Environ. Sci. Technol. **2008,** *42,* 3394–3400

Anthropogenic Nickel Cycle: Insights into Use, Trade, and Recycling

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Received August 22, 2007. Revised manuscript received February 5, 2008. Accepted February 11, 2008.

The anthropogenic nickel cycle for the year 2000 was analyzed using a material flow analysis at multiple levels: 52 countries, territories, or country groups, eight regions, and the planet. Special attention was given to the trade in nickel-containing products at different stages of the cycle. A new circular diagram highlights process connections, the role and potential of recycling, and the relevance of trade at different life stages. The following results were achieved. (1) The nickel cycle is dominated by six countries or territories: USA, China and Hong Kong, Japan, Germany, Taiwan, and South Korea; only China also mines some of its nickel used. (2) Nickel is mostly used in alloyed form in stainless steels (68%). (3) More scrap is used for the production of stainless steels (42%) than for other first uses (11%). (4) Industrial machinery is the largest end use category for nickel (25%), followed by buildings and infrastructure (21%) and transportation (20%). (5) 57% of discarded nickel is recycled within the nickel and stainless steel industries, and 14% is lost to other metal markets where nickel is an unwanted constituent of carbon steel and copper alloy scrap.

1. Introduction

The study of anthropogenic resource cycles can offer new perspectives on a variety of topics, including resource availability, resource utilization, recycling potential, and environmental policy. Nickel is an example of a widely utilized industrial metal which is selected for its qualities of toughness, ductility, high-temperature stability, elevated corrosion resistance, and other industrial and aesthetic attributes. It is commonly utilized in alloys, and about two-thirds of its total usage goes into the manufacture of stainless steels (*1*). It is an indispensable constituent in a wide range of end use applications, from the chemical, petrochemical, and food industries to construction, transportation, and consumer applications. In some cases, the high price of nickel may lead to other material choices even if quality, durability, or reliability of products may be compromised. At trace levels, nickel is essential to the nutrition of most living organisms (*2*).

As with many other materials, the use of nickel has grown exponentially over the past century, roughly half of all the circulating nickel having been put into use between 1980 and 2000 (see Supporting Information, Figure S2). The current annual world mine production is about a factor of 100 times smaller than the estimated nickel reserve base of 140 Tg; thus, nickel does not seem to be supply limited over the next few generations (*3, 4*). However, new mining operations take at least a decade for planning and building, and existing operations are running near their technical maximum. Therefore, temporary shortages in nickel supply are of concern. In fact, over the past decade a sharp increase in demand (mainly from China) has resulted in over a 10-fold increase in nickel price (*5, 6*), driving some nickel users to seek economically less volatile alternatives (*7*).

Nickel can be supplied in primary ("virgin") and secondary ("scrap") form. From an environmental standpoint, the mining and smelting of primary nickel raises concerns due to energy (*8*) and water (*9*) consumption, carbon dioxide emissions, and its generation of wastes (tailings and slags). In comparison, the use of scrap reduces the energy requirements and CO_2 emissions by up to 60% (*10*). Increasing the nickel supply through secondary sources also cuts demand for primary nickel and hence may help to reduce exposure to the volatile primary nickel market.

Knowledge of the types of products using nickel is the basis for understanding the ensuing scrap flows which originate from products in use becoming obsolete. However, information to assess future quantities and qualities of nickel in scrap is limited. Together with their geographical distribution, the analysis of the entire nickel life cycle on a global scale addresses this issue.

There have been limited attempts to develop anthropogenic cycles for nickel. One is for the city of Stockholm in 1995 (*11*) and it focuses on dissipative emissions. Two other studies were at country level: for Denmark in 1992/1993 (*12*) and for Japan (*13*). These studies, like those on nickel stocks (*14, 15*), have a different scope and a more limited geographical focus than necessary to respond to the issues identified above. Indeed, the quantitative aspects of most parts of the nickel cycle throughout the planet have been almost totally unknown until this present work. For industry and policymakers, this work forms the basis for an understanding of the magnitude and spatial distribution of societal nickel stocks and thus provides information and perspective for future resource planning.

2. Materials and Methods

By applying the principles of material flow analysis, a metal cycle can be expressed through four principal processes: production, fabrication and manufacturing (F&M), use, and waste management and recycling (WM&R), as discussed in detail within the Yale Stocks and Flows (STAF) project for other elements (e.g., see refs *16–21*). To illustrate the cycle, this study introduces a circular display (Figure 1). It is characterized by processes that are linked through markets (*22*), each indicating the trade with other regions at the respective life stages. The scrap market plays a central role in that it connects WM&R with production and fabrication. The cycle is surrounded by entities lying outside of the system boundary: trade partners (other regions), the lithosphere from which ore extraction takes place, and repositories for nickel in tailings and slag (i.e., production wastes) and in landfilling. (A nickel cycle containing more detailed information at the process level is shown in the Supporting Information, Figure S1.)

