

# On the Spatial Dimension of the Circular Economy

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## S1 Introduction

A detailed discussion and related references for the Australian material flow analysis (MFA) cycles that were produced as part of this research are reported below. The MFA model that was developed enabled us to track primary and secondary resource flows, with the latter further distinguished between “new scrap” (i.e., manufacture waste), and “old scrap” (i.e., end-of-life waste). Absolute amounts of resources in metallic equivalents per life cycle stage were combined with related life cycle inventory per unit of mass of resource to estimate the gross energy requirements allocated to production, trade, and consumption for Australia. A Cumulative Energy Demand indicator was used to derive gross energy requirement results. The energy embodied in trade was then computed as a fraction of total production and of total consumption (i.e., flow into use). A description of the life cycle inventory database (i.e., Ecoinvent, Classen et al., 2009) and literature references for accounting energy embodied in metal production, trade and consumption is following reported.

### S1.1 Aluminum

In 2010, Australia produced about 35% of world bauxite and alumina; annual production increased compared to that in 2009 due to expanded mining activity from re-opened and new natural deposits. Australia is estimated to have about 20% of known world resources (USGS, 2012).

Bauxite is extracted from open cut mining at Weipa (QLD), Gove (NT), and Darling Range (WA). Further known bauxite deposits are in the Mitchell Plateau and Cape Bougainville regions in Western Australia, but these reserves are not economic to mine at current levels (Australian Mines Atlas, 2016). Bauxite mining extraction includes surface methods such as front-end loaders, hydraulic excavators, and power shovels. The extracted ore is then crushed (with or without former washing and subsequent drying, for clay and sand waste removal), loaded, and transported by trucks and railways to refineries or shipped abroad. Refining of aluminum ore commonly follows the Bayer refining process, in which four stages enable the extraction of aluminum oxide, or alumina, from bauxite. The stages are bauxite digestion with a hot solution of caustic soda, clarification to separate the alumina-bearing solution from “red mud” waste, precipitation of alumina from the liquor, and calcination of alumina hydrated to dried pure alumina. Aluminum metal is commercially produced from alumina by electrolysis (Hall-Heroult process), in which an electric current is passed through a molten solution of alumina and a bath of cryolite (Australian Mines Atlas, 2016).

Historical bauxite mine production and refined alumina production in Australia are reported in national statistics (BREE, 2013). All flows are expressed in mass of aluminum by assuming a content of aluminum in bauxite ore and alumina (% w/w) at 28% and 52.9% respectively. Mining extraction rates and process efficiency for alumina refining and aluminum smelting have been previously described (Ciacci et al., 2013). Casting process shapes ingots of pure aluminum metal that are utilized for alloys production, the fabrication of semi-finished and intermediate products through rolling, extrusion, foundry casting or other processing operations. Processing losses are based on previous analysis of aluminum stocks and flows (Chen and Graedel 2012).

Major end-use application sectors of aluminum-containing products include building and construction, infrastructure, machinery and equipment, transportation, consumer durables, containers and packaging, and other minor uses (e.g., aluminum's use in steelmaking for de-oxidation purposes). Historical market shares for end-use application sectors of aluminum and associated lifespan distributions are derived from the Global Aluminium Flow Model (GARC), (World Aluminium, 2012). A lifetime of 1 year is assumed for containers and packaging, as these products are generally discarded within a few months of their placement on market. The GARC model was also applied to estimate waste collection rates, separation and recovery efficiency of obsolete products and aluminum scrap processing at end-of-life.

In-use dissipation of aluminum may occur from its use in transportation due to friction corrosion, but such flow appears virtually negligible (Ciacci et al., 2015).

Additional data were collected to identify and quantify aluminum flows contained in traded goods. A balance of historical aluminum imports and exports in Australia was conducted by considering records of aluminum-containing commodities, according to the Harmonized System classification, from the United Nations Commodity Trade Statistic Database (UN Comtrade), (UN, 2018). Estimates for the content of aluminum in ores and concentrates, unwrought metal forms, semi-finished and finished aluminum-containing goods, end-of-life products, and aluminum scrap from various literature sources (Chen and Graedel, 2012; Ciacci et al., 2015) were utilized to express imports and exports values in terms of mass flow of aluminum.

