A Report on the environmental benefits of recycling – A critical review of the data for steel

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. Using their 'benchmark' value for BF–BOF steelmaking and their mean value for scrap melting in the EAF, the report concludes that only a 16% saving in energy is achieved by recycling but a 58% reduction in CO_2 emissions result. Using their mean values for the BF-BOF, the energy saving increases to 46.6% and using alternative industrial data, which reflects a higher energy requirement for the BF-BOF route and a far lower requirement for the EAF than the BIR Report, energy savings are as high as 69%.

By Editor Steel Times International

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 CO_2 emissions for the production of steel, aluminium, copper, lead, nickel, tin and zinc.

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

This article reviews the data for steel production and finds some to be at odds with the industrial accepted norms and draws on comments from representatives 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 aluminium.

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. The Tables use data taken from the BIR Report except Table 8 derived from data supplied by SGL, and Table 12 which is from the International Aluminium Institute (IAI). Also Table 11 is derived from the BIR data but is not published in the format presented here. For clarity, the tables are referred to by number in this text although the BIR report does not number the tables.

The BIR Report states: *In 2006, world production of steel was 1245Mt in which scrap consumption amounted to approximately 440Mt.*

The figure for crude steel total production is in accord with the data published by the World Steel Association (formerly International Iron & Steel Institute) but the consumption of scrap is 4.1% lower, worldsteel quoting 459Mt. This difference equates to some 37Mt of CO_2 emissions saved that year.

The energy requirements reported for the whole life cycle of steel production from ore to metal via the blast furnace – oxygen steelmaking (BF-BOF) route and for the conversion of ore concentrate to steel by this route, are presented in the following two tables (Tables 1 & 2).

Source	MJ/kg Steel
Das and Kandpal	29.2
Hu et al	25.5
Sakamoto	25
Norgate	22
Price et al (Open Hearth)	20.1
Price et al	16.5
Phylipsen et al	15.17
Mean (SD)	**21.9 (5.1)**

Table 1 Energy requirements for steel production from ore via the BF-BOF route

	MJ/kg Steel
Ertem and Gurgen	16.58
Price et al	15.6
Phylipsen et al	15.47
Sakamoto	13.4
Mean (SD)	**15.3 (1.3)**

Table 2 Energy requirements for steel production from ore concentrate via the BF-BOF route

The energy requirements reported in **Table 1** for the BF-BOF route from ore range from 29.2 to 15.7MJ/kg steel – a factor of nearly two (192%). This results in a high standard deviation (SD) for the mean value (21.9+/–5.1). We must also assume that all the values refer to liquid steel production but this is not stated in the Report.

The range is much more limited when considering the smaller sample of energy data starting from concentrate (**Table 2**) which vary from 16.58 to 13.4 ie 23% resulting in a mean of 15.3+/–1.3. From this the authors derive a minimum value of 14.0 MJ/kg and use this as the 'benchmark' figure.

The World Steel Association (worldsteel) in its 2008 Sustainability Report for the 2006 Fiscal Year presents an average energy intensity value of 20.6GJ/t of liquid crude steel produced (tls). This is a weighted average for both the BF-BOF integrated steelmaking route from ore/concentrate and the EAF route using mainly scrap and is provided by 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 worldsteel data is not broken down between the BF-BOF and EAF routes but, since, using the BIR Reports own figures, the average energy requirement for the EAF route alone is 11.7MJ/kg (see **Table 7** later) the BF-BOF contribution to the average must be greater than the worldsteel quoted average of 20.6GJ/t and may be estimated in the order of 22.3GJ/t. Thus the mean values reported in **Table 1** of 21.9MJ/kg (=GJ/t) from ore is broadly acceptable but it is unclear if this figure includes energy to produce sinter. The 15.3MJ/kg from concentrate appears to exclude the energy to produce the concentrate.

Data from the US DOE and MIT provide values of 19.40 and 19.28GJ/tls (metric tonne) respectively for the BF-BOF route including the energy to make sinter and pellet (Ref 33).