Production includes mining/milling, smelting, and refining of either laterite or sulfide ore. The blended or concentrated ore is smelted to a nickel matte and then refined into

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10.1021/es072108l CCC: $40.75

Published on Web 03/25/2008

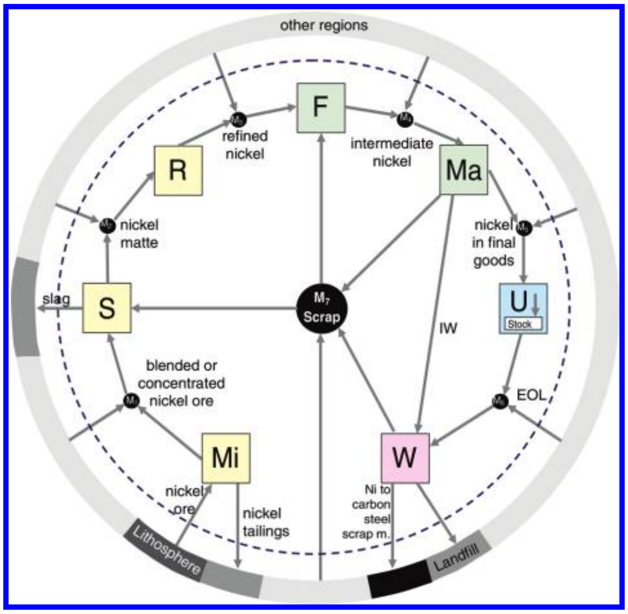

FIGURE 1. (a) Circular diagram for nickel, with the main processes mining/milling (Mi), smelting (S), refining (R), fabrication (F), manufacturing (Ma), use (U), and waste management and recycling (W). The processes are connected through seven markets, each related to other regions through net import flows. "Carbon steel scrap market" stands for "carbon steel and copper scrap markets"; EOL, for end-of-life; IW, for industrial wastes.

nickel metal, ferronickel, nickel oxide sinter, and a variety of nickel chemicals. Data for these primary nickel products are based on ref *23*. Losses to the environment consist of nickel in tailings and slag and were calculated on the basis of company information.

In fabrication, primary and secondary nickel is used for the production of intermediate nickel products (e.g., wire) which are then used in manufacturing for the production of final goods (e.g., cars). In- and outflows at the fabrication, manufacturing, and use stage are further differentiated: at the fabrication level into six main groups (stainless steels, alloy steels, nickel and nickel−copper alloys, nickel plating compounds, foundry nickel, and other "first uses" such as batteries, catalysts, and chemicals). At the level of manufacturing and use, flows are grouped into five categories: building and infrastructure, transportation, industrial machinery, household appliances and electronics, and metal goods.

Data for the fabrication and manufacturing life stage are generated from the literature (*23, 24*), a model developed to quantify the use and generation of scrap in fabrication (Table 1), and a combination of the two for the inflow into manufacturing. Nickel traded in the form of intermediate and final goods is determined by using data from trade statistics (*27, 28*), and multiplying the reported or calculated mass flows of the relevant commodities (36 and 58, respectively) by the estimated nickel content (Supporting Information, Tables S2 and S3).

At the use life stage, the inflow equals the outflow from F&M as adjusted by trade flows. The outflow from use is based on two simplified models: outflows from transportation and industrial machinery through a lifetime model, and outflows from B&I, HA&El, and MG through an inflow/outflow model (for details see Supporting Information, Table S5). The difference between in- and outflow into use is the net addition of nickel in in-use stock. The corrosion of nickel and nickel-containing alloys while in use is negligible (*29*).

Waste management includes the collection, separation, treatment, recycling (mostly as scrap), and deposition (mostly as landfilling) of waste (for details on the methodology see Supporting Information, section VI). Whereas nickel in stainless steel and nickel alloy scrap is collected and recycled within the nickel cycle (*30*), the economics are such that this is usually not the case for nickel as a minor constituent in carbon steels (e.g., low-alloy steels, plating) and copper alloys (*31*). It is estimated that 80% of postconsumer nickel scrap is recovered within the nickel cycle while 20% become a constituent of carbon and copper scrap. The latter is unrecoverable for uses that take advantage of nickel's properties.

