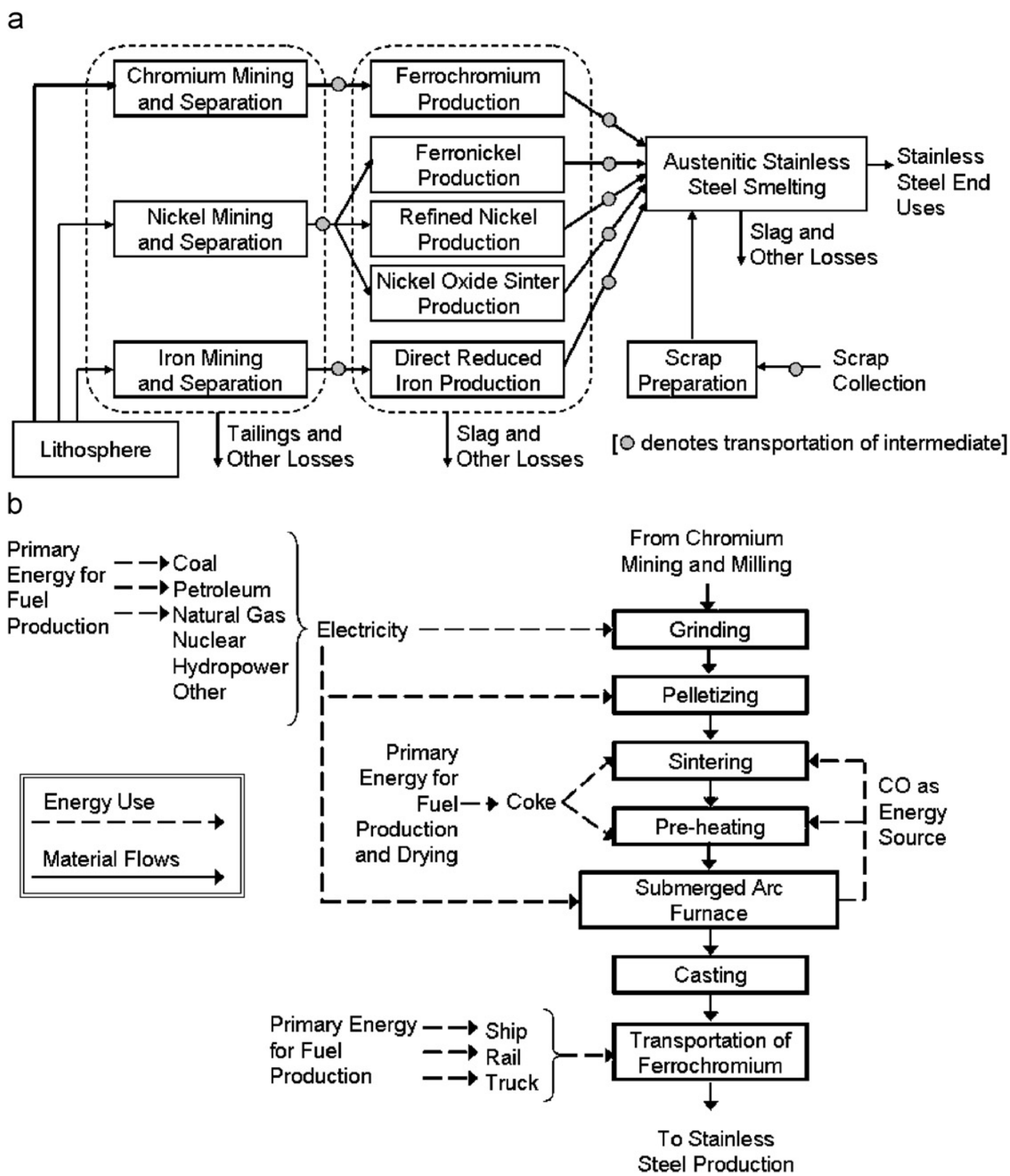

Fig. 1. (a) System boundary diagram for the stainless-steel life cycle; (b) energy used for the production of ferrochromium, representative of Outokumpu processes.

requiring adequate scrap availability), while the Virgin Production scenario assumes no scrap recycling. The scrap that is utilized in Current Operations and Maximum Recycling can be prompt scrap (internal to the process), new scrap from industrial processes, or old scrap for post-consumer discards. Any and all of these forms are used to meet scrap requirements. Although the primary units of chromium are predominately in the form of ferrochromium and primary iron is assumed to come from direct reduced iron (DRI), primary nickel may come from ferronickel, refined nickel, or nickel oxide sinter. The share of primary nickel used for stainless-steel production was assumed to be 30%, 65%, and 5%, respectively, for each of these forms.

The indirect (or "hidden") energy use throughout the life cycle makes a significant contribution to total energy use. To capture as much of this indirect energy use as possible, the following factors were included in the system boundary: (1) the energy used in electricity production; (2) the energy used in the acquisition and production of fuels; and (3) intermediate good transportation by ship, rail, and truck. There are other indirect energy use factors that, for tractability, were not included in this study. To assess the magnitude of these other factors, economic input–output life-cycle assessment (EIO-LCA) was employed. (Carnegie Mellon University Green Design Institute, 2007) The categories that are included in this study (e.g., "ferroalloy and related product manufacturing") account for 87% of

Please cite this article as: Johnson, J., et al., The energy benefit of stainless steel recycling. Energy Policy (2007), doi:10.1016/j.enpol.2007.08.028

Table 1
Elemental losses of production processes associated with stainless steel and its alloying elements