#### Energy Embodied in Aluminum Production, Trade, and Consumption

For aluminum, mining, (alumina) refining, smelting, fabrication, and manufacturing were the main life cycle stages considered in the assessment. As a first approximation, the content of metal scrap in aluminum imports was set equal to that of national production and export at a given stage. The Ecoinvent processes "*Bauxite, at mine*", "*Aluminium oxide, at plant*", and "*Aluminium, primary, at plant*" were used as life cycle inventories for gross energy requirements associated with primary aluminum, while "*Aluminium, secondary, at plant*" was the main dataset reference for aluminum scrap recycling. Table S1 lists the energy requirement per unit of aluminum processed employed in the analysis.

**Table S1.** Energy requirement per unit of aluminum processed. Values in MJ/kg Al.

Aluminum Source	Mi			R			S			F		Mfg	
	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.
Primary	0.5 <sup>1</sup>	0.5 <sup>1</sup>	0.5 <sup>1</sup>	36.3 <sup>2</sup>	36.3 <sup>2</sup>	36.3 <sup>2</sup>	157.2	194.0	194.0	194.0	194.0	194.0	194.0
Secondary	-	-	-	-	-	-	23.8	23.8	23.8	23.8	23.8	23.8	23.8

Mi – mining, R – refining, S – smelting, F – fabrication, Mfg – manufacturing.

<sup>1</sup> Assumes 0.281 kg Al/kg bauxite.

<sup>2</sup> Assumes 1 kg Al from 1.530 kg aluminum hydroxide.

## 51.2 Copper

Most abundant copper mineral in Australia is chalcopyrite and the largest copper deposits are at Olympic Dam and Mount Isa, where copper is extracted from underground mines (Geoscience Australia, 2016). The traditional mining process involves the ore being broken and brought to surface to be grinded finely. The copper recovery efficiency is typically around 90%, while about 95% of the ore input ends up in tailings stored near the mine (Lossin, 2000). Copper content in Australian ores has been estimated at about 2% (Mining Technology, 2016); a concentration step is needed to achieve a concentrate that contains about 30% copper. The concentration process involves comminution fragments from the ore (i.e., through blasting, crushing and grinding). The resulting fine particles are sent to froth flotation (Schlesinger, et al., 2011a), where sulfide mineral is separated from the gangue by froth flotation. Concentration of copper-sulfide minerals has generally 85%-90% recovery efficiency (Schlesinger, et al., 2011b).

The copper concentrate may undergo various refining methods adopted by smelters to purify copper. Generally, the process includes the production of copper matte (50%-70% Cu), which is converted into blister copper (98%-99% Cu). The converting process converts the copper matte into metallic copper. The outputs are molten blister copper that is sent to refining for sulfur and oxygen removal and then to anode casting, and molten iron slag, which is sent to copper recovery. Cu smelters produce two slags: smelting furnace slag (1%-2% Cu) and converter slag (4-8% Cu), which contain considerable amounts of copper. Copper recovery efficiency from slag treatment is 90%-98%. Blister copper is then refined in an anode furnace (99.5% Cu), and pure cathodes of copper (99.99%) are produced electrolytically (Schlesinger, et al., 2011b). In some Australian mines, Cu is extracted by leaching: the ore is broken and dissolved by sulfuric acid to leach out the copper. The Cu-rich solution is pumped to the extraction plant, where copper cathodes are produced by the electrowinning process (Geoscience Australia, 2016).

Market shares for first uses and the distribution of copper in the end-use application sectors are derived from US proxy data (Copper Development Association, 2013). Around 70% of metal copper is used to produce rectangular bars (for rolling to rod and drawing to wire), round billets (for extrusion and drawing to tube), and flat strips (for rolling to sheet and forming into welded tube) by melting and casting processes. The remaining fraction is employed in brass and bronze production (Schlesinger, et al., 2011c). Losses of copper to waste repositories from fabrication and manufacturing are assumed to be negligible (Bertram et al., 2002).