A fraction of each waste stream is landfilled. While the inflows to waste management and landfilling are calculated on the basis of nickel use, the scrap outflows are calculated on the basis of fabrication (Table 1) and manufacturing (available preconsumer scrap). As a result, mass balance cannot always be achieved, and, if necessary, the difference is indicated on the resulting cycle diagrams as dashed "phantom flows" (to the left of the "waste" process).

TABLE 1. Fabrication In- and Outflows (in Percent)[a]

	fabrication inflows		fabrication outflows		
nickel fabrication	primary nickel[b]	scrap	intermediate Ni products[b]	scrap[c]	IW[c]
stainless steel	57	43[d]	98.9	0.5	0.6
alloy steels	83[b,e]	17[c,e]	98.9	0.5	0.6
nickel (Ni) alloys	92	8[c]	99	0.5	0.5
copper (Cu) alloys	55	45[c]	99	0.5	0.5
Ni and Cu alloys (total)	86	14[f]	99	0.5	0.5
plating	100	0[c]	97	0	3
foundry	75	25[g]	99	0.5	0.5
others (total)[h]	100	0[c]	99.5	0	0.5
total	66	34	98.8	0.4	0.7

[a] Nickel enters fabrication in the form of primary (virgin) and secondary (scrap) nickel units. The main fabrication outflows are intermediate nickel products; others are processing losses in the form of preconsumer scrap and industrial wastes (IW). All values refer to the world average in 2000. [b] Calculated by difference. [c] Informed estimate, based on Nickel Institute (*1*). [d] Based on information for 20 most relevant countries (*25*). [e] Different assumptions made for North America: 80% primary Ni, 20% scrap (*26*). [f] Total result of separate country-level calculations for nickel and copper alloys. [g] Different assumptions made for North America: 68% primary Ni, 32% scrap (*26*). [h] Includes batteries, catalysts, chemicals, dyes, and unallocated nickel units.

3. Results

The anthropogenic nickel cycle in 2000 has been characterized at three levels: 52 countries, territories, or country groups, eight world regions, and the planet. The bulk of the available data is at the country level, and their information provides the foundation for most of the analysis in this study.

3.1. Country-Level Nickel Cycles. Data show that the stages of the global nickel cycle are dominated by a set of 10 countries or territories that account for 60−70% of production, fabrication and manufacturing, use, and waste management. More than half of all virgin nickel is extracted by Russia, Canada, and Australia. At the later stages of the cycle, half the flows involve only five or six countries or territories, with three countries standing out: United States, China (including Hong Kong), and Japan. Germany and, at different life stages, Korea, Taiwan, the United Kingdom, and Canada are also significant (Supporting Information, Table S7). Complete quantitative nickel cycles of all 52 countries, territories, or country groups can be found in the Supporting Information.