Process	Losses	Source
Chromite mining and separation losses	17% of chromium mined	Johnson et al. (2006)
Ferrochromium production losses	20% of chromium	Johnson et al. (2006)
Nickel mining and separation losses	20% of nickel mined	Reck et al. (2007)
Ferronickel production losses	5% of nickel	Reck et al. (2007)
Nickel oxide sinter production losses	5% of nickel	Reck et al. (2007)
Refined nickel production losses	Negligible	Reck et al. (2007)
Iron mining and separation losses	19% of iron mined	Wang et al. (2007)
Direct reduced iron production losses	0.43% of iron	Wang et al. (2007)
Stainless-steel smelting in an electric arc furnace	1.4% of entering chromium	Johnson et al. (2006)
	0.7% of entering nickel	Reck et al. (2007)
	1.8% of entering iron	Wang et al. (2007)

the energy use results of the EIO-LCA findings. The remaining 13% includes such items as "water transportation," "paper and paperboard mills," and "petroleum lubricating oil and grease manufacturing," which were determined to be outside the scope of this analysis. It is important to note that this study captures the first-degree energy use; it does not, for example, account for the energy use to make steel that is used in the construction of the capital equipment at a stainless-steel smelter. Therefore, it can be estimated that this study captures, at most, 87% of the life cycle primary energy use.

It is essential when quantifying energy use to consistently look at the primary energy. To do so, it was necessary to link electricity consumption with the fuel needed to generate that electricity. On a country-level basis, electricity generation data and fuel consumption rates (International Energy Agency, 2004a, b) were used to calculate the country-wide efficiency of electricity generation. The International Energy Agency's hybrid substitution method was employed, meaning that hydropower was assumed to be 100% efficient and the substitution equivalence (i.e., the efficiency of fossil fuel-based generation) was assumed for other non-fuel-based generation means. In addition, the energy required in the production, refining, and transportation of coal, petroleum, and natural gas is accounted for, using the results of three studies by the National Renewable Energy Laboratory that detailed the life-cycle impacts of these fuels (Sheehan et al., 1998; Spath et al., 1999; Spath and Mann, 2000.

To quantify the energy required for mining and beneficiation processes, several data sources were used. Anecdotal evidence of mine blasting showed that approximately 6 ton of explosives are required to mobilize 30,000 ton of rock (Bergstrom, 2005). Assuming an energy content of 2.7 MJ/kg of TNT (note: $1\,MJ = 10^6\,J$), relatively small energy expenditures result; although much power is required during the blast, it is only needed over a short period of time. Liquid fuel use for heavy equipment was estimated using data from a generic mine provided by Western Mine (2006). The data stated that 1.1 l of diesel fuel was required per ton of ore, with an assumed lower heating value of 128,400 BTU/gallon, resulting in 38 MJ/ton ore.

For chromite beneficiation, it was found that the concentrator requires 40 kWh/ton of ore feed and the grinder uses 10 kWh/ton of mill feed (Bergstrom, 2005). Iron mining was shown to require approximately 87 MJ/ton ore, predominately in liquid fuels, and beneficiation used 12.4 MJ/ton ore in electricity (US Department of Energy, 2002). Nickel mining processes differ for sulfide and laterite ores; in this model, it is assumed that refined nickel was produced from sulfide ores and ferronickel and nickel oxide sinter were produced from laterite ores. Data for diesel and electricity use during nickel mining and concentrating were taken from a study by Norgate and Rankin (2000). Although the primary data sources used in this study were from the early 1990s, nickel mining and concentrating are minor contributors to the overall energy used in stainless-steel production, so this is not believed to have a significant effect on the final results. Country-level production rates for chromium, iron, and nickel, used to determine the primary fuel associated with electricity generation, were taken from the International Chromium Development Association (2006) and the United States Geological Survey (USGS) (Jorgenson and William, 2003; Kuck, 2005).

Ferrochromium production involves four major production methods: traditional, Outokumpu, Premus, and DC arc. The total production share by mass of these methods was estimated to be 60%, 25%, 10%, and 5%, respectively. Electricity demands for each technology were assumed to be 4.0, 3.3, 2.4, and 4.8 MWh/ton of FeCr and reductant (e.g., coke) demands were 0.60, 0.52, 0.20, and 0 ton coke/ton of FeCr, respectively (Daavittila et al., 2004; McLaughlan, 2006; Niemelä, 2001). A lower heating value of 28.8 MJ/kg coke was assumed (United States Geological Survey, 2006) and country-level FeCr production data were taken from ICDA (2006).

The average electricity, coal, oil, and natural gas consumption for six ferronickel producers were used (Kerfoot, 2002). To quantify the energy used to produce refined nickel, the results for matte production were added to nickel refinery data (Kerfoot, 2002). Laterite smelting unit energy was a based on a comprehensive survey of global smelters (Warner et al., 2006). Data for nickel oxide sinter production were taken from a life-cycle assessment conducted by the Nickel Institute (2006) The results of this life-cycle assessment were also used to check the accuracy of the ferronickel and refined nickel calculations; the results of this study were close for ferronickel and significantly lower for refined nickel. Country-level production data were obtained from the International Nickel Study Group (2004).

The energy required to produce DRI was estimated from seven production methods. Based on a weighted average of each method's global plant capacity, the average reductant and electricity use were determined to be 11.3 GJ of natural gas/ton DRI and 99 kWh/ton DRI, respectively (Oeters et al., 2006). Country-level production was taken from the International Iron and Steel Institute (2005).

Data for stainless-steel electric arc furnaces were taken from Outokumpu (2006), who detailed use of electricity propane, carbon monoxide, natural gas, and fuel oil. Country-level stainless-steel production was taken from ICDA (2006). Scrap is processed and prepared using presses, shears, bundlers, cutting, and crushing, with most of the energy being used in the form of electricity. An analysis of six scrap-processing facilities yielded an average electricity consumption of 6.8 kWh/ton scrap.

