# Report on the Environmental Benefits of Recycling – 2016 edition

*Bureau of International Recycling (BIR)*

**BIR-Nominated Commodities:**
**Aluminium, Copper, Ferrous and Paper**

# Report on the Environmental Benefits of Recycling – 2016 edition

**Prepared By Hopeman Associates Limited on behalf of the Bureau of International Recycling**
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# Contents

# Executive Summary

**Use of a more detailed and refined methodology reveals that carbon dioxide emission savings achieved through recycling as compared to primary production are greater than concluded by the 2008 BIR report which arrived at a figure of around 500 million tonnes per annum for seven metals (ferrous, aluminium, copper, nickel, tin, zinc and lead) plus paper – equivalent at the time to the annual carbon dioxide emissions of the global aviation industry.**

**The latest in-depth study conducted on behalf of BIR concludes that, for just three metals (ferrous, aluminium and copper), the annual $CO_2$ savings made through secondary production rather than primary production is 572 million tonnes (see table). The report also highlights the energy and emissions benefits of recycling paper.**

**The report supplements literature-based and benchmark data from the 2008 study with "real data" derived from industry, including use of a novel "Front-end" tool for "normalisation" of industry-acquired data in terms of energy requirements and associated $CO_2$ emissions.**

**The methodologies described in the report can be used to obtain potential $CO_2$ savings for any company's recycling operations for any material on a case-by-case basis.**

| Material | Energy Savings (achieved by industry against Primary Benchmark) (TJ/100,000t) | Annual Worldwide Secondary Production* (Mt) | Estimated Savings in Annual $CO_2$ Emissions (Mt) |
|---|---|---|---|
| **Aluminium** | 4434 | 18 | 63.3 |
| **Copper** | 1033 | 6 | 4.8 |
| **Ferrous** | 206 | 580 | 503.9 |
| **Total Estimated Savings in Annual $CO_2$ Emissions** for the Production of the Secondary Metals Studied [Current Study] | | | **572.0** |

* Annual worldwide secondary production (Mt) as quoted in 2014 for Aluminium and in 2013 for Copper and Ferrous.

The benefits of the 2008 research, a desk-based study of the available literature of the primary and secondary production of seven metals and paper which made use of the best available and most justifiable energy data for primary and secondary production in calculations to highlight the carbon footprint savings associated with secondary production, have been widely acknowledged in the recycling industry worldwide. It is in this context that the current study is carried out: "... to update the findings of the 2008 study, applying the methodology developed to more recent data on four of the original commodities, namely, aluminium, copper, ferrous metals and paper".

In the current study use was made of industry-acquired data drawn from real secondary recovery operations to improve the input data for secondary production and, as in the 2008 study, to avoid complications associated with the early stages of the whole lifecycles of the materials benchmark, energy requirements and carbon footprints were taken from ore or raw material delivered, respectively, at the production plant for primary material, and at the production plant for secondary material. The data provided by industry permit calculations of energy requirements and carbon dioxide emissions for both single-stream processes for each of the BIR-nominated commodities, and separately, for mixed-metal streams containing all three target metals. For the single-stream process, the data provided allow for calculations to be made for the recovery of a fully-refined product for each commodity whilst for the mixed-stream process, the data allow for calculations to be made for the recovery of a "saleable" product which would require further refinement to a fully-refined product.

To realise the full potential and value of applying the methodology used in this study, industry engagement is important so that the energy requirements and carbon footprints are determined on industry-acquired data (i.e. "real" data). To this end, a novel "Front-end" tool has been developed for "normalisation" of industry-acquired data (in terms of energy requirements and associated $CO_2$ emissions), as input to the methodology. To optimise the value of the output from the analysis, the nature and type of information required from industry on recycling operations form the basis of a questionnaire developed to assist BIR in the acquisition of information from its members and other stakeholders. In situations where industry is handling mixed streams from which value can be derived from more than one commodity, account is taken of the energy apportioned to each metal and non-metal fraction. Use of the "Front-end" tool allows fractionation and attribution of energy data in the process and for the energy and $CO_2$ emissions for each recovered commodity to be determined. In situations where there is less than 100% recovery of useful material, the tool can be extended to attribute that energy to further recovery of the product(s).

The $CO_2$ emissions for aluminium, copper, ferrous metals and paper are calculated using an electricity energy conversion factor, for the UK, of 0.50935kg$CO_2$e/kWh. Energy conversion factors vary considerably between countries and regions and the $CO_2$ emissions can be re-calculated for any specific country or region by using the appropriate conversion factor. The effects of other variables, for example, plant and operation efficiencies as well as energy source/fuel mix, can be determined using the sensitivity analyses tables provided.

The $CO_2$ emissions savings achieved by secondary production over primary production for the industry-derived data are presented in the following sets of comparisons:

1 For the metals and paper, with a calculation from benchmark primary energy data, from the 2008 study, using the 0.50935kg$CO_2$e/kWh electricity energy conversion factor, assuming that primary and secondary production can be carried out in the same geographical region where this conversion factor is appropriate. The comparative calculation can be extended to processes carried out in any region or country by use of the relevant conversion factor; and

2 For the metals only, with the benchmark primary calculations from the 2008 study representing the most efficient production processes available with the lowest energy consumption in situations where the best possible energy mixes are used anywhere in the world, using the most recent worldwide secondary production tonnages for these metals, the total estimated savings in annual $CO_2$ emissions arising from the secondary production of aluminium, copper and ferrous metals, in comparison with primary production, are 572Mt.

Furthermore, the methodology described in this report can be extended and used to obtain energy and carbon emissions data on any recycling operations of any process operator and for any material.

# Context of the Brief

## Background

The environmental benefits of recycling have been expressed in many ways, including savings in energy and in use of virgin materials. Very little attempt had been made, however, to express these benefits in terms of carbon footprint and particularly as savings in $CO_2$ equivalent emissions, which would have implications in terms of both the environment and carbon emissions, until BIR commissioned a research study on behalf of its members in 2008:

***" …to prepare a report on the environmental benefits of recycling, identifying the savings that can be made by using recyclables as opposed to primaries, and thereby the carbon credentials of the recycling industries".***

The research, directed by Professor Sue Grimes, was presented as a lead industry document, entitled *Environmental Benefits of Recycling*, referred to in this work as the *'2008 BIR report'*.

This desk-based research involved a detailed review of available scientific and technical literature on seven metals – aluminium, copper, ferrous metals, lead, nickel, tin and zinc – and also paper. The study introduced the concept and application of a benchmark methodology to determine the best available and most justifiable carbon emission data for primary production processes, and used best estimates from the literature of benchmark data for energy and carbon footprint calculations for both primary and secondary production. For primary production, the benchmark data represented the most efficient production processes available with the lowest energy consumption per tonne of metal produced in situations where the best possible energy mixes were used. The conversion factors used to express the primary production energy data as benchmark carbon emission data were also based on those for the best possible energy mixes. Benchmark data were, thus, defined as those data that represented material production situations that were achievable and gave values that were most acceptable and justifiable as the best achievable, but would not necessarily be achieved by all primary production processes. The calculations of benchmark values for secondary production in the 2008 study were similarly derived from literature-based data.

The benchmark data were used to highlight the advantages (environmental impacts) of secondary production over primary production and were reported per 100,000 tonnes of material produced to provide a means of direct comparison between primary and secondary production and expressed as $CO_2$ savings per 100,000 tonnes of production. To avoid complications associated with the early stages of the whole lifecycles of these materials, benchmark energy requirements and carbon footprints were taken from ore or raw material delivered at the production plant for primary material, and delivered at the secondary plant for secondary material. Sensitivity analyses were then developed and used to show how the comparisons can be handled to deal with variations in different production processes, for example, variations in efficiency, and fuel and energy balances.

The concept of benchmarking was a novel approach to calculating environmental parameters such as carbon footprints and carbon dioxide savings and, combined with the provision of sensitivity analyses, provides a means of obtaining the best available calculated data for individual situations.

The benefits of the 2008 research have been widely acknowledged in the recycling industry worldwide, and, for the recycling industries, the value of expressing environmental benefits in terms of $CO_2$ emissions savings is becoming increasingly necessary. It is in the context of the success of this work that Alexandre Delacoux, Director General of BIR, approached Professor Sue Grimes to consider carrying out further research on behalf of BIR:

***"… to update the findings of the 2008 study, applying the methodology developed to more recent data on four of the original commodities, namely, aluminium, copper, ferrous metals and paper".***

## Scope and Assumptions

The scope outlined for the current report is based on the above brief.

In carrying out the project, the following assumptions have been made:

1. The scope for determination of carbon and energy savings will focus on four of the original commodities, as proposed by BIR, and referred to in this report as the BIR-nominated commodities: aluminium, copper, ferrous metals and paper;
2. The update of the 2008 study, applying the methodology developed to more recent data, will make use of primary and secondary literature as information sources, supplemented by published data from commodity associations and data that can be provided by BIR or other industry sources. Data on the material and energy balances provided by industry will be used, where available, to determine the carbon status of the recovery process of each material under study and will be compared with data obtained on primary material production;
3. The key deliverables will include:
   a) A report setting out the results of $CO_2$ emissions savings and energy savings updated (from most recent data) for the BIR-nominated commodities;
   b) A list of questions/key indicators for BIR to present to its members to encourage their support for and participation in the industry-specific aspects of the study to permit the assessment of $CO_2$ emissions savings and energy savings applying the methodology using verifiable industry-acquired data for specified materials, specified plants in specified countries; and
   c) Support to BIR in disseminating the results of the study to its members and other stakeholders, in the form of headline non-technical statements, based on the scientific findings of the study.

To avoid complications associated with the energy usage and carbon footprints of the early stages of primary and secondary production, the 2008 study compared data across production plants based on: (i) ore concentrate delivered to the primary process facility converted to final product; and (ii) scrap and secondary material delivered to the secondary recovery facility converted to final product.

This assumption provides the most direct comparison between the environmental impacts of primary and secondary production because it focuses on the part of the life cycle that deals only with the actual production process and avoids problems associated with assessing the effects of mining and beneficiation of primary ores and with the collection and transport/delivery of scrap. It is likely however that the energies and carbon footprints associated with mining and concentration of ores would be much larger than collection and delivery of scrap and this would only serve to increase the benefits of secondary recovery.

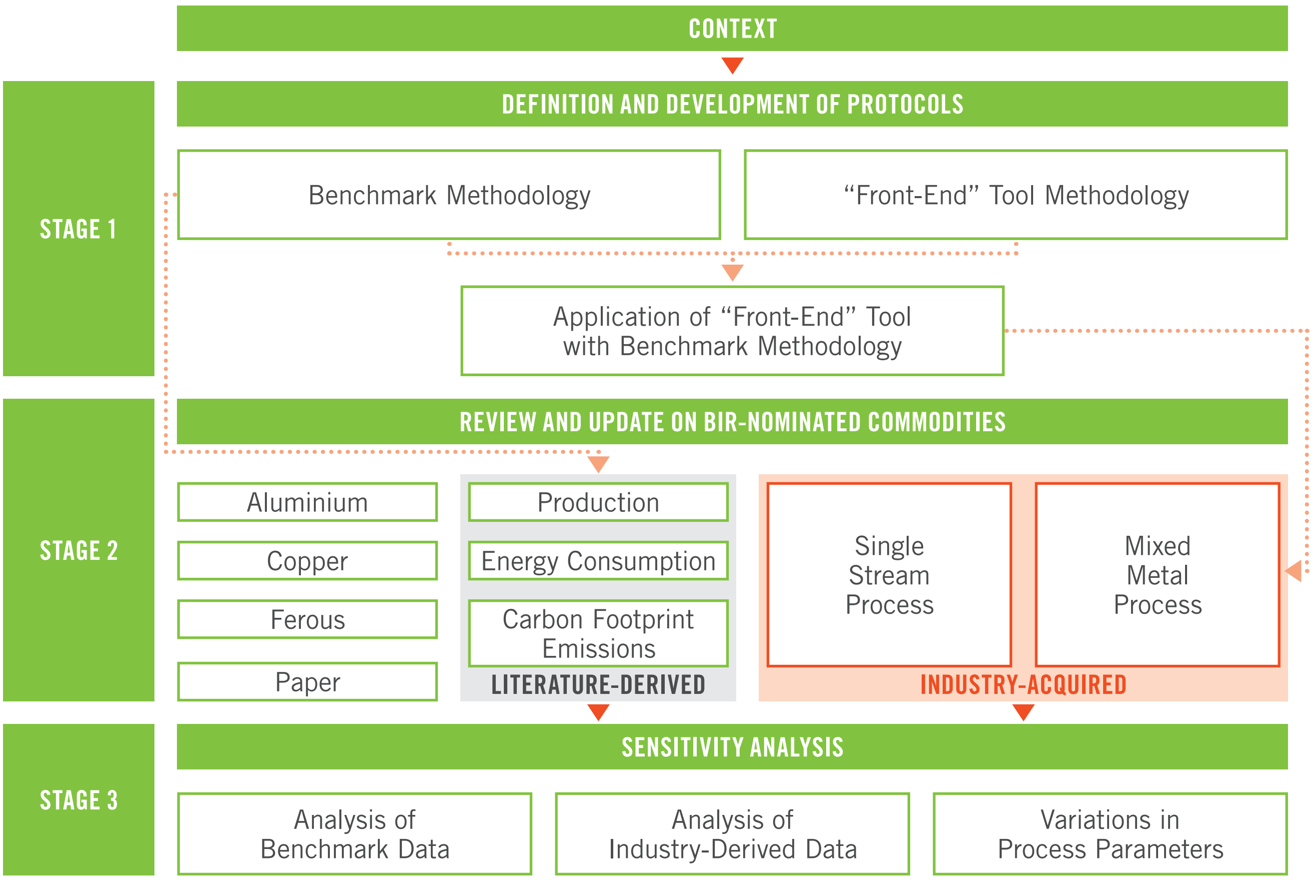
It should be noted that the benchmark carbon footprints from the 2008 study essentially assume the use of the most appropriate and best available technologies. The assumptions made in the 2008 study will be upheld in the current study with the unit of comparison of 100,000 tonnes of produced material applied.