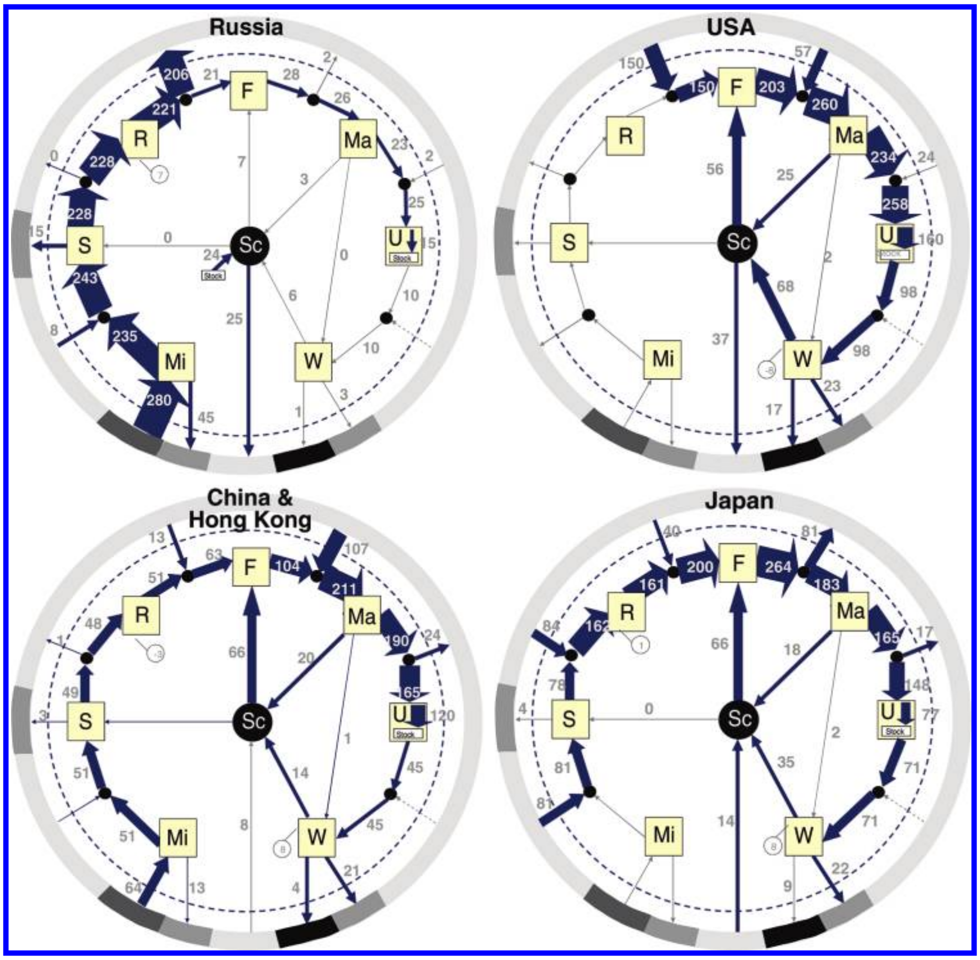

FIGURE 2. Circular nickel diagrams for year 2000 (a) for the largest extractor, Russia, and the three principal users, (b) United States, (c) China, and (d) Japan. The units are gigagrams of nickel per year (Gg of Ni/annum, 1 Gg = 1000 tons). The widths of the arrows are proportional to the flow magnitudes. No data are available for dashed flows (trade of end-of-life goods). Unlabeled flows are 0 Gg of Ni/annum.

With 68%, stainless steel is the largest first-use sector. It is predominantly produced in Japan (14%), South Korea (10%), and Taiwan (9%). The production of high-nickel alloys (used in the aerospace, electric power, and petrochemical industries) is largest in the U.S. (40%), Japan (21%), and Germany (17%). The latter two also produce significant amounts of alloy steels (used in the automotive industry), and plating is another important first use of nickel in the U.S., China, and Taiwan. The U.S. dominates the manufacturing of nickel contained in final goods for industrial machinery and transportation, followed by Japan, Germany, and China. Final goods for building and infrastructure and metal goods are mostly produced in China, and for household appliances and electronics in Japan. (The Supporting Information contains detailed multilevel information on nickel entering fabrication (Table S1) and nickel entering use (Table S6), and on the mostly traded intermediate nickel products (Table S4).)

Figure 2 shows the cycles for four countries that mine and use nickel very differently. With 280 Gg, Russia was the world's largest nickel miner in 2000. Following the smelting and refining steps, almost the entire refined nickel production is exported, with only 21 Gg primary nickel entering the domestic fabrication and manufacturing industry. From fabrication onward, nickel flows in Russia are very small. In contrast, with no domestic nickel mining, the U.S. cycle is characterized by large imports of refined nickel, of intermediate nickel, and, to a lesser extent, of nickel in final goods. Globally, the U.S. has the largest nickel flows from manufacturing (260 Gg) through discard and landfilling.

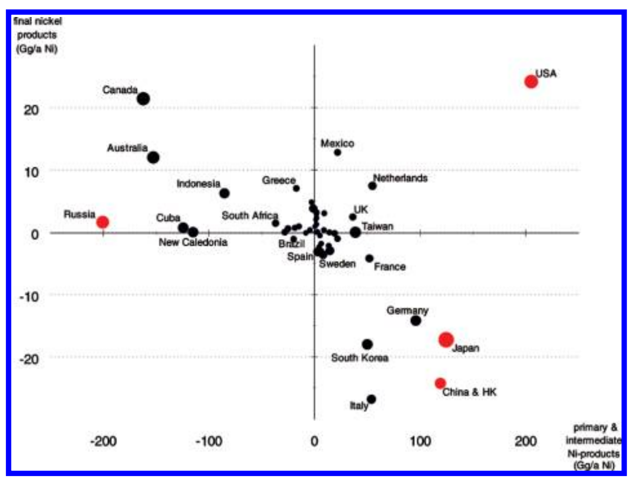

FIGURE 3. Scatterplot of traded nickel products for year 2000, showing the net import of nickel in final goods as a function of the net import of primary plus intermediate nickel goods. Highlighted in red are the four countries shown in Figure 2. The size of the bubbles reflects the sum of the three net imports (primary, intermediate, and final). For nickel in intermediate and final goods, no trade data were available for the Dominican Republic and Uzbekistan. For Taiwan, trade data of intermediate nickel only include stainless steels; none were available for nickel in final goods. The units are Gg of Ni/annum.