Principal end-use sectors for copper (Glöser et al., 2013) include building and construction, infrastructure, industrial machinery and equipment, transportation, and consumer and general products. Lifespans of copper products in use (van Beers and Graedel, 2007; van Beers et al., 2007) were applied to estimate the accumulation of copper in in-use stock and the generation of copper waste and obsolete products at end-of-life. In-use dissipation rates (Ciacci et al., 2015) were applied to estimate the release of copper flows in the environment as a function of the in-use stock. Rates for waste collection, copper separation, and copper remelting (Glöser et al., 2013; Hyder Consulting, 2011; Environment Australia, 2002) were used to compute the fraction of secondary copper functionally recycled (i.e., preserving copper functionality in the new products). Secondary refined copper production is derived from the amount reported for Oceania in the International Copper Study Group report (ICSG, 2013).

More than 200 copper-containing commodities are reported in the UN Comtrade database (UN, 2018); this information on historical trade flows of various copper forms were considered to balance annual imports and exports in Australia. Estimates for the content of copper in ores and concentrates, unwrought copper forms, semi-finished and finished copper-containing goods, end-of-life products, and copper scrap from various literature sources (Rechberger and Graedel, 2002; Norgate et al., 2007; Otero et al., 2012; Ruhrberg, 2006; Vexler et al., 2004; Zhang et al., 2009; Jody et al., 2010) were utilized to express imports and exports in terms of mass flow of copper.

## Energy Embodied in Copper Production, Trade, and Consumption

For copper, ore mining, smelting, refining, fabrication, and manufacturing were the main life cycle stages considered in the assessment. As a first approximation, the content of metal scrap in copper imports was set equal to that of national production and export at a given stage. The Ecoinvent processes “Copper concentrate, at beneficiation”, “Copper primary, at refinery” were used as life cycle inventories for gross energy requirements associated with primary copper. Based on Norgate and Haque (2010), a split ratio for energy requirements in smelting and refining was set at 3:1. “Copper, secondary, at refinery” was the main dataset reference for copper scrap recycling. Table S2 lists the energy requirement per unit of copper processed employed in the analysis.

**Table S2.** Energy requirement per unit of copper processed. Values in MJ/kg Cu.

Copper Source	Mi			S			R			F		Mfg	
	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.
Primary	27.8 <sup>1</sup>	27.8 <sup>1</sup>	27.8 <sup>1</sup>	24.5	45.8	45.8	8.2	60.5	60.5	60.5	60.5	60.5	60.5
Secondary	-	-	-	21.1	21.1	21.1	7.0	28.1	28.1	28.1	28.1	28.1	28.1

Mi—mining, R—refining, S—smelting, F—fabrication, Mfg—manufacturing. In both primary and secondary copper, the smelting:refining ratio for gross energy requirement is set at 3:1 based on Norgate and Haque (2010).

<sup>1</sup> Assumes 0.36 kg Cu/kg Cu concentrate.

### S1.3 Nickel

Nickel is extracted from either laterite or sulfide ore. The blended or concentrated ore is smelted to a nickel matte and then refined into nickel metal, ferronickel, nickel oxide sinter, and a variety of nickel chemicals. Data for these primary nickel products are based on International Nickel Study Group (2013). 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 (Pariser, 2004; International Nickel Study Group, 2013), a model developed to quantify the use and generation of scrap in fabrication, 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 (INCO, 2004; UN, 2018), and multiplying the reported or calculated mass flows of the relevant commodities by the estimated nickel content.

At the use life stage, the inflow equals the outflow from manufacturing as adjusted by trade flows. The outflow from use is based on a simplified residence time model for transportation and industrial machinery, and on an inflow/outflow model for the remaining applications (for details see Reck et al., 2008). 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 (Leygraf et al., 2016).

Waste management includes the collection, separation, treatment, recycling (mostly as scrap), and deposition (mostly as landfilling) of waste. Whereas nickel in stainless steel and nickel alloy scrap is collected and recycled within the nickel cycle (Igareshi et al., 2007), 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 (Sano et al., 1998). It is estimated that 80% of postconsumer nickel

scrap is recovered within the nickel cycle while 20% becomes 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 (Reck et al., 2008, Table 1) and manufacturing (available pre-consumer scrap).