The energy requirements for transportation of all intermediate goods were also quantified. Matrices were created that detailed the mass of each intermediate good by the exporting country and the importing country, including chromite ore and concentrate (International Chromium Development Association, 2006), ferrochromium (International Chromium Development Association, 2006), blended and concentrated nickel ore (International Nickel Study Group, 2004), ferronickel (Kuck, 2005), refined nickel (International Nickel Study Group, 2004), nickel oxide sinter (International Nickel Study Group, 2004), iron ore and concentrate (United Nations Comtrade Database, 2006) and DRI (United Nations Comtrade Database, 2006). While there is certainly the potential for hundreds of country-to-country exchanges, it was found that 95% of the traded mass could be accounted for by less than 50 exchanges per material. By assuming trade routes and means of transfer, the distances between the exporters and the importers were used to create an average distance traveled by each transport method. The collection and transportation of scrap is difficult to estimate with high certainty due to the high variability of transportation distances and the lack of detailed trade data. Discussions with experts in the scrap industry and internal calculations based on the distances between major scrap-generating areas, collection areas, and stainless-steel smelters have lead to travel estimates of approximately 180 miles by truck, 160 miles by rail, and 2100 miles by ship. Using EIA energy intensities (US Department of Energy, 2006), the energy consumed per ton-mile was applied and the energy use was calculated. (Note: the transportation of fabricated stainless steel is not included in this study; the end goal of this study is to calculate the energy requirements to produce 1 ton of stainless-steel slab and that is where the system boundary ends.)

The results of mining, alloy production, scrap preparation, stainless-steel smelting, and transportation of intermediates were aggregated to determine the total primary energy used to produce 1 ton of austenitic stainless steel. These results were then coupled with CO_2 emission factors (Energy Information Administration, 2006), which include linking country-level electricity generation data to emissions by source.

There are many inputs to this model and all values contain a degree of uncertainty. In order to assess this uncertainty and variability, a Monte Carlo analysis was performed. A probabilistic method, such as a Monte Carlo analysis, provides more information than deterministic models, giving a range of results linked to their likelihood (McCleese and LaPuma, 2002). For each of the variables, including energy demands, material losses, transportation distances, scrap concentrations, and metal sourcing, an estimate was made of the uncertainty of the data. These estimates were based on data variability and assumed confidence in their accuracy, with normal distributions around the weighted mean applied. Dependant variables were linked and 400 simulations were then run for each scenario to determine the range and distribution of the results.

The model's sensitivity to changes in each of these variables is also important. Forty-three of the variables included in the analysis were increased by 25% to examine the effect on the total primary energy of the Current Operations scenario.

3. Results

The energy used at each production process is underpinned by the amount of material that is required. Fig. 2 details the material flows of chromium, nickel, and iron in the production of 1 ton of austenitic stainless steel under each of the three scenarios. The material flows shown in the figures represent the contained mass of the elements in each flow. For example, the flow into chromium mining for Current Operations (Fig. 2a) is 146 kg of contained chromium in ore; the total mass of the chromite ore is estimated to be 490 kg, a value that is not shown in this figure. It should also be noted that the iron contained in ferrochromium and ferronickel was not quantified for stages prior to alloy production (i.e., during the mining processes for chromium and nickel) and, therefore, is not shown in the figure.

In order to achieve material balance for each of the elements, the amount of austenitic, ferritic, and carbon steel scrap that is recycled has to correspond with recycling rates and material loss flows. In Fig. 2a, this constraint meant that only austenitic stainless-steel scrap and carbon steel scrap were included, so as to not have an overabundance of secondary chromium units that would have come with ferritic stainless-steel scrap recycling. Because it is known that ferritic scrap is included in actual production, this is a limitation of the material flow data and could be updated to improve the accuracy of this study.