The range of CO_2 emissions reported arising from the integrated BF-BOF route are presented by the BIR Report in **Table 3** which provides a mean value of 1.97tCO_2/t crude steel. This figure is higher than may be expected from the energy requirements presented in **Table 1** but is close to the 2tCO_2/t frequently quoted by the steel industry for the BF-BOF route.

Again, worldsteel do not report separate carbon footprint data for the BF-BOF and EAF routes but quote a weighted average of 1.7tCO_2/tls using a 69% BOF, 30% EAF, 1%OH mix of production processes.

Source	tCO_2/t Steel
Norgate	2.3
Orth et al	2.23
Sakamoto	2.15
Orth et al	2.14
Das and Kandpal	2.12
Gielen and Moriguchi	2
Hu et al	1.97
Orth et al	1.82
Orth et al	1.69
Wang et al	1.32
Mean (SD)	**1.97 (0.30)**

Table 3 Carbon footprint for steel production via the BF/BOF route

Integrated DRI route

The BIR Report also looks at energy and CO_2 emissions for the production of Direct Reduced Iron (DRI) from ore and its melting in an electric arc furnace (EAF) as an alternative to the BF-BOF route. The report presents data for DRI production alone and for production plus melting in the EAF (**Tables 4 & 5**).

Comparing Tables 4 & 5, the values for DRI production alone are evidently for the more common natural gas based production rather than from coal since a mean value of 11.7MJ/tls is attributed to the EAF alone (**Table 7**). The high value in **Table 5** of 36.6MJ/kg for DRI production in India from coal would relate to production in a rotary kiln.

The energy reported to be required to produce molten steel by this route is in the same order as that for the BIR average for BF-BOF route from ore of 21.9MJ/kg. Worldsteel do not provide figures of energy requirements for producing DRI but Midrex, whose DRI plants accounted for 58.2% of global production in 2008, have made extensive calculations on the

	MJ/kg Steel
Gielen and Moriguchi	10
Phylipsen et al	10.93

Table 4 Energy requirements for DRI production

	MJ/kg Steel	Note
Das and Kandpal	36.9	DRI from Coal (India)
Das and Kandpal	24	DRI from Gas (India)
Price et al	19.2	80% DRI + 20% scrap

Table 5 Energy requirements for steel production for the DRI + EAF process

carbon footprint of the DRI-EAF route for various charge mixes covering hot DRI, cold DRI and scrap in various ratios (**Fig 1**) (Ref 32).

Data for the carbon footprint for the production and melting of DRI is presented by the BIR Report in **Table 6** in which the mean value is 1.76tCO_2/t steel. The value of 3.31tCO_2/t for India refers to production of DRI in a coal fired kiln.

	Carbon Footprint (tCO_2/t Steel)	Note
Das and Kandpal	3.31	Coal (India)
Orth et al	1.74	Coal + Circofer
Das and Kandpal	1.57	Gas
Orth et al	1.46	Gas + Circofer
Gielen and Moriguchi	0.7	Gas
Mean (SD)	**1.76 (0.96)**	

Table 6 Carbon footprint for steel production for the DRI + EAF steps

The average carbon footprint of 1.76tCO_2/t for the DRI + EAF route reported in **Table 6** is a simple average of the data presented taking no account of the relative amounts of DRI produced by each process. In 2008, 74.3% of the global total 68.45Mt of DRI produced was by gas based processes and of this 72.7% was produced by the Midrex and HYL/Energiron shaft furnaces (Ref 33). Thus the high carbon footprint attributed to coal based production is unrepresentative of global production. Likewise, those processes quoting Circofer (a fluidised bed process) refer to a single commercial plant which has only operated intermittently since its commissioning, and a pilot plant. The DRI produced by such alternative gas based processes as this (and Fastmet) accounted for only 1.6% of global output in 2008.

Midrex reports a carbon footprint of 1.140tCO_2/tls for a charge of 80% cold DRI (gas based production) plus 20% scrap to an EAF, providing an estimate of approximately 1.4tCO_2/tls for a 100% DRI feed to the EAF.

