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Metal recycling: The need for a life cycle approach

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Executive summary

Concerns in recent years regarding the sustainable utilisation of natural resources have seen a life cycle thinking approach being applied to the production of goods and services. Life cycle assessment (LCA) is a methodology that has been developed to assist in this task, and essentially accounts for all the inputs and outputs, and associated environmental impacts, over the life cycle of a product. CSIRO Minerals Down Under Flagship has been conducting research into the sustainable production of primary metals (copper, nickel, lead, zinc, aluminium, titanium, iron and steel, ferroalloys and gold) using LCA methodology over a number of years. Given the critical role that recycling will play in the sustainable production and utilisation of metals into the future by reducing the rate of depletion of metal reserves by the recycling of "metals-in-use", it is essential that LCA methodology also be applied to secondary metal production by various recycling systems and processes, if the principles of sustainability are to be incorporated into these processes.

However, there are a number of issues relating to metal recycling and its incorporation into LCA methodology that must be addressed before any metal recycling LCA studies can be carried out. These issues include:

- inconsistencies in the use of recycling metrics in reports and publications giving metal recycling data;
- quantifying the number of times a metal has been recycled – this is related to the type of metal product and its typical lifetime;
- the quality (ie. presence of contaminants) of the recycled metal, which influences its subsequent use;
- sourcing reliable and consistent inventory data for the various stages of metal recycling;
- whether the recycled metal is used in a closed-loop or open-loop recycling system;
- the allocation method used in the LCA to account for recycling.

These issues are discussed in some detail in the report and some guidelines given.

The results of some preliminary analysis described in the report for an arbitrary recycling scheme showed that a maximum recycling rate (in embodied energy terms) exists for any particular recycling scenario (ie. metal, product nature, geographical location, etc). Beyond this maximum recycling rate, the embodied energy of the recycled metal exceeds that of the corresponding primary metal. Furthermore, it could be expected that, all other things being equal, the maximum recycling rate would be greatest for those metals having the highest embodied energy values for primary metal production, eg. aluminium. Similarly, it was shown there is likely to be an optimum recycled content (again in embodied energy terms) for a given product system, depending on the available scrap to primary metal ratio.

Some metal recycling data for Australia are also presented in the report, along with the results (primarily greenhouse gas and water impacts) of a number of metal recycling LCA studies where recycling was compared with other waste disposal options such as incineration and landfill.

This report represents the first step by the Australia's Mineral Futures theme (Value Chain Innovations and Analysis stream) under the Minerals Down Under Flagship in applying LCA methodology to metal recycling, and aims to provide a framework for more detailed LCA studies of recycling of specific metals such as steel or copper in the Australian context.

1 Introduction

All materials and products have a life cycle. A life cycle is the journey a material or product goes through during its entire life. Every material starts in some raw form, is processed, and is made into a finished product. After some period of time, the material or product reaches the end of its useful life. When a product (or other materials object) reaches the end of its useful life, the question arises as to what to do with it. In some situations it may be reusable through simple processing (eg. washing of glass bottles), repairs, modifications or remanufacturing. In other situations, the product may be recycled as secondary material to a manufacturing process, or the individual components or materials from which it is made may be able to be separated and recycled as secondary materials. Eventually, reuse or recycling may no longer be possible, and some form of disposal is necessary. The most common disposal option used is to bury it in landfill sites, but this should only occur if the material is deemed not too polluting. Other disposal options include burning (usually to produce useful energy) if combustible, or put into permanent storage if it is too hazardous to the environment or humans (eg. radioactive materials). A schematic diagram of the materials or product life cycle is shown in Figure 1, which starts with materials being obtained from the Earth, transformed into a product, then used before finally being returned to the Earth.

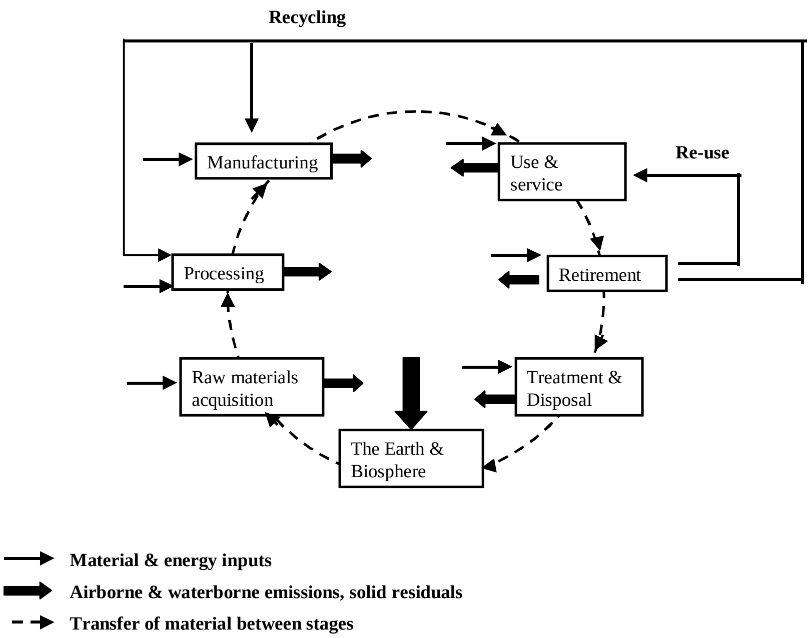


Figure 1. Schematic flowsheet of the materials or product life cycle.

At all stages over this life cycle there are material and energy inputs, and various airborne and waterborne emissions, along with solid residuals. Concerns in recent years regarding the sustainable utilisation of natural resources have seen a life cycle thinking approach being applied to the production of goods and services. Life cycle assessment (LCA) is a methodology that has been developed to assist in this task, and essentially accounts for all the inputs and outputs for the product life cycle shown in Figure 1. The product life cycle is generally considered in two parts:

- cradle-to-gate – that part of the cycle extending from raw materials extraction from the Earth through to the production of refined materials;
- gate-to-grave – the remaining part of the cycle extending from product manufacture using refined materials through to disposal back to the Earth.

Extensive 'cradle-to-gate" LCA studies of primary metal production have been carried out at Process Science and Engineering over many years involving various processing routes (eg. pyrometallurgical versus hydrometallurgical), energy sources and ore grades. Metals considered include copper, nickel, lead, zinc, aluminium, titanium, iron and steel, ferroalloys and gold. However, recycling will play a critical role in the sustainable production and utilisation of metals into the future, and it is essential that LCA methodology also be applied to secondary metal production by various recycling systems and processes if the principles of sustainability are to be achieved. This report represents the first step by the Australia's Mineral Futures theme (Value Chain Innovations and Analysis stream) under the Minerals Down Under Flagship in applying LCA methodology to metal recycling. The purpose of the report is to provide a review of some of the issues relating to metal recycling, as well as a framework for more detailed LCA studies of recycling of specific metals such as steel or copper in the Australian context.

2 Metal recycling

Reducing the rate of depletion of metal reserves by recycling of "metals-in-use" will contribute to the sustainable use of metals. Re-use and re-manufacture complement recycling and although generally more desirable than recycling, finite product lives means that eventually the product will have to be recycled. It is widely recognised that recycling of metals results in significant savings in energy consumption (and hence reductions in associated greenhouse gas emissions) when compared to primary metal production. While the amount of energy used in metal recycling depends largely on the metal in question, its application and the recycling process used, typical energy savings reported for metal recycling over primary metal production are aluminium 95%, nickel 90%, copper 84%, zinc 75%, lead 65% and steel 60% (Norgate and Rankin, 2002) as shown in Figure 2[1]. The circle areas in this figure are proportional to the embodied energies of production of the respective primary metals, with the areas of the segments below the horizontal line representing the proportions of these primary embodied energies used in recycling of the metals. Thus the areas above the horizontal line represent the primary metal embodied energies saved by recycling.

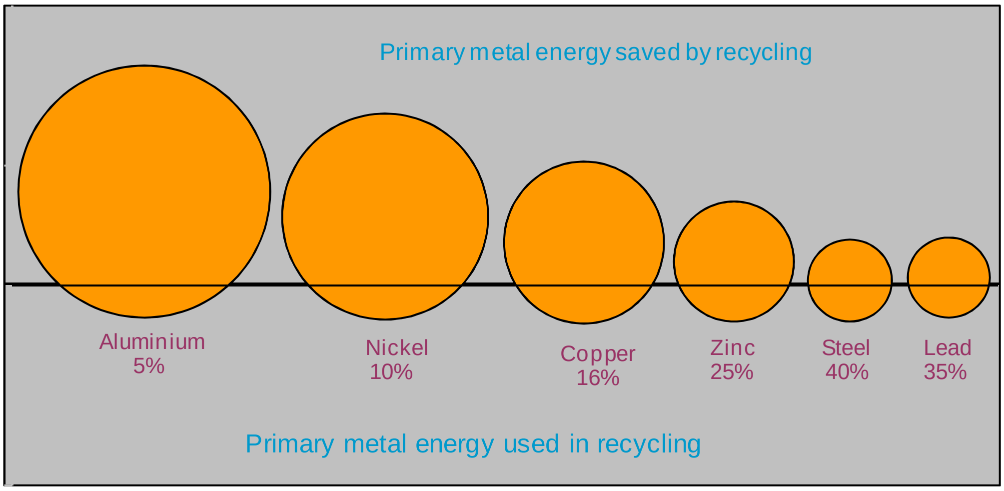


Figure 2: Primary versus secondary (recycled) metal production energy.

2.1 Recycling metrics

The term recycling rate is frequently used in the literature but its meaning is not always clear, and is sometimes used interchangeably with collection rate, recovery rate or return rate (recycled content). Reuter et al (2005) suggest that the 'real' recycling rate of a metal should refer to the ratio of the production from secondary raw material (scrap) in the present year to the total production "n" years ago, where "n" is a weighted average lifetime of all goods manufactured from this metal. However, this is a purely theoretical figure as the number of goods and products and their respective differing lifetimes is

[1] The ordinate (Y-axis) in Figure 2 is used for presentation purposes only.

impossible to determine. Practical recycling rates are based on current or present flows of materials. The various recycling metrics (adapted from Quinkertz et al, 2001) are shown in Figure 3, where recycling rate is the amount of scrap that is remelted for product manufacture as a percentage of the total amount of scrap available, while recycled content (or return rate) is the amount of scrap remelted for product manufacture as a percentage of the total amount of material (primary plus scrap) used for product manufacture.

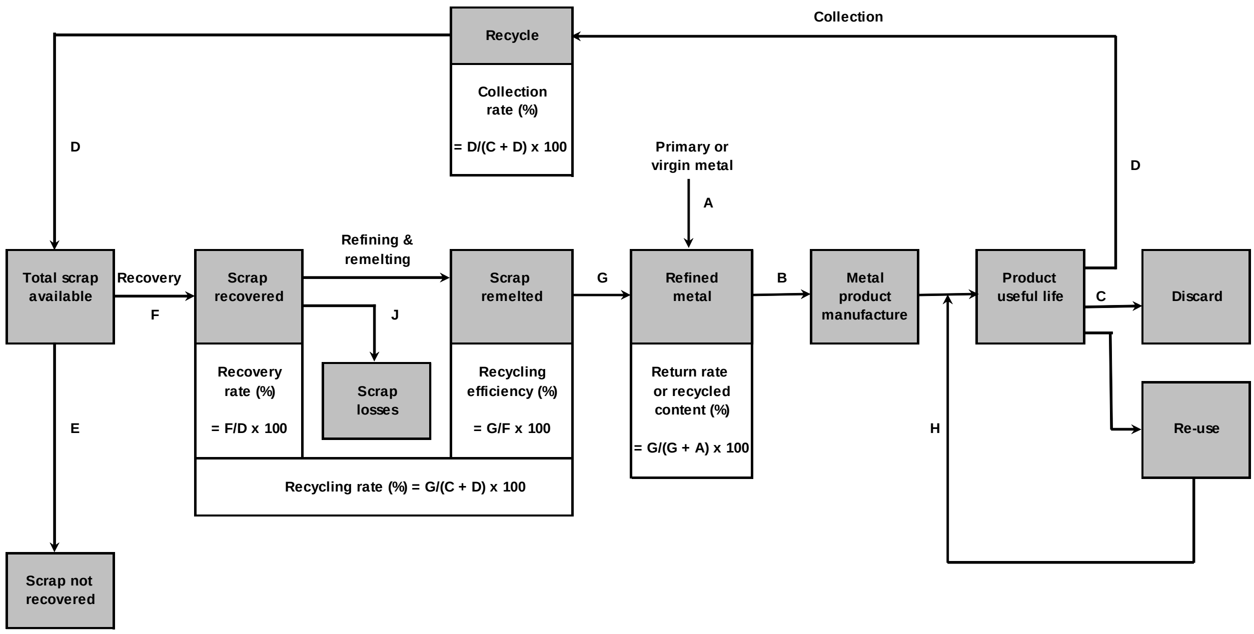


Figure 3. Recycling metrics.

Scrap is generally categorised as home, new or old with these types being as follows:

- home scrap is material generated during material production or during fabrication or manufacturing that can be directly re-inserted in the process that generated it, and it is therefore excluded from recycling statistics and not considered further here;
- new scrap, where new indicates pre-consumer sources (eg. turnings, trimmings, cuttings and off-specification material produced during metal shaping and part manufacture) – although also originating from a fabrication or manufacturing process, unlike home scrap it is not recycled within the same facility but rather transferred to the scrap market;
- old scrap, which indicates post-consumer sources (eg. used beverage cans, motor vehicles) – recycling of old scrap requires more effort, particularly when the metal is a small part of a complex product.

Some reported metal recycling rates are based on both new and old scrap, but as much of new scrap supply is derived from new mine production, it hardly seems to be secondary supply. Old scrap, by contrast, comes from products that have reached the end of their useful lives. Therefore recycling rates based on old scrap only are probably more appropriate measures of society's recycling performance. Recycling rates and recycled contents for some common metals derived from a number of sources (eg. US Geological Survey, International Aluminium Institute, World Steel Association, Bureau of International Recycling) are shown in Table 1. Recycling rate and recycled content information for sixty metals have recently been reported as part of a comprehensive study of metals stocks and flows by the UNEP 's Resource Panel (UNEP, 2011, Graedel et al, 2011). However, this information is reported in the form of ranges rather than specific values as shown in Figures 4 and 5 respectively. The values given in Table 1 fall within the ranges reported by UNEP, with the exception of the recycled contents for copper and zinc which are slightly higher than the UNEP data, and the world recycling rate for copper which is slightly lower than the UNEP data. Recycling rates are very dependent on application, location and metal prices, and when metal prices drop, recycling rates tend to drop. Recycled content targets must take into account market growth and metal durability (ie. product life). The maximum amount of a material that can be recovered at any time is a function of the quantity put into service one average product lifetime earlier. The estimation of such a lifetime is by no means simple, although typical lifespans of various metal products have been reported by Henstock (1996), Bruggink (2000), Satlow et al (2002); Bruggink and Martchek (2004), Brooks and Pan (2004); Matsuno et al (2007), ranging from less than a year for steel and aluminium cans up to sixty to eighty years for copper in buildings.

Table 1. Recycling rates and recycled contents (%) for various metals.