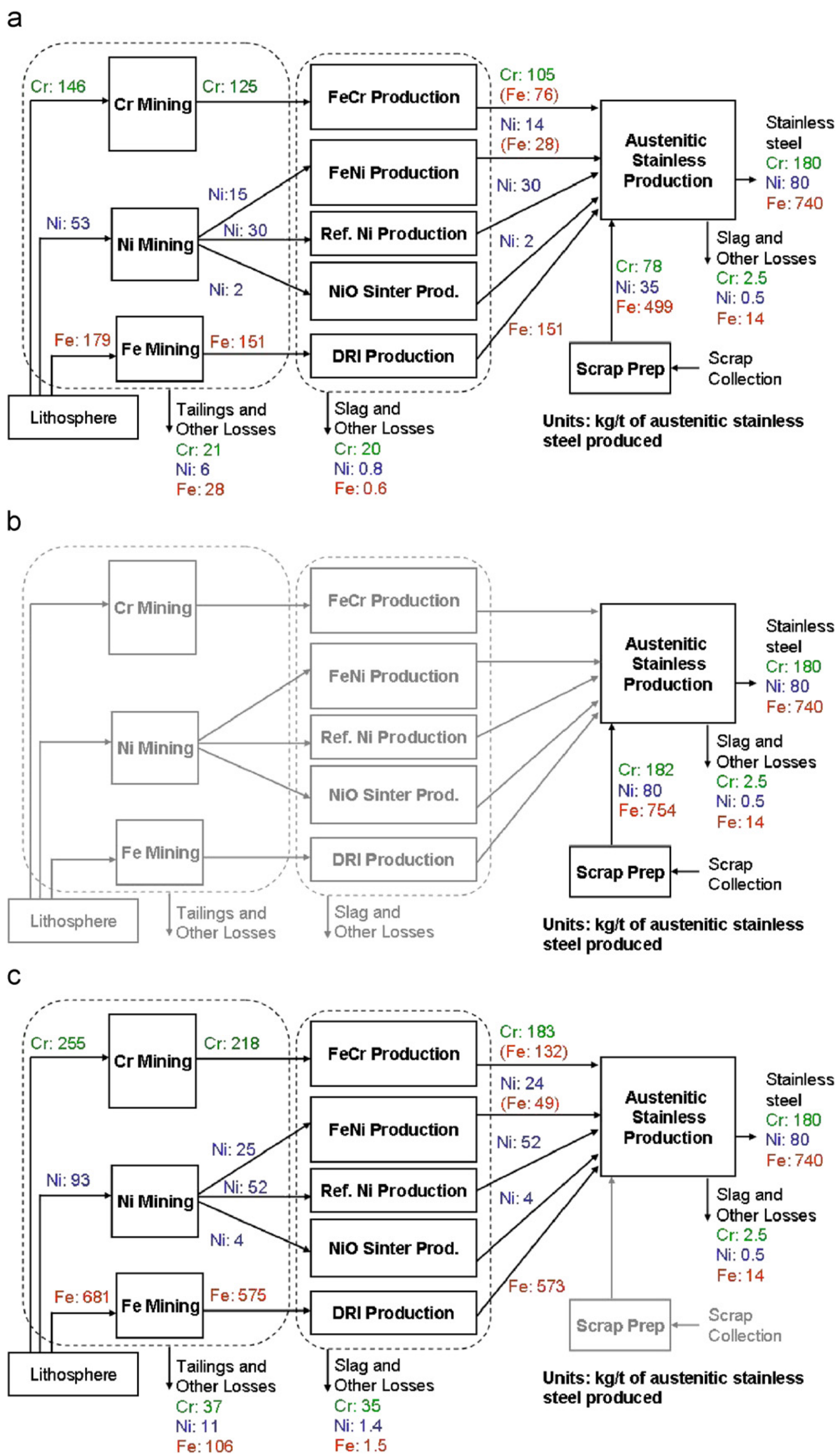

Fig. 2. Material flows of chromium, nickel, and iron required to produce 1 ton of austenitic stainless steel, ca. early 2000s, under (a) Current Operations, (b) Maximum Recycling, and (c) Virgin Production. Totals may not be additive due to rounding. DRI = direct reduced iron; FeCr = ferrochromium; FeNi = ferronickel; and NiO = nickel oxide.

Please cite this article as: Johnson, J., et al., The energy benefit of stainless steel recycling. Energy Policy (2007), doi:10.1016/j.enpol.2007.08.028

Combining the results of the material flows with the unit energy use of each production process, the transportation matrices, and the country-level electricity generation profiles resulted in quantification of the energy use. The model produced distinct and significantly different results for each of the three scenarios. The Current Operations scenario required 53,000 MJ/ton of stainless steel produced, the Maximum Recycling scenario required 26,000 MJ/ton, and the Virgin Production scenario required 79,000 MJ/ton. Fig. 3 shows the resulting energy requirement to produce 1 ton of austenitic stainless steel. The primary energy to produce electricity and fuels are included in the results for each process and explicitly shown.

Global austenitic stainless-steel production in 2004 was approximately 17 million tons (International Chromium Development Association, 2006). Thus, under Current Operations, global production uses 9.0×10^{17} J of primary energy throughout the life cycle. By comparing these results to the Virgin Production scenario, it was determined that the recycling of austenitic stainless steel saved 33% (4.4×10^{17} J) of primary energy. If complete recycling were to occur (Maximum Recycling), which is not currently possible due to scrap availability, global energy use would be 67% less (9.0×10^{17} J) than the Virgin Production scenario and 51% less (4.6×10^{17} J) than Current Operations.

Fig. 4 subdivides these results in three different ways: by process, by material (e.g., "chromium" contains chromite mining, ferrochromium production, and transportation of ore, concentrate, and ferrochromium), and by fuel with the electricity consumption taken back to its original fuel source. The energy required to produce and transport coal, petroleum, and natural gas accounts for approximately 10% of the total energy requirements.

The scenario results broken down by process (Fig. 4a) show the dominance of alloy production and stainless-steel smelting in required energy. Transportation accounted for 7–8% of the total primary energy for each of the scenarios, mining and beneficiation accounted for less than 3%, and scrap preparation energy use was negligible. The breakdown by material (Fig. 4b) shows that nickel is the largest user of energy, even though its mass is dwarfed by iron and chromium. This would imply that the production of ferritic stainless steels (i.e., those containing little or no nickel) would require much less energy throughout the life cycle than does austenitic. Fig. 4c shows that coal, petroleum, and natural gas dominate the fuel inputs. Fossil fuels constitute between 81% and 88% of the total primary energy use.

For each scenario, a Monte Carlo analysis was conducted, which is a probabilistic analysis used to assess the range of potential results. The 44 major factors (e.g., unit energy used in the production of FeCr) were varied by assigned distribution ranges based on their minimum, maximum, and expected values. Four hundred simulations were run, provided the range of expected results for each scenario. The error bars on Fig. 3 show the range within which 90% of the trials fell. This range was approximately 46,100–60,200 MJ/ton of stainless steel produced for Current Operations, 22,400–29,300 MJ/ton for Maximum Recycling, and 73,000–87,500 MJ/ton for Virgin Production.

A recent study by Norgate et al. (2004) found that the production of stainless steel from virgin sources using ferronickel as the primary nickel source requires 75,000 MJ/ton of stainless steel, with 59% of the energy used in the production of ferronickel. Our study, which assumed that primary nickel came from refined nickel (65%), ferronickel (30%), and nickel oxide sinter (5%), found that Virgin Production required 79,000 MJ/ton of stainless steel produced. To more accurately compare our results to Norgate et al.'s study, we ran a simulation under the Virgin Production scenario where all primary nickel was sourced from ferronickel. This resulted in energy use of 97,000 MJ/ton of stainless steel, with 44% of that total coming from ferronickel production and transport. We believe that inclusion of the upstream energy use for fuel production and transportation of intermediate materials, in addition to data variability, account for most of the difference between these two studies.