China (including Hong Kong) and Japan, the next biggest nickel users from fabrication onward, differ from one another

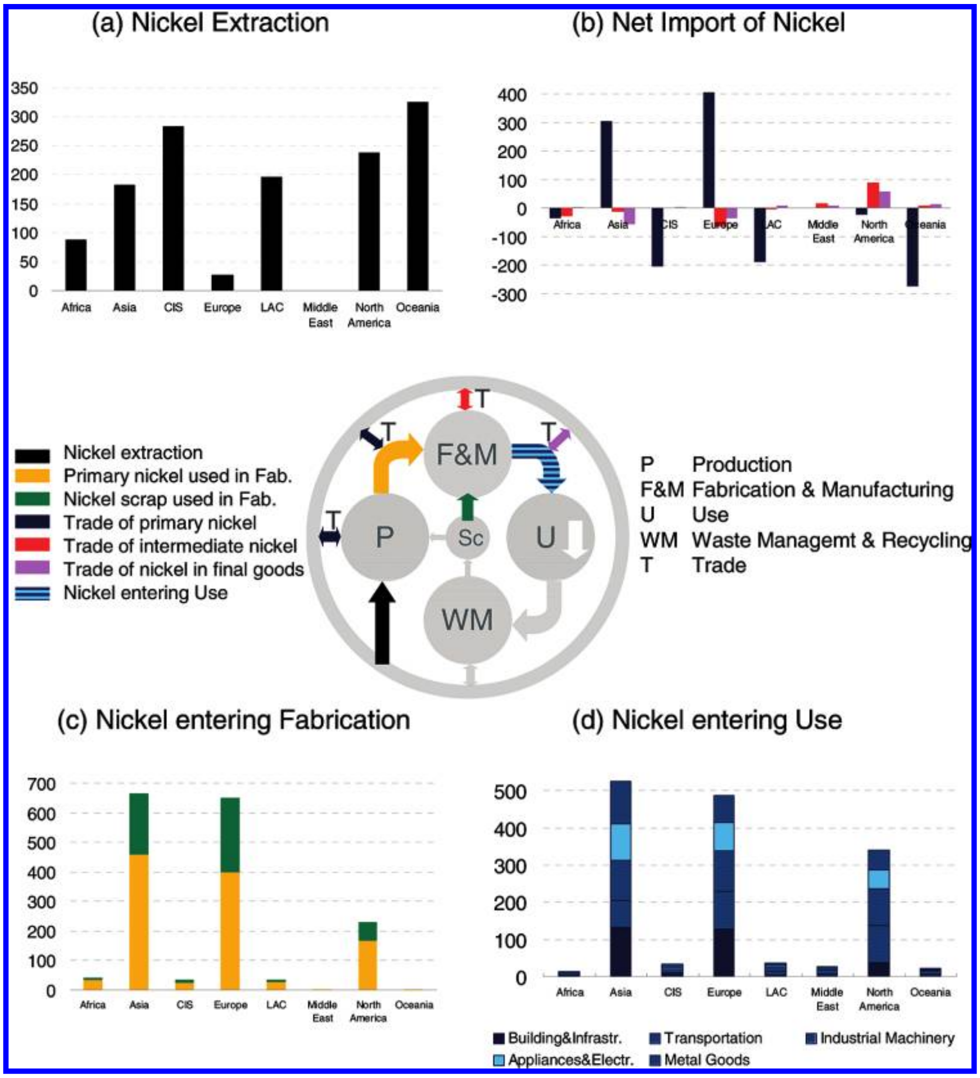

FIGURE 4. Nickel extraction, trade, scrap use in fabrication, and end use in the eight world regions (year 2000, regions as defined in Supporting Information, section VIII): CIS, Commonwealth of Independent States; LAC, Latin America and the Caribbean. Flow colors in the central cycle are repeated in the surrounding diagrams: (a) nickel extraction (black); (b) net import flows for production (blue), fabrication (red), and manufacturing (violet); (c) input into fabrication of primary nickel (yellow) and of nickel in scrap (green); (d) nickel entering use (blue) into five end use sectors. The units are Gg of Ni/annum.

in various ways: Because China is a nickel extractor, the trade of primary nickel products plays only a minor role. Japan, in contrast, imports large amounts of nickel concentrate, nickel matte, and refined nickel at the production level. This makes Japan the biggest user of primary nickel (200 Gg, mainly stainless steel) and the leading fabricator of intermediate nickel goods (264 Gg). Japan then exports about one-third of its intermediate nickel production, while China imports intermediate nickel (107 Gg) in the order of its domestic production (104 Gg), making it the second largest player from manufacturing (211 Gg) onward next to the U.S. China exports more final nickel goods than Japan. In summary, Figure 2 shows the largest nickel miner (Russia), the largest nickel fabricator (Japan), and the two leading manufacturers and users of nickel in final goods (U.S. and China).