Metal	Recycling rate			Recycled content
	United States		World	World
	Old scrap	Old & new scrap		
Aluminium				
- general	25	56		33
- cans	54	-	63	80
Steel				
- general	NA	67	50	40
- cans	65	-	68	
Copper	6	32	40	32
Nickel	NA	48	70	33
Lead	77	79	66	63
Zinc	10	27	70	30

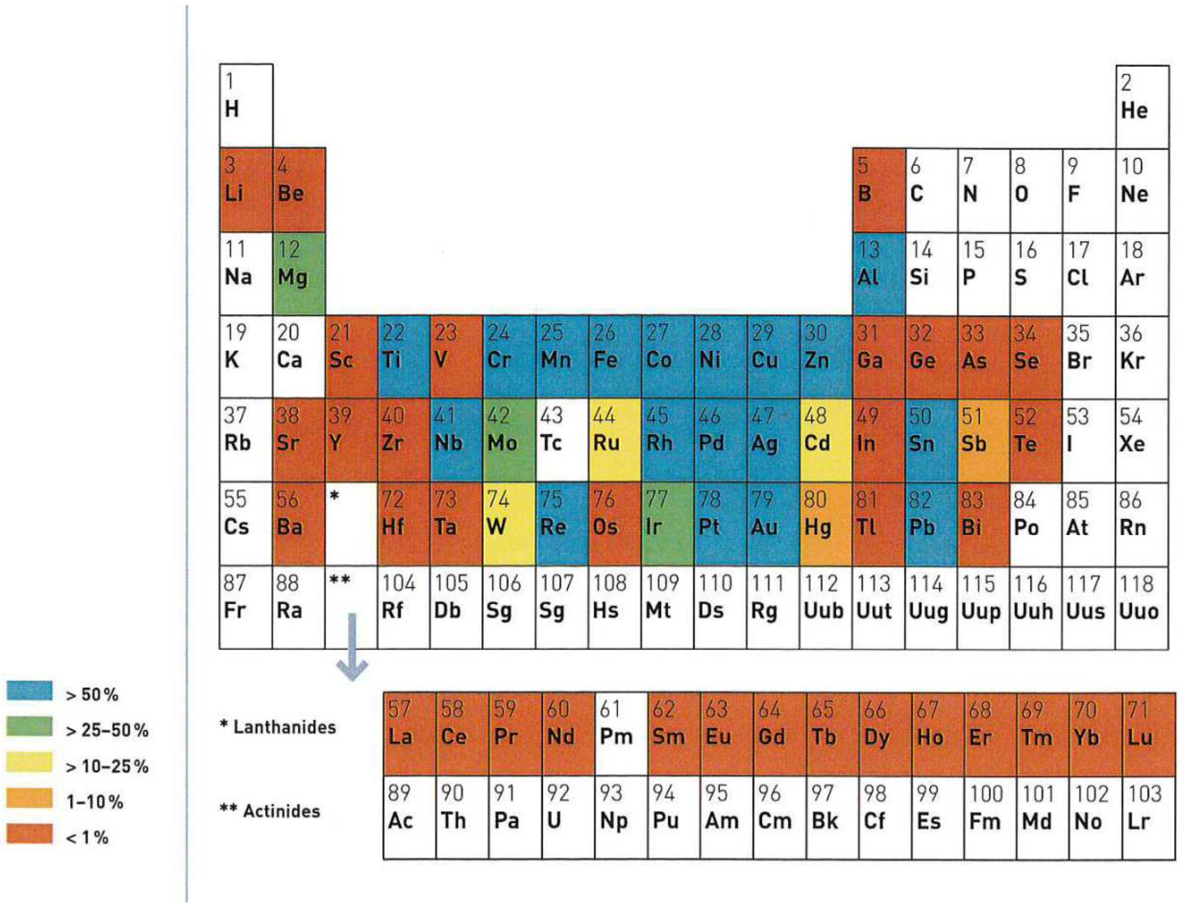


Figure 4. Recycling rate ranges for sixty metals (UNEP, 2011).

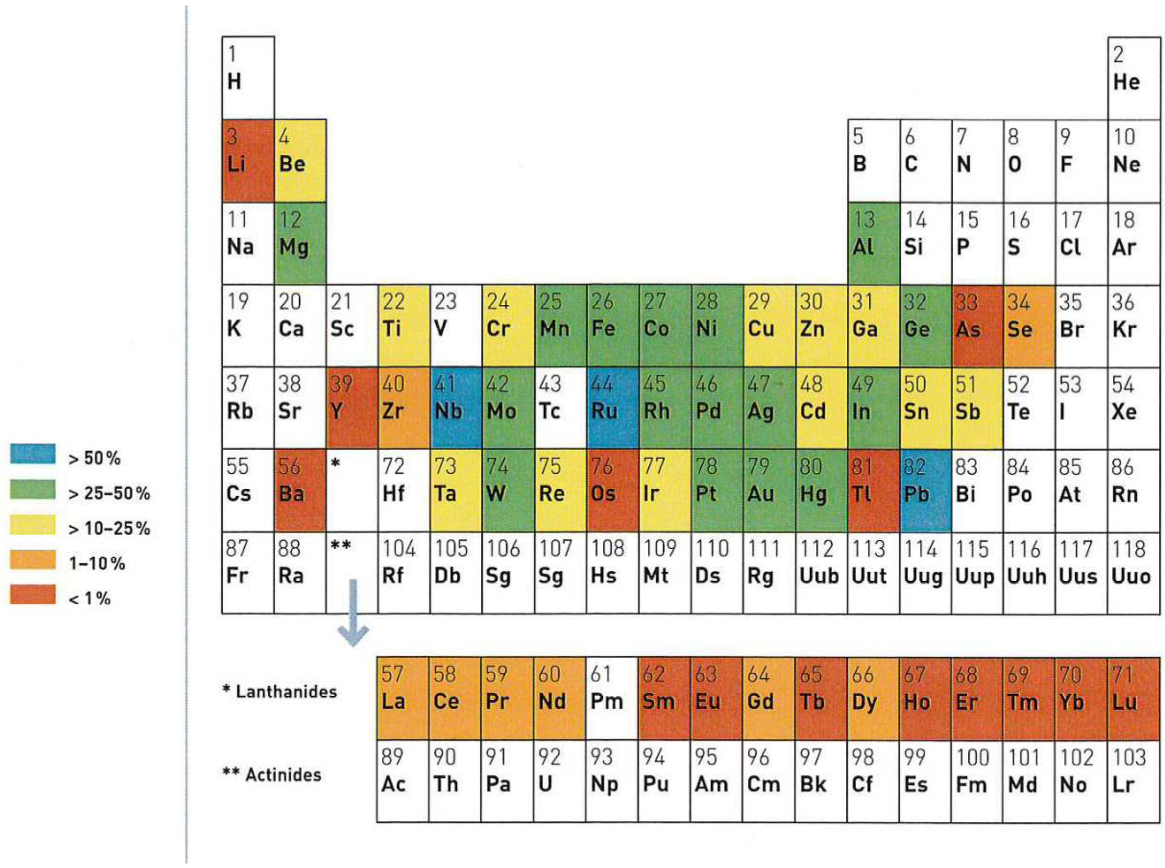


Figure 5. Recycled content ranges for sixty metals (UNEP, 2011).

Metals extracted from natural resources can escape recycling via losses over their life cycles. These losses occur mainly in four ways (Reck and Gordon, 2008):

- in production by metal losses to tailings and slags;
- in fabrication by scrap and industrial waste generation;
- in use by dissipation from products being used;
- in waste management by losses to landfill or to other material cycles (scrap markets).

According to these authors, production losses account for roughly half the amount of losses for nickel and chromium, with the remaining share consisting mostly of landfilling for nickel (36%) and losses to other scrap markets for chromium (26%). While metals dispersed to other scrap markets are still retained in "metals-in-use" stocks, they are downgraded and the particular services that these metals provide are lost through dilution.

2.2 Effect of metal recycling on embodied energy of metal production

The cumulative amount of input energy over the various stages of the life cycle is known as the Gross Energy Requirement (GER) or embodied energy of the product, process or service. The embodied energy, along with the associated greenhouse gas emissions, were two of the main environmental impacts included in the various primary metal LCAs referred to earlier. As the energy consumed in secondary metal production by recycling (at current collection and recycling rates) is generally appreciably less than that consumed in primary metal production as illustrated in Figure 2, the more times a metal is recycled, the more the embodied energy per application decreases.

Using aluminium as an example, Figure 6 shows the effect of the number of recycles, assuming a closed-loop recycling system, on the embodied energy per application of aluminium at various recycled contents and a hypothetical 100% recycling rate (ie. all material is returned to the original process). In plotting this figure it was assumed that the energy for aluminium recycling is 8.9 MJ/kg irrespective of the recycle number as estimated later (Section 2.3). This value agrees well with reported values for secondary aluminium production (Anon, 1997) and is about 5% of the energy of the aluminium smelting step (180 MJ/kg (Norgate et al, 2007)), ie. 0.05 x 180 = 9 MJ/kg, which agrees with Figure 2. Furthermore, it was assumed that there are no metal quality issues in substituting secondary aluminium for primary aluminium. The results in Figure 6 illustrate how the environmental impacts associated with the initial primary production of aluminium (in this case embodied energy) are progressively distributed over each recycle and how the embodied energy of aluminium metal used for product manufacture decreases with increasing recycled content. At 100% recycled content (ie. the same mass of aluminium being continuously recycled) the embodied energy asymptotes towards the recycling energy value of 9 MJ/kg as the number of recycles increases. Metal quality and product recovery issues will affect the number of recycles possible in practice. Figure 6 shows that the embodied energy of aluminium used in product manufacturing is largely a function of the recycled content. A similar observation has been made by Quinkertz et al (2001). The corresponding results for steel are shown in Figure 7 using a recycling energy of 3.2 MJ/kg as estimated later in Section 2.3.

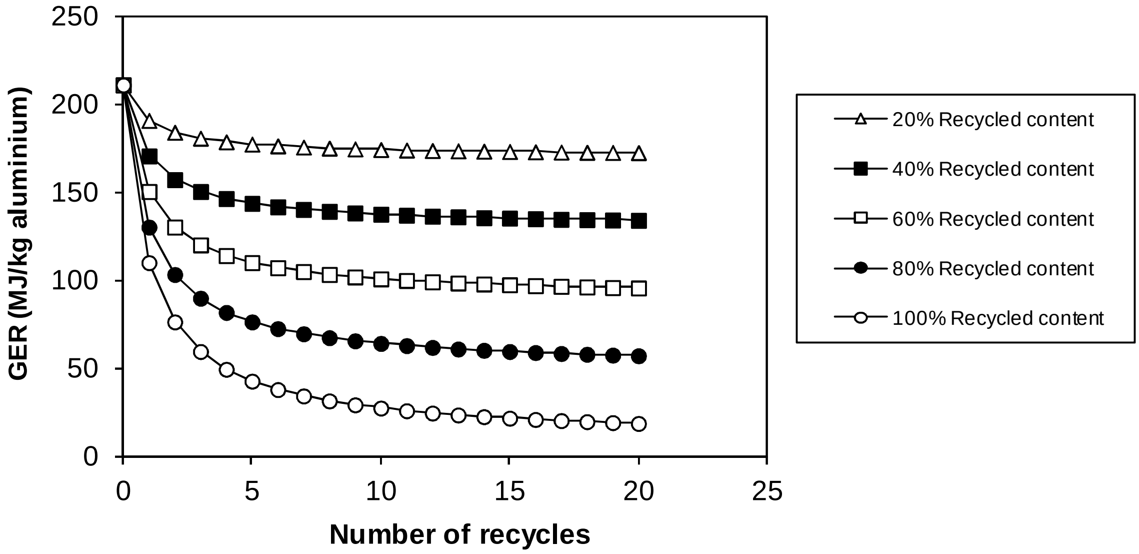


Figure 6. Effect of number of recycles and recycled content on the embodied energy per application of aluminium.

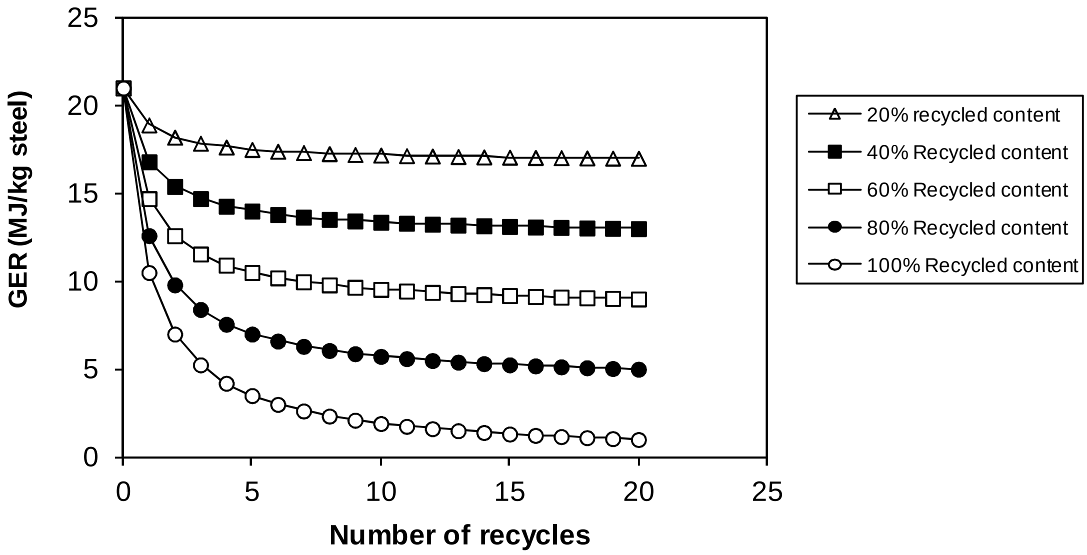


Figure 7. Effect of number of recycles and recycled content on the embodied energy per application of steel .

However, the number of recycles or number of times a metal is used is difficult to quantify. As reported by Yamada et al (2006), Ekvall suggested that that the number of times a material is used from cradle to grave can be calculated from:

$$N = 1/(1 - R) \quad [1]$$

where R is the rate of collection for recycling of the material from post-consumer products (see Figure 3) as given by:

$$R = D/(C + D) \quad [2]$$

This equation is shown plotted in Figure 8 and indicates that at a collection rate of 80%, the material is used about five times in society, while at 100% collection rate the figure asymptotes to infinity. According to Yamada et al (2006), this method is effective when R is constant over a long time and there is a consistency between inflow and outflow of the material to and from the society.

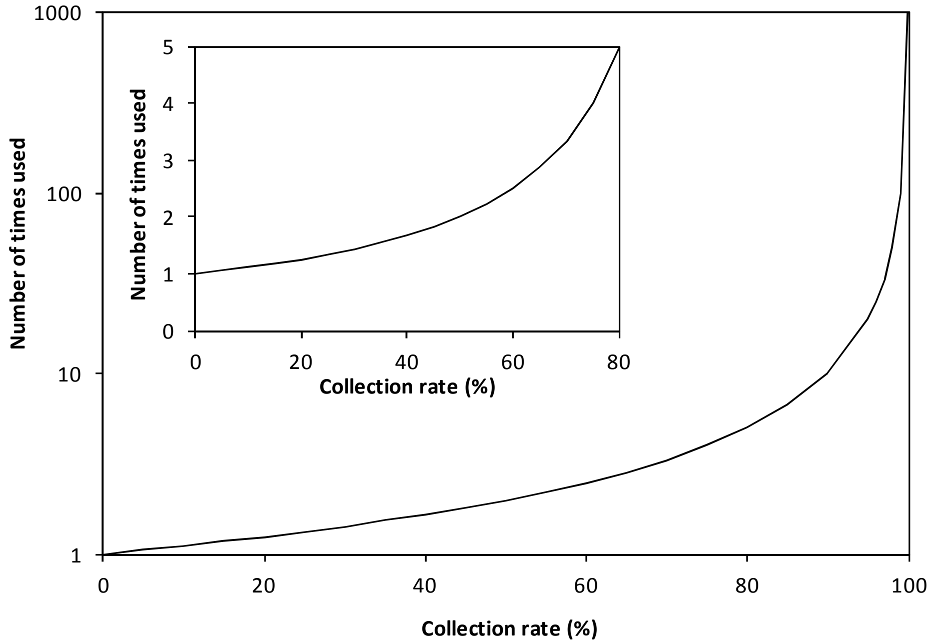


Figure 8. Number of times a material is used in society as a function of collection rate.