## Approach

To achieve the key deliverables in line with the scope of the brief, the work is carried out in three stages, as illustrated in the schematic below, such that the following objectives are met:

- Agree the scope and deliverables of the brief with BIR;
- For the purposes of benchmarking, carry out a review of relevant primary literature on the materials under study;
- Obtain where possible process data from industry for use in carbon and energy consumption calculations;
- Compare the data from known secondary recovery operations with benchmark values for primary production, which represent the best available and most justifiable carbon data;
- Assess the quality of the data in terms of sensitivity analysis;
- Analyse and interpret the findings;
- Prepare headline non-technical statements, based on the study;
- Produce a draft final report for review and acceptance by BIR; and
- Provide a list of questions/key indicators for use by BIR in encouraging member participation in the industry-specific aspects of the study.

The focus of the current study is designed to update the 2008 work, with emphasis on the three metals aluminium, copper and ferrous and on paper, extended to use industry-acquired data to calculate the energy requirements and carbon footprint data of each of the commodities; allow comparison of the energy-specific data with the 2008 benchmark values for primary and secondary production; and apply sensitivity analyses to the industry-acquired data to take account of other situations such as different efficiencies in a plant.



# Definition and Development of Protocols

The most common greenhouse gas emitted is carbon dioxide and a carbon footprint is a quantitative measure of the carbon dioxide released as a result of an activity expressed as a factor of the greenhouse gas effect of carbon dioxide itself. Many environmental impacts, including the production of any electricity used in the materials recovery industry, can be converted into carbon dioxide-equivalent ($CO_2$-e) emissions.

## Benchmark Methodology

As a basis for reference, the benchmark methodology developed in the 2008 study, and applied here, involves:

1. A detailed survey of the literature to extract the data available on energy consumption in primary and secondary material recovery and the carbon emissions associated with these processes;
2. Use of energy data and associated carbon emissions, extracted to highlight differences between primary and secondary production of the BIR-nominated commodities. The assumptions made in all information provided are identified and the units used in the calculations are expressed as MJ/kg (or GJ/kg) of product for energy and tonnes of $CO_2$ per tonne of product for carbon emissions;
3. For each material for both primary and secondary production, best estimates of benchmark energy consumptions and carbon footprints are used in the comparisons as examples of what can be achieved;
4. A comparative analysis of energy consumption and carbon footprint data from the primary and secondary production of the BIR-nominated commodities, expressed per 100,000 tonnes of product. For all materials, the life cycle boundaries are set to compare the production of (a) primary material from raw material extraction to production of final concentrate/product, and (b) recovered secondary materials ready for delivery to the recycling plant to final product. This enables a direct comparison to be made between the energy consumption required to produce primary and secondary refinery feedstocks for the same quantity of contained recyclate; and
5. Sensitivity analyses are carried out on the data obtained using the benchmark values derived from the study to show how these data can be modified/handled to deal with variations in input such as energy sources used, energy/fuel mix for different countries, and energy efficiency of specific recovery plants.

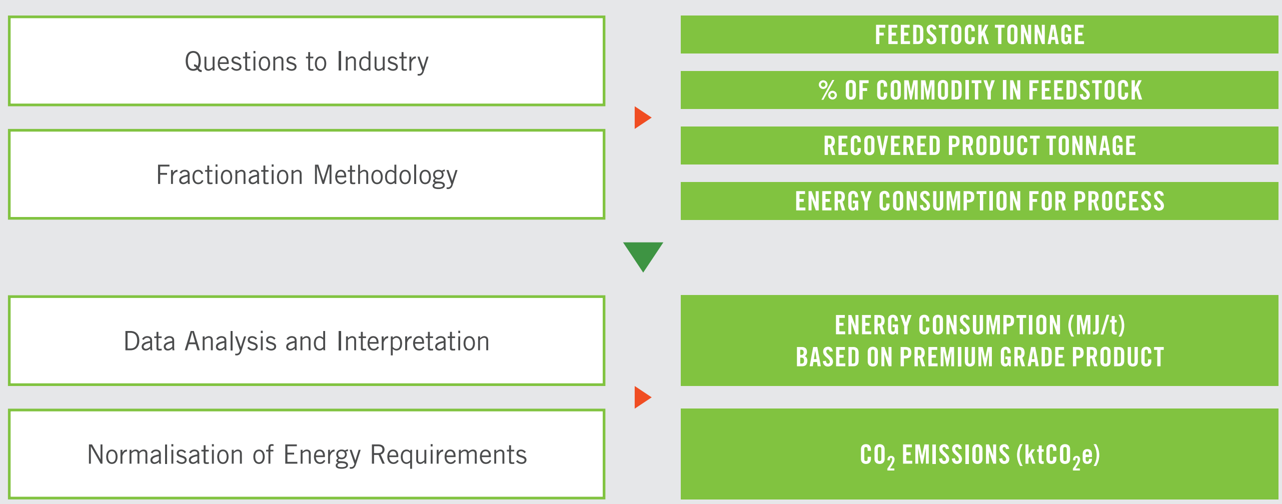
Building on the acknowledged benefits of the 2008 research, it is clear that to realise the full potential and value of applying the benchmark methodology relies on industry engagement such that the energy requirements and carbon footprints are determined based on industry-acquired data (i.e. “real” data). Of further benefit is the ability to apply sensitivity analyses to these “real” data to take account of differences in, for example, plant and operation efficiencies, energy mix and other country/region-specific data to provide a basis for realistic and reasonable comparison.

## “Front-End” Tool Methodology

To this end, as part of the current work, a novel “Front-end” tool has been developed for “normalisation” of industry-acquired data (in terms of energy requirements and associated $CO_2$ emissions), as input to the benchmark methodology. To optimise the value of the output from the analysis, the nature and type of information required from industry about its recycling operations include:

- Commodity/commodities recovered at the plant
- Tonnage of feedstock through the plant per day
- Typical percentage of commodity fraction(s) in the feedstock
- Total energy consumption through the plant per day
- Indication of fuel source
- Tonnage of finished recovered product
- For a multi-commodity process, the fraction of energy usage attributable to the recovery of each commodity fraction.

**Front-End Tool**




As part of this approach, a questionnaire (Annex) has been designed to assist BIR in the acquisition of information from members and other stakeholders, and a fractionation flowchart methodology, shown in the following schematic, has been developed to take account of the information sought in situations where operations are handling either single- or multi-commodity materials at a plant, or are operating globally. Although presented as a metal fractionation flowchart, the cascade methodology can equally well be applied to non-metal fractions, such as high-grade polymers, paper/card or other materials.

The "Front-end" tool, which uses a 2-step formula to determine the energy requirements and associated $CO_2$ emissions based on industry-acquired data, is presented below.

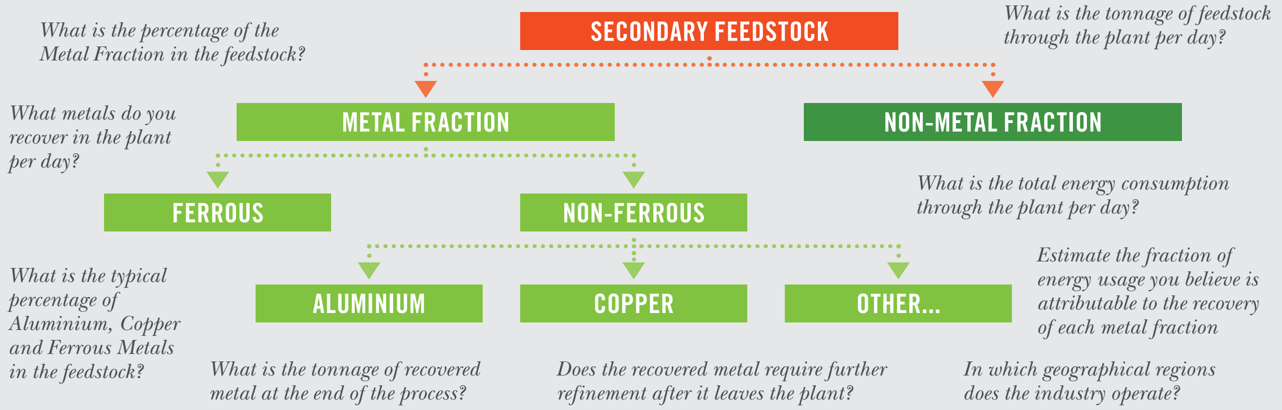
## Step 1 – Data Acquisition and Fractionation Handling

This step involves acquisition of standardised data from industry through the use of a questionnaire (see p. 11) and the subsequent identification and apportionment of the energy usage, within the system boundary, for handling of each commodity fraction.

Based on the tonnage of feedstock (expressed as metric tonnes) identify the target fraction **[A]** and determine the percentage of each commodity fraction in **[A]** as **[$B_{(1...n)}$]**

Calculate the total energy consumption through the plant **[C]** per tonne of feedstock, taking account of the sum of energy use by fuel type **[$\Sigma(C_{1...}C_n)$]** and,

**Fractionation Flowchart Methodology**



**Data sought from Industry**

- Commodity/commodities recovered at the plant
- Tonnage of feedstock through the plant per day (t/d)
- Typical percentage of commodity fraction(s) in the feedstock (%)
- Total energy consumption through the plant per day per tonne of feedstock (MJ/t)
- Indication of "fuel" energy source (e.g. grid electricity, oil, diesel, coal etc)
- Tonnage of finished recovered product (t)
- For a multi-commodity process, the fraction of energy usage attributable to the recovery of each commodity fraction to deliver a product output

where applicable, the value for energy efficiency conversion **[$cf^0$]** required to deliver the end product.

For each commodity fraction recovered **[$D_{(1...n)}$]**, assign the energy usage **[$E_{(1...n)}$]**:

**Energy usage through plant in MJ per commodity fraction recovered:**

$$E_{(1...n)} = D_{(1...n)} \times (\Sigma(C_{1...}C_n) + cf^0)$$

## Step 2 – Analysis and Normalisation of Energy Requirements

Express energy consumption in TJ as energy per 100,000t for each commodity product **[$F_{(1...n)}$]** according to the following equation:

**Energy in TJ/100,000t of product:**

$$F_{(1...n)} = (E_{(1...n)} \div B_{(1...n)}) \div 10$$

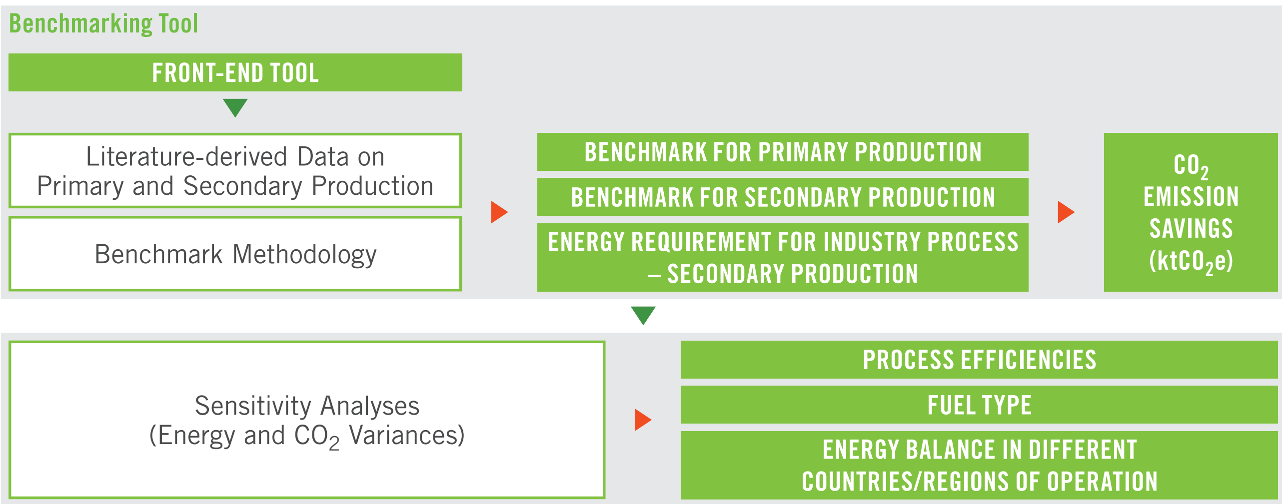
Express energy requirement for each commodity product **[$F_{(1...n)}$]** in kt$CO_2$ emission equivalent **[$G_{(1...n)}$]** per 100,000t of product based on:

1 Use of a conversion factor, **[$cf^1$]**, to convert energy in TJ to energy in kWh (where 1TJ = 277,777.78kWh);
2 Grid electricity as the fuel source;
3 Use of a conversion factor, **[$cf^2$]**, to convert energy in kWh to $CO_2$ emissions in kg$CO_2$e; and
4 Use of a conversion factor, **[$cf^3$]**, to convert $CO_2$ emissions in kg$CO_2$e to $CO_2$ emissions in kt$CO_2$e (where 1kg$CO_2$e = 0.000001kt$CO_2$e)

**$CO_2$ emissions per 100,000t of product:**

$$G_{(1...n)} = F_{(1...n)} \times cf^1 \times cf^2 \times cf^3$$

For the purposes of comparison of the industry-acquired energy consumption and carbon footprint data with the literature-derived data, obtained in the 2008 study, for both primary and secondary production, the choice of life cycle boundaries is important to avoid the complications associated with differences in mining and beneficiation of ores and in the collection and transport of scrap to a recycling process, and is set as: (i) conversion of ore concentrate to metal in primary production, and (ii) from scrap and other secondary materials delivered to a recycling process and converted to metal in secondary production.



# Benchmarking for BIR-Nominated Commodities

The commodities of interest to BIR in the current study are aluminium, copper, ferrous and paper. The production of each of these materials is set out below in the context of the processes involved, the energy consumption in these processes and the resulting carbon dioxide emissions. For the purpose of comparison, only those processes within the system boundaries are considered.