Carbon releases were quantified by utilizing the energy use by fuel type together with CO_2 emission factors. For each ton of austenitic stainless steel produced, 3.6 ton of CO_2 are generated on a global average basis ("Current Operations"). The Maximum Recycling scenario would reduce this to 1.6 ton of CO_2, while the Virgin Production scenario would produce 5.3 ton CO_2 per ton stainless steel. Because 17 million tons of austenitic stainless steel was produced in 2004 (International Chromium Development Association, 2006), the global CO_2 releases totaled 61 million tons. If no recycling occurred, CO_2 emissions would have increased to 90 million tons. Thus, austenitic stainless-steel recycling in 2004 reduced CO_2 emissions 29 million tons, or by 32%. If unlimited scrap was available and no virgin resources were used, the CO_2 releases would be 27 million tons, a reduction of 63 million tons (70%) compared with virgin-based production.

For the Current Operations scenario, 43 of the variables were increased in isolation to determine the model's sensitivity to each. Table 2 shows that there are 16 of the variables that, when increased by 25%, had a greater than 1% change on the total primary energy required to produce 1 ton of austenitic stainless steel. Twenty-seven of the variables had less than a 1% effect on the final results, including material loss rates of all forms, ore grades, the energy required to produce coal and petroleum, the nickel content of ferronickel, the chromium content of ferritic stainless-steel scrap, the percent of primary nickel from nickel oxide sinter, truck and rail transport energy intensities, and the unit energy used for mining, nickel oxide sinter production, and scrap preparation.

Please cite this article as: Johnson, J., et al., The energy benefit of stainless steel recycling. Energy Policy (2007), doi:10.1016/j.enpol.2007.08.028

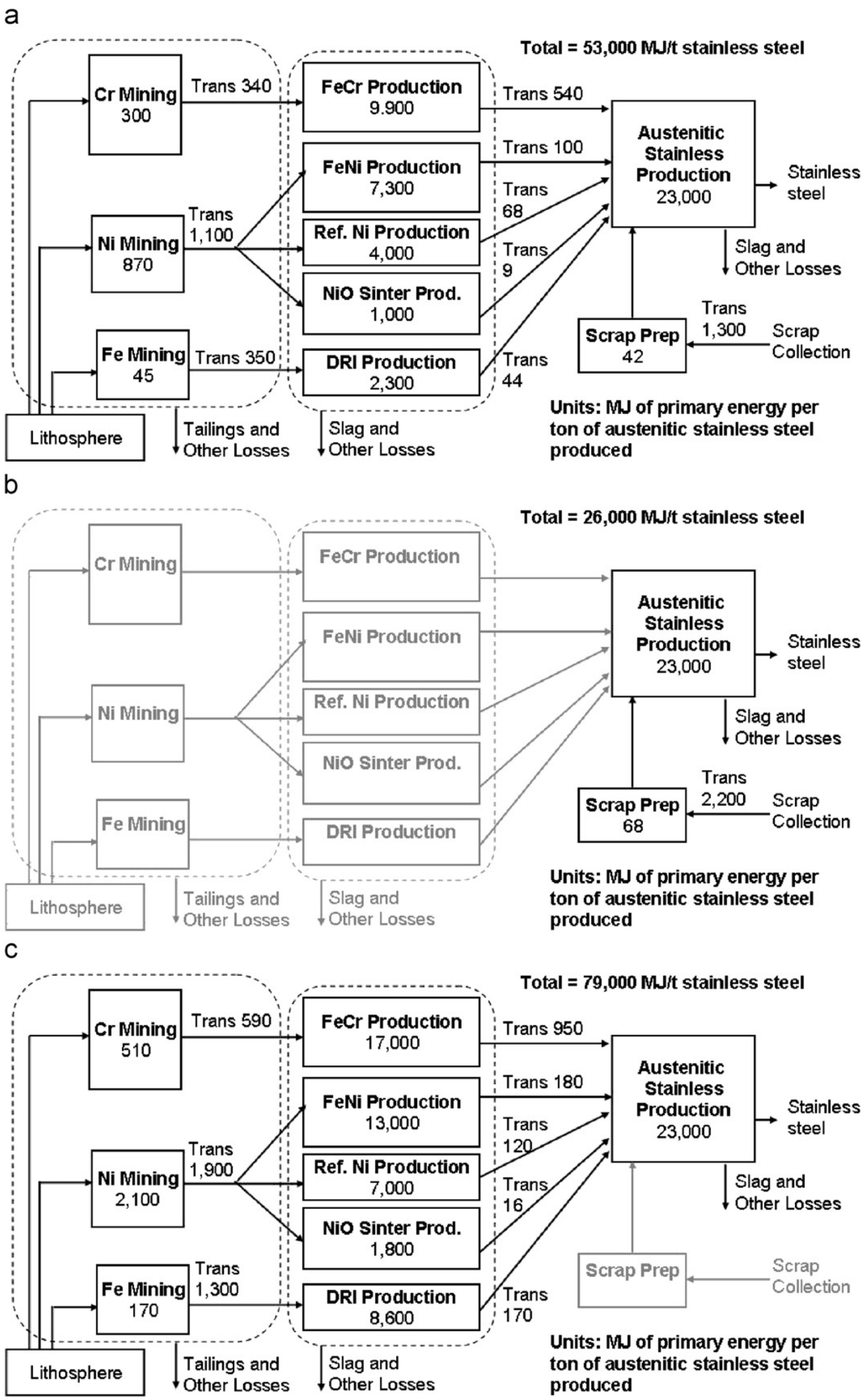

Fig. 3. Primary energy required to produce 1 ton of austenitic stainless steel, ca. early 2000s, under (a) Current Operations, (b) Maximum Recycling, and (c) Virgin Production. Units are MJ/ton stainless steel. Totals may not be additive due to rounding. Trans = transportation; DRI = direct reduced iron; FeCr = ferrochromium; FeNi = ferronickel; and NiO = nickel oxide.