Because there is fluctuation in production, discard and recycling of materials in each year in a society, the flow of a material usually has a dynamic aspect. In addition, many products have long lifetimes, so some materials stay in the products for many years in a society. There is always accumulation (or release) of the material to and from the society. For these reasons, Yamada et al (2006) suggested that a probabilistic method should be applied to estimate the average number of times a material is used in a society from cradle to grave. These authors developed a methodology based on the Markov chain model, a probabilistic method using matrix-based numerical analysis. Markov chain modelling is a versatile technique that has been used for decades in various disciplines and for a variety of applications, particularly those involving random processes (Eckelman and Daigo, 2008). Using this methodology, Matsuno et al (2007) estimated that the number of times steel produced in Japan is used in society in all states (ie. construction, machines, cars, containers, other products) was 2.7, with an average residence time in use (covering all the times used) of 63 years. Similarly, Eckelman and Daigo (2008) applied Markov chain modelling to the global flow of copper metal and estimated that virgin copper, freshly mined, will experience an average of 1.9 cycles through the use phase and a technological lifetime of approximately 60 years before it is deposited in landfill or otherwise lost to the environment. These authors point out that this result compares with a value of 2.5 cycles using equation [1] above with a global collection rate of 60% as reported by Gerst and Graedel (2007). They further point out that the reason for this difference is that the simple analysis upon which equation [1] is based assumes an implicit first use, whereas copper is lost in tailings and slag in the Markov chain model in its first cycle through production. If the initial state for the analysis was copper refining not copper mining (thus ensuring a first use), the global average number of times used increased to 2.3.

2.3 Energy consumption for metal recycling

Metal recycling involves the following stages, as shown schematically in Figure 3:

- collection
- recovery
- refining and remelting.

Energy (primarily fossil fuel-based) is consumed in all of these stages as discussed below.

2.3.1 COLLECTION

Fuel consumption for collecting and transporting waste materials (including metals) to a material recovery facility (MRF) is largely dependent on the duration of the collection route, which in turn depends on the source of the waste, eg. city centre or suburban or regional areas – the lower the population density, the greater the transport distance between collection points (Eisted et al, 2009). Another issue that affects collection energy is the type of collection system, eg. single-stream (all materials combined) or dual stream (two streams – one for paper fibre and the other for commingled plastic, metal and glass) (Fitzgerald, et al, 2012). Table 2 gives some energy data reported in the literature for the collection and transportation of waste material.

Table 2. Energy consumption for collection and transport of waste materials.

	Energy consumption[2]			Comments	Reference
Collection	4.1	L/t	Diesel		
Transport					
- *Truck*	0.123	L/t.km	Diesel	*< 16 tonne*	Eisted et al (2009)
- *Truck*	0.045	L/t.km	Diesel	*> 16 tonne*	Eisted et al (2009)
- *Train (diesel)*	0.0095	L/t.km	Diesel		Eisted et al (2009)
- *Train (electric)*	0.058	kWh/t.km	Electricity		Eisted et al (2009)
- *Barge*	0.0084	L/t.km	Diesel	*(Europe average)*	Eisted et al (2009)
- *Ship*	0.0051	L/t.km	Diesel	*(2000-50,000 dwt*)*	Eisted et al (2009)
	0.0010	L/t.km	Diesel	*(>50,000 dwt*)*	Eisted et al (2009)
	0.0040	L/t.km	Diesel		Chester et al (2008)

*dwt = deadweight tonnage

Using the data in Table 2 to estimate the energy consumption and associated GHG emissions for collecting and transporting waste material a total distance of 20 km using a truck with over 16 tonne capacity gives the following result:

Energy consumption = 4.1 + (0.045 x 20)

[2] Back-calculated from mean GHG emissions of 12.9 kg CO_2e/t (Eisted et al (2009), Table 2) for collection and Table 3 for transport, using diesel GHG factor used by these authors of 3.15 kg CO_2e/L diesel).

= 5.0 L diesel/t waste

GHG emissions = 5.0 x 3.0 kg CO_2e/L (LCA-based GHG emission factor for diesel)
= 15 kg CO_2e/t waste

The latter result compares with a value of 9-17 kg CO_2e/t waste for a similar example (apartment block collection in city area, 20 km transport distance) reported by Eisted et al (2009). Increasing the transport distance to 200km, increases the diesel consumption to 13.1 L/t and the GHG emissions to 39 kg CO_2e/t waste. The latter value is not too different to the values of 38 and 59 kg CO_2e/t waste reported by Fitzgerald et al (2012) for dual stream and single stream collection respectively, although these authors did not report the transport distance involved.

2.3.2 RECOVERY (SORTING)

Metals are a major fraction of waste, primarily as a fraction from demolition waste, from end-of-life vehicles and from household appliances, and secondly from the municipal waste stream in the form of packaging materials such as cans, foil and containers. Metals from industry and construction have traditionally been recycled as they are generally available in large quantities (mainly iron and steel), whereas recycling of metals in municipal solid waste (MSW) has mainly increased over the last decade. Recycling of metals requires that foreign elements are removed and that the metals are sorted into their respective metal types, which takes place at a material recovery facility (MRF). The purpose of the MRF is to sort and upgrade the recovered material to a suitable quality grade for reprocessing. Large clean fractions of steel or aluminium are sent directly from the MRF to recycling. Bulky waste products with a large content of metals are sent to an electrical shredder which divides the large pieces into smaller, cleaner metaland residual fractions that can be further mechanically sorted. The shredded waste is sent to drum magnets where the magnetic fraction is sorted out, followed by an eddy current separator where the aluminium is sorted out. In a third sorting step, the remaining metals (copper, zinc, lead, magnesium, etc.), glass and plastics are sorted out (Damgaard et al, 2012). Gaustad et al (2012) have surveyed sorting and impurity removal technologies for aluminium recycling. Various technologies used for recovering metals from recyclates and residues are also described in UNEP (2013, p. 183).

While a general description of the scrap metal sorting and recovery steps is given above, the actual processing flowsheet and equipment items used depends strongly on the nature/source of the scrap being treated. Some typical energy consumption data for the various steps in metal scrap sorting and recovery are given in Table 3. Damgaard et al (2009) reported losses of 2% for steel and 5% for aluminium during sorting.

Table 3. Energy consumption for sorting and recovery of metal scrap.

	Energy consumption		Comments	Reference
Sorting	37	kWh/t scrap	Electricity	Quinkertz et al (2001)
	28	kWh/t scrap	Electricity	Alsema (2000)
Shredding	50	kWh/t scrap	Electricity	Damgaard et al (2009)
	97	MJ/t scrap	Diesel	
	40-60	kWh/t scrap	Electricity	Nijkerk & Dalmijn (2001)
	42	kWh/t scrap	Electricity	Schlesinger (2007)
	41	kWh/t scrap	Electricity	Henry (2004)
	28	kWh/t scrap	Electricity	Fraunholcz et al (2000)
	25	kWh/t scrap	Electricity	Woldt et al (2002)

2.3.3 REMELTING AND REFINING

As steel and alumium are the two most abundant metals in municipal solid waste, the focus below is on these two metals.

Steel

The electric arc furnace (EAF) process accepts 100% steel scrap and this is where the majority of the post-consumer steel scrap ends up. The main steps of the EAF process are (Damgaard et al, 2012):

- the scrap is first preheated (offgas generated in latter processing steps may be used for this purpose);
- the scrap loaded into baskets together with lime, which is used as a flux;
- the furnace anodes are then lowered into the scrap and the energy to the arcs is progressively increased until melting is complete;
- oxygen can be added to the early stages of melting to boost the process;
- when the final temperature has been reached the liquefied steel is tapped into a ladle, alloying and deoxidising agents are added, and it is then sent for casting.

Aluminium

Aluminium recyclers can be divided into two groups- remelters and refiners. Remelters mainly use aluminium scrap which is obtained directly from manufacturers and can be directly remelted. Refiners use “old scrap” aluminium which comes from a variety of sources such as end-of-life vehicles, household goods and MSW. Most of the post-consumer aluminium scrap is processed by refiners.

Aluminium scrap refining generally takes place in rotary or reverbatory furnaces. For aluminium scrap from MSW, such as used beverage cans, it is necessary to pre-treat the aluminiumto remove contaminants and de-coat or de-oil the scrap depending on the source. This improves the thermal efficiency of refining and reduces potential emissions from the melting process. The scrap is then loaded into the furnace. The melted aluminium is tapped for either direct casting or sent to another furnace where alloys can be made. In this process the aluminium is also refined to remove the last impurities in the aluminium.

Some typical energy consumption data for steel and aluminium remelting and refining are given in Table 4. Damgaard et al (2009) reported losses of 5% for both steel and aluminium in the remelting/refining stage.

Table 4. Energy consumption for remelting and refining steel and aluminium scrap.

	Energy consumption		Comments	Reference
Steel	1.5	GJ/t steel	Electricity	Norgate and Langberg (2009)
	1.7	GJ/t steel	Electricity	Natural Resources Canada (2007)
	2.2	GJ/t steel	Electricity	Fruehan et al (2000)
Aluminium	8.7	GJ/t aluminium		Anon (1997)
	8.8	GJ/t aluminium	96% gas 3% electricity 1% diesel	Quinkertz et al (2001)
	7.6	GJ/t aluminium		Milford et al (2011)
	7.0	GJ/t aluminium		Kear et al (2000)
	5.6	GJ/t aluminium		Schifo & Radia (2004)

3 Recycling issues

3.1 Lifetimes of metal products

The lifetime of metal products was touched upon briefly in Section 2.2 and is considered in more detail here. A simplified metal product life cycle was shown in Figure 1. The finished product enters the use phase and becomes part of the in-use stock of metals. When a product is discarded, it enters the end-of-life (EOL) phase. The life cycle of a metal product is closed if EOL products are entering appropriate recycling chains, which leads to scrap metal in the form of recyclates displacing primary metals. The life cycle is open if EOL products are neither collected for recycling or do not enter those recycling streams that are capable of recycling the particular metal efficiently. Open life cycles occur as a result of products discarded to landfills, products recycled through inappropriate technologies, and metal recycling in which the functionality (ie. the physical and chemical properties) of the EOL metal is lost (Graedel et al, 2011).

The lifetime of a metal product depends on the nature of the product, and some typical lifetimes for various products are given in Table 5. Product lifetimes also differ widely from country to country (Eckelman and Daigo, 2008). The quantity of a metal available for recycle is not the current level of consumption of that metal, but the sum of the consumption of the metal one product life cycle ago for each of the end-use categories. The long lifetimes for many metal products, together with high growth rates in metal demand in the past has resulted in available old scrap quantities that are typically much smaller than the metal demand in production, leading to recycled contents much smaller than 100% (Gradel et al, 2011). The relatively short lifetime of steel associated with vehicles and consumer goods compared with the structural steel associated with building and construction explains why the former makes up a significant proportion of obselete scrap feedstock for recycling (Brooks and Pan, 2004).

3.2 Maximum recycling rates

In carrying out the calculations for plotting Figures 6 and 7 it was assumed that the GER for recovering, transporting, processing and melting the recycled metal remained essentially constant (at the nominally assumed value of 9 MJ/kg metal) irrespective of the recycling rate. However, the law of diminishing returns dictates that the closer the recovery of the scrap metal approaches 100%, the greater becomes the energy required for each increment of improvement in recovery. This is not unexpected, as metal that is widely dissipated (both in terms of distance and mass) will require more energy to recover and recycle than metal which is not dissipated extensively. This means that the assumption of constant recycling energy made in plotting Figures 6 and 7 is not strictly valid, particularly at high recycling rates. It also means that a 100% recycling rate is essentially impossible, a view supported by Reuter et al (2006) based on thermodynamic considerations. This effect of increasing recycling rates on the GER for recycling can be illustrated by using the data in Tables 2-4 together with the following assumptions[3]:

- a combined collection and recovery rate (see Figure 3) of 45% for a collection transport distance of 100 km, and 55% for a transport distance of 250 km;
- a recycling efficiency (see Figure 3) of 95% (Damgaard et al, 2009).

Figure 9 shows how the collection transport distance increases as the combined collection and recovery rate increases in accordance with the above assumptions. The recycling rate can be calculated from the above parameters by the following equation derived from Figure 3:

[3] Nominal collection plus recovery rates and collection transport distances assumed for illustrative purposes only.

Table 5. Typical lifetimes of various metal products.

Metal	Application	Average lifetime(years)	Reference
Steel	Building & construction	60	Davis et al (2007)
		30	Matsuno et al (2007)
		20-60	Brooks & Pan (2004)
	Machines	30	Brooks & Pan (2004)
		12	Matsuno et al (2007)
	Vehicles	5-15	Brooks & Pan (2004)
		13	Matsuno et al (2007)
	Containers	1	Matsuno et al (2007)
		1	Davis et al (2007)
		<1	Brooks & Pan (2004)
	Consumables	7-15	Brooks & Pan (2004
	Other products	12	Matsuno et al (2007)
Copper	Building & construction	38	Eckelman & Daigo (2008)
	Transportation	15	Eckelman & Daigo (2008)
		10	Norgate et al (2009)
	Consumables	11	Eckelman & Daigo (2008)
	Machinery	22	Eckelman & Daigo (2008)
	Vehicle	12	Ruhrberg (2006)
	Transformers	20	Ruhrberg (2006)
	Electronic components	10	Ruhrberg (2006)
	Household appliances	15	Ruhrberg (2006)
	Power lines	30	Ruhrberg (2006)
	Housing	35	Norgate et al (2009)
Aluminium	Building & construction	40	Norgate et al (2009)
	Consumables	12-15	Norgate et al (2009)
	Electrical	35	Norgate et al (2009)
	Machinery & equipment	20-25	Norgate et al (2009)
	Containers & packaging	0.25-1	Norgate et al (2009)
Zinc	Dry batteries	1	Norgate et al (2009)
	Building & plumbing	25	Norgate et al (2009)

Recycling rate (%) = Collection rate (%) x Recovery rate (%)/100 x Recycling efficiency (%)/100
= D/(C+D) x 100 x (F/D) x (G/F)
= G/(C+D) x 100
= 45 x 95/100 = 42.8% at a collection transport distance of 100 km.

and = 55 x 95/100 = 52.3% at a collection transport distance of 250 km

For a given combined collection and recovery rate, the corresponding recycling rate can be calculated along with the collection distance (using equation shown in Figure 9) and the energy consumption for collection and recovery by the equation given in Table 6. Using steel as an example, the energy consumption for the other recycling stages is given in Table 6 (taken from Tables 2-4). Figure 10 shows the results of these calculations in terms of GER for recycling versus recycling rate. This figure shows that there is a maximum recycling rate, beyond which the energy consumed in recycling steel exceeds the energy consumed in producing primary steel metal. Steel recycling becomes unsustainable in embodied energy terms beyond this point. The maximum recycling rate shown in Figure 10 is about 91% but this is for an arbitrary recycling system based on the assumptions outlined above. Each particular recycling scenario (eg. metal, product

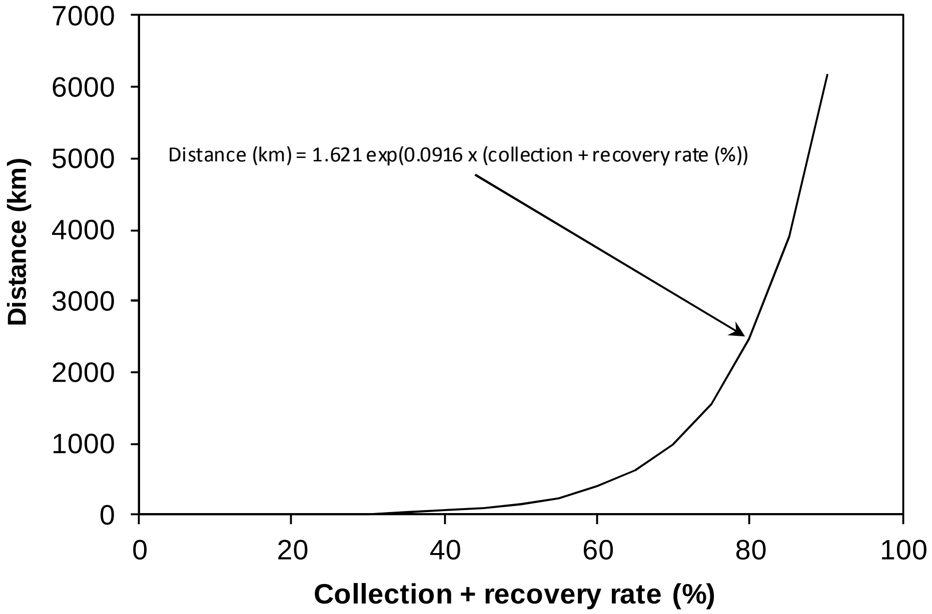


Figure 9. Collection transport distance versus combined collection and recovery rate.

nature, geographical location, etc.) will have its own maximum recycling rate. It could be expected that, all other things being equal, the maximum recycling rate would be greatest for those metals having the highest embodied energy values for primary metal production, eg. aluminium.