#### Energy Embodied in Nickel Production, Trade, and Consumption

For nickel, ore mining, smelting, refining, fabrication, and manufacturing were the main life cycle stages considered in the assessment. As a first approximation, the content of metal scrap in nickel imports was set equal to that of national production and export at a given stage. The Ecoinvent processes "*Nickel, 99.5%, at plant*", were used as life cycle inventories for gross energy requirements associated with primary nickel production. Depending on grade standards (e.g., Class I Nickel), additional energy inputs may increase the gross energy requirements at more than 250 MJ/kg Ni (Eckelman, 2010). According to the same author, the process contribution of mining, smelting, and refining were derived from the aggregated result of Ecoinvent process. "*Nickel, secondary, from electronic and electric scrap recycling, at refinery*" was used for nickel recycling. Table S3 lists the energy requirement per unit of copper processed employed in the analysis.

**Table S3.** Energy requirement per unit of nickel processed. Values in MJ/kg Ni.

Nickel Source	Mi			S			R			F		Mfg	
	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.
Primary	6.2	6.2	6.2	106.8	113.0	113.0	74.0	187.0	187.0	187.0	187.0	187.0	187.0
Secondary	-	-	-	-	-	-	14.6	14.6	14.6	14.6	14.6	14.6	14.6

Mi—mining, R—refining, S—smelting, F—fabrication, Mfg—manufacturing.

<sup>1</sup> Assumes 6.5% Ni content in ores (Eckelman, 2010).

#### S1.4. Zinc

The Australian zinc cycle, and associated references and data sources, are illustrated and described in Meylan and Reck (2016). After zinc ores extraction, beneficiation processes and smelting deliver zinc concentrates and slab. A small fraction of zinc concentrates is directly used in the chemical industry. Zinc slab is the input material to the production of several zinc intermediates such as galvanizing zinc, zinc alloys, brass, zinc semi-fabricated products, zinc dust, and zinc chemicals. Zinc intermediates are further processed into finished goods and find main uses in construction, transportation, industrial and metal working machinery, electrical and electronic equipment, and agriculture.

During use, zinc can undergo dissipative processes from several applications. For instance, in steelmaking zinc is employed to provide a protective coating to steel from corroding. Similarly, zinc use in agriculture is entirely dissipative, while further dissipation may occur from abrasion of tyres, in which zinc is added as a vulcanizing agent during manufacturing.

At end-of-life, zinc is collected for recycling with process efficiency that varies between first-uses and end-use application segments. Collected galvanized steel scrap containing zinc is returned to steel production in electric arc furnaces, from which crude zinc oxide is generally recovered.

#### Energy Embodied in Zinc Production, Trade, and Consumption

For zinc, mining, smelting and refining, fabrication, and manufacturing were the main life cycle stages considered in the assessment. As a first approximation, the content of metal scrap in zinc imports was set equal to that of national production and export at a given stage. The Ecoinvent processes "*Zinc, concentrate, at beneficiation*" and "*Zinc, from combined metal production, at refinery*" were used as life cycle inventories for gross energy requirements associated with primary zinc stages. Gross energy required for secondary zinc was estimated assuming that recycling offsets 75%

(Grimes et al., 2008) of energy input to primary zinc. Table S4 lists the energy requirement per unit of aluminum processed employed in the analysis.

**Table S4.** Energy requirement per unit of zinc processed. Values in MJ/kg Zn.

Zinc		Mi			S & R			F		Mfg	
Source	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.	
Primary	8.7 <sup>1</sup>	8.7 <sup>1</sup>	8.7 <sup>1</sup>	27.6	36.3	36.3	36.3	36.3	36.3	36.3	
Secondary	-	-	-	24.5	24.5	24.5	24.5	24.5	24.5	24.5	

Mi—mining, R—refining, S—smelting, F—fabrication, Mfg—manufacturing.

<sup>1</sup>Assumes 0.62 kg Zn/kg Zn concentrate.

### S1.5. Stainless Steel 15Cr9Ni

This study characterizes the stainless steel life cycle through material flow analysis by following the framework of Figure 1 and Figure 2e in the main paper.

In a process called “crude production”, most stainless steels are produced in an electric arc furnace that is charged with primary and secondary raw materials (Cunat, 2002). Primary input materials include ferrochromium, often ferronickel, and sometimes ferromolybdenum and other specialty metals; secondary metals include scrap of stainless steels, alloy steels, and carbon steels. The molten stainless steel is either continuously cast or cast into a semi-finished form (“semis”) before the subsequent hot- and cold-rolling steps. The result are semi-finished and finished stainless steel products that can, in a broad sense, be distinguished by shape into “flat” and “long” products (Reck et al., 2010).