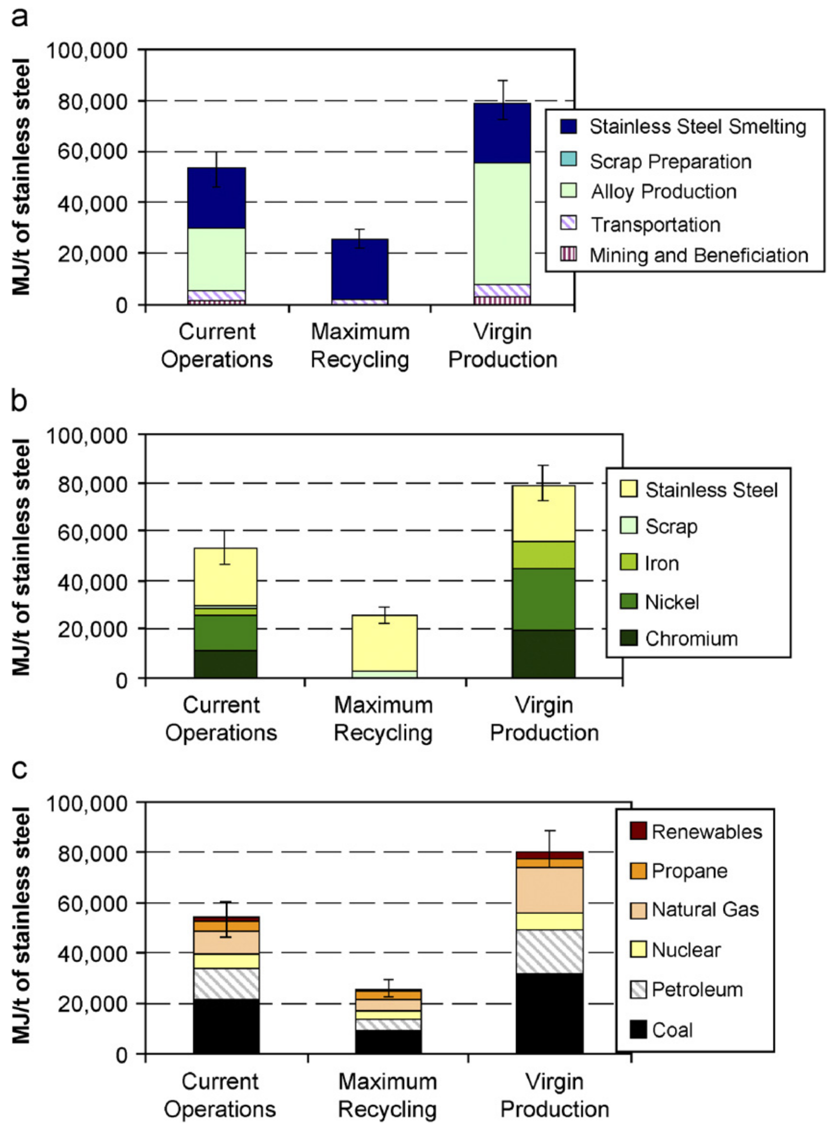

Fig. 4. Energy required to produce 1 ton of austenitic stainless steel throughout its entire life cycle for three scenarios, subdivided by (a) process, (b) material, and (c) fuel. The error bars represent the range in which 90% of the trials in the Monte Carlo analysis fell.

The most sensitive variables include those related to the amount and type of scrap fed into the electric arc furnace, the unit energy of the electric arc furnace, ferrochromium and ferronickel production, the form of primary nickel, and the nickel and chromium contents of austenitic stainless-steel scrap.

Fig. 5 shows the effect on carbon intensity of two of the sensitive variables: scrap amount and scrap type. The abscissa is the percent of the charge that is scrap; for example, if one-quarter of the feed into the electric arc furnace is scrap and three-quarters is primary metals, the x-coordinate would be 25%. Each line within this plot represents constant proportions of the types of scrap: carbon steel scrap, austenitic stainless-steel scrap, and ferritic stainless-steel scrap. For example, the line with square data points shows the case of half the scrap being carbon steel and the other half being ferritic stainless steel. As one moves to the right along this line, the total amount of scrap increases, but this proportion of scrap types remains constant.

This figure shows that the use of austenitic stainless-steel scrap has the greatest effect on CO_2 emissions, followed by the use of ferritic stainless-steel scrap, and then by carbon steel scrap. By solving the system of equations that underpins this model, which are comprised of such factors as the material loss rates, the unit energy requirements, and the emission factors for each fuel source, an equation was developed to describe the relationship between carbon dioxide releases and scrap amount and type.

$$\Gamma = 5.32 - 0.83 \times \xi - 3.72 \times \alpha - 1.99 \times \phi,$$

where Γ is the carbon dioxide intensity in tons of CO_2 per ton of austenitic stainless steel produced, ξ the

Please cite this article as: Johnson, J., et al., The energy benefit of stainless steel recycling. Energy Policy (2007), doi:10.1016/j.enpol.2007.08.028

Table 2
Model sensitivity to variables under the current operations scenario

An increase of 25% for	Results in an increase in total primary energy of	An increase of 25% for	Results in a decrease in total primary energy of
Electric arc furnace unit energy	+11%	Total amount of scrap in EAF load	−12%
Ferrochromium unit energy	+4.7%	Share of EAF load that is austenitic stainless-steel scrap	−11%
Ferronickel unit energy	+3.5%	Share of primary nickel provided by refined nickel	−5.1%
Share of primary nickel provided by ferronickel	+2.5%	Nickel content in austenitic stainless-steel scrap	−4.7%
Transport distances	+1.9%	Chromium content in austenitic stainless-steel scrap	−2.7%
Refined nickel unit energy	+1.9%	Chromium content in ferrochromium	−2.7%
Ship transport energy intensity	+1.5%	Share of EAF load that is carbon steel scrap	−1.3%
Energy used in the production of natural gas	+1.2%		
DRI unit energy	+1.1%		

