A Report on the environmental benefits of recycling

– A critical review of the data for aluminium

The Bureau of International Recycling (BIR) commissioned Imperial College, London to obtain the energy requirements and carbon footprint impact for the production of primary and secondary metals. Data presented in the report enables an estimated saving of 136MtCO_2 in 2006 to be derived by recycling aluminium scrap based on mean energy figures, but that primary production generates 80% more CO_2 when compared with primary production of steel. **By Editor *Aluminium International Today***

The Report, *'Report on the environmental benefits of recycling'* prepared by the Centre for Sustainable Production and Resource Efficiency (CSPRE) of Imperial College London, provides an extensive review of energy requirements and associated CO2 emissions for the production of aluminium, steel, copper, lead, nickel, tin and zinc – although surprisingly not magnesium.

The data brings together numerous sources to present energy requirements for primary production of these metals from their ores and secondary production from recycled (scrap) metal and uses these results to calculate an average for the carbon footprint of each process route.

This article reviews the data for aluminium production and finds some to be at odds with the industrial accepted norms and draws on comments from representative organisations of these industries in an attempt to reconcile the data. A comparison is also made with data from the Report for primary and secondary production of steel.

Much of the anomaly between the report's conclusions and the industrial accepted values arise from the limited data sources used in the report and the lack of any weighting to account for the global share of various production methods cited when calculating mean values.

Text taken from the BIR Report is presented in italics and comments are made in Roman text. All Tables use data taken from the BIR Report except **Tables 3** and **8** which are from the International Aluminium Institute (IAI). Also **Tables 9** and **10** are derived from the BIR data but are not published in the format presented in this article. For ease of reference, the tables are referred to by number in the text although the BIR report does not number the tables.

Primary aluminium

*The gross energy requirement for primary aluminium production is estimated at 120MJ/kg Al based on using hydroelectricity with 89% energy efficiency. As alternatives to hydroelectricity, use of black coal for electricity generation with an efficiency of 35% or natural gas with an efficiency of 54% would give gross energy estimates of approximately 211 and 150MJ/kg Al respectively. The data in the following table (**Table 1**) are the gross energy requirements that have been quoted in various publications for production of primary aluminium by the Bayer-Hall Héroult route, (ie taking the energy to refine alumina from bauxite ore into account) along with the assumptions that the authors made on the fuel used.*

Source	MJ/kg Al	Notes
Norgate	211	Coal (c.e. 35%)
Norgate	150	Gas (c.e. 54%)
Norgate	120	Hydro (c.e. 89%)
Cambridge	260	Coal (c.e. 35%)
Aus Alu Council	182-212	Coal (c.e. 35%)
Grant	207	Coal (c.e. 35%)
Choate and Green	133	US average

(c.e. – refers to conversion efficiency)

Table 1 Energy requirements Bayer Hall Héroult route (alumina and aluminium production)

Source	MJ/kg Al	Notes
Schwarz	47	Electricity benchmark
IAI	54	Electricity average
Norgate	66	Electricity max
Norgate	46	Electricity benchmark
IAI	69	Electricity max
Cambridge	55	95% Hydro efficiency
Cambridge	160	35% Coal efficiency
Cambridge	50	100% efficient
Choate and Green	56	US average

Table 2 Energy requirements of Hall Héroult electrolysis process alone

Stage	Typical Energy	Multiplier	Total Energy
Mining	0.15	5	0.75
Refining	16	1.9	30
Anode	9	0.44	4
Smelting	117	1.02	120
Total Primary			**155**
Remelting	10	1	10

Table 3 IAI global energy averages for primary and secondary (remelted) aluminium production (MJ/kg)

Source IAI

*The electricity consumption in the Hall Héroult process is the most energy-demanding aspect of primary production of aluminium. The energy requirements reported in the literature for the Hall Héroult process alone (ie for conversion of treated ore to metal) are in **Table 2** along with the assumptions made on the fuel used.*

Electrolysis alone

The Report accepts that the electricity consumption in the Hall Héroult process alone (ie the electrolysis of alumina dissolved in cryolite) is the most energy-demanding aspect of primary production of aluminium.