Table 6. Energy consumption for steel recycling.

Recycling stage	Energy consumption
Collection & recovery	4.1 + 0.045 x distance (km) L/t (diesel)[1]
Sorting	32.5 kWh/t (electricity) 0.33 GJ/t (thermal)[2]
Shredding	50 kWh/t (electricity) 0.51 GJ/t (thermal)[2]
Melting & refining	1.8 GJ/t
Total (excluding collection & recovery)	2.6 GJ/t

1. Calorific value of diesel = 38.6E-3 GJ/L.
2. Thermal energy based on black coal at 35% generation efficiency.

The observations made above highlight the need for policy makers to take a life cycle approach when formulating recycling regulations in order to avoid inappropriate policies being established. For example, the European Union introduced legislation imposing very strict rules on recycling of post-consumer goods, including end-of-live vehicles (ELV). The ELV directive (Directive 2000/53/EC) enacted in 2002 requires member states to achieve very tight recycling/recovery targets of 85% by January 2006 and 95% by January 2015 (Millet et al, 2012). However, Reuter et al (2006) and Ignatenko et al (2008) point out that setting such recycling rate targets is inappropriate and the focus should instead be on a less recycling rate driven system for ELV treatment.

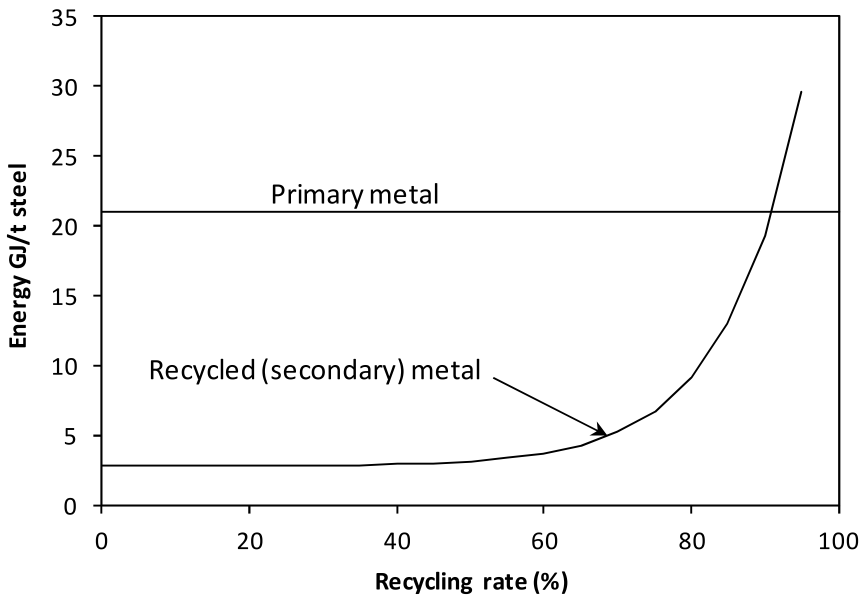


Figure 10. Effect of recycling rate on the GER for steel recycling.

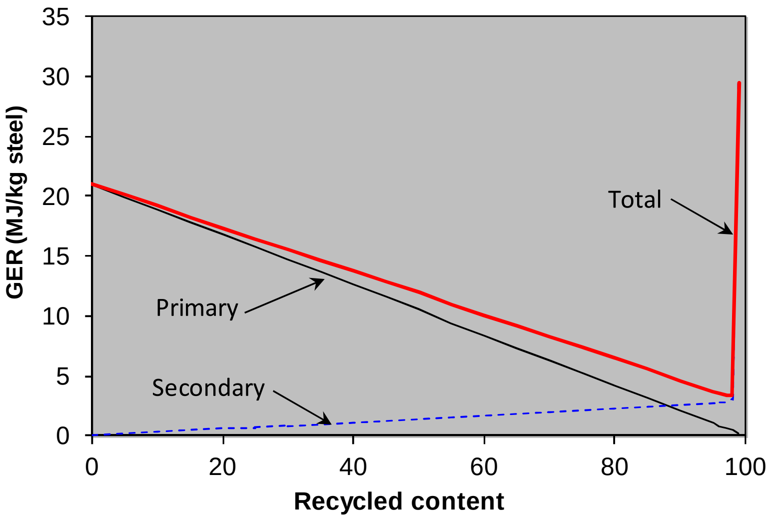
3.3 Optimum recycled contents

The observation made in the preceding section with regard to maximum recycling rates, means that it is likely that there will be an optimum (in terms of embodied energy) recycled content for a given product system depending on the recycling rate needed to give the quantity of secondary metal required to achieve the target recycled content of the product. This can be illustrated using the results shown in Figure 10 for recycled steel and is shown in Figure 11 for various scrap to primary metal ratios. When there is a large amount of scrap available compared to the amount of primary metal, relatively high recycled contents can be achieved with relatively low recycling rates, and the optimum recycled content in this case is quite high as shown in Figure 10a. However, as the amount of scrap available compared to the amount of primary metal falls, higher and higher recycling rates are required to produce the amount of secondary metal required to achieve the target recycled content of the product. This is shown in Figures 10b and 10c. Quinkertz et al (2001) suggested that curves such as those shown in Figure 10, go to infinity as the recycled content approaches 100%.

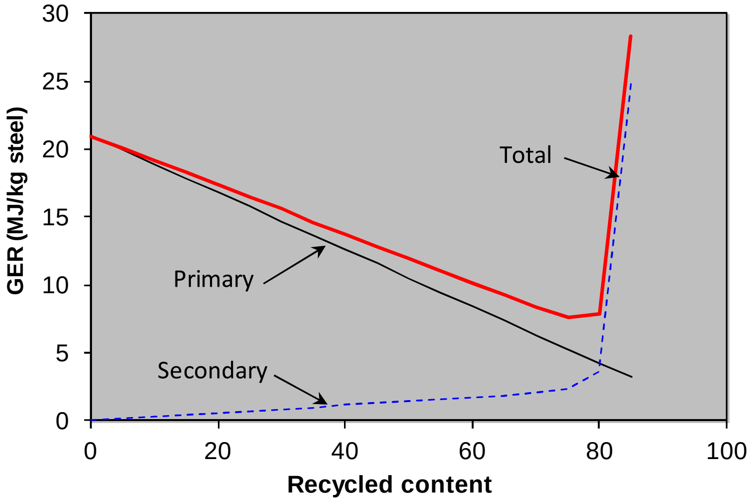
Optimum recycled contents have been reported in the literature for various recycling scenarios. Schenk et al (2004) estimated an optimum recycled content of 81% and 93% for paper recycling based on mechanical and chemical pulp respectively. Quinkertz et al (2001) estimated an optimum recycled content of 79% for light-weight aluminium packaging material in Germany. All of the above optimum recycled contents are based on minimising embodied energy, however, economic issues will also influence minimum recycled contents in practice.

3.4 Metal quality

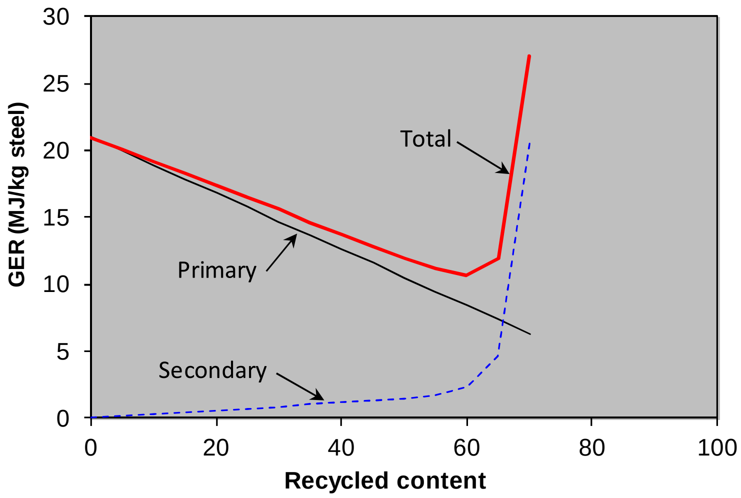
Commercial recycling systems never create pure material streams as they never achieve 100% material recovery during physical separation (dictated by separation physics) nor achieve 100% material recovery during high temperature metal production (dictated by thermodynamics) (Reuter et al, 2006). Therefore recycled materials always contain some degree of contamination, and this issue is of considerable importance in metal recycling. Contaminants such as copper in steel and iron and silicon in aluminium, are those elements that are more “noble” than the host metal and, hence, are very difficult (and expensive) to remove. Present strategies include better sorting of metals prior to remelting, diluting contaminants by addition of primary metal and using recycled metal for lower grade applications (eg. wrought products in



(a) Scrap metal/primary metal = 104



(b) Scrap metal/primary metal = 6.0



(c) Scrap metal/primary metal = 2.5

Figure 11. Effect of recycling content on the GER for steel recycling.

the case of aluminium). In the longer term, however, these strategies will need to be supplemented by the development of effective refining processes for removing contaminants. While this will presumably increase the total energy consumption of secondary metal production, it is likely to still compare favourably with primary metal production. The issue of contaminants in alumium recycling is discussed by Kevorkijan, 2010; Nakajima et al, 2010 and Peterson, 2003.

Reuter et al (2003) and Castro et al (2004) point out that the development of products (consumer goods) brings together metals that are not linked in natural resources, and as a consequence, many of these materials are not completely compatible with current processes in the metals production network. The formation of complex residue streams or undesired harmful emissions then inhibits processing and recovery of such products at their end-of-life. These authors proposed a thermodynamics-based model for the evaluation and selection of materials combinations regarding their compatibility for metallurgical recycling. The implementation of such an approach could be expected to help alleviate metal quality issues in the recycling of metals. Castro et al (2004) developed a decision tree model and a matrix was constructed for several metal and material combinations that might occur in industrial products which is shown in Figure 12. The objective of the decision tree model is to determine whether a given material combination should be avoided or mechanically separated before metallurgical processing, or can be left together because the metallurgical processing is able to handle it. Product designers taking a DFR approach can use this matrix to readily choose compatible materials combinations which will minimise recycling losses and contaminations, thereby increasing the resource efficiency of product systems. While lightweight metals are increasingly being used in products, the matrix in Figure 12 indicates that their combination with other materials should be carefully considered, as they are very sensitive to contaminations.

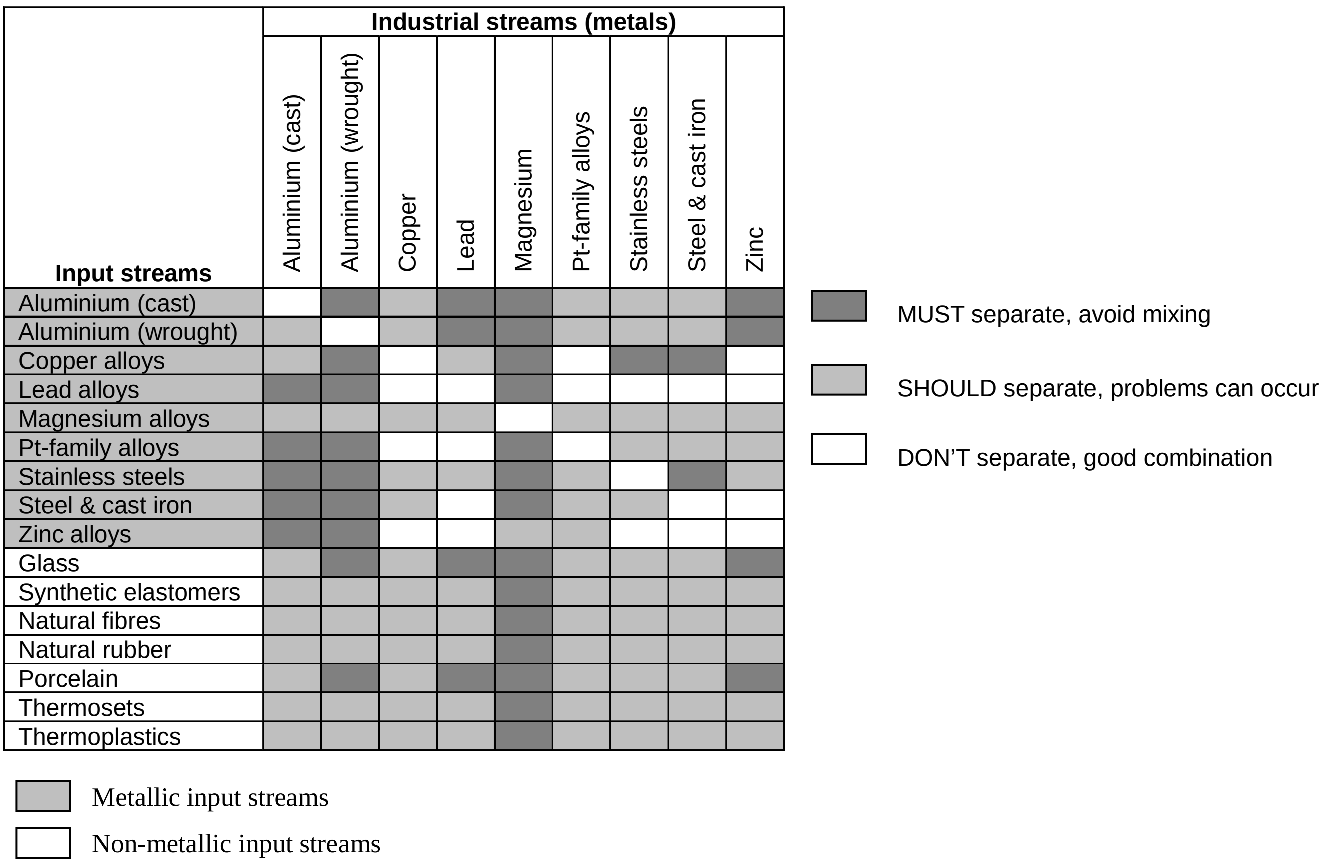


Figure 12. Material combination matrix (Castro et al (2004)).

3.5 Optimisation of metal recycling

According to Reuter et al (2004), the optimisation of the recycling of modern consumer products is only possible with a detailed understanding of the total recycling system as a dynamic feedback system and the use of fundamental theoretical models. Recycling design tools, including models and simulation, are described in UNEP (2013, p. 243). The application of such models to the recycling of end-of-life vehicles and E-waste (waste electric and electronic equipment) has been described by Reuter et al (2006) and van Schaik and Reuter (2010) respectively. Product design must be linked to these fundamental recycling models in order to integrate thermodynamics into product design to determine the ultimate destination and recyclability of all the elements in a product. As pointed out by Reuter and van Schiak (2008), the design engineer is the person who creates the "mineralogy" of end-of-life recyclates. This recognition of the importance of product design in optimising recycling systems has led to the concept of design for recycling (DFR) that is increasingly being included in recycling policy and regulations. The main principles of DFR are:

- use recyclable materials
- use recycled materials
- reduce the number of different materials used within an assembly
- mark parts for simple material identification
- use compatible materials within an assembly
- make it easy to disassemble
- avoid the use of toxic materials.

However, as pointed out in the UNEP (2013) report, DFR as outlined above focuses entirely on the recyclability of a product and disregards, for example, energy-efficiency considerations. These considerations and others are crucial to the Design for Sustainability approach, which requires product designers to take a life cycle perspective with regard to material selection.

Some other approaches that will also improve the sustainability of metal recycling are the development of new separation processes and linking these together in the correct manner, and the optimisation of scrap processing metallurgy, eg. computational fluid dynamic modelling of aluminium recycling furnaces (Reuter et al, 2004), and technology improvements in electric arc furnace steelmaking and ladle metallurgy (Brooks and Pan, 2004).

4 Metal recycling in Australia

In 2008-2009 the total quantity of metal waste generated in Australia was 4,649,100 tonnes, of which 4,122,100 tonnes was reprocessed into recycled materials (Hyder Consulting, 2011), representing a recycling rate of 89%, which was the highest recycling rate for any material type examined in the study by Hyder Consulting. Brulliard et al (2012) reported corresponding values of 5,001,300 tonnes and 4,512,700 tonnes respectively (90% recycling rate) supposedly based on the Hyder Consulting report. The state-by-state breakdown of the quantities of metal waste generated and metal recycled from the Hyder Consulting report is shown in Figure 13, while the corresponding recycling rates are shown in Figure 14. Further breakdown of the state-by-state quantities of metal recycled into steel, aluminium and other non-ferrous categories is shown in Figures 15-18.