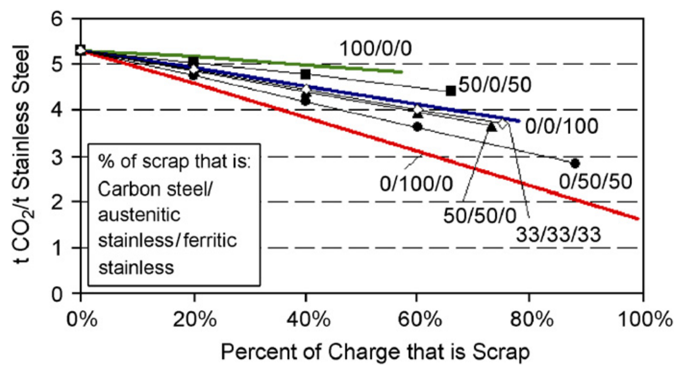

Fig. 5. CO_2 emissions per ton of austenitic stainless steel produced as a function of amount and type of scrap recycled.

percent of the charge that is carbon steel scrap, α the percent of the charge that is austenitic stainless-steel scrap, and φ the percent of the charge that is ferritic stainless-steel scrap.

And, due to material balances for each of the elements,

$$\alpha \leqslant 0.99,$$
$$\alpha + 0.89 \times \phi \leqslant 1.00,$$
$$\alpha + 1.14 \times \phi + 1.32 \times \xi \leqslant 1.00.$$

For example, if austenitic stainless steel were produced using 70% scrap and 30% virgin material, and if the scrap was 50% austenitic stainless steel, 20% ferritic stainless steel, and 30% carbon steel, the variables would be $\alpha = 0.35$, $\varphi = 0.14$, and $\xi = 0.21$. Inserting these values into the equation, we find that the life-cycle carbon intensity of this system is 3.6 ton of CO_2 per ton of austenitic stainless steel produced.

In the carbon intensity equation, the coefficients on each of the scrap variables are proportional to the decrease in carbon intensity. Thus, each percent of the charge that is austenitic stainless-steel scrap has a reducing effect on carbon emissions 1.9 times greater than the use of 1% of ferritic stainless-steel scrap, and 4.5 times greater than recycling 1% of carbon steel scrap.

4. Discussion

Comprehensive energy policy and system analysis must examine the energy demands by industry, and the metal-producing industries are certainly high-energy consumers. By examining the energy requirements for the entire life cycle of austenitic stainless-steel production, we were able to quantify both the energy and carbon intensity of this product. Comparing scenarios with different recycling rates determines the true impact of recycling on energy use; the energy required to produce stainless steel from scrap is less than a third of the energy used to produce stainless steel from virgin sources. This finding helps support recycling efforts beyond the justifications of material use and waste impacts.

Scrap availability is a limiting factor in the recycling of stainless steel. With stainless-steel production growth averaging 9% over the past few years (International Chromium Development Association, 2006) and the product lifetimes of some applications extending for years and even decades, scrap will not be able to meet production demand. Should stainless-steel production level off and scrap collection continue to be high, we would anticipate increased recycling rates and, thus, lower system-wide energy use.

While this study aims to offer a comprehensive look at the entire life-cycle associated with stainless-steel production, practicality and tractability limit how far the system boundaries of this study can be extended. A more robust study could also include the energy used for the capital equipment at the mine sites and alloy plants, and have more extensive data to detail energy performance differences among plants and nations. Utilizing country-wide electricity profiles is also a limitation of this work; on-site electricity generation may not be well represented by country-wide statistics. Data, however, are not available to provide this added level of detail. With each material flow

Please cite this article as: Johnson, J., et al., The energy benefit of stainless steel recycling. Energy Policy (2007), doi:10.1016/j.enpol.2007.08.028

and unit energy factor, there is a degree of uncertainty. Through the Monte Carlo analysis and the uncertainty analysis, we determined the factors that had the most influence on the final results (e.g., the amount and type of scrap, the form of primary nickel) and those that had the least influence on the final results (e.g., material loss rates, ore grades).

The methodology employed in this study is readily transferable to other metals. Generating such results for a wide suite of metals would allow broader analysis of the energy impacts of the mining and metallurgy industries, as well as allowing for cross-metal comparisons; the energy effect of metals substitution could then be assessed. In addition, countries that import a significant share of their refined metals could analyze the effect of outsourcing such production based on energy and carbon impact, allowing for such factors to inform greenhouse gas mitigation policies.

Acknowledgements

This material is based upon work supported by the Nickel Institute and the US National Science Foundation under Grant nos. BES-9818788 and BES-0329470. The authors would also like to acknowledge Friedrich Teroerde of ELG Haniel Metals Ltd. and the members of the International Stainless Steel Forum's TEAM STAINLESS for continued insight and assistance.

References

Bergstrom, R., 2005. Personal communication, Outokumpu Oy.

Bhaktavatsalam, A.K., Choudhury, R., 1995. Specific energy consumption in the steel industry. Energy 20, 1247–1250.

Carnegie Mellon Green Design Institute, 2007 ⟨www.eiolca.net⟩, accessed March 2007.

Choudhury, R., Bhaktavatsalam, A.K., 1997. Energy inefficiency of Indian steel industry—scope for energy conservation. Energy Conversion and Management 38, 167–171.

Daavittila, J., Honkaniemi, M., Jokinen, P., 2004. The transformations of ferrochromium smelting technologies during the last decades. In: Proceedings of the 10th International Ferro Alloys Congress.

Das, A., Kandpal, T.C., 2000. Analysis of energy demand and CO_2 emissions for the Indian aluminum industry using a dynamic programming model. International Journal of Energy Research 24, 51–59.

Energy Information Administration, 2006. Fuel and Energy Source Codes and Emission Coefficients ⟨http://www.eia.doe.gov/oiaf/1605/factors.html⟩, last accessed June 2006.