Comparing **Tables 1** & **2**, there is sometimes a discrepancy between the Report's statement that the electrolysis stage is the most energy intensive part of the process. For example, taking the US average figure given by Choate & Green from **Table 1** for alumina plus aluminium production of 133MJ/kgAl and subtracting from this their US average figure of 56MJ/kgAl for the electrolysis stage alone (**Table 2**) we obtain 77MJ/kgAl for the refining stage (Bayer process) alone, ie 58% of the total energy requirement.

For alumina (not aluminium) production, the International Aluminium Institute (IAI) reports a weighted average energy consumption of 11.7MJ/kgAl_2O_3 (see http://stats.world-aluminium.org/iai/stats_new/formServer.asp?form=8). This averaged value is derived from the performance of 80% of the world's refiners constituting low temperature digestion (Av 10.9 MJ/kgAl_2O_3), high temperature digestion (Av 13.7MJ/kgAl_2O_3) and Bayer-Sinter (Av 27.9 MJ/kgAl_2O_3). Plants treating Nepheline ores are excluded. Taking the approximation that, by mass, it requires 1.9 times the amount of alumina to produce one unit of aluminium metal, this equates to 22.2 MJ/kgAl. The BIR report figure of 77MJ/kgAl for the alumina stage of production is thus 3.46 times higher than the IAI which reports values ranging from 10.74 to 14.64 MJ/kg Al_2O_3 (~20.4 – 27.8MJ/kgAl metal).

Backing up the IAI evidence is data from UC Rusal's Aughinish refinery in County Limerick, Ireland which reports a total energy requirement of 10.5MJ/kg of alumina produced of which 6.6MJ/kg is used in the digestion process, 3.3MJ/kg in calcining and 0.7MJ/kg for plant power (see *AIT Nov/Dec 2007 p 40*).

The European Aluminium Association (EAA) reports an average thermal energy requirement of 10GJ/t of alumina plus 230kWh/t alumina (64MJ) making a total of 10.064GJ/tAl_2O_3 (=MJ/kg).

In some other examples in the BIR report, greater energy is seen to be required for the electrolysis stage, but in all cases the energy requirement for refining is far higher than that stated by the IAI. For example, if we compare the worst case reported in **Table 1** which is for coal based power generation at 35% efficiency as reported by Cambridge we obtain: 260 – 160 = 100MJ/kgAl for the alumina stage of production, ie less than the electrolysis stage as expected but over three and a half times greater than the IAI worst case reported of 14.64MJ/kgAl_2O_3 (ie 27.8MJ/kgAl metal).

In correspondence, the authors of the BIR report claim the IAI figure to be an under estimate and consider their sources to be more reliable. The IAI in turn dispute this, pointing out that their data is collected directly from refineries which account for approximately 80% of global production and dates back to 1985. Also, close to 100% of US refineries report their energy consumptions to IAI. The only major region absent from the IAI figures is China. The BIR data they point out is from secondary sources.

The data from the commercial operating refinery at Aughinish backs the IAI figure as being the more realistic as does the EAA data.

The author of the BIR report confirms that the data in **Table 1** excludes energy required to mine and transport the bauxite, which, anyway IAI say, accounts for less than 0.5% of the total energy to produce aluminium.

Indeed, the IAI calculates a global average total energy of 155MJ/kg of aluminium produced taking into account mining, refining, anode production, and smelting. Each contributor is given a weighting related to the volume consumed eg x5 for mining since it takes about four units of bauxite to produce one of aluminium metal plus transporting this quantity from the mine to the refinery. The IAI calculation is presented in **Table 3**. This table is not presented in the BIR report.

Despite the much higher BIR figure at the refining stage the average total energy requirement reported in **Table 1** of 133MJ/kg for the US average is just 1.4% less than the IAI global figure of 155MJ/kg (**Table 3**).