Crude production data were taken from Vale Inco (2007) and ISSF (2009). The latter also provided most of the data used to characterize the stainless steel-making processes. Estimates of the share of scrap input into crude production were based on Pariser (2002) for year 2000 and ISSF (2009) for 2005. Estimates on yield losses are based on expert interviews.

In manufacturing, semi-finished and finished stainless steels are used to make products for the following five end use sectors: building and infrastructure, transportation, industrial machinery, household appliances and electronics, and metal goods. The yield loss in manufacturing was estimated to be 10% in 2000 and 8% in 2005 (of which 0.7% in 2000 and 0.5% in 2005 were industrial wastes, the remainder reprocessed as new scrap).

Manufactured final goods are often traded before being used. To quantify the trade of final goods (i) the most relevant commodities for stainless steel were identified, a total of 66, and their trade data collected (UN, 2018); (ii) their stainless steel content was estimated, and (iii) the stainless steel content in traded final goods was calculated by combining mass data with metal concentrations.

The flow of stainless steel into use was calculated by adding the net import of final goods to the outflow from manufacturing. This was done separately for the five end use sectors discussed earlier. Final goods remain in use until their lifetime expires, with lifetimes varying from a few years in the case of electronics to as much as a century in buildings. The net addition to in-use stocks is determined for each sector by the difference between the flows into and out of use.

The end-of-life flow was calculated with a dynamic model estimating the historic flows into use at the country-level. This was done independently for each end-use sector, which allowed us to account for the different lifetimes. Historic product discards were estimated to follow a normal distribution. Reck et al., (2010) summarizes for each sector the estimated lifetimes and coefficients of variation. The collected stainless steel is further distinguished into a larger fraction that is recycled as stainless steel and a smaller fraction that is lost to the carbon and alloy steel scrap markets. These losses occur when stainless steel scrap is not separated from other metal scrap but rather processed together with carbon and alloy steel scrap where its alloying elements become an impurity. The separated end-of-life “old scrap” is used together with “home scrap” from the stainless steel making process and “new scrap” from manufacturing as secondary raw material in the crude production of stainless steel, together with carbon steel scrap and primary metals.

When data from independent sources would not lead to mass balance within the material flow framework, expert interviews and cross checks with trade partners were performed. The remaining data gaps are indicated on the cycle diagrams as “phantom flows”, and shown as circled dashed lines. Phantom flows were most frequently assigned to the scrap market, reflecting a generally higher uncertainty at end-of-life.

Uncertainties were estimated for each of the 24 flows, with uncertain data assumed to be normally distributed (for details see Supporting Information). Error propagation and data reconciliation were performed using the STAN software (Cencic and Rechberger, 2008).

### Energy Embodied in Stainless Steel 15Cr-9Ni Production, Trade, and Consumption

Because no production of 15Cr-9Ni occurs in Australia, the total amount of this alloy demanded in the country was assumed to be imported and energy embodied along with it. However, this is a simplification as Australia is a producer of each of these alloy metals and part of their energy embodied in production could be allocated to the country profile. The Ecoinvent processes “Pig iron, at plant”, “Ferrochromium, 68% Cr, at plant”, “Ferro-nickel, 25% Ni, at plant” prorated for their mass content were utilized to estimate the gross energy required to produce 1 kg 15Cr-9Ni. Table S5 lists the energy requirement per unit of alloy processed employed in the analysis.

**Table S5.** Energy requirement per unit of stainless steel 15Cr-9Ni processed. Values in MJ/kg 15Cr-9Ni.

15Cr-9Ni Source	Mi			R			S			F		Mfg	
	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Prod.	Imp.	Exp.	Imp.	Exp.	Imp.	Exp.
Primary	-	-	-	-	-	-	-	-	-	81.7	81.7	81.7	81.7
Secondary	-	-	-	-	-	-	-	-	-	-	-	-	-

Mi—mining, R—refining, S—smelting, F—fabrication, Mfg—manufacturing.

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