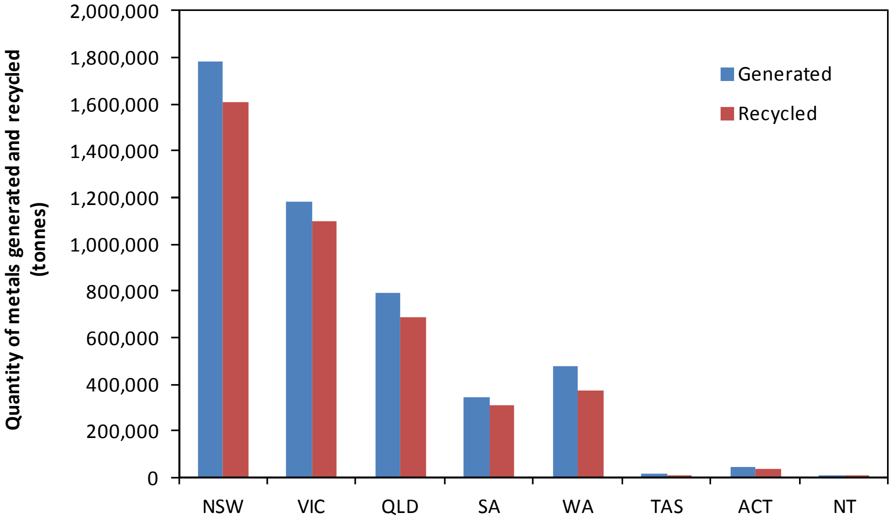


Figure 13. Quantities of metal waste generated and metal recycled in Australia, 2008-2009 (Hyder Consulting, 2011).

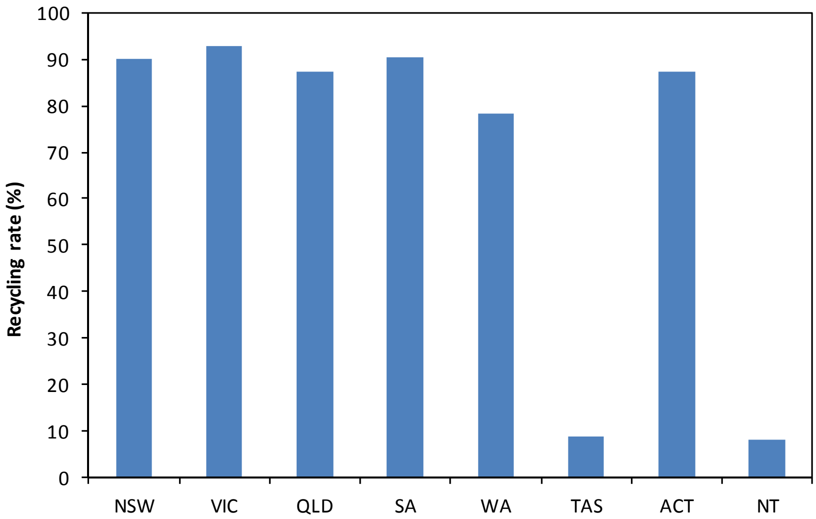


Figure 14. Metal recycling rates in Australia, 2008-2009 (Hyder Consulting, 2011).

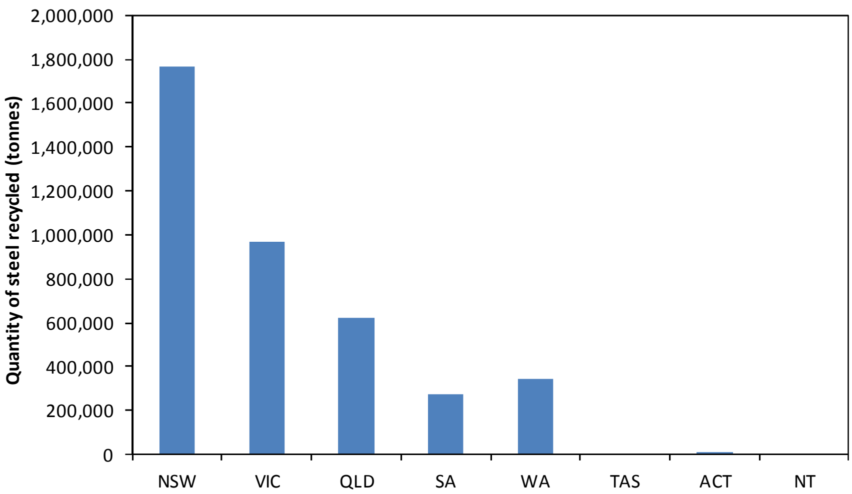


Figure 15. Quantity of steel in metal recycled in Australia, 2008-2009 (Brulliard et al, 2012).

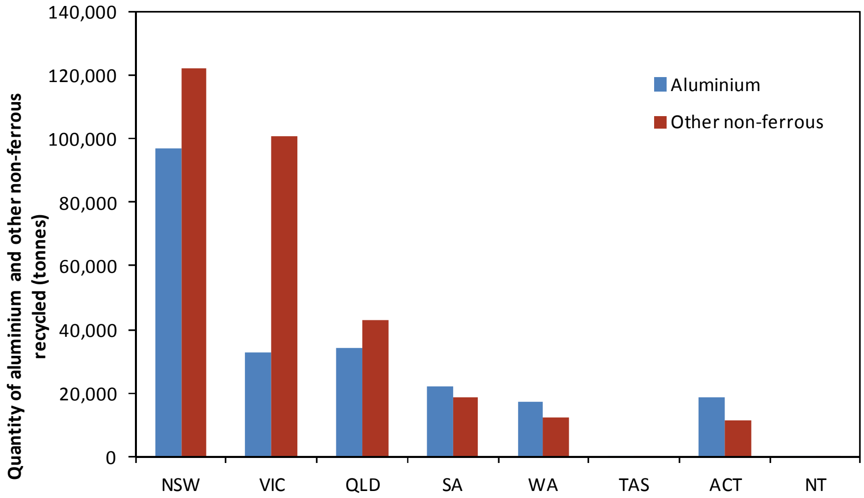


Figure 16. Quantity of aluminium and other non-ferrous metals in metal recycled in Australia, 2008-2009 (Brulliard et al, 2012).

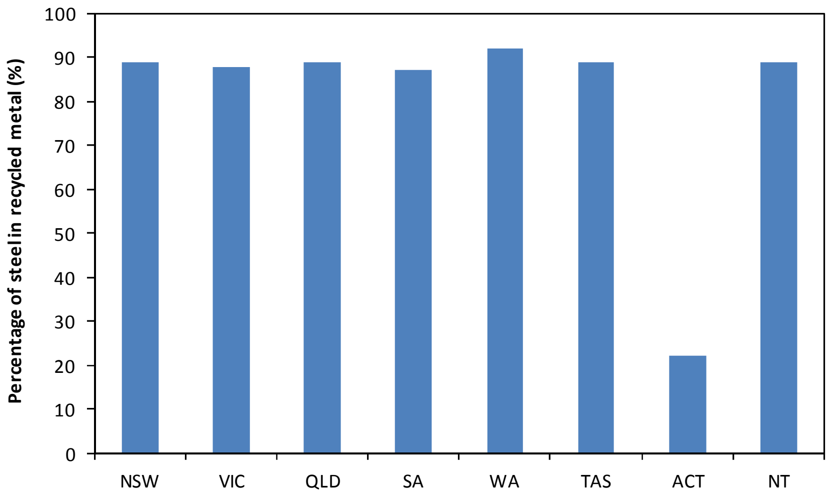


Figure 17. Percentage of steel in metal recycled in Australia, 2008-2009 (Brulliard et al, 2012).

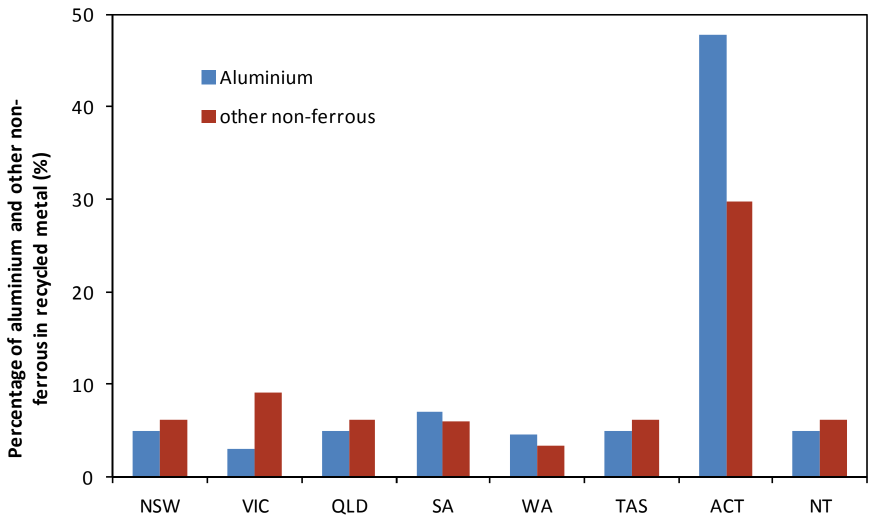


Figure 18. Percentage of aluminium and other non-ferrous metals in metal recycled in Australia, 2008-2009 (Brulliard et al, 2012).

5 Life cycle assessment of metal recycling

While metals are theoretically infinitely recyclable due to their elemental nature (unlike molecular-based materials such as plastics), this is not the case in practice. Leaks from the metal stocks in society occur through corrosion, wear and dispersive uses, or via landfilling or similar activities that return metals to the earth. In order to provide a technically sound and transparent assessment of metal recycling, a methodology such as Life Cycle Assessment (LCA) should be used. By taking a life cycle perspective, the beneficial recycling properties of metals can be evaluated in a manner that enables appropriate comparisons with other materials or product systems that do not have recycling loops. In practice, mixtures of primary and secondary metals are often used in new products, and also at the end-of-life stage various processing methods are used, as outlined earlier. The difficulty of introducing recycling into LCA is to set the right boundaries for the different flows ending in different product systems. Which observed material flow belongs to the first product system and which one to the second or subsequent systems. Recycling is part of any product LCA, however it is often a complex issue which requires specific considerations.

However, as pointed out by Yellishetty et al (2011) and Birat et al (2006), LCA practitioners are left with much freedom in allocation of environmental burdens to account for reycling, thus making subjective judgements on recycling and allocation of credits to recycling. This often makes it difficult to compare the results of LCA studies conducted by two different practitioners even on the same processes. As LCA is often used to define policy in government, business and society circles, it should be based on a sound, objective and unbiased description of recycling.

5.1 Recycled content versus an end-of-life recycling approach

Two approaches or viewpoints for assessing the benefits of recycling are commonly used in LCA practice:

- recycled content approach (also known as the cutoff approach) – the amount of recycled material used in a product should be accounted for
- end-of-life recycling approach (also known as the avoided burden approach) – the amount of used material which is collected and recycled should be accounted for.

Their usefulness and appropriateness have been discussed widely in the literature, eg. Dubreuil et al (2010), Frischknecht (2010), Frees (2008), Atherton (2007). The recycled content approach considers the share of recycled material (metal) in the manufacture of a product. The environmental impacts of extraction, beneficiation and refining of primary metal are attributed to the first use of that metal product. The second use of the metal bears the environmental impacts of collection, beneficiation and refining of scrap. Secondary metals do not bear any environmental load from the primary metal production activities. Figure 19 shows how the cut-off approach would be applied over the life cycle stages. More specifically, Figure 20 compares the results of applying this approach to the GER of copper recycling with the theoretical result in this figure derived similarly for aluminium and steel (100% recycled content) in Figures 6 and 7 respectively.The recycled content approach is commonly used in environmental labelling, and focuses on material feedstock sourcing, providing an incentive towards waste diversion (Dubreuil et al (2010), Frischknecht (2010)).

The end-of-life recycling approach focuses on considering the whole lifecycle of the product including its end disposition. This method is based on the premise that materials not recycled need to be replaced by primary materials (metals). The metal input to the product under analysis always bears the environmental impacts of primary metal production, irrespective of whether or not secondary metal is used in the product. The specific origin of input material (whether primary or recycled) is not relevant because it is the net conservation of material that typically minimises total environmental impacts (Atherton, 2007). Another way of thinking about this method is in terms of system expansion where the boundary of the study is extended to include another product system. Where a metal is recycled at the end of life the

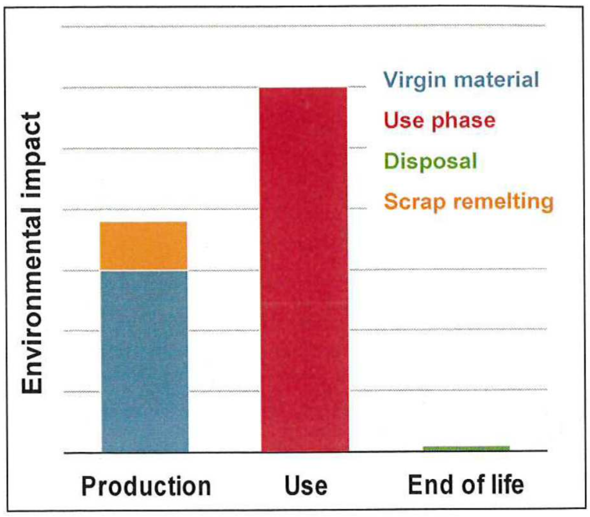


Figure 19. Cut-off approach for a product system that uses both primary and secondary metal inputs (WSA (2011)).

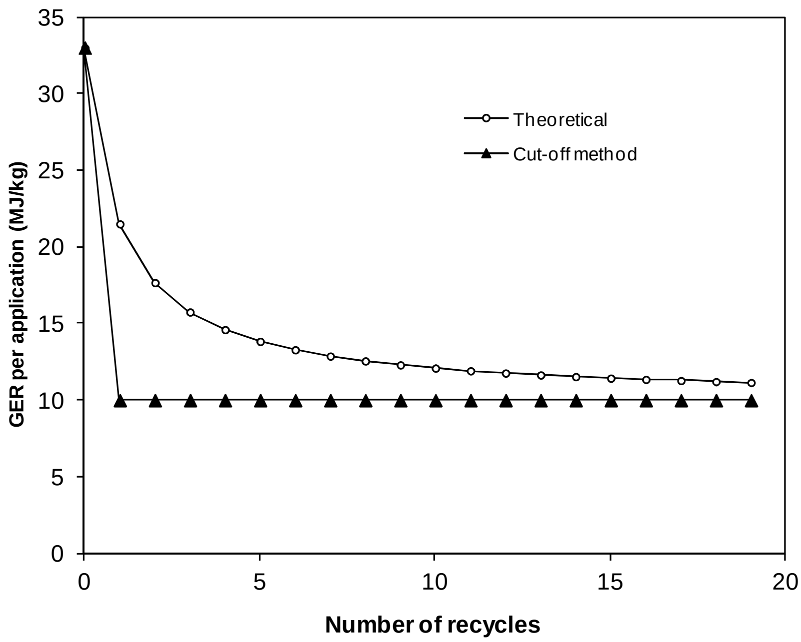


Figure 20. Copper GER showing cut-off approach versus theoretical (Norgate (2004)).

product system is credited with an avoided burden based on the reduced requirement for virgin (primary) metal production in the next life cycle. Figure 21 shows how the end-of-life approach would be applied over the life cycle stages.

The metals industry strongly supports the end-of-life recycling approach (Atherton (2007), Dubreuil et al (2010)) over the recycled content approach for the purposes of environmental modelling, decision-making and policy discussions involving recycling of metals. The weakness of the recycled content approach arises from the fact that the recycled content of a product does not tell anything about the degree to which the product is recycled after use. Frischknecht (2010) points out that neither approach is more scientifically correct than the other, and that LCA practitioners need to decide on the most appropriate approach for any particular LCA based on relevant selection criteria (eg. sustainability concept, risk perception and eco-efficiency – see Table 7). This author also suggests that national authorities may have a rather long-term and risk-averse perspective, whilst industries may prefer a short-term perspective leading them to select the recycled content and end-of-life recycling approach respectively.