In addition, the weighted average energy requirement for electrolysis to the metal alone reported by IAI is similar to that reported in the BIR Report. IAI reports energy consumption in terms of kWh/t Al providing a weighted global average across regions of 15384kWh per metric tonne (15.38kWh/kg). Using a conversion factor of 1MJ = 3.6kWh this equates to 55.4MJ/kg close to the 56MJ/kg stated in the BIR Report as the US average (**Table 2**), but is some 9MJ higher (19%) than the 47MJ/kg electricity benchmark figure presented in that Table which the BIR Report authors use to calculate the carbon footprint. In reality, the IAI average figure of 15.38kWh/kg Al is bettered by modern high amperage smelters which can achieve power consumptions of the order of 13kWh/kg equating to 47MJ/kg in line with the BIR reported benchmark figure in **Table 2**.

The European Aluminium Association report an average electricity consumption for European smelters of 14.914kWh/kg aluminium with a range of 13 to 18kWh/kg. In terms of MJ/kgAl the average equates to 53.6MJ/kg. The calculation takes into account: - Rectifying loss; - DC power usage; - Pollution control equipment; - Auxiliary power (general plant use); and - Electric transmission losses of 2%.

Surprisingly the BIR Report does not attribute any data from the EAA despite that Association publishing a very extensive 72 page report on all stages of aluminium production and fabrication. One reference to the EAA is provided in the bibliography.

Source	tCO_2/t Al	Energy Source
Norgate	22.4	Coal
Grant	18.2	Coal
Kvande	24	Coal
IAI	20	Coal
IAI	9.8	Hydro 57%, Coal 28%, Natural Gas 9%, Nuclear 5%, Oil 1%
Choate and Green	9.11	US Average
Choate and Green	5.48	Inert Anode, Wetted Cathode, ACD 2cm
Choate and Green	8.56	Carbothermic Reaction
Choate and Green	6.71	Wetted Cathode and ACD of 2cm
Choate and Green	8.95	Chloride Reduction of Kaolinite Clays

Table 4 Carbon footprint Bayer Hall Héroult route for alumina plus primary production of aluminium

Source	tCO_2/t Al	Notes
Norgate	7.2	Drain Cathode, Inert Anode, Low Temp Electrolyte, Natural Gas 54%
Norgate	4.6	Drain Cathode, Inert Anode, Low Temp Electrolyte, Hydroelectricity 89%
IAI	7.7	Average IAI
Choate and Green	3.83	US Average (Typical)

Table 5 Carbon footprint Hall Héroult aluminium production only

Process	Mean in MJ/kg	Benchmark in MJ/kg
Remelting	4.5	2.1
Casting	0.5	0.3
Total	5.0	2.4

Table 6 Energy requirement of secondary processes for aluminium production from scrap

Emissions

The BIR Report states: *For the purpose of comparison of the energy requirements and associated carbon emissions for primary aluminium production with data for secondary aluminium production, the Report assumes that the benchmark process would involve an electricity benchmark figure of about 47MJ/kg.*

*The literature data on the carbon footprint for primary production of aluminium following the Bayer-Hall Héroult route and for the Hall Héroult process alone are given in **Tables 4** & **5** respectively, along with the assumptions made by the authors on the fuel used.*

The CO_2 emissions presented in the BIR Report for alumina plus aluminium production (**Table 4**) are in line with the industrial accepted average norm of close to 10tCO2 per tonne aluminium. As reported in **Table 4**, the IAI, for example, estimate a value of 9.8tCO_2/tAl based on a power generation mix of Hydro 57%, Coal 28%, Natural Gas 9%, Nuclear 5%. The US average is given as 9.11tCO_2/tAl. The European average (not quoted) is reported by EAA as 8.566tCO_2/tAl in 2005. Of this, 1.804t is generated in the cell from consumption of the anode and PFC CO_2 equivalent emissions, 4.584t from electricity generation and 1.758t as thermal energy. Auxiliary demands and transport account for a further 353 and 68kgCO_2/tAl respectively.