## Aluminium

### Primary and Secondary Aluminium Production

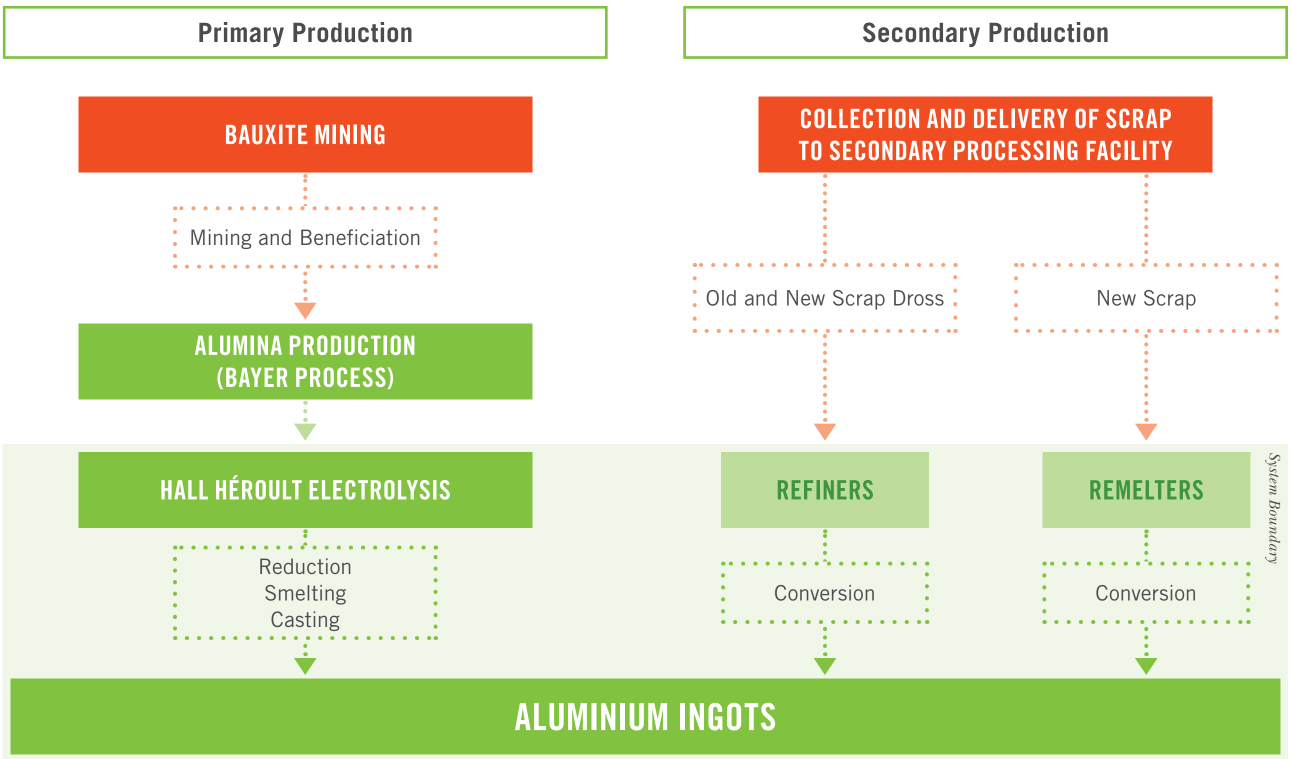
In 2014, the tonnages of primary and secondary aluminium produced were approximately 53Mt with about one third of aluminium demand satisfied from secondary production. According to the International Aluminium Institute (IAI), it has been reported that by 2020 metal demand is projected to have increased to around 97Mt (with around 31Mt recycled from scrap).

In the Bayer process, the bauxite ore is treated by alkaline digestion to beneficiate the ore. Although the red mud produced in this process is a waste, which has major environmental impacts, comparison between primary and secondary aluminium production applying the benchmark methodology starts at the point of delivery of the alumina concentrate to the processing plant.

Primary production of aluminium from the ore concentrate is achieved by an electrolytic process in molten solution. The Hall Héroult process consists of electrolysis in molten alumina containing molten cryolite ($Na_3AlF_6$) to lower the melting point of the mixture from 2050°C for the ore concentrate to about 960°C.

The electrolysis cell consists of a carbon-lined reactor which acts as a cathode, with carbon anodes submerged in the molten electrolyte. In the electrolysis process, the aluminium produced is denser than the molten electrolyte and is deposited at the bottom of the cell, from where it is cast into ingots. At the anodes, the anodic reaction is the conversion of oxygen in the cell to carbon dioxide by reaction with the carbon of the anodes, and it is this reaction that is the major contributor to carbon

Primary and Secondary Production of Aluminium



dioxide emissions from the aluminium production process. The process results in the production of between 2% and 4% dross.

All secondary aluminium arisings are treated by refiners or remelters. Remelters accept only new scrap metal or efficiently sorted old scrap whose composition is known. Refiners, on the other hand, can work with all types of scrap as their process includes refinement of the metal to remove unwanted impurities. In both processes, the molten aluminium undergoes oxidation at the surface which has to be skimmed off as a dross. In Europe, about 2.5% of the feedstock aluminium in the refining process is converted to dross.

### Process Energy Consumption and Carbon Dioxide Emissions

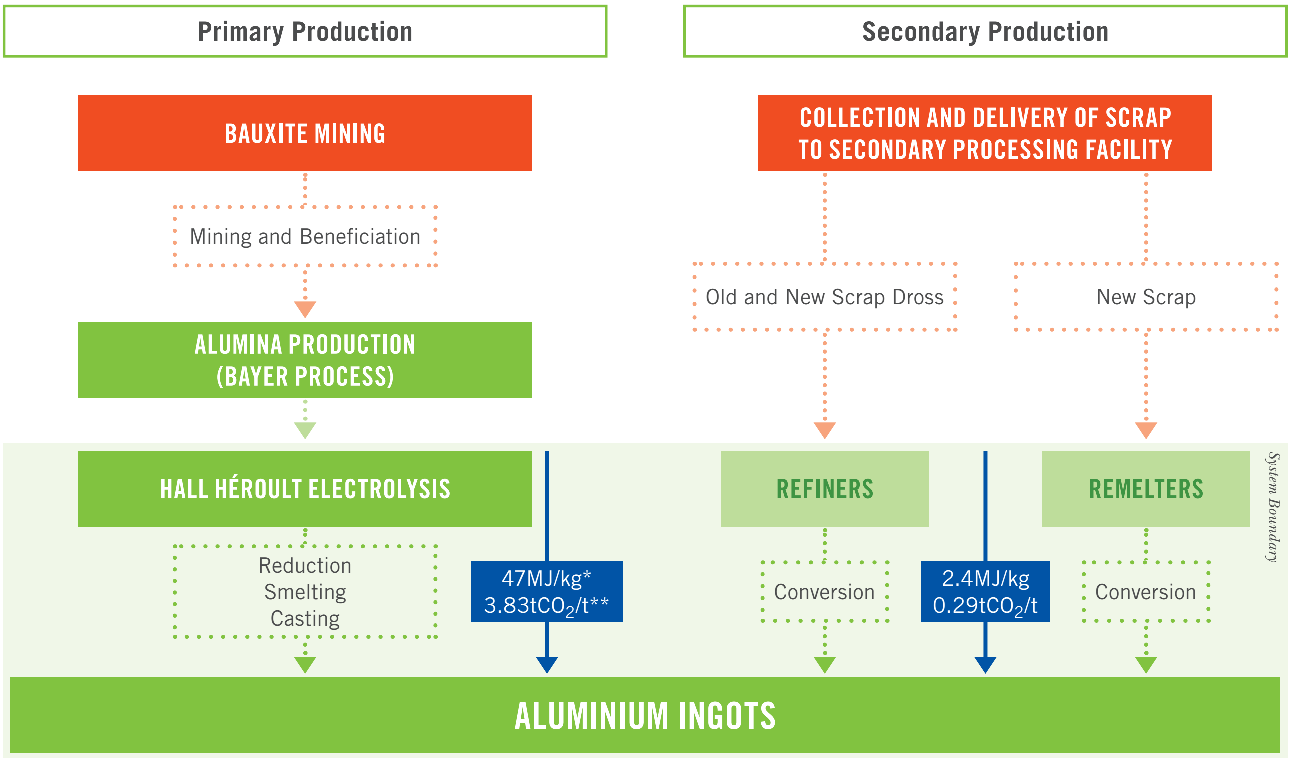
The gross energy requirement for primary aluminium production, via the Bayer Hall Héroult route, has been estimated at 120MJ/kg based on using hydroelectricity with 80% energy conversion efficiency [Norgate, CSIRO Minerals]. As alternatives to hydroelectricity, use of black coal for electricity generation with an efficiency of 35% or natural gas with an efficiency of 54% would give gross energy estimates of approximately 211 and 150MJ/kg respectively.

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 (i.e. for conversion of treated ore to metal) vary depending on the type of fuel used, with the values for electricity, for example, shown in the following table.

**Energy Requirements – Hall Héroult Process only**

| 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. |

**Aluminium Production (Primary/Secondary): Process Energy Consumption and $CO_2$ Emission**




Source: For Primary Production: Benchmark Energy Value. *Schwarz: Carbon Footprint Value. **Choate and Green.

In the same way, 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 vary on the type of fuel used as well as the conditions of the electrolysis reaction. For the Hall Héroult process alone, the carbon footprint values along with observations and assumptions made by the authors are shown in the following table.

**Carbon Footprint – Hall Héroult Process only**

| Source | Carbon Footprint ($tCO_2$/t Al) | Observations |
|---|---|---|
| Norgate | 7.2 | Drained cathodes, Inert anodes, Low-temperature electrolytes, Natural gas 54% |
| Norgate | 4.6 | Drained cathodes, Inert anodes, Low-temperature electrolytes, Hydroelectricity 89% |
| IAI | 7.7 | Average IAI |
| Choate and Green | 3.83 | US Average (typical) |

For the purpose of comparison of the energy requirements and associated carbon emissions for primary aluminium production with data for secondary aluminium production, an electricity benchmark figure of 47MJ/kg and a $CO_2$ emission value of 3.83 $tCO_2$/t are used.

It has been reported that the production of one tonne of 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 the 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.

Energy requirement data for secondary aluminium production from scrap are reported in the table below as: mean values for melting and casting; and benchmark values for melting and casting. The corresponding carbon footprint data have been calculated on the basis of these energy requirement data using a carbon emission factor equivalent for the UK, for example, of 0.42857-0.47990$ktCO_2$e/kWh. According to the IAI, in 2009, the aluminium industry itself was reported as responsible for around 1% of the man-made greenhouse gas emissions, 40% of which result from the aluminium production process itself (direct emissions) with 60% resulting from electricity power generation (indirect emissions).

**Secondary Production of Aluminium**

| Source | Energy Requirement | | $CO_2$ Emissions | |
|---|---|---|---|---|
| | Mean (MJ/kg) | Benchmark (MJ/kg) | Mean ($tCO_2$/t) | Benchmark ($tCO_2$/t Al) |
| Remelting | 4.5 | 2.1 | 0.54 | 0.25 |
| Casting | 0.5 | 0.3 | 0.06 | 0.04 |
| **Total** | **5.0** | **2.4** | **0.60** | **0.29** |

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

| | |
|---|---|
| **Energy requirement for primary production:** | **4700TJ** |
| **Energy requirement for secondary production:** | **240TJ** |

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

| | |
|---|---|
| **Carbon footprint for primary production:** | **383$ktCO_2$** |
| **Carbon footprint for secondary production:** | **29$ktCO_2$** |

***The benchmark energy and carbon footprint savings between primary and secondary aluminium production are 4460TJ/100,000t in energy and 354$ktCO_2$e/100,000t in $CO_2$ emissions, respectively.***

# Copper

### Primary and Secondary Copper Production

According to the US Geological Survey, world copper production in 2013 was 17.9Mt. Copper recovered from scrap as a percentage of total copper produced is reported by the Copper Development Association in 2013 to be 35% for 2010 and 2011.