Fig 1 illustrates Midrex's findings for a range of different charge conditions using the US power generation mix of: 50% coal; 18%NG, 20% Nuclear, 7% Hydro, 2% oil and 2% renewable other than hydro. Units refer to metric tonnes and DRI produced from reformed natural gas.

An independent analysis for the Multi-pollutant Emission Reduction Analysis Foundation (MERAF) for the Iron and Steel Sector by Charles E Napier Co Ltd, Canada, (September 11, 2002, p. xviii) reported by Midrex concludes: 'DRI plants using natural gas as the reduction material have lower CO_2 emissions than coal-based plants… It was estimated that the BAT plant [MIDREX Plant] would emit 24% less CO_2 and at least 24% less TPM, NOx, SOx, and VOCs than a conventional integrated [BF-BOF] plant.'

Using the BIR Report average of 1.76tCO_2/t for the BF-BOF route a 24% reduction equates to around 1.5tCO_2/tls in line with a calculated Midrex figure of 1.37tCO_2/tls for 100% DRI charge (From Fig 1 80% DRI charge = 1.14 therefore 100% DRI charge equates to 1.368).

The BIR Report gives no credit for the hot charging of DRI which is increasingly being practiced and results in a power saving of approximately 20kWh/t at the EAF for each 100°C rise in charging temperature. Since a hot charging temperature in the order of 600°C is possible, a power saving of 120kWh/t is achievable. Countering this is the increased slag volume resulting when DRI is charged, but again additional positive influences of charging DRI are the ease by which it can be continuously charged through the roof so conserving energy by keeping the roof closed and also the chemical energy content due to the higher carbon content of DRI compared with a typical scrap mix.

One final point that should be made in favour of gas based DRI production is the fact that the CO_2 must be removed from the gas circuit in order that the reducing gas can be recirculated through the reactor. Thus the gas is already captured and so could be sequestrated. In the Midrex process the CO_2 is recycled to the gas reformer and there is no CO_2 effluent stream. In the HYL process, some companies sell the gas as a by-product. For example, Hylsamex in Mexico supplies a carbonated drinks factory thereby removing the need to generate the gas by other means. Emirates Steel in UAE plans to sell the gas to an oil producer for injection into oil wells to increase recovery.

EAF scrap charge

The BIR Report presents the *energy requirements and carbon footprints for the electric arc furnace route for production of steel from secondary sources in the following two tables:* (**Tables 7 & 8**).

The values presented in **Table 7** are all significantly higher than recognised by operators. SGL Carbon have compiled an extensive database of EAF parameters from which they conclude the energy requirements of a typical EAF with 100% scrap charge to be 703kWh/t, equating to just 2.53GJ/tls. This takes into account electrical power input, chemical energy input (fuel, electrode consumption) and the energy arising from oxidation of the charge (Fe, Si, Al etc), but not the efficiencies of conversion at each stage (**Table 8**). When these are factored in the total energy requirement rises to 8.11GJ/tls, but still significantly lower than the 11.7 mean stated in the BIR Report.

Midrex reports a total value some 35% lower than SGL of 1447kWh/tls for 100% scrap operation taking into account a 33% generation efficiency which converts to 5.93GJ/tls (Ref 34).

The average carbon footprint of 0.70tCO_2/tls steel is significantly higher than the 0.466t presented by Midrex for a 100% scrap charge (**Fig 1**). Midrex calculates the carbon footprint for power generation based on the DOE accepted mix for US power generation of 50% coal; 18%NG, 20% Nuclear, 7% Hydro, 2% oil and 2% renewable. In an earlier publication, (Ref 33) Midrex attributes an energy requirement of 1647kWh/t (5.93GJ/tls) for an EAF with 100% scrap charge, and assuming a 33% power generation efficiency they attributes a CO_2 emission of 0.441tCO_2/tls.

In **Table 9**, the carbon footprint value of 1.18tCO_2/t for EAFs using 100% scrap is not consistent with the remaining data in the Table and refers to data from an Indian operation. Disregarding the value for India, the average carbon footprint drops from 0.7 to 0.58tCO_2/t which is more in line with the Midrex data of 0.466tCO_2/t presented in **Fig 1**.