Emissions for the electrolysis stage alone reported in **Table 5** are low for the US average at 3.83tCO_2/tAl compared with the IAI average of 7.7tCO_2/tAl. The data quoted for Norgate using inert anodes (a process not yet commercially developed) would expect to see a reduction of the order of one tonne less CO_2/tAl assuming a typical net carbon consumption in a conventional pre-baked carbon anode of around 400kg/tAl producing 32/12 x 1.06tCO_2.

Secondary production

The BIR Report says: *It has been reported that the production of one tonne aluminium from scrap requires only 12% of the energy required for primary production. Energy savings of between 90 and 95% have also been reported for secondary aluminium production compared with primary production, starting with mining the ore and not with as-received concentrate.*

The energy requirement to recycle aluminium has been calculated at between 6 and 10MJ/kg *assuming efficiencies of 60-80% in the recycling process.*

The energy requirement data for secondary aluminium production are reported in **Table 6** *as mean values for melting and casting and benchmark values for melting and casting. The carbon footprint data presented in* **Table 7** *have been calculated on the basis of these energy requirement data, using the carbon emission factor for the UK.*

The IAI average energy consumption for remelting scrap is 10GJ/t (10MJ/kg) (**Table 3**) which accords with the range of values stated in the text of the BIR Report but is significantly above the mean values quoted in **Table 6** of 5.0MJ/kg (melting plus casting) and well above the benchmark value of 2.4MJ/kg which the authors use to calculate the carbon footprint.

BIR report summary

In its summary findings, the Report presents its benchmark findings per 100kt of aluminium produced as:

– *Energy requirement* (for 100kt) *primary production: 4700TJ* (therefore 47GJ/t)

– *Energy requirement* (for 100kt) *secondary production: 240TJ* (therefore 2.4GJ/t)

Confirming the industrial accepted value of a 95% saving in energy by the secondary remelting route.

Using this energy data, the carbon footprints for primary (electrolysis stage only) and secondary production of aluminium on the same basis are:

– *Carbon footprint for primary production: 383kt CO_2 (3.83tCO_2/tAl)*

– *Carbon footprint for secondary production: 29kt CO_2 (0.29tCO_2/tAl)*

Representing a 92% saving in CO_2 emissions between the two methods.

However, in terms of absolute emissions the figure for primary production corresponds only to the US typical average figure (**Table 5**) and is well below the other values quoted in **Table 5** eg IAI = 7.7t CO_2/tAl. Also, this figure is for the electrolysis stage of smelting only. If the refining of bauxite to alumina is also included, the US average rises to 9.11t and the IAI figure to 9.8t for hydro generated power and 20t for coal generation (**Table 4**).

The IAI figure of 9.8tCO_2/tAl is an 'ore to metal' figure taking into account emissions contributed by mining, refining, anode production, smelting and casting and includes a weighting factor for each stage of production eg 1.9 for alumina production since on average it requires 1.9 units of alumina to produce one unit of aluminium. It also includes the CO_2 equivalent emissions arising from PFC emissions during smelting as well as the contribution from the different fuels employed ie electricity and fossil fuel. **Table 8** from the IAI –which is not included in the BIR Report – summarises the contribution of each of these inputs.

The secondary production route footprint of 0.29tCO_2/tAl represents the benchmark figure in **Table 7** and is only about half the average 0.60tCO_2 emissions to remelt and cast also presented in **Table 7**.