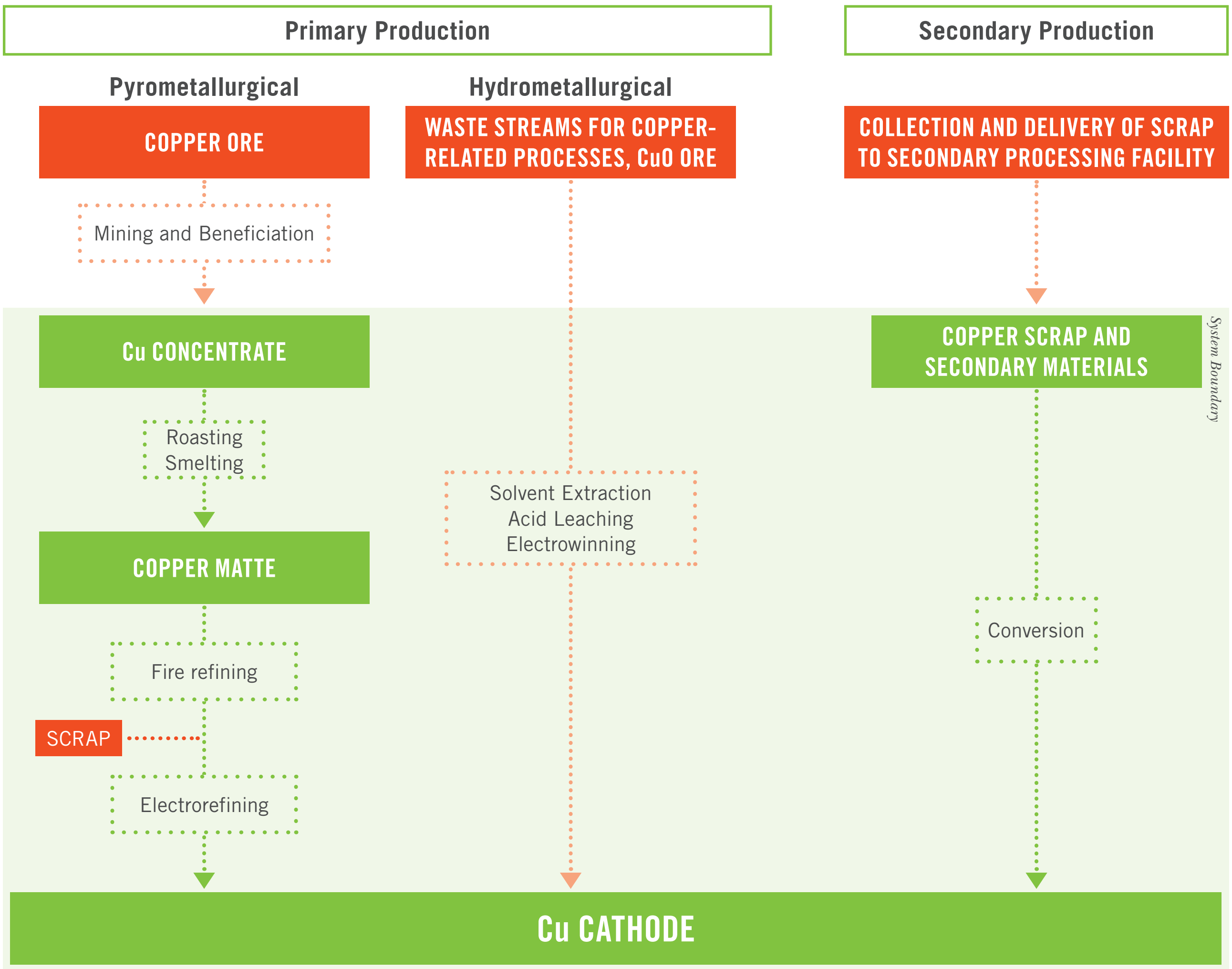
The major approach to primary copper production is the pyrometallurgical route from copper sulfide ores that have been concentrated usually by flotation to give the concentrate used in the pyrometallurgical process. A very small percentage of primary copper is recovered from copper ores hydrometallurgically.

In the pyrometallurgical process, the concentrates are roasted to produce a copper matte which contains between 30 and 50% copper. The matte is reduced to copper metal in a converter process, and the final product is generally purified by dissolving the copper metal obtained in sulfuric acid and recovering high-purity copper from this solution by electrowinning.

The hydrometallurgical route involves leaching of the copper oxide ore with sulfuric acid to produce a solution from which copper metal can be recovered on the cathodes of an electrowinning process.

Secondary copper can be produced from scrap and other copper-containing materials by pyrometallurgical and hydrometallurgical processes that are similar to those used in primary metal production.

Primary and Secondary Production of Copper



### Process Energy Consumption and Carbon Dioxide Emissions

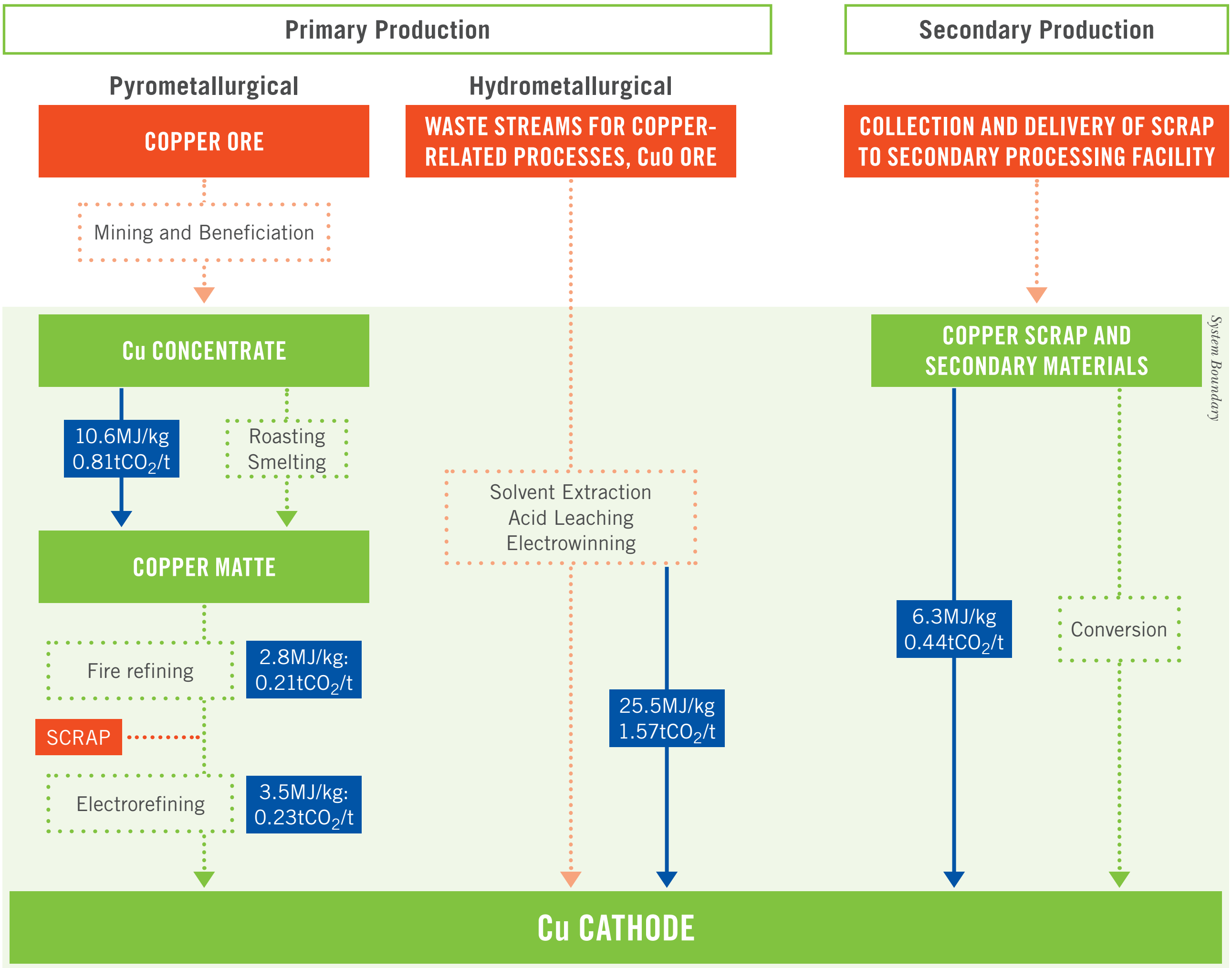
There are literature reports suggesting that the energy requirement for secondary copper production is between 35 and 85% of that for primary production. The International Copper Association (Copper Alliance) endorses the higher figure, commenting further that this equates to a saving of 40Mt of $CO_2$ annually and the equivalent of 100,000 GWh of electricity.

The data for energy required for primary copper production via pyrometallurgical and hydrometallurgical routes are given in the following schematic, which also shows the point in the energy requirement diagram at which scrap copper would enter the pyrometallurgical process. These are the data on which comparisons between primary and secondary production have to be based.

The benchmark energy requirements for the production of cathode copper metal from primary copper ore concentrate, by pyrometallurgy, from soluble copper ores, by hydrometallurgy, and from scrap and secondary sources are shown in the above schematic and in the following table.

| Copper Recovery Method | Energy Requirement (MJ/kg Cu) | Carbon Footprint ($tCO_2$/t Cu) |
|---|---|---|
| Pyrometallurgy from ore concentrate | 16.9 | 1.25 |
| Hydrometallurgy from oxide ores | 25.5 | 1.57 |
| Secondary production from scrap | 6.3 | 0.44 |

**Copper Production (Primary/Secondary): Process Energy Consumption and $CO_2$ Emissions**



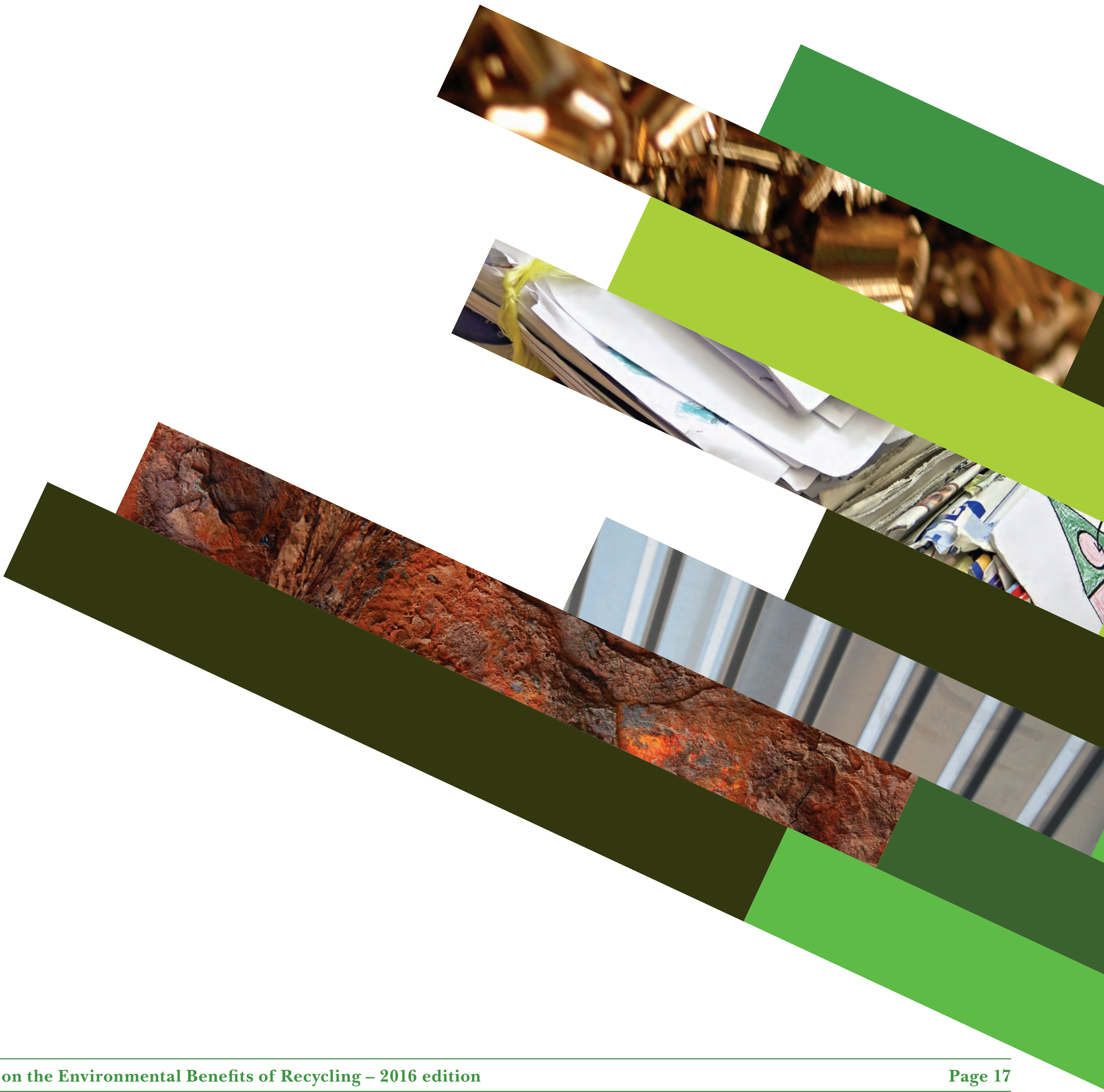
Using the benchmark data for primary and secondary copper production from delivered ore concentrate and scrap respectively, taken from the BIR 2008 report, the energy requirements for the production of 100,000 tonnes of copper are:

| | |
|---|---|
| **Energy requirement for pyrometallurgical primary production:** | **1690TJ** |
| **Energy requirement for hydrometallurgical primary production:** | **2550TJ** |
| **Energy requirement for secondary production:** | **630TJ** |

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

| | |
|---|---|
| **Carbon footprint for pyrometallurgical primary production:** | **125kt$CO_2$** |
| **Carbon footprint for hydrometallurgical primary production:** | **157kt$CO_2$** |
| **Carbon footprint for secondary production:** | **44kt$CO_2$** |

***The benchmark energy and carbon footprint savings between primary (via the pyrometallurgical route) and secondary copper production are 1060TJ/100,000t in energy and 81kt$CO_2$e/100,000t in $CO_2$ emissions, respectively.***



# Ferrous

**Primary and Secondary Ferrous Production**

In 2013, world production of steel was reported by BIR and others as 1,607Mt with around 580Mt of scrap produced in the same year.

A schematic representation of iron recovery and steel manufacture is given in this section.