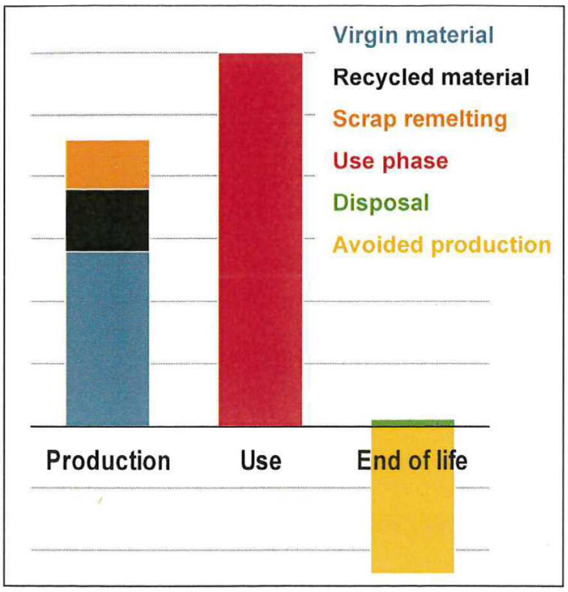


Figure 21. End-of-life approach for a product system that uses both primary and secondary metal inputs (WSA (2011)).

Table 7. Synopsis of characteristics of the two modelling approaches of recycling (Frischknecht, 2010)

	"End-of-life" recycling or 'avoided burden"	"Recycled content" or "cutoff"
Future utility	Yes	Uncertain
Sustainability concept	Weak	Strong
Environmental grants from future generations	Yes	No
Shift of burdens into future	Yes	No
Risk perception	Risk seeking	Risk averse
Eco-efficiency primary versus secondary metal	Primary > secondary	Secondar . primary

5.2 Closed-loop and open-loop recycling

A distinction is made between closed-loop recycling and open-loop recycling for including end-of-life recycling in LCA. A closed-loop recycling product system occurs when the materials associated with a product are recycled and used again in the same product at the same level of material quality, ie. the inherent properties are maintained by closed-loop recycling. The recycling of post-consumer aluminium can scrap to make new aluminium cans is an example of a closed-loop recycling system. Closed-loop recycling also applies when a material is recycled in another product system where its inherent properties are maintained. For example, scrap nickel turbine blades can be blended with carbon steel scrap to make stainless steel, thereby displacing the need to make primary nickel (Dubreuil, et al, 2010). This type of recycling system has also been referred to as semi closed-loop recycling (Ligthart and Ansems, 2012). As the inherent properties of the recycled metal are retained it can replace primary metal and therefore, according to ISO 14044 (see next section) there is no need for allocation.

An open-loop recycling product system occurs when the materials associated with a product are recycled to a different product system and the material has undergone a change in its inherent properties. Recycling of metals can generally be categorised as closed-loop recycling. By characterising the recycling of metals as closed-loop, the environmental burdens associated with the primary production of metals can be allocated over the many useful "lives" of the metal (IZA, 2007). The various recycling systems are shown in Figure 22.

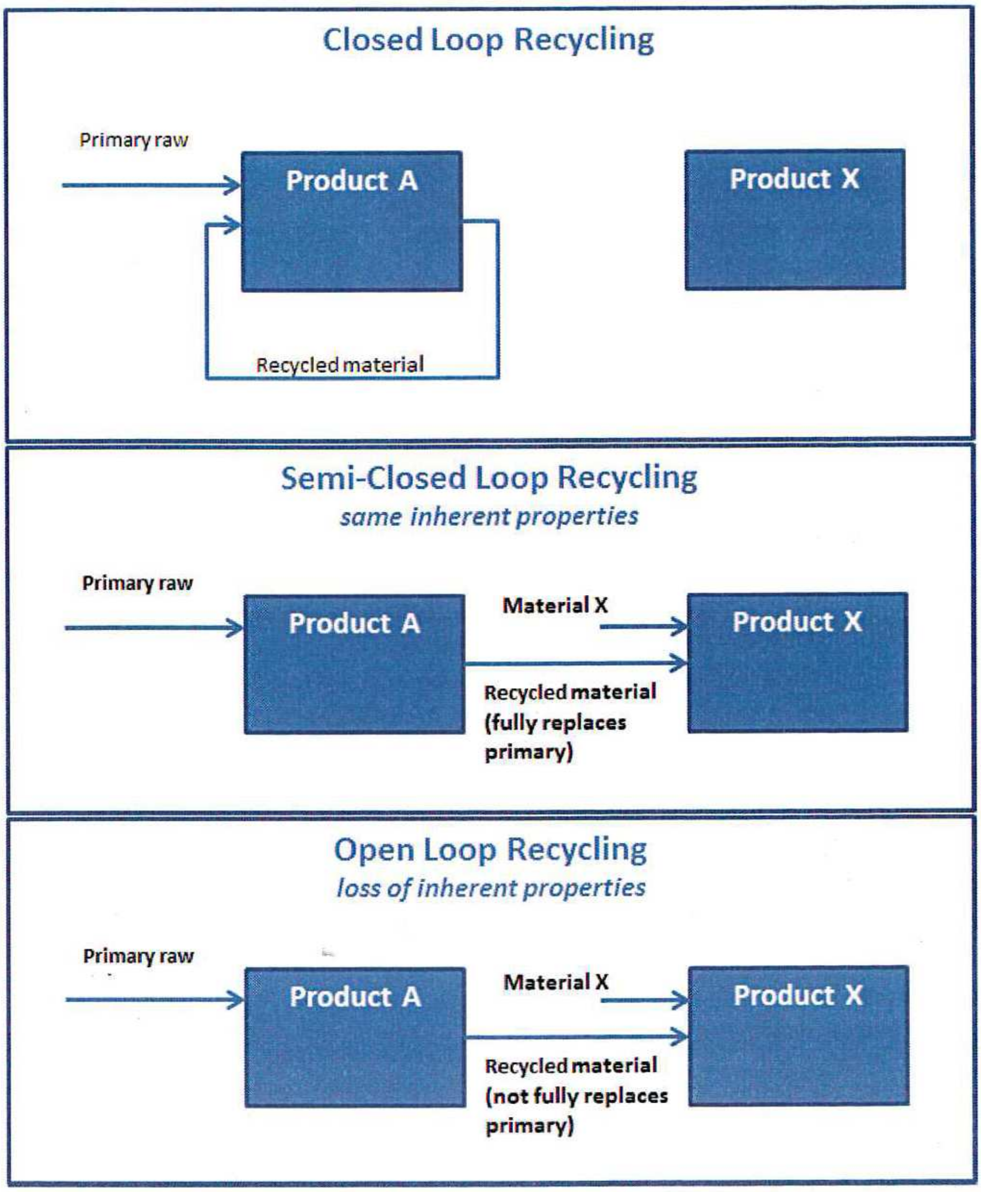


Figure 22. Recycling schemes (Ligthart and Ansems (2012)).

5.3 Allocation

The life cycle assessment standard, ISO 14044 (2006), Section 4.3.4.3 provides guidance on allocation procedures for re-use and recycling with the underlying principle that allocation should be avoided wherever possible. However, where allocation is unavoidable, allocation procedures are based on the closed-loop and open-loop recycling concepts outlined above as shown in Figure 23. Section 4.3.4.3.4 of this standard states that these procedures should use the following as the basis of allocation, where feasible, in the order shown:

- physical properties (eg. mass)
- economic value (eg. market value of the scrap metal or recycled metal in relation to market value of primary metal)
- the number of subsequent uses of the recycled metal.

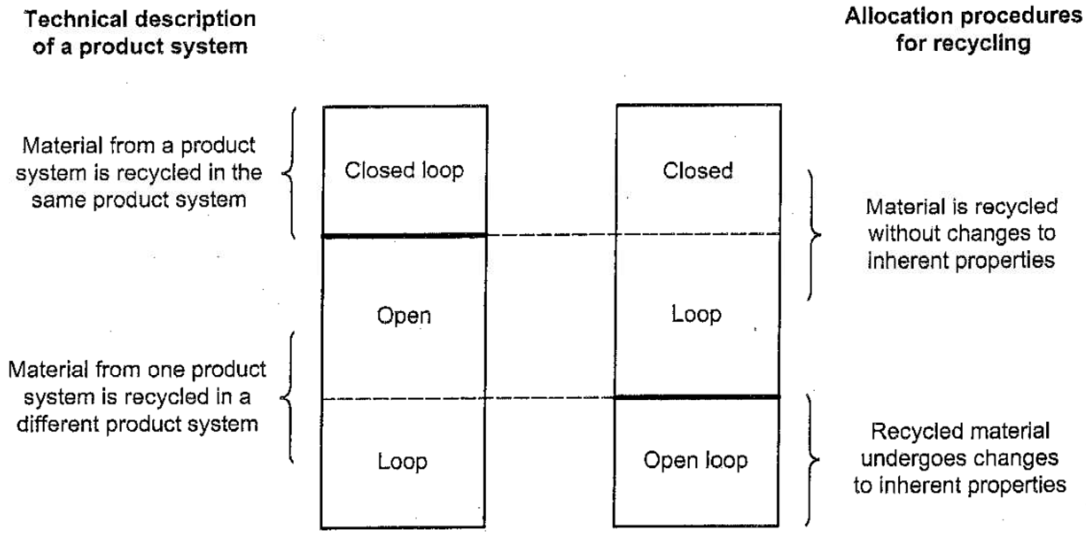


Figure 23. Allocation procedures for recycling (ISO 14044 (2006)).

Given that steel is the world's most used and recycled metal, the World Steel Association has provided a few guidelines to assist LCA practitioners conducting studies involving metals, particularly when recycling of the metal is involved (WSA, 2011). The WSA methodology follows the end-of-life approach using closed-loop recycling. Birat et al (2005) presented a review of several methods for allocating environmental impacts to account for recycling, and these methods were further discussed by Yellishetty et al (2011). Three of these methods (models) based on the above approach are compared in Table 8.

Table 8. Different models for incorporating metal recycling into LCA methodology (Birat et al (2005), Yellishetty et al (2011)).

Model	Model description	Empirical formula	comments
A	Credits for recycling	$X = X_{primary} - (X_{primary} - X_{recycled}) \cdot rY$	Commonly used by LCA practitioners to account for recycling and assumes that if recycling is perfect (100%) then the primary route becomes equal to the recycled route.
B	One-step recycling	$X = X_{primary} + X_{recycled} \cdot rY/(1 + rY)$	Gives due credit to recycling and recognises the fact that impact is lower when recycling is higher. It takes a more pragmatic approach to mimic the real-life situation of recycling.
C	Multi-step recycling	$X^n = X_{primary}(1 - rY) + X_{recycled}(rY\text{-}(rY)^{n+1})/(1 + (rY)^{n+1})$	This model takes into account that metals (eg. steel) are recycled several times.

Note: X = environmental impact
r = recycling rate
Y = ratio of metal to scrap yield (ie. >1 kg scrap is required to produce 1 kg steel when recycling in the EAF)
n = number of recycling cycle

With model A, the value of the environmental impact allocated to scrap is equal to the credit associated with the avoided primary production of steel (assuming 0% scrap input) minus the burden associated with the recycling of steel scrap to make new steel, multiplied by the yield of this process to consider losses in the process. Thus this value is equal to $(X_{primary} - X_{recycled}) \cdot Y$ in the equation for model A in Table 8. Figures 24 and 25 show the Global Warming Potential (GWP, in kg CO_2e/t steel) and GER as a function of recycling rate based on model A using the following values:

$GWP_{primary}$ = 2170 kg CO_2e/t steel – integrated route (Norgate et al, 2012; Norgate and Langberg, 2009)[4]

[4] Birat et al (2005) reported values of 2100 and 600 kg CO_2e/t steel for primary steel (integrated route) and recycled steel (EAF route) respectively.

$GWP_{recycled}$ = 510 kg CO_2e/t steel – EAF route (Norgate et al, 2012; Norgate and Langberg, 2009)
$GER_{primary}$ = 21.0 GJ/t steel – integrated route (Norgate and Langberg, 2009)
$GER_{recycled}$ = 4.8 GJ/t steel – EAF route (Norgate and Langberg, 2009)
Y = 0.916 (WSA, 2011, page 78)

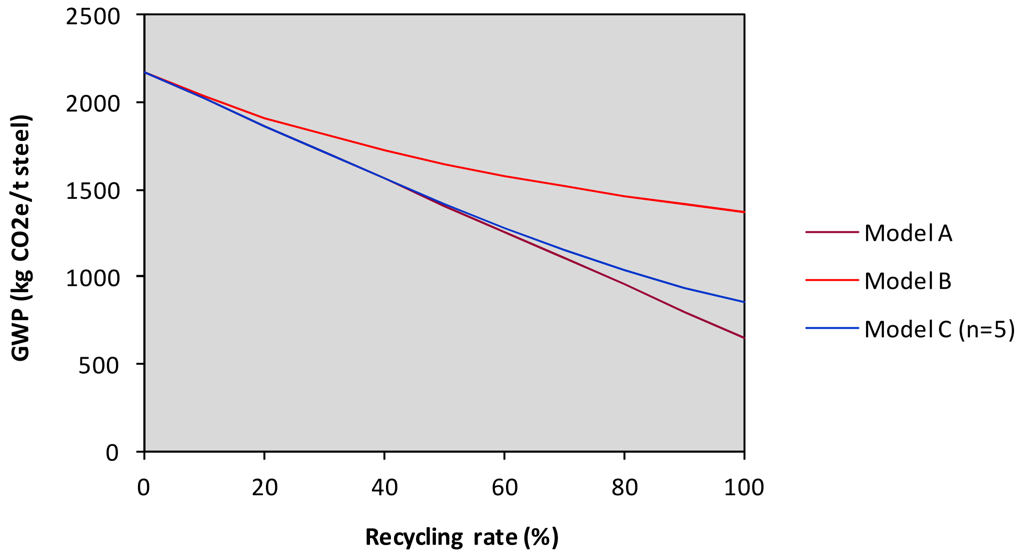


Figure 24. GWP for steel recycling based on different allocation methods.

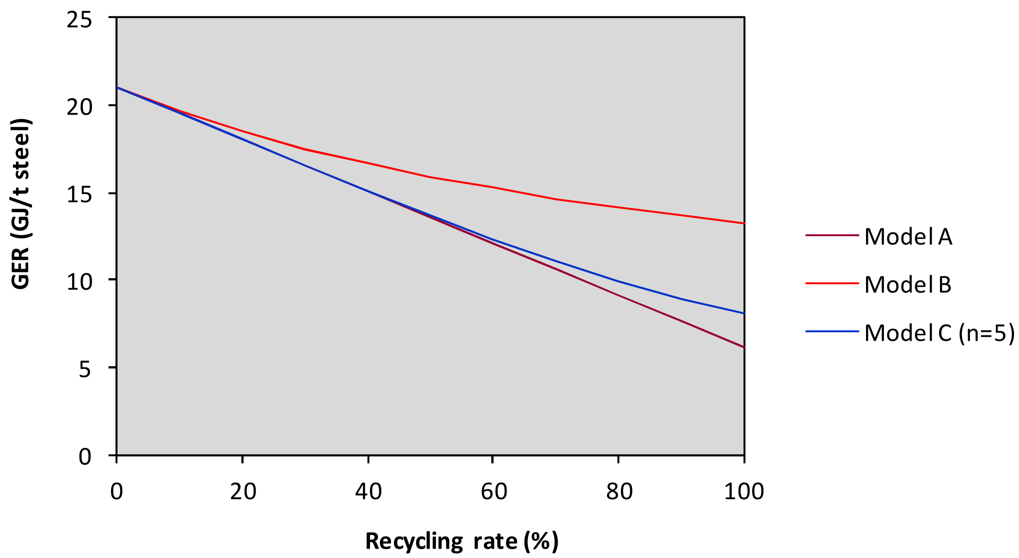


Figure 25. GER for steel recycling based on different allocation methods.