An overview of the global trade situation can be achieved by comparing nickel trade flows at different life stages. Figure 3 plots the net import flows of nickel in final products as a function of the sum of those of primary and intermediate nickel goods. Countries exporting at all levels would be found in the left lower quadrant; those importing at all levels, in the right upper quadrant. It becomes apparent that most countries either export their primary and intermediate nickel products and import final goods (upper left quadrant; e.g., Canada, Australia, and Russia) or vice versa (lower right quadrant; e.g., Japan and China). Only a few countries import at all levels, with the U.S. standing out as the largest importer at both life stages shown.

3.2. Regional-Level Nickel Cycles. From the perspective of a central simplified cycle, Figure 4 provides an overview on the spatial distribution of nickel flows. For eight major world regions, it illustrates the magnitude of extraction (a), trade (b), scrap use in fabrication (c), and end use (d). Three regions, Asia, Europe, and North America, dominate the nickel cycle by accounting for more than 90% of the main flows (except for extraction).

Nickel mining appears to be more evenly distributed across the regions than suggested by the country-level analysis (Figure 4a). Australia and New Caledonia alone make Oceania the world's largest nickel mining region. The trade of primary and intermediate nickel and of nickel contained in final goods is analyzed in Figure 4b, based on total net imports. The largest trade flows occur at the production stage, with Europe and Asia importing large amounts of nickel, mostly from Oceania, Commonwealth of Independent States (former Soviet Union), and Latin America and the Caribbean. In turn, Europe, Asia, and Africa are the principal net exporters