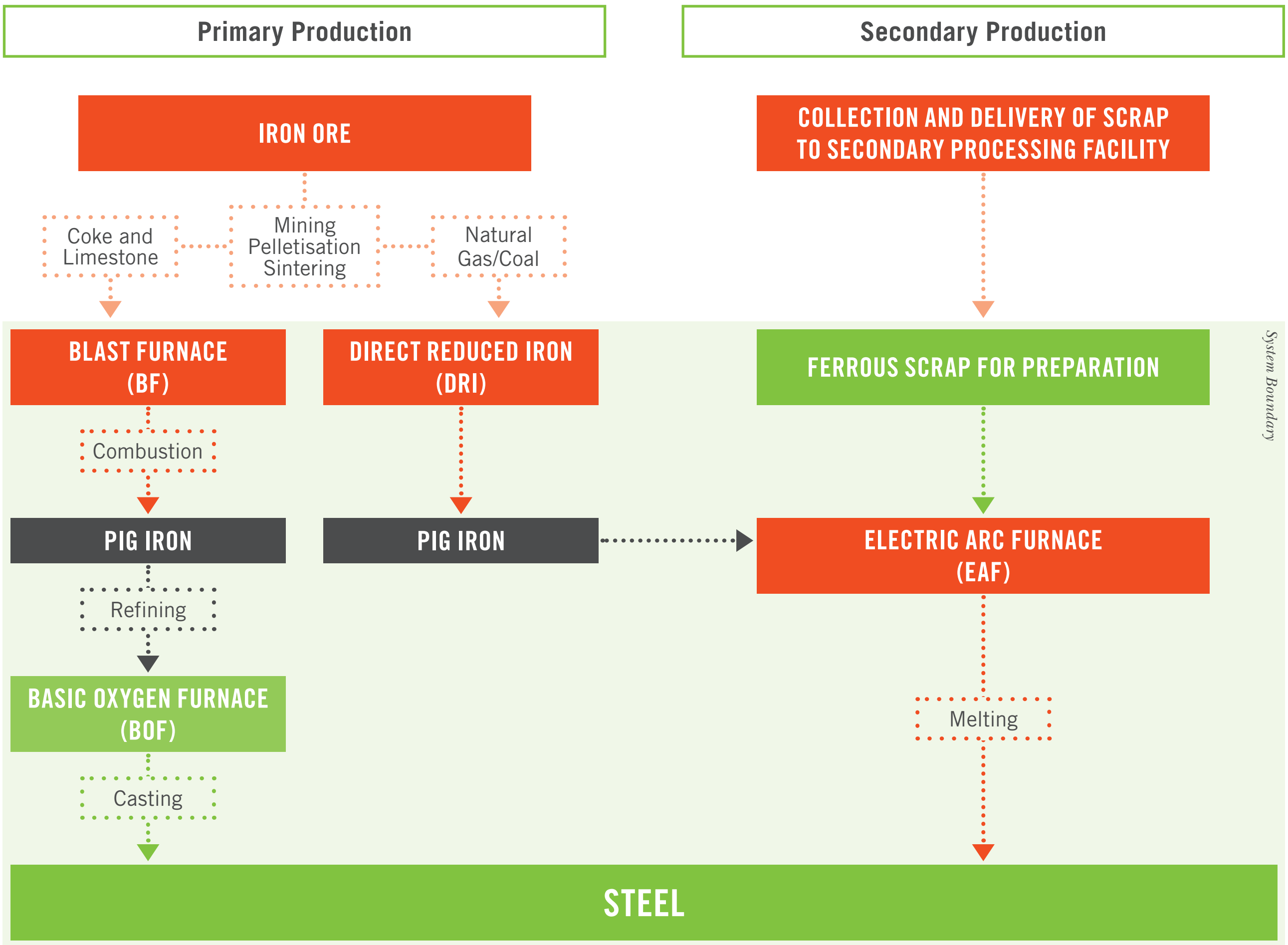
There are four main routes used for the production of steel, namely: blast furnace/basic oxygen furnace (BF-BOF); electric arc furnace (EAF); direct reduction (DR); and smelting reduction (SR).

The BF-BOF route is the most complex and involves the reduction of iron oxide ore with carbon in the furnace.

Liquid iron produced in the blast furnace is referred to as pig iron and contains about 4% carbon. The amount of carbon has to be reduced to less than 1% for use in steelmaking, and this reduction is achieved in a basic oxygen furnace (BOF) in which carbon reacts with oxygen to give carbon dioxide. The oxidation reaction is exothermic and produces enough energy to produce a melt. Scrap or ore is introduced at this stage to cool the mix and maintain the temperature at approximately 1600-1650°C. Blast furnaces consume about 60% of the overall energy demand of a steelworks, followed by rolling mills (25%), sinter plants (about 9%) and coke ovens (about 7%).

Direct reduction involves the production of primary iron from iron ores to deliver a direct reduced iron (DRI) product from the reaction between ores and a reducing gas in the reactor. The DRI product is mainly used as a feedstock in an electric arc

**Primary and Secondary Production of Ferrous**



furnace. The main advantage of this process is that the use of coke as a reductant is not required, thus avoiding the heavy burden on emissions resulting from coke production and use.

The electric arc furnace process involves the melting of DRI using the temperature generated by an electric arc formed between the electrode and the scrap metal, producing an energy of about 35MJ/s which is sufficient to raise the temperature to 1600°C. Depending on the quality of product required, the output of the EAF might need further treatment by secondary metallurgical and casting processes.

Smelting reduction (SR) is a current development that involves a combination of ore reduction and smelting in one reactor, without the use of coke. The product is liquid pig iron which can be treated and refined in the same way as pig iron from the blast furnace.

In secondary ferrous production, electric arc furnaces are used to produce steel from scrap using the same process as that described for the use of DRI as feedstock. Production of steel from scrap has been reported to consume considerably less energy compared to production of steel from iron ores.

### Process Energy Consumption and Carbon Dioxide Emissions

The production of primary steel is more energy intensive than the production of secondary steel due to the chemical energy required to reduce iron ore to iron using reducing agents.

The literature values for the energy requirements and carbon footprints for the production of steel by different routes are in the following tables.

**Energy Requirements for Steel Production from Ore Concentrate via BF-BOF Route**

| Source | Energy requirement (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)** |

**Carbon Footprint for Steel Production from Ore Concentrate via BF-BOF route**

| Source | Carbon footprint ($tCO_2$/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)** |

**Energy Requirements for Steel Production via DRI + EAF Combined Route**

| Source | Energy requirement (MJ/kg steel) | Note* |
|---|---|---|
| Das and Kandpal | 36.9 | Coal (India) |
| Das and Kandpal | 24 | Gas (India) |
| Price et al | 19.2 | 80% DRI+20% scrap |
| **Benchmark** | **19.2** | |

* Noted assumptions made on the energy source used

**Carbon Footprint for Steel Production via DRI + EAF Combined Route**

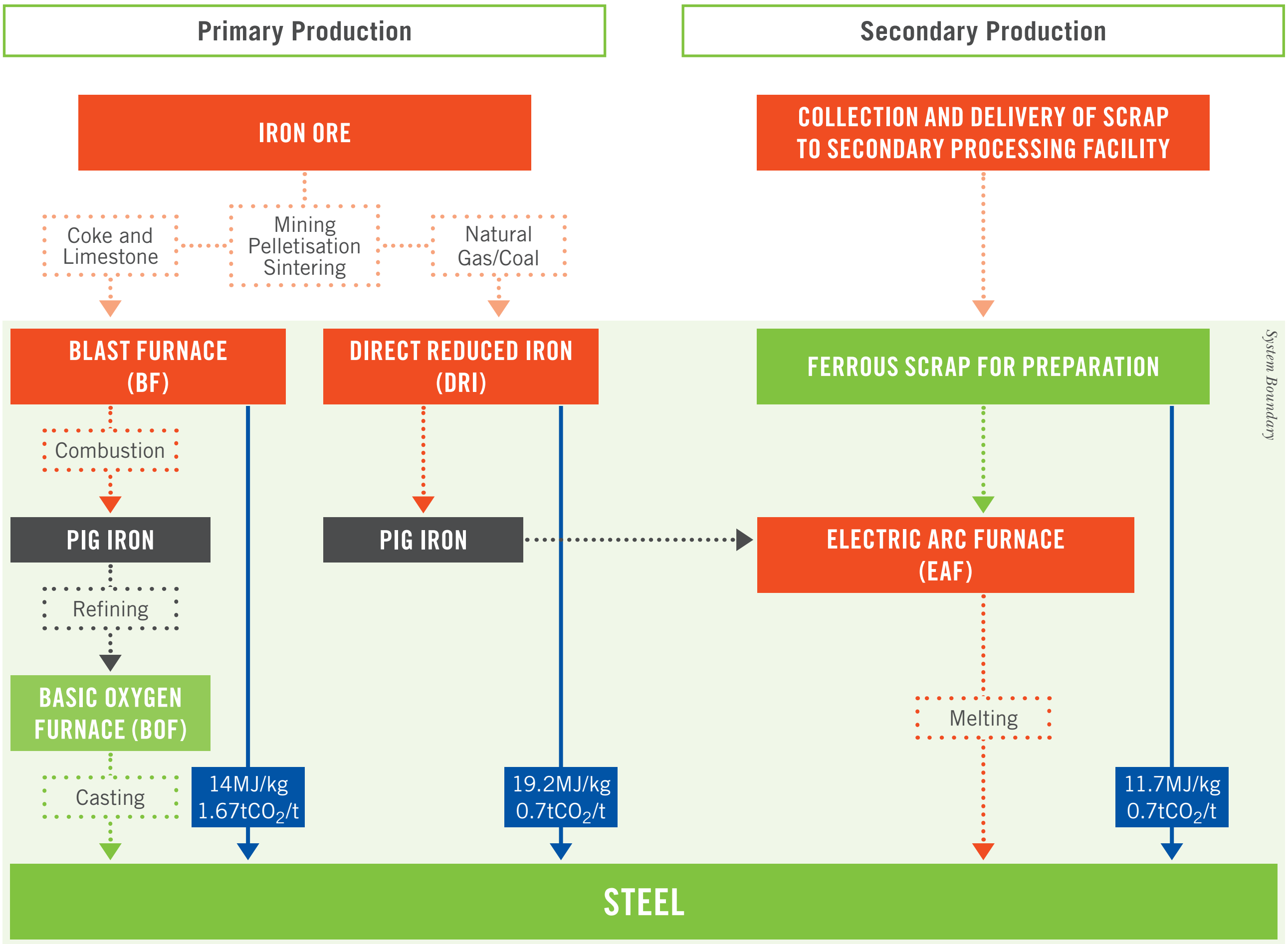
| Source | Carbon footprint ($tCO_2$/t steel) | Note |
|---|---|---|
| Das and Kandpal | 3.31 | Coal (India) |
| Orth et al | 1.74 | Coal + Circofer |
| Das and Kandpal | 1.57 | Gas |
| Orth et al | 1.46 | Gas + Circofer |
| Gielen and Moriguchi | 0.7 | Gas |
| **Mean (SD)** | **1.76 (0.96)** | |
| **Benchmark** | **0.7** | |

* Noted assumptions made on the energy source used

| Energy Requirements for Steel Production from Scrap via EAF Route | |
|---|---|
| **Source** | **Energy requirement (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)** |

| Carbon Footprint for Steel Production from Scrap via EAF Route | |
|---|---|
| **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)** |

### Ferrous Production (Primary/Secondary): Process Energy Consumption and $CO_2$ Emissions



The benchmark energy requirements for the production of steel from primary ore concentrate by the BF-BOF route, by the DRI + EAF route and from scrap and secondary sources via the EAF route are shown in the above schematic and in the following table.

| Steel Recovery Method | Energy requirement (MJ/kg steel)* | Carbon Footprint ($tCO_2$/t steel)* |
|---|---|---|
| BF/BOF route | 14 | 1.67 |
| DRI + EAF route | 19.2 | 0.7 |
| EAF route | 11.7 | 0.7 |

*As reported and used in the 2008 study

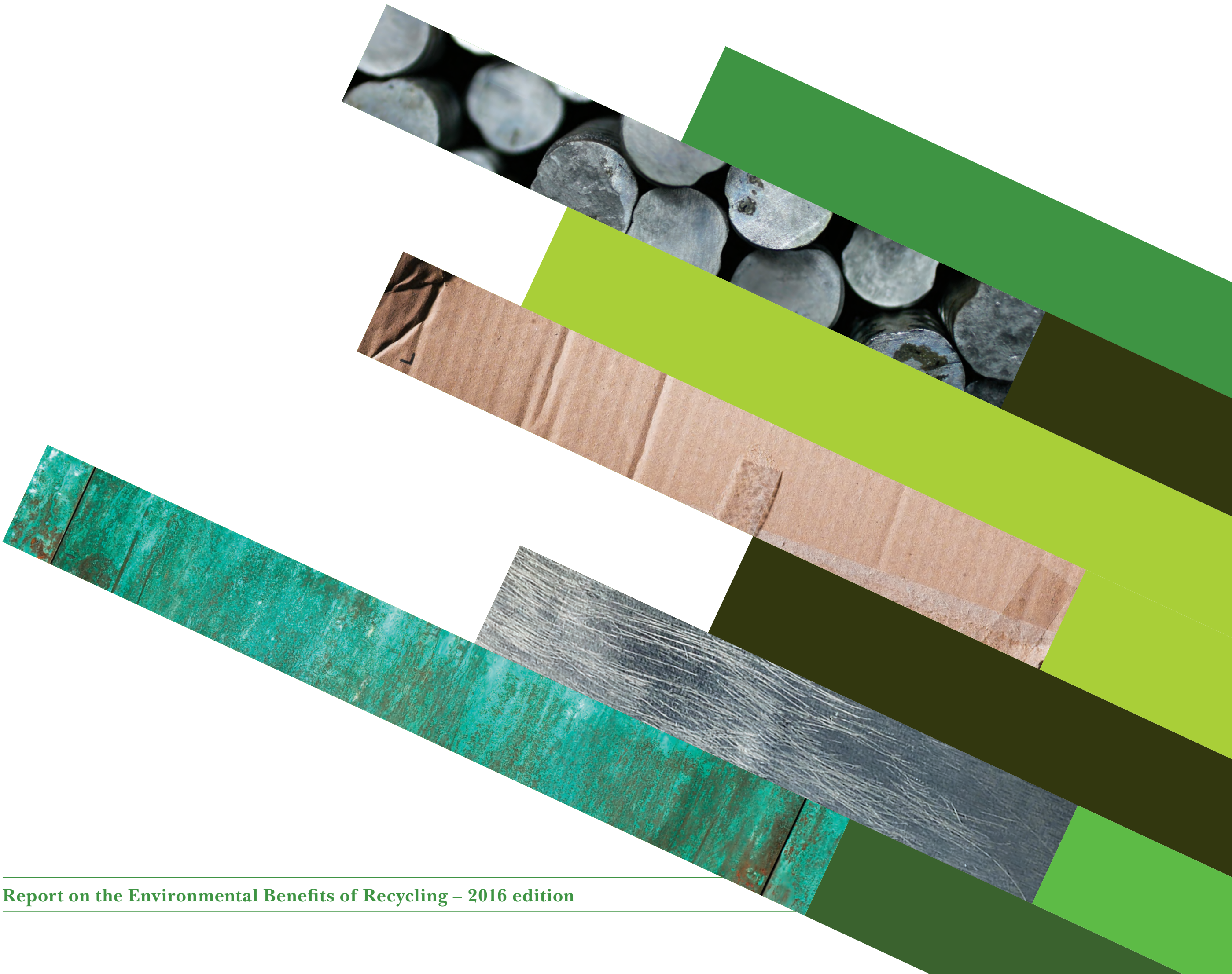
Using the benchmark data for primary and secondary steel production from delivered ore concentrate and scrap respectively, the energy requirements for the production of 100,000 tonnes of steel are:

| | |
|---|---|
| **Energy requirement for primary production (BF-BOF route):** | **1400TJ** |
| **Energy requirement for primary production (DRI + EAF route):** | **1920TJ** |
| **Energy requirement for secondary production (EAF route):** | **1170TJ** |

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$CO_2$** |
| **Carbon footprint for primary production (DRI + EAF route):** | **70kt$CO_2$** |
| **Carbon footprint for secondary production (EAF route):** | **70kt$CO_2$** |

***The benchmark energy and carbon footprint savings between primary (via the BF-BOF route) and secondary ferrous production are 230TJ/100,000t in energy and 97kt$CO_2$e/100,000t in $CO_2$ emissions, respectively.***



# Paper

**Primary and Secondary Paper Production**

In 2012, global paper production amounted to 400Mt, according to BIR and other sources, with Asia accounting for 45% (182Mt), by far the largest paper producer. Europe (104Mt) and North America (85Mt) are also significant producers. Approximately 230Mt of recovered paper is collected worldwide from secondary sources, equivalent to 57% of primary production volumes.