Method A is commonly used in many LCA studies to account for recycling. However, if recycling is perfect (r = 100%) and the yield (Y) is unity, then the primary (integrated) route ends up being equal to the recycled EAF scrap route. Thus this method is very favourable to the primary route because it brings its environmental impact down to the level of the recycled route. In effect, it ignores the fact that the primary (integrated route) emissions have already taken place because it is subtracting a virtual credit from actual physical emissions (Birat et al, 2005). Models B and C seek to overcome this problem by applying a correction to share the benefits of recycling between the two routes. Model B considers the simple case of recycling once, while model C considers multi-step recycling, ie. the metal (steel) is recycled several times. Contrary to model A, when recycling is perfect model with B, the environmental impact (GWP) is not equal to that of the EAF route but to an average between the integrated and EAF routes, because the primary integrated route impacts are not "forgotten" as is the case with model A. In the case of model C, when recycling is perfect, the equation in Table 8 becomes indeterminate , but it has a finite value for finite n values, and asymptotes towards $X_{recycled}$ as n approaches infinity. The GWP and GER results based on models B and C (5 recycles) are also shown in Figures 24 and 25 respectively. Birat et al (2005) and Yellishetty et al (2011) recommend the multi-step recycling method as the best way to introduce recycling into LCA methodology.

5.4 Case studies

There have been a considerable number of metal recycling LCA studies reported in the literature, with many of these studies focussing on steel and aluminium due to the relatively high recycling rates of these metals. In 2006, WRAP (Waste & Resources Action Programme) published a major research report based on an international review of 55 ‘state of the art’ LCAs on paper and cardboard, glass, plastics, aluminium, steel, wood and aggregates. In 2010 WRAP updated this report (WRAP, 2010) by reviewing over 200 recycling LCA studies published worldwide since 2006 to take into account the emergence of new waste management options and new waste streams. However, some materials – aluminium, steel, glass and aggregates – were excluded from the revised report as the results of the first study were not impacted by the new technologies. Most studies showed that recycling offers more environmental benefits and lower environmental impacts than other waste management options. In the case of steel and alumium, recycling was compared with incineration and landfilling, and the results in terms of greenhouse gas (GHG) reductions are shown in Figures 26 and 27 respectively.

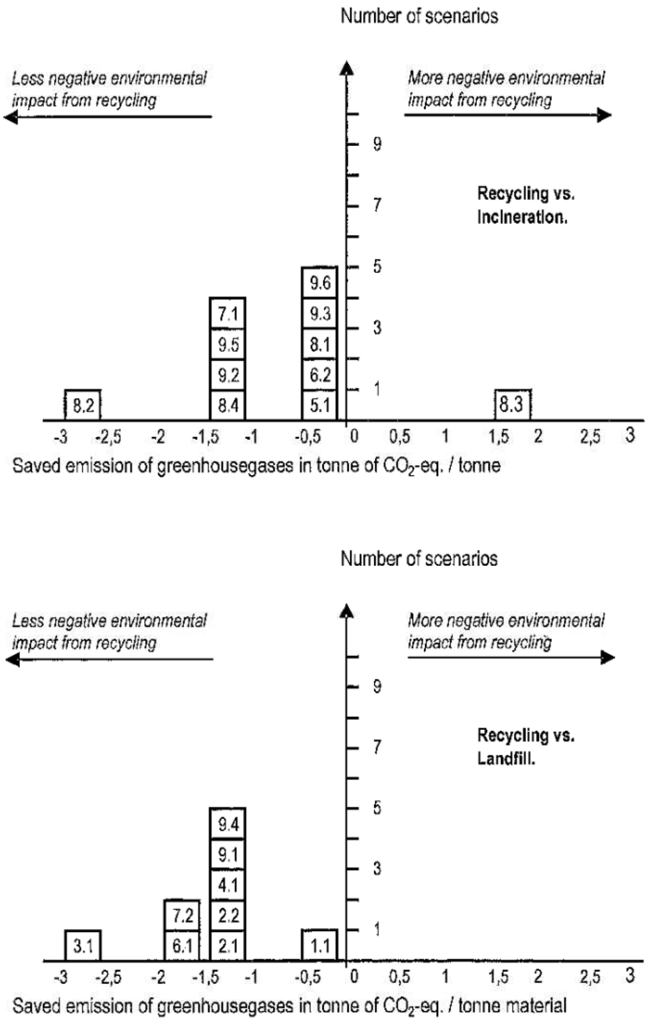


Figure 26. GHG savings from steel recycling (WRAP, 2010). Number in boxes refers to study/scenario number.

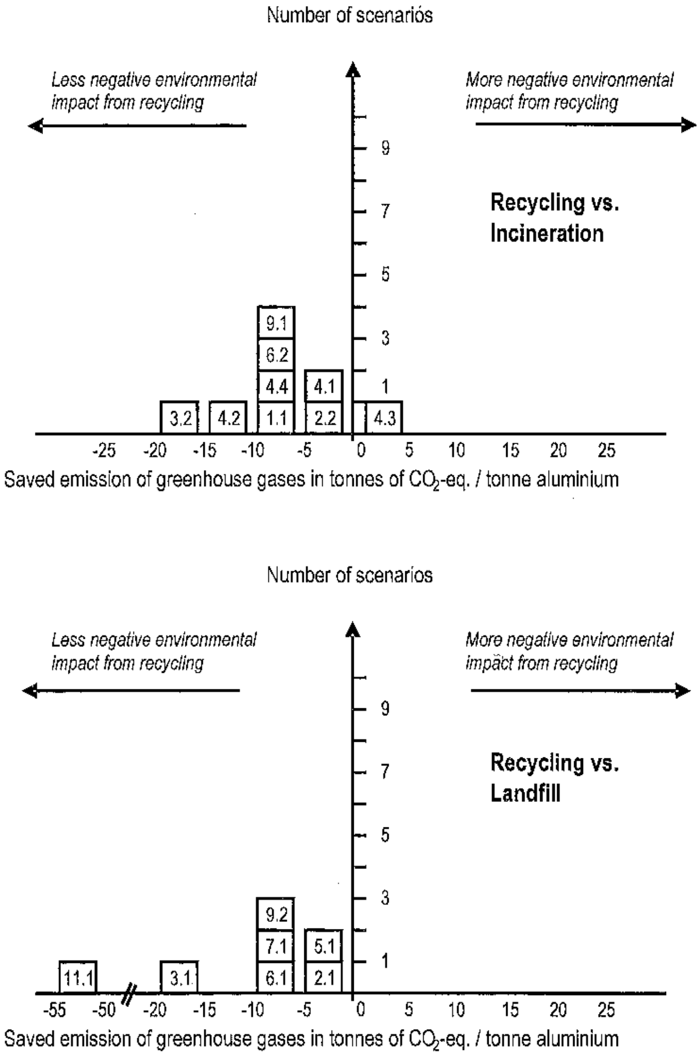


Figure 27. GHG savings from aluminium recycling (WRAP, 2010). Number in boxes refers to study/scenario number.

The average reduction in GHG emissions for recycling steel was 0.94 t CO_2e/t steel over incineration, and 1.33 t CO_2e/t steel over landfill. The corresponding values for recycling aluminium were 5-10 t CO_2e/t aluminium over incineration, and 5-10 t CO_2e/t aluminium over landfill. The full list of steel and aluminium LCA case studies reviewed is given in Appendix 1.

Brulliard et al (2012) also examined five LCA studies in which recycling was compared with landfill disposal, and the various environmental benefits of recycling over landfill were quantified. The results for greenhouse gas emissions and water are shown in Figures 28 and 29 respectively in terms of annual reductions or savings, while Figures 30 - 35 show the individual reductions per tonne of metal recycled. The average reduction in GHG emissions for recycling steel over landfill was 1.25 t CO_2e/t steel, similar to the WRAP result above. The value for recycling aluminium was 16.5 t CO_2e/t aluminium, copper 3.9 t CO_2e/t and mixed metal 5.4 t CO_2e/t. The corresponding water savings for recycling over landfill were 203 kL/t aluminium, 1.6 kL/t steel and 5.9 kL/t copper.

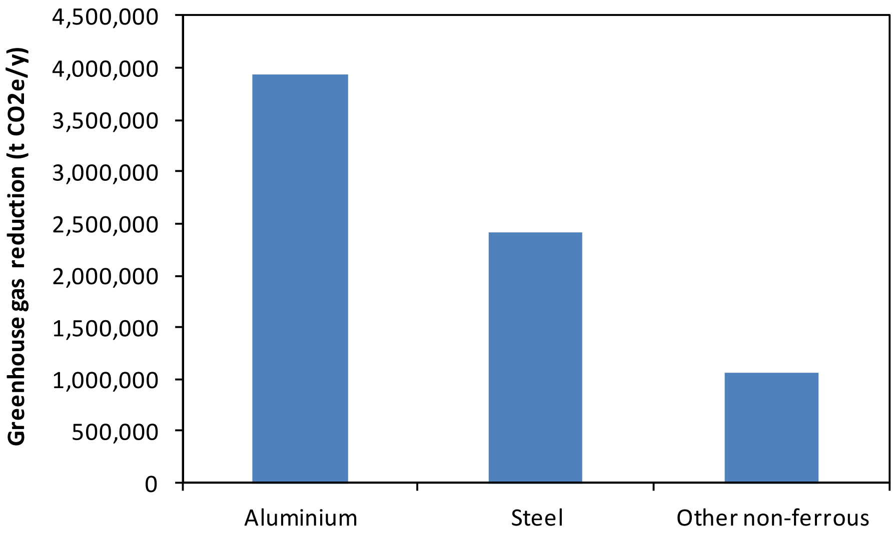


Figure 28. Annual GHG reductions for recycling over landfill in Australia, 2008-2009 (Brulliard et al, 2012).

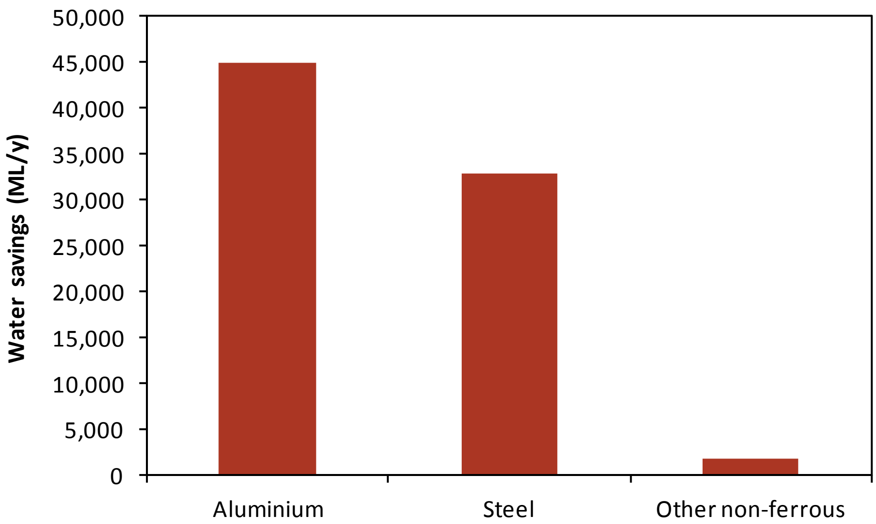


Figure 29. Annual water savings for recycling over landfill in Australia, 2008-2009 (Brulliard et al, 2012).

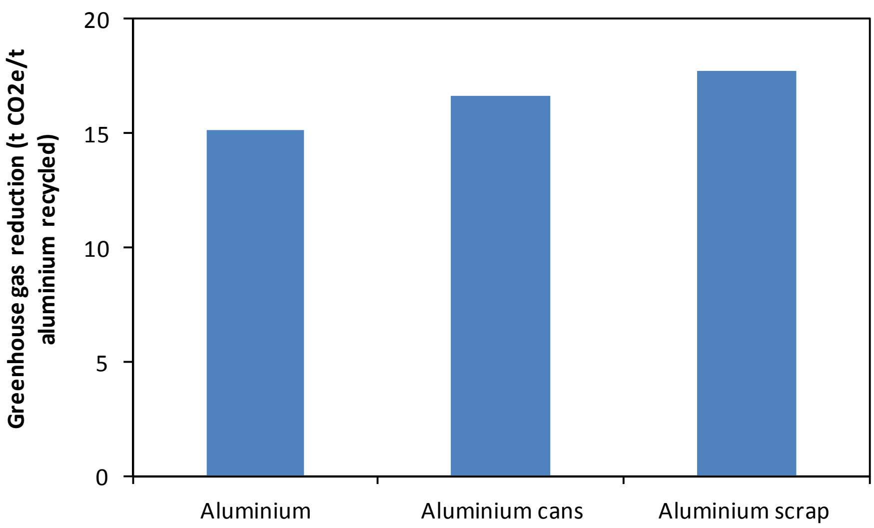


Figure 30. Specific GHG reductions for aluminium recycling over landfill in Australia, 2008-2009 (Brulliard et al, 2012).

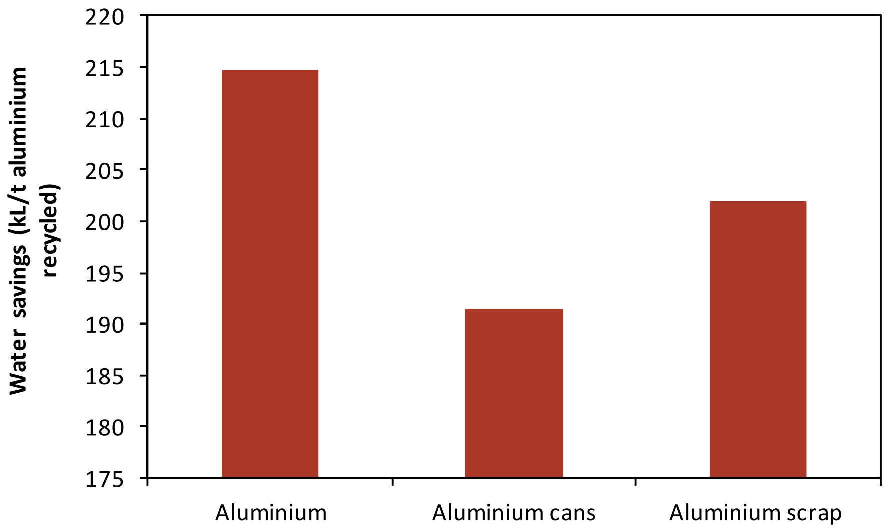


Figure 31. Specific water savings for aluminium recycling over landfill in Australia, 2008-2009 (Brulliard et al, 2012).

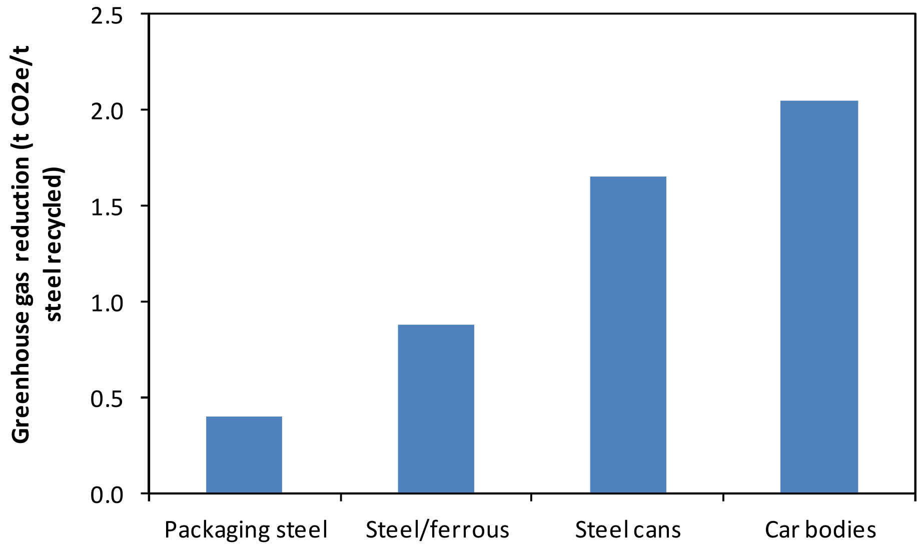


Figure 32. Specific GHG reductions for steel recycling over landfill in Australia, 2008-2009 (Brulliard et al, 2012).