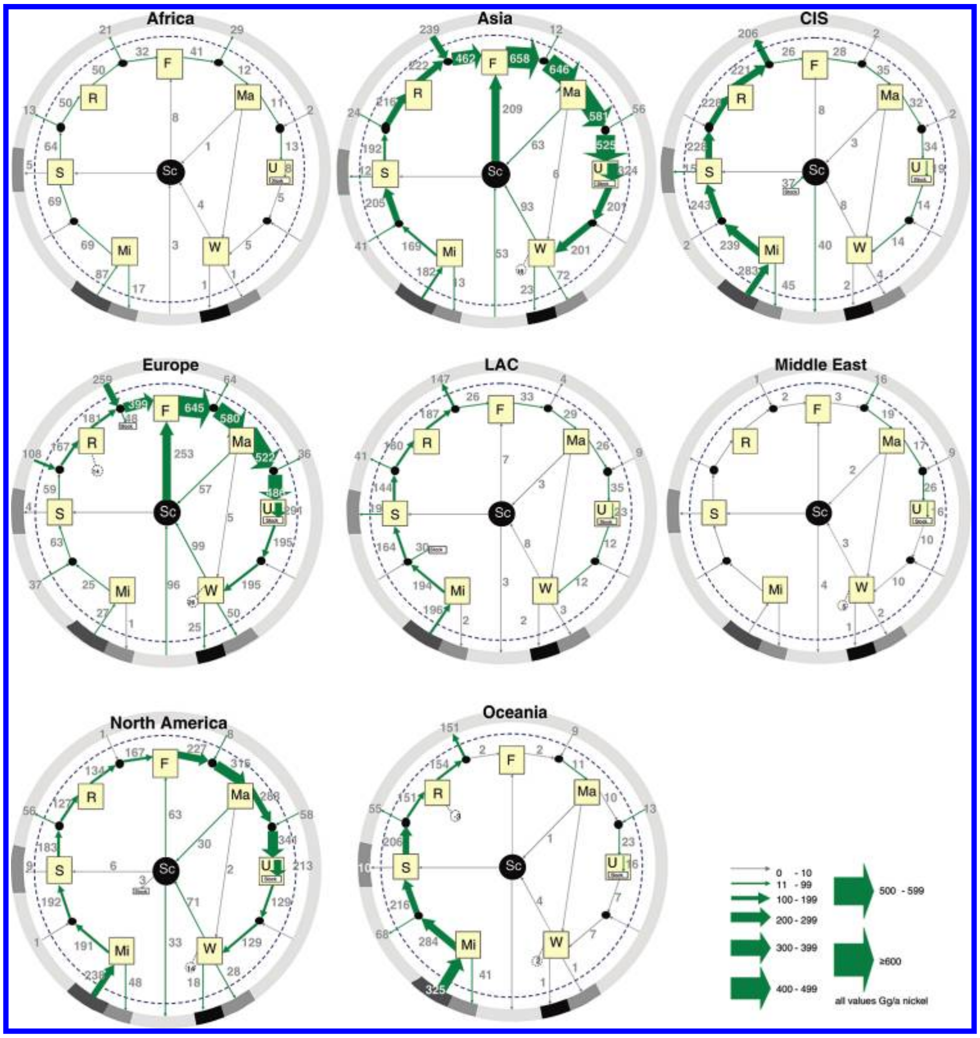

FIGURE 5. Circular nickel diagrams for year 2000 for the eight world regions. The units are Gg of Ni/annum.

of nickel in intermediate and final products, while North America is the main net importer of these goods.

The flow of primary and secondary nickel entering fabrication is shown in Figure 4c. Asia and Europe dominate the world's nickel fabrication (both around 660 Gg), followed by North America which produces about a third (230 Gg) as much. Scrap accounts for one-third of the nickel used in fabrication. Most scrap is used for the production of stainless steels, where scrap shares in North America (53%) and Europe (47%) are higher than in Asia (40%) as a consequence of these mature economies seeing more nickel products reaching their end-of-life.

At the global level, the largest use sector is "industrial machinery" (25%), followed by "building and infrastructure" (21%), "transportation" (20%, with half-being used in the automotive industry), "metal goods" (18%), and "household appliances and electronics" (16%). Figure 4d shows the flow of nickel into use, for each region subdivided into the five end use sectors. Asia and Europe are the dominant users of nickel, covering together 68% of the world's nickel use. Although they are the leaders in the manufacture of industrial machinery, they are the only two regions where nickel is mostly used in buildings and not in machinery. There are two reasons: their construction technologies use nickel more than elsewhere, and nickel containing goods used in construction are much less traded than any others, particularly machinery. As for the other sectors, Asia dominates the world's manufacture of nickel in appliances and metal goods such that it is the only net exporter in both sectors. In particular, Asia manufactures around 75% of the world's cutlery and tableware (*24*). Asia and Europe are also net exporters of nickel in transportation, whereas North America imports large amounts in the form of automotive goods (especially trucks). Globally, 61% of nickel entering use is added to in-use stocks, with little regional differences.

The overall regional cycles are shown in Figure 5. The distinction between the principal extractors (former Soviet Union and Oceania) and the principal users (Asia and Europe) is immediately apparent. North and Latin America are also extractors to some degree, but differ in that Latin America largely exports what it mines while North America imports additional nickel at later life stages. Nickel flows in Africa and the Middle East are quite small relative to the other regions.

3.3. Global-Level Nickel Cycle. A best estimate of the global nickel cycle for the year 2000 is shown in Figure 6. Some basic characteristics are (a) scrap accounts for 33% of nickel input into fabrication, being the average of scrap use in stainless steel production (43%) and in nickel's other first use industries (11%); (b) 29% of nickel entering the waste management is discarded to landfills; the remaining 71% is recycled as scrap, with 57% entering the nickel and stainless steel scrap markets and 14% leaving to carbon and copper alloy scrap markets. The global cycle has one inflow (nickel mining at about 1.3 Tg, 62% from sulfide mining and 38% from laterite mining), and four outflows, totaling 510 Gg nickel (36% landfills, 33% tailings, 15% slags, and 12% nickel leaving to other metal's scrap markets).