The report presents the benchmark energy requirements for the production of steel from primary ore concentrate by the BF-BOF, by the DRI + EAF and from scrap and secondary sources via the EAF route in (**Table 10**).

In its summary the BIR Report uses a unit of 100kt to present its findings:

Using the benchmark data for primary and secondary steel production from delivered ore concentrate and scrap respectively, the energy requirements for the production of 100 000 tonnes of steel are:

- *Energy requirement for primary production BF-BOF route: 1400TJ (14GJ/t)*
- *Energy requirement for primary production DRI + EAF route: 1920TJ (19.2GJ/t)*
- *Energy requirement for secondary production EAF route: 1170TJ (11.7GJ/t)*

The authors derive the benchmark energy requirement of the BF-BOF route of 14GJ/t as the mean less the standard deviation for iron made from concentrate (**Table 2**). This is significantly lower than the mean they present for

EAF Route Source	MJ/kg Steel
Das and Kandpal	14.4
Hu et al	11.8
Hu et al	11.2
Sakamoto et al	9.4
Mean (SD)	**11.7 (2.1)**

Table 7 Energy requirements for steel production from scrap in an EAF

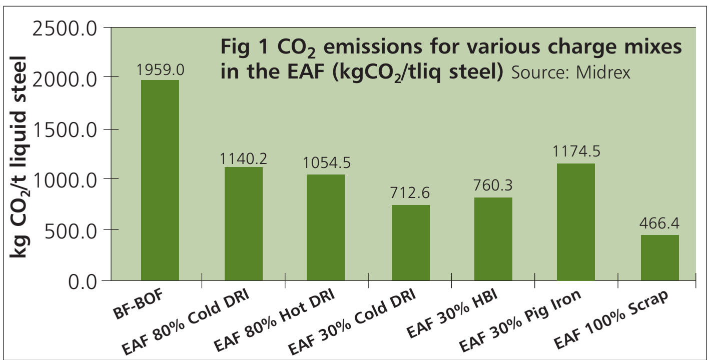

Fig 1 CO_2 emissions for various charge mixes in the EAF (kgCO_2/tliq steel) Source: Midrex

	Electric Energy	Chemical Energy	Metallic charge Oxidation	Total (kWh/tls)
	385	167	151	**703**
Efficiency (%)	77 in EAF 33 in generation	32	70 (Av)	
Total	**1515**	**522**	**216**	**2253**

Conversion to Joules – 1J = 1Watt/sec so 1kWh = 3.6MJ therefore the total 2253kWh = 8.1GJ

Table 8 Energy efficiency of a typical scrap based EAF (kWh/tls)
Source: Table derived from SGL Carbon data

Source	Carbon Footprint (tCO_2/t Steel)
Das and Kandpal	1.18
Wang et al	0.64
Hu et al	0.59
Sakamoto et al	0.56
Hu et al	0.54
Mean (SD)	0.70 (0.27)

Table 9 Carbon footprint for steel production from scrap in an EAF

Steel Recovery Method	Energy Requirement (MJ/kg Steel)	Carbon Footprint (tCO_2/t Steel)
BF/BOF Route (Mean less SD)	14	1.67
DRI + EAF Route (Benchmark)	19.2	0.7
EAF Route (Mean)	11.7	0.7

Table 10 Energy requirements for steel production by various routes

Aluminium	Max	Min	Mean	Note
Primary (Bayer &HH)*	22.4	5.48	9.11	US Av
Primary (HH)	7.7	3.83	3.83	US Av
Secondary (scrap)	0.6	0.29	0.29	Benchmark
*Bayer = refining of ore to Alumina; HH = Hall Heroult ie electrolysis stage				
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 11 Comparison of carbon footprint for production of aluminium and steel (tCO_2/tmetal)

iron made from ore of 21.9GJ/t with a standard deviation of 5.1 (**Table 1**). This figure is more in keeping with the industry's norm.