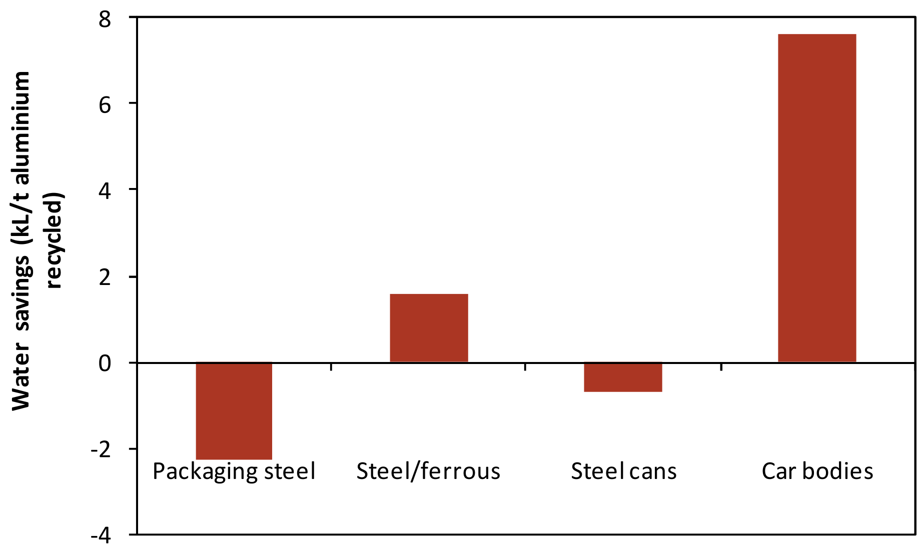


Figure 33. Specific water savings for steel recycling over landfill in Australia, 2008-2009 (Brulliard et al, 2012).

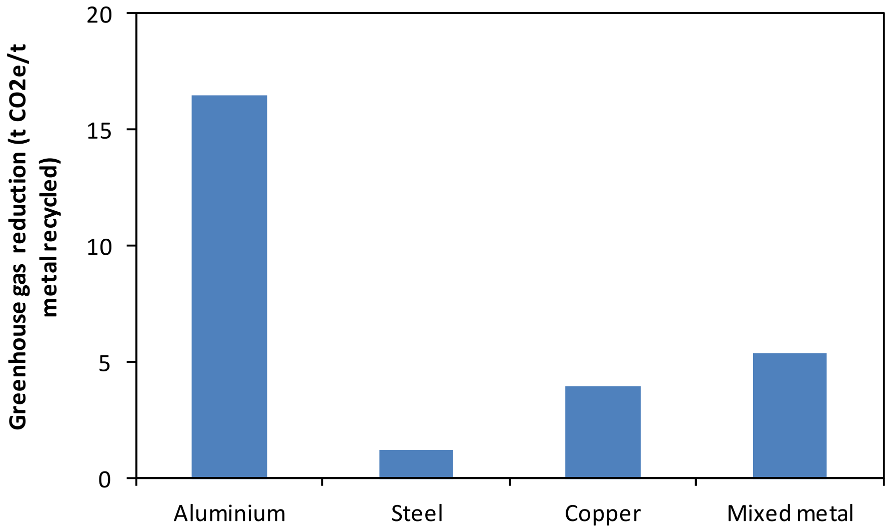


Figure 34. Specific GHG reductions for metal recycling over landfill in Australia, 2008-2009 (Brulliard et al, 2012).

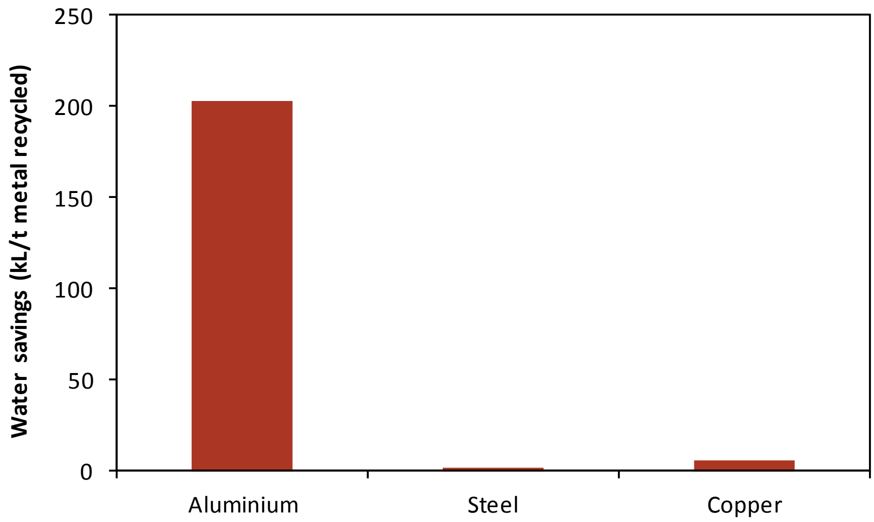


Figure 35. Specific water savings for metal recycling over landfill in Australia, 2008-2009 (Brulliard et al, 2012).

Various metal associations provide LCA inventory data, methodology and results (including recycling) on their websites, eg.

- World Steel Association (www.worldsteel.org)
- World Aluminium Institute (www.world-aluminium.org)
- International Zinc Association (www.zinc.org)

Gatti et al (2008) carried out an LCA of aluminium can production and recycling in Brazil and showed that various environmental impacts (total energy, air emissions (including GHGs), water emissions and solid waste) of aluminium can production are reduced as the recycling rate increases. Van Beers and Graedel (2007) developed a methodology to estimate the in-use stocks of copper and zinc in Australia, and van Beers et al (2007) used these estimates to derive a quantative assessment and spatial characterisation of end-of-life copper and zinc generation rates in Australia in order to investigate the potential recycling of copper and zinc in Australia over the next two to three decades (to 2030). These latter authors estimated that a total of about 72,000 t of copper per year and 57,000 t of zinc per year of end-of-life material is generated in Australia, of which approximately 49,000 t of copper per year and 22,000 t of zinc per year is recycled, corresponding to recycling rates of 68% for copper and 39% for zinc. They estimated that by 2030, the flows of end-of-life copper and zinc will have increased to 150,000 t of copper per year and 145,000 t of zinc per year.

6 Conclusions

Metal recycling will play a critical role in the sustainable production and utilisation of metals into the future by reducing the rate of depletion of metal reserves by the recycling of "metals-in-use". However, if the principles of sustainability are to be incorporated into metal recycling systems and processes, it is essential that life cycle assessment (LCA) methodology be used to assess these systems and processes. But there are a number of issues relating to metal recycling and its incorporation into LCA methodology that must be addressed before any metal recycling LCA studies can be carried out. These issues include:

- inconsistencies in the use of recycling metrics in reports and publications giving metal recycling data;
- quantifying the number of times a metal has been recycled – this is related to the type of metal product and its typical lifetime;
- the quality (ie. presence of contaminants) of the recycled metal, which influences its subsequent use;
- sourcing reliable and consistent inventory data for the various stages of metal recycling;
- whether the recycled metal is used in a closed-loop or open-loop recycling system;
- the allocation method used in the LCA to account for recycling.

These issues have been discussed in detail, with some guidelines provided to help in addressing them..

Furthermore, it has been shown by some preliminary analysis of an arbitrary metal recycling scheme that a maximum recycling rate (in embodied energy terms) exists for any particular recycling scenario (ie. metal, product nature, geographical location, etc). Beyond this maximum recycling rate, the embodied energy of the recycled metal exceeds that of the corresponding primary metal. It could be expected that, all other things being equal, the maximum recycling rate would be greatest for those metals having the highest embodied energy values for primary metal production, eg. aluminium. Similarly, it was shown there is likely to be an optimum recycled content (again in embodied energy terms) for a given product system, depending on the available scrap to primary metal ratio.

The issues and results above emphasise the need for detailed LCA studies of proposed metal recycling schemes to be carried out in order to establish the environmental benefits of secondary metal production by recycling over primary metal production, as well as establishing the environmental benefits of metal recycling over other methods of waste metal disposal. Such a life cycle approach will also essential for policy makers in formulating recycling regulations in order to avoid inappropriate policies being established.

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Appendix 1

List of steel and aluminium LCA case studies reviewed in WRAP (2010) report

Aluminium

Selected LCA Case studies

ID	Material	Authors (Year), Title, Publisher	Country
AL-1	Packaging systems - including aluminium	**Ryberg, A.; Ekvall, T.; Person, L. and Weidema B. (1998)**: Life Cycle Assessment of Packaging Systems for Beer and Soft Drinks – Technical Report 3, Danish EPA (Environmental Project no. 402) http://www.mst.dk/udgiv/Publications/1998/87-7909-023-0/pdf/87-7909-023-0.PDF [MAIN REPORT: Ekvall T, Person L, Ryberg A, Widheden J, Frees N, Nielsen P H, Weidema B and Wesnaes M (1998), Life Cycle Assessment of Packaging Systems for Beer and Soft Drinks – Main Report 3, Danish EPA (Environmental Project no. 399)	Denmark
AL-2	Packaging waste-including aluminium	**Tillman A-M, Baumann H, Eriksson E and Rydberg T (1991)**: Packaging and the Environment – Life Cycle assessments of packaging materials – calculations of environmental impact, Statens offentliga utredningar 1991:77, Miljødepartementet.	Sweden
AL-3	Waste packaging-including aluminium	**US EPA (2002)** Solid Waste Management and Greenhouse Gases. A Life-Cycle Assessment of Emissions and sinks. 2nd edition EPA530-R-02-006, May 2002	USA
AL-4	Waste packaging-including aluminium	**RDC-Environment and Coopers & Lybrand - Belgium (1997)** Eco-balances for policy-making in the domain of packaging and packaging waste. European Commission, DG Environment. Reference no.: B4-3040/95001058/MAR/E3	(EU)
AL-5	Waste packaging-including aluminium	**Grant, T., K. James, S. Lundie and K. Sonneveld (2001);** Stage 2 Report for Life Cycle Assessment for Paper and Packaging Waste Management Scenarios in Victoria. Melbourne, EcoRecycle Victoria. Australia http://www.ecorecycle.vic.gov.au/asset/1/upload/Stage_2_Report_for_Life_Cycle_Assess_for_Packaging_Waste_Mg.pdf	Australia
AL-6	Waste packaging-including aluminium	**RDC-Environment and Pira International. (2003)** Evaluation of Costs and Benefits for the Achievement of Reuse and the Recycling Targets for the Different Packaging Materials in the Frame of the Packaging and Packaging Waste Directive 94/62/EC. (Final consolidated report) Brussels: European Commission, 2003. http://europa.eu.int/comm/environment/waste/studies/packaging/costsbenefits.pdf	(EU)
AL-7	Materials recycling, including aluminium	**Smith A, Brown K, Ogilvie S, Rushton K and Bates J (2001)**, Waste management options and climate change. Final report to the European Commission, DG Environment. http://europa.eu.int/comm/environment/waste/studies/climate_change.htm	(EU)
AL-8	Waste packaging-including aluminium	**Pommer, K.; Wesnaes, M.S.; Madsen, C; Larsen, MH (1995)** Environmental assessment of packagings for beer and soft drinks –Sub report 3: aluminium cans (in Danish) Danish EPA (Work Report no. 72) [MAIN REPORT: Pommer, K.; Wesnaes, M.S. (1995) Environmental survey of Packaging Systems for Beer and Soft Drinks (in Danish) Danish EPA (Main Report), EPA Work Report no. 62]	Denmark
ID	**Material**	**Authors (Year), Title, Publisher**	**Country**
AL-9	Recycling of aluminium	**Edwards, D.W. and Schelling, J. (1996)**: Municipal Waste Life Cycle Assessment Part 1 and Aluminium Case Study, Transactions of the Institution of Chemical Engineers, B, 74, 1996, pp 205-222, ISSN 0957 5820	UK
AL-10	Packaging systems - including aluminium	**Schonert, M.; Motz, G.; Meckel, H.; Detzel, A.; Giegrich, J.; Ostermayer, A.; Schorb, A.; Schmitz, S. (2002)**: Ecobalance for beverage packaging - UBA II/ Phase 2, German EPA (in German) http://www.uba.de/uba-info-medien/index.htm [Plus one main report and two technical reports from 2000]	Germany

AL-11	Recycling of materials - including aluminium	**Craighill, A. and Powell, J., (1996)** Lifecycle assessment and economic evaluation of recycling:a case study. Resources, conservation and recycling, 17 (1996) 75-96 http://www.uea.ac.uk/env/cserge/pub/ext/295.htm [BACKGROUND REPORT: Craighill, A. and Powell, J (1995) Lifecycle assessment and economic evaluation of recycling: a case study. CSERGE Working paper WM 95-05. ISSN: 0967-8875.Centre for Social and Economic Research on the Global Environment, University of East Anglia and University College of London]	UK

Other evaluated references - rejected but useful for discussions

Material	Authors (Year), Title, Publisher
Aluminium in packaging	**BUWAL (1998)** Bundesamt für Umwelt, Wald und Landschaft (BUWAL) (Swiss Federal Office of Environment, Forests and Landscape): "Eco-inventories for Packagings - Volume 1 and Volume 2 (BUWAL 250/I/II)" (in German), BUWAL, Bern, Switzerland Incl. earlier reports (BUWAL 1996)
Aluminium in packaging	**BUWAL (1990)** Bundesamt für Umwelt, Wald und Landschaft (BUWAL) (Swiss Federal Office of Environment, Forests and Landscape): "Eco-balances for Packagings - Status 1990 (BUWAL 125)" (in German), BUWAL, Bern, Switzerland Incl. same reports in German (BUWAL 1996)
Aluminium in general	**Vroonhof et al. 2002** (Jan Vroonhof, Anne Schwenke, Harry Croezen, Berend Potjer), all "CE - Solutions for environment, economy and technology" (Dec. 2002) Legislation using LCA concerning Aluminium
Aluminium in general	**International Aluminium Institute (March 2003)** Life cycle assessment of aluminium: Inventory data for the worldwide primary aluminium industry Int. Aluminium Institute (review/comments by panel with Five Winds Inst. as leader)
Aluminium in general	**EAA (April 2000a)** Environmental Profile Report for the European Aluminium Industry European Aluminium Association, EAA (review by I. Boustead)
Aluminium in general	**EAA (April 2000b)** Guidelines for Life Cycle Assessment (LCA) of Aluminium Products European Aluminium Association, EAA
Aluminium in general	**EAA (April 2000c)** Key features how to treat aluminium in LCAs, with special regard to recycling issues, European Aluminium Association, EAA
Packaging incl. aluminium	**Pira & Ecolas (2005)** Study on the implementation of the Packaging Directive and options to strengthen prevention and re-use Final Report. European Commission (DG Environment) Report 03/07884/AL. In particular are of interest Appendices 1 and 2 (http://europa.eu.int/comm/environment/waste/ packaging_index.htm)

Steel

Selected LCA Case studies

ID	Material	Authors (Year) Title, Publisher	Country
ST-1	Recycling of materials - including steel	Craighill,A., and Powell,J., (1996) Lifecycle assessment and economic evaluation of recycling:a case study. Resources, conservation and recycling, 17 (1996) 75-96 [BACKGROUND REPORT: Craighill,A., and Powell,J (1995) Lifecycle assessment and economic evaluation of recycling:a case study. CSERGE Working paper WM 95-05. ISSN: 0967-8875.Centre for Social and Economic Research on the Global Environment, University of East Anglia, and University College of London]	UK
ST-2	Packaging waste- including steel	Tillman A-M, Baumann H, Eriksson E and Rydberg T (1991): Packaging and the Environment – Life Cycle assessments of packaging materials – calculations of environmental impact, Statens offentliga utredningar 1991:77, Miljødepartementet.	Sweden
ST-3	Waste packaging - including steel	Grant, T., K. James, S. Lundie and K. Sonneveld (2001); Stage 2 Report for Life Cycle Assessment for Paper and Packaging Waste Management Scenarios in Victoria. Melbourne, EcoRecycle Victoria. Australia Including Appendix Q: Steel-tin plate chapter http://www.ecorecycle.vic.gov.au/asset/1/upload/Stage_2_Report_for_Life_Cycle_Assess_for_Packaging_Waste_Mg.pdf	Australia
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