Comparison of the primary and secondary papermaking industry is complicated for the following reasons:

- Recycled pulp and virgin pulp are often combined before manufacture;
- Paper can be recycled only 3-6 times before it degrades;
- The paper product from recycling will be of a lower quality than from primary sources;
- Some types of paper can be made only from 100% virgin pulp;
- Recycled pulp cannot be used alone - some primary pulp is always required;
- Paper is produced from a renewable resource;
- As a waste, paper contains energy that can be recovered by incineration;
- Primary production removes trees and therefore reduces $CO_2$ uptake by the trees;
- Most literature compares disposal options rather than production options.

In the primary manufacture of paper, trees must be harvested, debarked, chipped at the sawmill and pulped with water. Pulping can be conducted by adding chemicals or by mechanical beating which will break down the lignin in wood and allow the pulp to form. Chemical pulping is expensive because the paper yield from wood is very low, but the paper produced is strong. Mechanical pulping is much cheaper despite the considerable use of electrical energy because it leads to a high yield of paper product from the wood, although this paper is much weaker. More water is introduced to the pulp before chemicals and dyes are added prior to the refining, screening and cleaning of the pulp which is then used in paper manufacture.

Waste paper from various sources is sorted, shredded, pulped with water and cleaned to remove impurities such as wire, plastic, paper clips and staples that may be in the mix. A de-inking cell cleans the pulp, removing ink and sticky substances. The pulp is fed into a blend chest where chemicals and dyes are added that will influence the character and appearance of the final product. The pulp is refined using a mechanical abrasive and bruising action before being screened, cleaned to remove any dirt or grit, and used in the manufacture of paper.

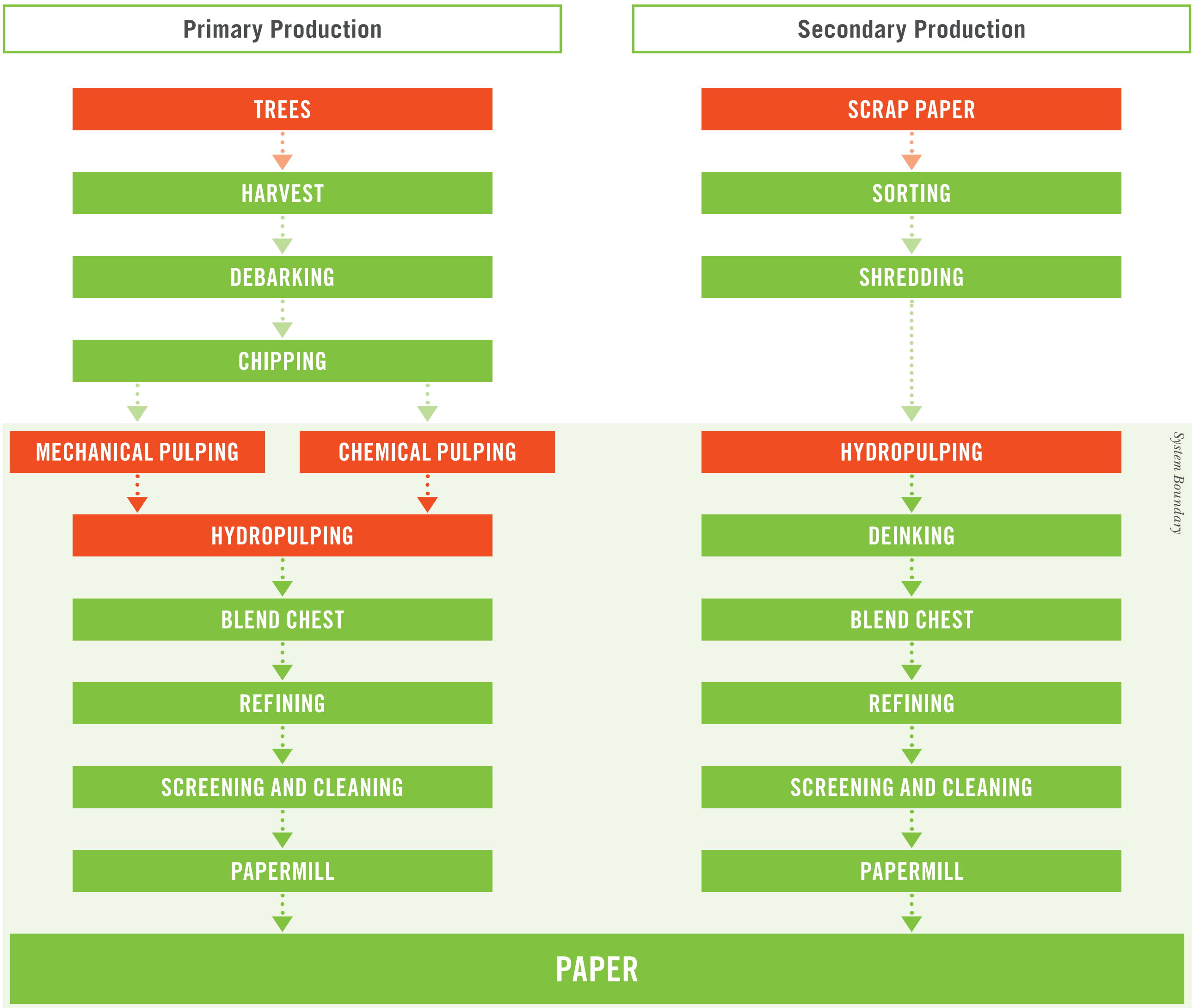
**Process Energy Consumption and Carbon Dioxide Emissions**

The global average energy requirements for the production of 1 tonne of paper has been reported as 10.8GJ of thermal energy and 4.5GJ of electrical energy, and it has been claimed that primary production requires 40% more energy than secondary production, but more fossil fuels are required to make secondary paper. It has also been reported that to produce paper from wood and then recycle it back into paper requires 22-53GJ/t, excluding transportation.

Schenk has compared energy requirements for chemically and mechanically processed paper manufacturing methods, using varying amounts of recyclate in the feedstock. For the use of 100% virgin pulp, the energy requirement is 12GJ/t for chemical processing and 28GJ/t for mechanical processing. If recycled pulp is added to the process, the energy consumption will be increased in the chemical process but decreased in the mechanical process.

A detailed report by The Paper Task Force in 2002 gave information on primary and secondary paper production. The types of paper considered were newsprint, corrugated, office paper and paperboard. The scope of the assessment was broad, including all activities involved from tree felling and waste paper collection to landfill consequences and incinerator ash disposal. For ease of comparison

Primary and Secondary Production of Paper



and simplification of analysis, it was considered that in the recycling scheme the pulp was 100% waste paper. In order to prepare paper of good quality, however, it would not be possible to use 100% pulp from recycled sources. Data obtained from the literature on energy use and direct $CO_2$ emissions are in the following table.

| Paper Recovery Method | Energy Requirement (MJ/kg paper) | Carbon Footprint ($tCO_2$/t paper) |
|---|---|---|
| Primary | 35.2 | 0.0017 |
| Secondary | 18.8 | 0.0014 |

The data in the table below, which are for paper manufacturing steps only (i.e. excluding tree harvesting and transport, and waste paper collection and sorting), show that the total energy requirement for the recycling process is always less than the total energy for paper produced from virgin sources (see graph p. 26).

The benchmark figures for the energy requirement and carbon footprint for the manufacture of newsprint from primary and secondary sources are given in the following table.

Using the benchmark data for primary and secondary paper production from virgin pulp and scrap respectively, the energy requirements for the production of 100,000 tonnes of paper are:

| | |
|---|---|
| **Energy requirement for primary production:** | **3520TJ** |
| **Energy requirement for secondary production:** | **1880TJ** |

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

| | |
|---|---|
| **Carbon footprint for primary production:** | **170kt$CO_2$** |
| **Carbon footprint for secondary production:** | **140kt$CO_2$** |

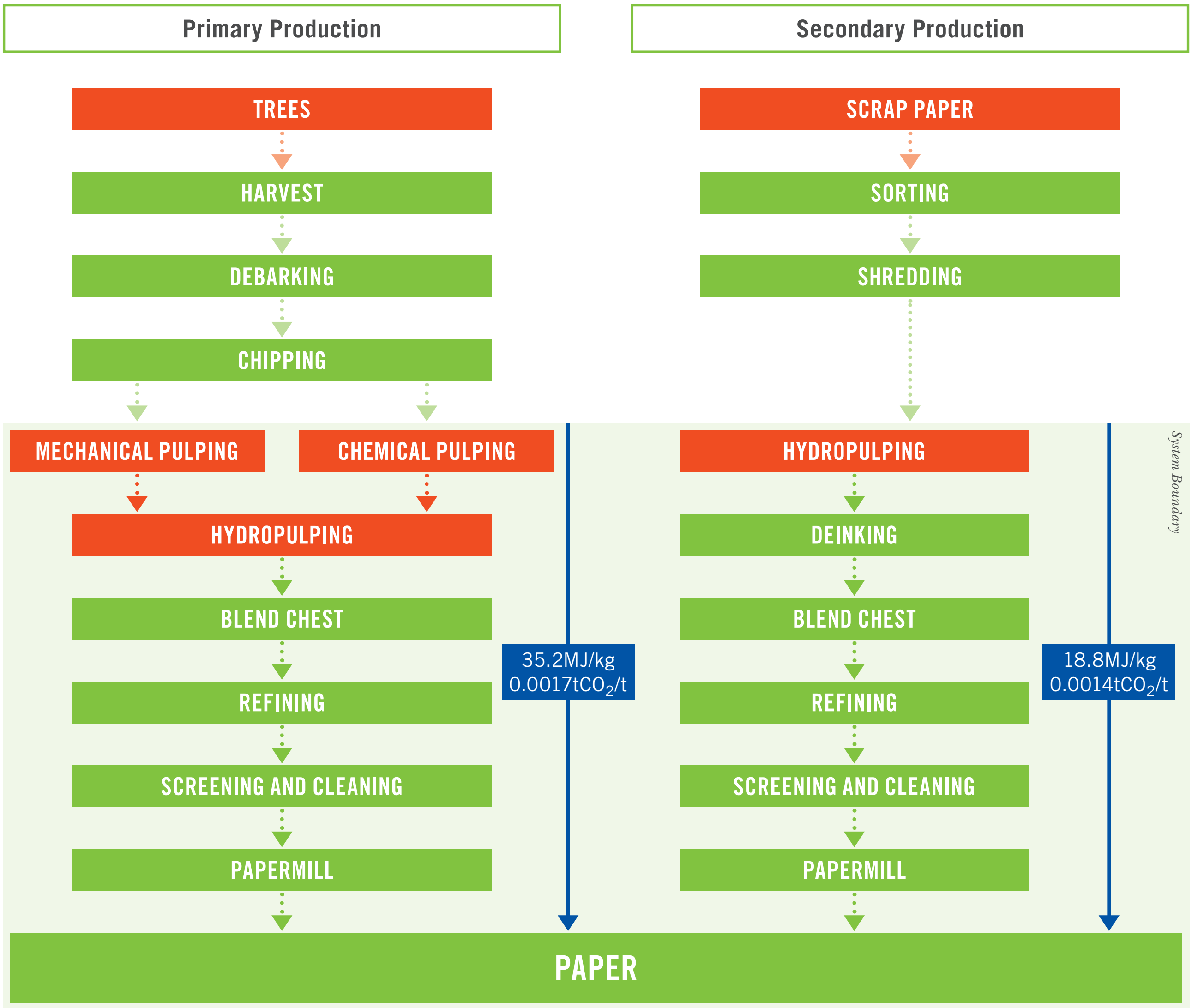
***The benchmark energy and carbon footprint savings between primary and secondary paper production are 1640TJ/100,000t in energy and 30kt$CO_2$e/100,000t in $CO_2$ emissions, respectively.***