Using the energy data, the carbon footprints for primary and secondary production of steel on the same basis are:

Carbon footprint for primary production BF-BOF route: 167kt CO_2 (1.67tCO_2/t)

Carbon footprint for primary production DRI + EAF route: 70kt CO_2 (0.70 tCO_2/t)

Carbon footprint for secondary production EAF route: 70kt CO_2 (0.70 tCO_2/t).

Based on these energy figures of 14GJ/t for BF-BOF and 11.7GJ/t for the EAF route, the 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 irrespective of whether produced from scrap or DRI, according to the Report. This is in contrast to the energy requirements of 11.7 and 19.2GJ/t for scrap and DRI charges to the EAF respectively. As a result of this exceptionally low energy requirement attributed to the benchmark BF-BOF route the energy saving by using the EAF with a 100% scrap charge is only 2.3GJ/t or 16% of the BF-BOF route energy. The reduction in CO_2 emission is, however, a more significant 0.97tCO_2/t or 58%.

A more realistic comparison is to use the mean energy value for the BF-BOF route and the mean value for the EAF 100% scrap route presented in the BIR Report as 21.9MJ/kg (**Table 1**) and 11.7MJ/kg (**Table 7**) respectively. The saving is then 10.2MJ/kg or 46.6%.

For US operations, the DOE and MTI report energy requirements for the BF-BOF route of around 19.3GJ/t liquid steel including production of sinter and pellet in the total. The data is presented in terms of kWh/tls and a conversion factor of 277.8 is used based on an average power generation efficiency of 33% (see Ref 33). In that same paper the energy requirement for an EAF charged with 100% scrap is given as 1647kWh/tls or 5.93GJ/t. Using these values the energy saving by melting 100% scrap in the EAF is 19.3 – 5.93 = 13.41GJ/tls or 69%.

Even if we accept the BIR Report benchmark figure for EAF steelmaking of 11.7GJ/tls, and compare this to the US DOE/MTI mean for the BF-BOF route of 19.34GJ/tls the energy saved by melting scrap is more than double that predicted by the BIR Report increasing to 7.64GJ/t or 39.5%.

Carbon footprint Al vs Steel

The BIR report also compares primary and secondary production of aluminium. As with steel, some of the figures presented are not recognised as the industrial norms although the final carbon footprints reported are in general agreement with industrial findings (**Table 11**).

The International Aluminium Institute (IAI) in fact presents a higher average CO_2 emission figure of 9.8t/CO_2/t aluminium from ore to ingot in which they take into account each stage of the process and give each a multiplication factor in line with the contributing mass required to produce a unit of aluminium (eg on average it requires 1.9t Al_2O_3 to produce one tonne of metal so the multiplication factor is 1.9). The results of this extensive review are tabulated in **Table 12** (not presented in the BIR Report).

Comparing the carbon footprints of aluminium and steel, BIR concludes 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 11**).

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 9.11tCO_2/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 and that of steel is 7.87, approximately two-thirds greater volume of aluminium results per tonne produced 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 1.97tCO_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 its report '*2008 Sustainability Report of the world steel industry*' the World Steel Association – 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 on weighted average (69% BOF 30% EAF, 1%OH) emitted 1.7tCO_2. In 2006, 1.25bnt of crude steel were produced thus emitting 2.125bnt CO_2. Thus recycling of scrap resulted in a saving of 827/2125 =38.9% of CO_2 emissions.

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.

In conclusion, the BIR Report highlights the large differences in mill practice worldwide that give rise to significant differences in energy consumption and carbon emissions.

Unfortunately, they then base their conclusions on simple averages of the data collected with no weighting factor for the contribution of each source to global data.

The carbon emissions relate directly to the carbon content of the energy source and the energy efficiency of the mill.

The calculated results depend greatly on the assumptions made but it should be recognised that all the carbon that comes into a steel mill leaves as CO_2, except for the tiny fraction of carbon that ends up in the steel. ■

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

	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 12 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%.

From BIR Report

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