International Chromium Development Association, 2006. Statistical Bulletin. Paris, France.

International Energy Agency, 2004a. Energy Balances of Non-OECD Countries: 2001–2002. Paris, France.

International Energy Agency, 2004b. Energy Balances of OECD Countries, 2001–2002. Paris, France.

International Iron and Steel Institute, 2005. Steel Statistical Yearbook. Brussels, Belgium.

International Nickel Study Group, 2004. World Nickel Statistics, The Hague, The Netherlands.

Johnson, J., Schewel, L., Graedel, T.E., 2006. The contemporary anthropogenic chromium cycle. Environmental Science & Technology 40, 7060–7069.

Jorgenson, J.D., William, S.K., 2003. Iron ore. In: USGS Minerals Yearbook 2003. United States Geological Survey (USGS), Reston, VA.

Kerfoot, D.G.E., 2002. Nickel. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co., KGaA, Weinheim.

Kuck, P., 2005. United States Geological Survey Minerals Yearbook—Nickel. Reston, VA.

Kusik, C., Kenahan, C., 1978. Information Circular 8781: Energy Use Patterns for Metal Recycling. United States Bureau of Mines, Washington, DC.

McCleese, D.L., LaPuma, P.T., 2002. Using Monte Carlo simulation in life cycle assessment for electric and internal combustion vehicles. International Journal of Life Cycle Assessment 7, 230–236.

McLaughlan, J., 2006. Challenges Facing the South African Ferrochrome Industry, CHROMIUM 2006, Cape Town, South Africa.

Michaelis, P., Jackson, T., 2000a. Material and energy flow through the UK Iron and Steel Sector—Part 2: 1994–2019. Resources Conservation and Recycling 29, 209–230.

Michaelis, P., Jackson, T., 2000b. Material and energy flow through the UK Iron and Steel Sector. Part 1: 1954–1994. Resources Conservation and Recycling 29, 131–156.

Nickel Institute, 2006. Life Cycle Assessment ⟨http://www.nickelinstitute.org/index.cfm/ci_id/114/la_id/1.htm⟩, last accessed September 20, 2006.

Niemelä, P., 2001. CO_2 Emissions in Production of Ferrochromium. Outokumpu Oy, Tornio, Finland.

Norgate, T.E., 2004. Metal Recycling: An Assessment Using Life Cycle Energy Consumption as a Sustainability Indicator. CSIRO Minerals, DMR-2616, Victoria, Australia.

Norgate, T.E., Rankin, W.J., 2000. Life cycle assessment of copper and nickel production. In: Minprex 2000, International Conference on Minerals Processing and Extractive Metallurgy.

Norgate, T.E., Jahanshahi, S., Rankin, W.J., 2004. Alternative routes to stainless steel a life cycle approach. In: Tenth International Ferroalloys Congress, Cape Town, South Africa.

Oeters, F., Ottow, M., Meiler, H., Lungen, H.B., Koltermann, M., Buhr, A., Yagi, J.-I., Formanek, L., Rose, F., Flickenschild, J., Hauk, R., Steffen, R., Skroch, R., Mayer-Schwinning, G., Bunnagel, H.-L., Hoff, H.-G., 2006. Iron. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH Verlag GmbH & Co., KGaA, Weinheim.

Outokumpu, 2006. Outokumpu and the Environment ⟨http://www.outokumpu.com/33954.epibrw⟩, last accessed September 5, 2006.

Reck, B., Müller, D.B., Rostkowski, K., Graedel, T.E., 2007. The anthropogenic nickel cycle: insights into use, trade, and recycling. Environmental Science & Technology, in review.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., Shapouri, H., 1998. Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. National Renewable Energy Laboratory.

Spath, P.L., Mann, M.K., 2000. Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generating System. National Renewable Energy Laboratory.

Spath, P.L., Mann, M.K., Kerr, D.R., 1999. Life Cycle Assessment of Coal-Fired Power Production. National Renewable Energy Laboratory.

Strubegger, M., 2003. Co2db Software: Carbon Dioxide (Technology) Database. Version 3.0. International Institute for Applied Systems Analysis, Laxenburg, Austria.

US Department of Energy, 2002. Energy and Environmental Profile of the US Mining Industry. Office of Energy Efficiency and Renewable Energy, Washington, DC.

United Nations Comtrade Database, 2006 ⟨http://unstats.un.org/unsd/comtrade/⟩, last accessed June 2006.

United States Department of Energy, 2006. Indicators of Energy Intensity in the United States ⟨http://intensityindicators.pnl.gov/total_transportation.stm⟩, last accessed June 2006.

United States Geological Survey, 2006. Energy Resources Program ⟨http://energy.usgs.gov/glossary.html⟩, last accessed September 5, 2006.

Wang, T., Müller, D., Graedel, T.E., 2007. Forging the anthropogenic iron cycle. Environmental Science & Technology 41, 5120–5129.

Warner, A.E.M., Diaz, C.M., Dalvi, A.D., Mackey, P.J., Tarasov, A.V., 2006. JOM World Nonferrous Smelter Survey, Part III: Nickel: Laterite. JOM, April 2006, pp. 11–20.

Western Mine, 2006 ⟨http://www.westernmine.com⟩, last accessed June 10, 2006.

World Commission on Environment and Development, 1987. Our Common Future. Oxford University Press, Oxford, UK.

Worrell, E., Levine, M., Price, L., Martin, N., 1996. Potentials and policy implications of energy and material efficiency improvement. A Report to the United Nations, Division for Sustainable Development.

Worrell, E., Price, L., Martin, N., 2001. Energy efficiency and carbon dioxide emissions reduction opportunities in the US Iron and Steel Sector. Energy 26, 513–536.

Please cite this article as: Johnson, J., et al., The energy benefit of stainless steel recycling. Energy Policy (2007), doi:10.1016/j.enpol.2007.08.028