**Energy Use and $CO_2$ Emissions for Primary and Secondary Paper Production**

| | UNITS | Newsprint | Corrugated containers | Office paper | Paperboard | |
|---|---|---|---|---|---|---|
| | | | | | CUK[1] | SBS[2] |
| **Virgin Manufacture** | | | | | | |
| **Total Energy** | MJ/kg paper managed | 39 | 28 | 40 | 28 | 41 |
| **Purchased Energy** | MJ/kg paper managed | 36 | 15 | 19 | 14 | 19 |
| **Fossil Fuel Energy** | MJ/kg paper managed | 26 | 13 | 14 | 12 | 14 |
| **Recycled Manufacture** | | | | | | |
| **Total Energy** | MJ/kg paper managed | 21 | 19 | 21 | 17 | 16 |
| **Purchased Energy** | MJ/kg paper managed | 21 | 19 | 21 | 17 | 16 |
| **Fossil Fuel Energy** | MJ/kg paper managed | 16 | 16 | 16 | 13 | 13 |
| **GHG Emissions – Whole system minus waste management and material recovery** | | | | | | |
| **Virgin** | $CO_2$eq t/t paper | 0.0023 | 0.0014 | 0.0014 | 0.0009 | 0.0027 |
| **Recycle** | $CO_2$eq t/t paper | 0.0013 | 0.0013 | 0.0017 | 0.0013 | 0.0014 |

[1] CUK – Coated Unbleached Kraft
[2] SBS – Solid Bleached Sulfate

Paper Production (Primary/Secondary): Process Energy Consumption and $CO_2$ Emissions



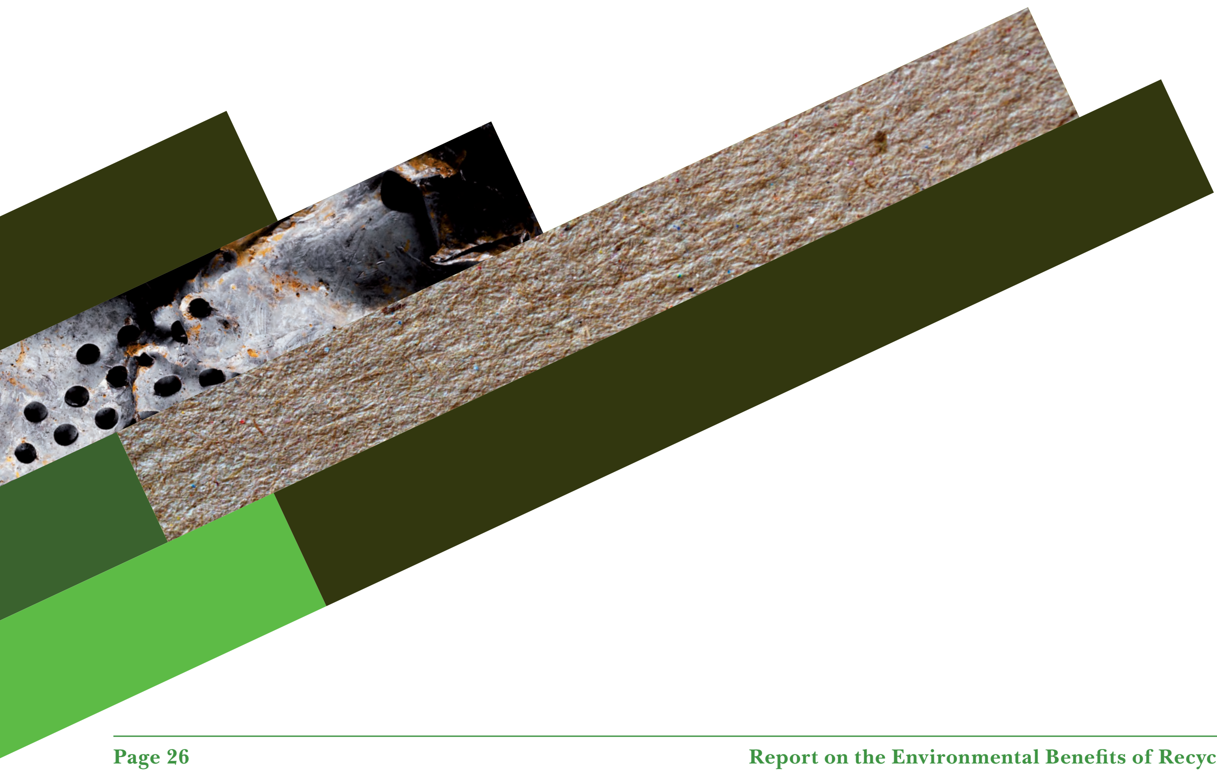
## Summary

Using the benchmark data (from the 2008 study, derived from the literature) for primary and secondary production for the four BIR-nominated commodities of relevance to the current study – metals from delivered ore concentrate and scrap respectively, and paper from virgin pulp and scrap respectively - the energy requirements for the production of 100,000 tonnes of each commodity are shown in the following table.

| Material | Primary (TJ) | Secondary (TJ) | Savings (TJ/100,000t) |
|---|---|---|---|
| Aluminium | 4700 | 240 | 4460 |
| Copper | 1690 | 630 | 1060 |
| Ferrous | 1400 | 1170 | 230 |
| Paper | 3520 | 1880 | 1640 |

Using these energy data, the carbon footprints for primary and secondary commodity production on the same basis are shown in the following table.

| Material | Primary ($ktCO_2e$) | Secondary ($ktCO_2e$) | Savings ($ktCO_2e$/100,000t) | % Savings ($CO_2e$) |
|---|---|---|---|---|
| Aluminium | 383 | 29 | 354 | 92 |
| Copper | 125 | 44 | 81 | 65 |
| Ferrous | 167 | 70 | 97 | 58 |
| Paper | 0.17 | 0.14 | 0.03 | 18 |



# Sensitivity Analysis and Impact of Externalities on Benchmark Data Interpretation

The benchmark energy and carbon emissions data for primary production calculated in the 2008 report represented the most efficient production processes available with the lowest energy consumption in situations where the best possible energy mixes are used anywhere in the world. It is important, however, to take account of operations that depart from the ideal benchmark conditions. Furthermore, in the current study, the effects of variations in energy conversion factors and energy source/fuel mix on the benchmark data are calculated to show the extent of their influence.

## Sensitivity Analysis of Benchmark Data

To account for any such deviation, sensitivity analyses can be carried out on any of the input data in order to show how differences in process parameters would be reflected in the overall energy saving and carbon footprint results. Sensitivity analysis can be applied to the benchmark data and used for deviations from benchmark conditions including, for example:

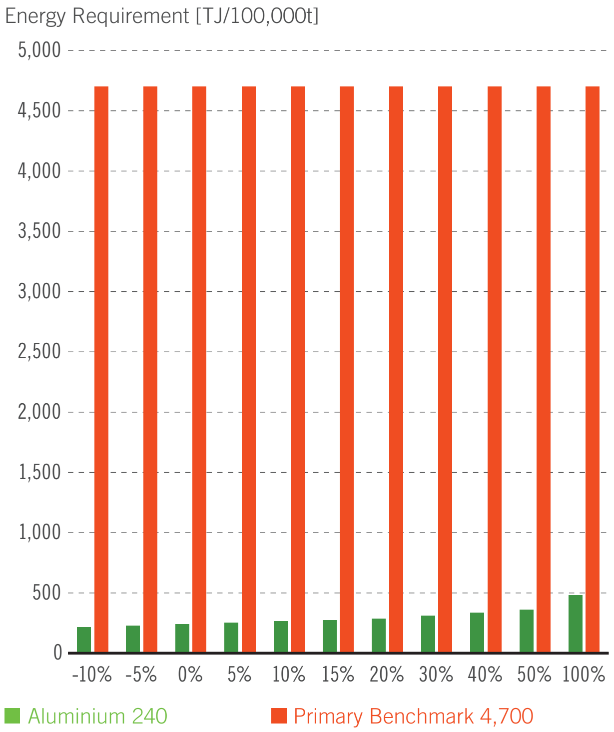
- Secondary production energy requirement data compared with the primary benchmark;
- Primary production energy requirement data from the benchmark;
- Primary production energy requirement data compared with secondary benchmark;
- Carbon footprint data for secondary recovery compared with the primary benchmark; and
- Carbon footprint data for primary production from the primary benchmark.

Both the primary and secondary benchmark figures will change with any plant inefficiencies compared to the benchmark conditions. The effect of these variations are shown numerically for an overall percentage deviation from the benchmark values (0% in the tables over the range -10% (i.e. more efficient) to +100% (less efficient)).

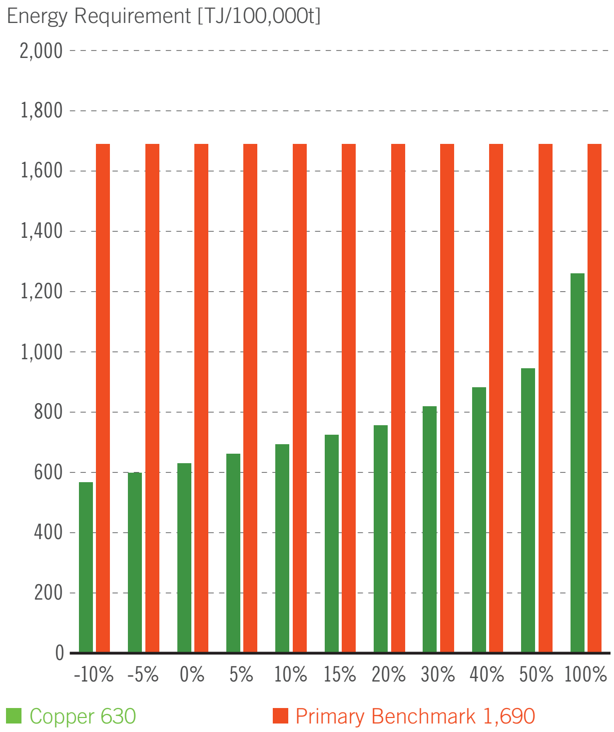
The variations are expressed for secondary energy requirement data vs. primary benchmark data in the table below, and diagrammatically in the charts on p. 28 for each of the BIR-nominated commodities.

| Material | Primary | Secondary | Sensitivity Analysis of Secondary Energy Data (expressed as TJ/100,000t) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | -10% | -5% | 0% | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 100% |
| **Aluminium** | **4700** | **240** | 216 | 228 | 240 | 252 | 264 | 276 | 288 | 312 | 336 | 360 | 480 |
| **Copper** | **1690** | **630** | 567 | 599 | 630 | 662 | 693 | 725 | 756 | 819 | 882 | 945 | 1260 |
| **Ferrous** | **1400** | **1170** | 1053 | 1112 | 1170 | 1229 | 1287 | 1346 | **1404** | **1521** | **1638** | **1755** | **2340** |
| **Paper** | **3520** | **1880** | 1692 | 1786 | 1880 | 1974 | 2068 | 2162 | 2256 | 2444 | 2632 | 2820 | **3760** |

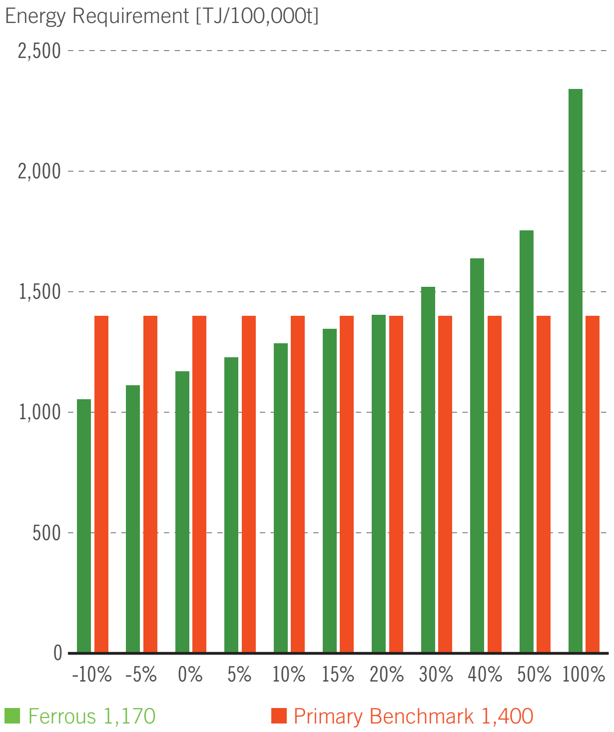
### Aluminium



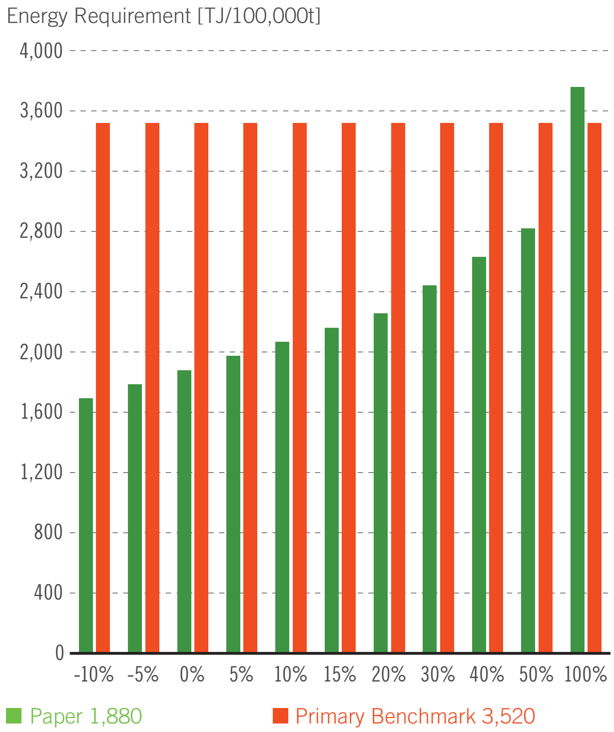

### Copper




### Ferrous




### Paper




The data show that, for aluminium and copper, even if a given process deviates by 100% from the benchmark, an energy saving would still be predicted. However, for ferrous and paper, deviations of less than 100% would result in the prediction of an energy balance in favour of primary production.