Process	CO_2 Mean	CO_2 Benchmark
	tCO_2/t	CO_2/tAl
Remelting	0.54	0.25
Casting	0.06	0.04
Total	0.6	0.29

Table 7 **Carbon footprint for the secondary processes for the production of aluminium from scrap**

	Bauxite Mining	Alumina Refining	Anode Production	Primary Smelting	Primary Casting	Total Mine to Ingot(2)
Process(1)	0	0	402	1557	0	1763
Electricity(3)	1	64	66	5225	42	5529
Fossil Fuel	4	707	150	0	82	1530
PFCs	0	0	0	970	0	989
Total	**5**	**771**	**617**	**7752**	**125**	**9812**
Mult Factor	5.272	1.923	0.435	1.02	1.00	

Table 8 **Contribution of CO_2 equivalent emissions for each stage of aluminium production (kgCO_2/t of product)**

Source IAI

Notes: (1) Contribution at process stage eg for Primary smelting CO_2 and CO_2 equivalents arising from net carbon consumption of anode + CO_2eq from fluoride emissions (PFCs are detailed separately)

(2) Sum of each production stage after multiplying by its respective contributing factor

(3) Hydro 57%, Coal 28%, Nat Gas 9%, Nuclear 5%, Oil 1%.

	Output 06	Share (%)	CO_2/t	Total O_2/t	CO_2Saving/t
Primary	34.0	68	9.11	309.74	
Secondary (benchmark)	16.0	32	0.29	4.64	8.82
Secondary (Mean)	16.0	32	0.60	9.6	8.51
Total & CO_2 Saving (Mt)	**50.0**				141.1 bench 136.2 mean

Table 9 **CO_2 saving resulting from secondary production**

Primary v Secondary Al

The BIR Report estimates that in 2006, 16Mt of secondary aluminium was produced from scrap and 34Mt of primary metal. Dross losses are estimated at 2.5% for secondary production (in Europe) and 2 - 4% for primary production.

The 34Mt primary output may be a little high. IAI reports primary production from data covering 64% of total production of 24Mt in 2007 equating to a global primary output 32.64Mt. The most significant absence from IAI production data is China (and some other less significant regions). China is estimated to produce close to 10Mt/y of primary metal.

The secondary production figure is more likely to be an underestimate as it cannot account for 'unrecorded' remelters which are common in parts of the world such as India and China. An estimate made at the Alcastek 2008 conference puts unrecorded secondary production in India to be over 0.5Mt, or nearly half the total secondary production. (*See AIT May/June 2008 p44*).

Using the BIR Report data, close to one third of the total 50Mt of aluminium produced in 2006 was from secondary sources. Using their Carbon footprint figures (**Tables 4** & **7**) a saving of 141.1MtCO_2 was achieved that year if the benchmark figure is used for secondary production or 136.2Mt if the mean value is taken, just 3.5% more than the benchmark (**Table 9**).

It is worth noting that moving from the mean energy value to the benchmark value results in a saving of just 3.4% in CO_2 emissions or 4.9MtCO_2 a year.

Carbon footprint Al vs Steel

The BIR report also compares steelmaking from ore by the blast furnace (BF) oxygen steelmaking (BOF) route and the Direct Reduced Iron (DRI) Electric Arc Furnace (EAF) route as well as from melting scrap in the EAF.

As with some of the data for aluminium, there are figures presented for steel which are not consistent with the industry norm, in particular the BIR energy data which suggests that there is only a 16% saving in energy when melting scrap in an EAF compared with the BF-BOF route. The impact of the saving in terms of the carbon footprint is more in line with the industry accepted figure, the BIR Report concluding a 35% reduction (**Table 10**) compared with the industry's estimate of 39% as estimated below:

In its report '2008 Sustainability Report of the world steel industry' the World Steel Association (formerly International Iron & Steel Institute) – whose members represent 85% of total world production – state: 'More steel is recycled worldwide annually than all other materials put together, with an estimated 459Mt being recycled in 2006, about 37% of the crude steel produced that year. Recycling this steel avoided 827Mt of CO_2 emissions, saved 868Mt of iron ore, and saved the energy equivalent of 242Mt of anthracite coal.' They also conclude that each tonne of crude steel produced 1.7tCO_2 on weighted average (69% BOF 30% EAF, 1%OH). In 2006, 1.25bnt of crude steel was produced thus emitting 2.125bnt CO_2. Thus recycling of scrap resulted in a saving of 827/2125 =38.9%.