3.4. Uncertainties of Trade Data. The trade of nickel plays a key role in understanding where nickel is eventually

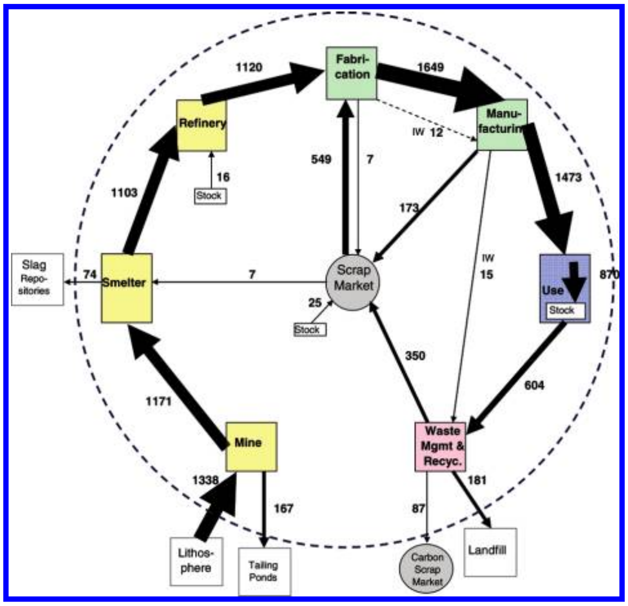

FIGURE 6. "Best estimate" nickel cycle for the world for the year 2000. The units are Gg of Ni/annum.

used. A sensitivity analysis was conducted by investigating the variability of the estimated nickel content in the trade of intermediate and final products (for details see Supporting Information, section IV). The results show that the overall impact is mitigated when looking at nickel use rather than nickel trade: ±2% for the use of nickel in manufacturing (Figure S6, Supporting Information) compared to –22%/+3% for nickel traded in intermediate form (Figure S3, Supporting Information), and ±6% for the end use of nickel (Figure S7, Supporting Information) compared to −41%/+45% for traded nickel contained in final products (Figure S4, Supporting Information).

4. Discussion

This study demonstrates the advantages of a circular depiction of a material cycle which facilitates the analysis of flows within and between cycles and makes trade interactions at different cycle stages transparent by linking them to their respective markets. The balance between the reuse of metal and its loss to the environment is also readily apparent.

The value of nickel embodied in products increases from mining to fabrication to manufacturing. The multilevel analysis reveals that countries and regions behave very differently in how they take advantage of nickel's increasing value. The big mining countries (Russia, Canada, and Australia) and regions (Oceania, CIS, and LAC) are not moving up in the value chain: they export primary nickel and then have to import nickel-containing intermediate and final goods. Europe is the region benefiting most of nickel's increasing value: it imports large amounts of primary nickel, processes them further in fabrication and manufacturing, and then uses most of this higher valued nickel while exporting the remainder, about a fifth of its production. Although similar, the situation in Asia is not as pronounced because China and Hong Kong's large imports of intermediate goods balance a large fraction of Japan's, Taiwan's, and South Korea's exports. The situation of the U.S., which imports nickel at all levels, is unique in that, despite being the world's largest manufacturer, it is also the world's largest importer of nickel contained in final goods. Overall, it is striking that the processing and use of nickel is dominated by less than 10 countries, making the nickel industry a highly specialized one in which a few players dominate the global market, and could control aspects of it should they choose to do so.

Over the past few decades, nickel use has risen markedly (Figure S1). Most of these uses have lifetimes of several decades (Supporting Information, Table S6). With the type of nickel applications changing over time, these lifetimes may also evolve. However, by knowing in which final products nickel is used, estimates can be made on nickel's future recycling flows. By providing nickel discard estimates at the country, regional, and global level, the present study can be useful for future supply management and for waste management planning.

Nickel stocks in use are growing rapidly, with nickel exiting use being less than 40% of the nickel entering. The long lifetimes of nickel products means that these stocks will only be available for recycling in a few decades, limiting the chance to replace more primary sources by postconsumer scrap in the near future. The resource efficiency can be increased at the primary mining and smelting stages and at end-of-life recovery. Particular attention should be paid to the latter. A significant amount of nickel is used in applications using low concentrations of nickel (e.g., electronics and alloys) where nickel may be recovered as a minor constituent of carbon steel or copper alloy scrap, but not as nickel metal or alloy. To the degree that eventual nickel recovery and reuse can become an integral part of product design, the global cycle of nickel can evolve to increasingly minimize losses and optimize the efficiency of use of this most utilitarian metal.

Acknowledgments

This research was funded by the Nickel Institute and by Natural Resources Canada. Related support was received from the U.S. National Science Foundation under Grant BES-0329470. We thank Bruce McKean from the Nickel Institute, Peter Kuck and the U.S. Geological Survey, the International Nickel Study Group, Friedrich Teroerde of ELG-Haniel, and the International Stainless Steel Forum for providing data and for helpful discussions.

Supporting Information Available

Methodological details, sector-specific results for fabrication and end use, an uncertainty analysis for nickel trade, and nickel cycles for each of the 52 countries and territories in this study. This information is available free of charge via the Internet at http://pubs.acs.org.

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ES072108L