The significant effect on the carbon footprint of recycling scrap is evident and in addition there is a substantial reduction in CO_2 emitted due to the removal of 868Mt of ore and 242Mt of hard coal from the processing route.

The BIR Report assumes a much lower energy requirement for the BF – BOF route of 14GJ/t for their carbon footprint calculation despite some of their own data showing an average of 21.9GJ/t (with a standard deviation of 5.1) as total energy requirement from the ore.

The World Steel Association in their 2008 Sustainability Report for the 2006 Fiscal Year presents an average energy intensity value of 20.6GJ/t of crude steel produced. This is a weighted average including both the BF-BOS route and the EAF route from 38 member companies and two industry associations (including a further 77 companies) with 70% BOF, 29% EAF and 1% OHF production route spread. Together, these companies produced 42% of the crude steel output worldwide in 2006. Unfortunately, the data is not broken down between the BF-BOF and EAF routes but, since, by the BIR Report's own figures, the average energy requirement for the EAF route alone is 11.7GJ/t, the BF-BOF contribution to the average must be greater than the average 20.6GJ/t and may be estimated in the order of 22.3GJ/t.

Based on their energy figures of 14GJ/t for BF-BOF and 11.7GJ/t for the EAF route, the BIR Report attributes the mean carbon footprint per tonne of steel to be 1.97t CO_2 for the BF-BOF route and 0.70tCO_2 for the EAF route (**Table 10**).

Comparing the carbon footprints of aluminium and steel, BIR Report data shows that primary aluminium production emits 7.14t more CO_2/t metal than steel but 0.41t CO_2/t less for the secondary route (**Table 10**).

The generally accepted industry figure for the BF-BOF route alone is close to 2tCO_2/t steel and the BIR carbon footprint is thus in reasonable agreement for the BF-BOF primary route for steel production and somewhat conservative for aluminium primary production accepting a mean figure of 9.11tCO2/t some 7% lower than the IAI average of 9.8tCO_2/t.

Comparing the representative Association figures for aluminium and steel production of 9.8 and 2.0 respectively we must conclude that primary aluminium production has a carbon footprint nearly 80% greater than that of steel, but in contrast, using the BIR figures for secondary production, there is a 41% reduction in CO_2 emissions per tonne of metal produced when melting aluminium scrap compared with steel scrap.

In terms of volume production, since the density of aluminium is 2.70 compared with that of steel of 7.87, approximately two-thirds greater volume of aluminium results per tonne compared to steel. Thus by volume, the carbon footprint for primary production of aluminium reduces to 9.11 x 0.33 = 3.0tCO_2/m^3 while that for steel remains 1.97 tCO_2/m^3 ie the difference falls to 34%. However, it should be noted that the lower yield strength and modulus of aluminium requires thicker sections than an equivalent section in steel to achieve the same load bearing capacity, hence replacement of steel by aluminium is not on a one for one basis.

In balance, the BIR Report has come up with the broadly accepted conclusions of industry regarding the advantages of recycling but by using selected data based on benchmark rather than mean industrial values.

Aluminium	Max	Min	Mean	Note
Primary (Bayer &HH)	22.4	5.48	3.83	US Av
Primary (HH)	7.7	3.83	7.7	US Av
Secondary	0.60	0.29	0.29	Benchmark
Steel				
Primary BF+BOF	2.30	1.32	1.97	(SD 0.30)
Primary DRI+EAF	3.31	0.7	1.76	(SD 0.96)
Secondary (scrap)	1.18	0.54	0.70	(SD 0.27)

Table 10 Comparison of carbon footprint for production of aluminium and steel (tCO_2/tmetal)

The 'Report on the Environmental benefits of Recycling' is available from the Bureau of International Recycling (BIR), Avenue Franklin Roosevelt 24, 1050 Brussels, Belgium. Tel +32 2 627 5770 Fax +32 2 627 5773 email bir@bir.org, website www.bir.org

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