By way of example, for the metals studied in the current work, the data in the following tables show:

1 How variations would arise in carbon footprint data for secondary production if a given process deviated from the primary benchmark data. The sensitivity analysis is calculated across the same range; for all the metals studied, deviations by plus 100% from the benchmark still lead to the prediction of carbon dioxide savings from the secondary process;

2 The variation in energy requirement and in $CO_2$ emissions with deviations from the primary benchmark data that would have to be compared with the energy requirement and the carbon footprint for secondary production in given situations.

Sensitivity analysis can also be applied to consider variations in energy and carbon footprint by country arising from differences in energy conversion factors and sources of energy and fuel/energy balance.

| Metals Studied in Current Work | Primary | Secondary | Sensitivity Analysis of Secondary $CO_2$ Data (expressed as $ktCO_2e$/100,000t) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | -10% | -5% | 0% | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 100% |
| **Aluminium** | **383** | **29** | 26 | 28 | 29 | 30 | 32 | 33 | 35 | 38 | 41 | 44 | 58 |
| **Copper** | **125** | **44** | 40 | 42 | 44 | 46 | 48 | 51 | 53 | 57 | 62 | 66 | 88 |
| **Ferrous** | **167** | **70** | 63 | 67 | 70 | 74 | 77 | 81 | 84 | 91 | 98 | 105 | 140 |

| Metals Studied in Current Work | Primary | Sensitivity Analysis of Primary Energy Data (expressed as TJ/100,000t) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -10% | -5% | 0% | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 100% |
| **Aluminium** | **4700** | 4230 | 4465 | 4700 | 4935 | 5170 | 5405 | 5640 | 6110 | 6580 | 7580 | 9400 |
| **Copper** | **1690** | 1521 | 1606 | 1690 | 1775 | 1859 | 1944 | 2028 | 2197 | 2366 | 2535 | 3380 |
| **Ferrous** | **1400** | 1260 | 1330 | 1400 | 1470 | 1540 | 1610 | 1680 | 1820 | 1960 | 2100 | 2800 |

| Metals Studied in Current Work | Primary | Sensitivity Analysis of Primary $CO_2$ Data (expressed as $ktCO_2e$/100,000t) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -10% | -5% | 0% | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 100% |
| **Aluminium** | **383** | 345 | 364 | 383 | 402 | 421 | 440 | 460 | 498 | 536 | 575 | 766 |
| **Copper** | **125** | 113 | 119 | 125 | 131 | 138 | 144 | 150 | 163 | 175 | 188 | 250 |
| **Ferrous** | **167** | 150 | 159 | 167 | 175 | 184 | 192 | 200 | 217 | 234 | 251 | 334 |

## Impact of Externalities on Benchmark Data

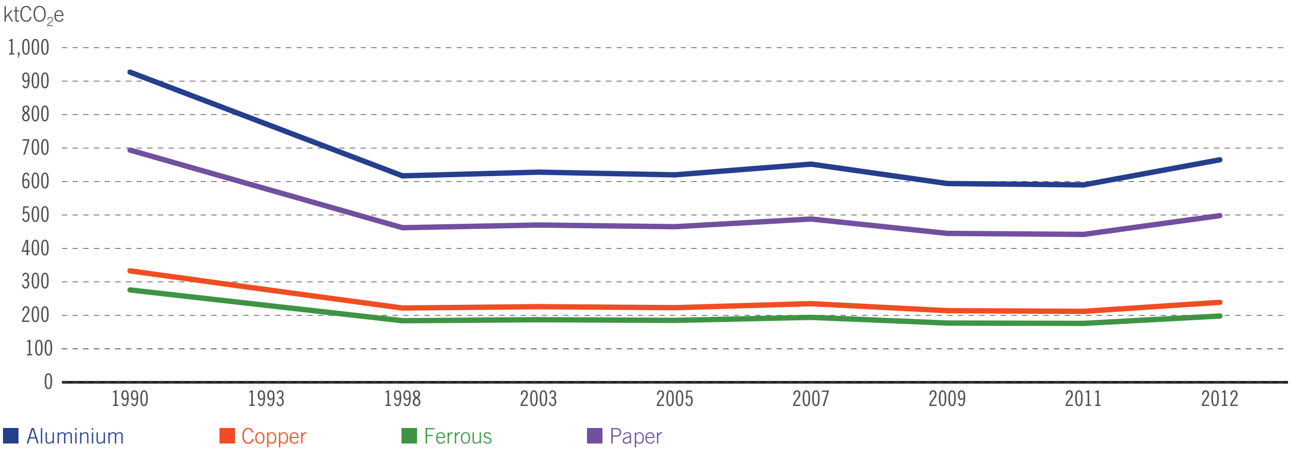
In this section the effects of variations in energy conversion factors and energy source/fuel mix on the benchmark data are calculated to show the extent of their influence.

### Energy Conversion Factors

Energy conversion factors, reported annually by country and region, in general, change year on year. The UK Grid electricity generated (excluding imports), for example, has changed from a value of 0.70991$kgCO_2e$/kWh in 1990 to the latest reported value of 0.50935$kgCO_2e$/kWh in 2012 and calculated here to show the variation in the primary benchmark energy data (tabled and shown graphically on p. 30) for each of the BIR-nominated commodities over the last two decades.

| Year | Energy Conversion Factor $kgCO_2e/kWh$ | Aluminium ($ktCO_2e$) | Copper ($ktCO_2e$) | Ferrous ($ktCO_2e$) | Paper ($ktCO_2e$) |
|---|---|---|---|---|---|
| | | Primary Benchmark Energy Data (TJ) | | | |
| | | 4700 | 1690 | 1400 | 3520 |
| 1990 | 0.70991 | 927 | 333 | 276 | 694 |
| 1993 | 0.59098 | 772 | 277 | 230 | 578 |
| 1998 | 0.47226 | 617 | 222 | 184 | 462 |
| 2003 | 0.48084 | 628 | 226 | 187 | 470 |
| 2005 | 0.47515 | 620 | 223 | 185 | 465 |
| 2007 | 0.49956 | 652 | 235 | 194 | 488 |
| 2009 | 0.45501 | 594 | 214 | 177 | 445 |
| 2011 | 0.45192 | 590 | 212 | 176 | 442 |
| 2012 | 0.50935 | 665 | 239 | 198 | 498 |

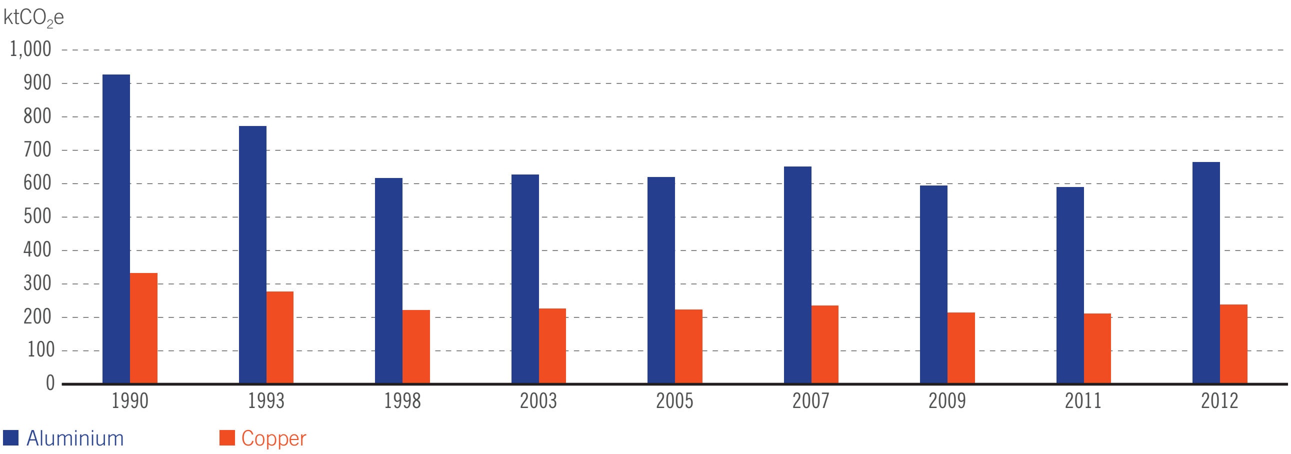
## Effect of Grid Electricity Emission Factor (in $ktCO_2e/kWh$) on Conversion of Primary Benchmark Energy Data to $CO_2$ Emissions




Based on DECC's GHG Conversion Factors – June 2014

Using copper as an example commodity, it is noted from the calculated values for the energy requirement benchmark of 1690MJ, in the table above, that there is a variance of 121$ktCO_2e$ in $CO_2$ emissions between a maximum of 333$ktCO_2e$ recorded in 1990 to a minimum of 212$ktCO_2e$ in 2011. By comparison, for aluminium there is a variance of 337$ktCO_2e$ in $CO_2$ emissions over the same time period. A profile for both commodities is shown below.

## Effect of Grid Electricity Emission Factor (in $ktCO_2e/kWh$) on Conversion of Primary Benchmark Energy Data to $CO_2$ Emissions: Profile for Aluminium and Copper




Based on DECC's GHG Conversion Factors – June 2014

### Energy Source/Fuel Mix

One obvious potential variation in energy use between countries or regions depends upon the nature of the energy source, ranging from efficient hydroelectric production of electricity to the use of low-grade coals.

Many primary and secondary production processes for metals rely, for example, on electricity as a source of energy, and the following table lists different sources of electricity (GWh) extracted from data contained in DECC's guidance document on GHG Conversion Factors (June 2014).

| Source | Electricity (GWh) |
|---|---|
| Gas | 176,748 |
| Coal | 126,699 |
| Nuclear | 52,486 |
| Hydro | 9,257 |
| Biomass | 8,090 |
| Wind | 7,097 |
| Oil | 6,101 |
| Waste | 2,871 |
| Solar PV | 17 |

Source: Based on DECC's GHG Conversion Factors - June 2014

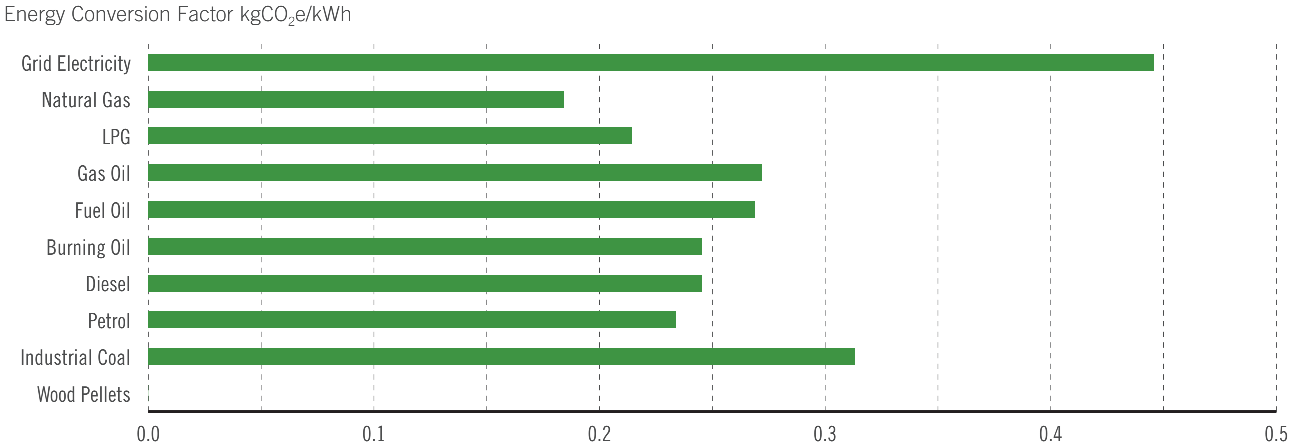
The associated $CO_2$ emission factors for different fuel types, taken from the Carbon Trust (drawn from DECC's GHG Conversion Factors for 2011, published in June 2013 (DECC, 2013)), are shown in the following table, with the most recently reported value of 0.50935kg$CO_2$e/kWh for grid electricity from DECC (2014) – the value used in the current study – included for reference.

| Fuel Type | Energy Conversion Factor (kg$CO_2$e/kWh) |
|---|---|
| **Grid Electricity[a]** | **0.50935** |
| Grid Electricity | 0.44548 |
| Coal | 0.31304 |
| Gas Oil | 0.27176 |
| Fuel Oil | 0.26876 |
| Burning Oil | 0.24555 |
| Diesel (contains biofuel content) | 0.24512 |
| Petrol (contains biofuel content) | 0.23394 |
| LPG | 0.21452 |
| Natural Gas | 0.18404 |
| Wood Pellets | 0 |

Source: Carbon Trust drawn from DECC's GHG Conversion Factors – June 2013.
[a] Based on DECC's GHG Conversion Factors - June 2014.

The energy conversion factors are quoted as total "direct" kg$CO_2$e per unit of fuel, as representing the emissions at the point of use of a fuel or at the point of generation for electricity. A profile of the comparative energy conversion factors is shown in the graph below.

### Comparative Energy Conversion Factors per Fuel Type




Source: Carbon Trust drawn from DECC's GHG Conversion Factors – June 2013

### Influence of Energy Conversion Factors & Source/Fuel Mix on Benchmark Data

According to the International Energy Agency (IEA), in 2012 global $CO_2$ emissions were 31.7 $GtCO_2$, representing a 1.2% year-on-year increase in emissions, about half the average annual growth rate since 2000, and four percentage points less than in 2010, the year of initial recovery after the financial crisis. The IEA provides information on the electricity emission factors (expressed as $CO_2$ emissions per kWh) worldwide between 1990 and 2012, as well as averaged for 2009-2011. These data are used here in calculations to take account of variations in electricity-based energy conversion factors in different EU countries and across different world regions; and energy conversion data for any fuel or mixed fuel use. Using copper as an example, the results of the calculations are reported in tables and profiles below.

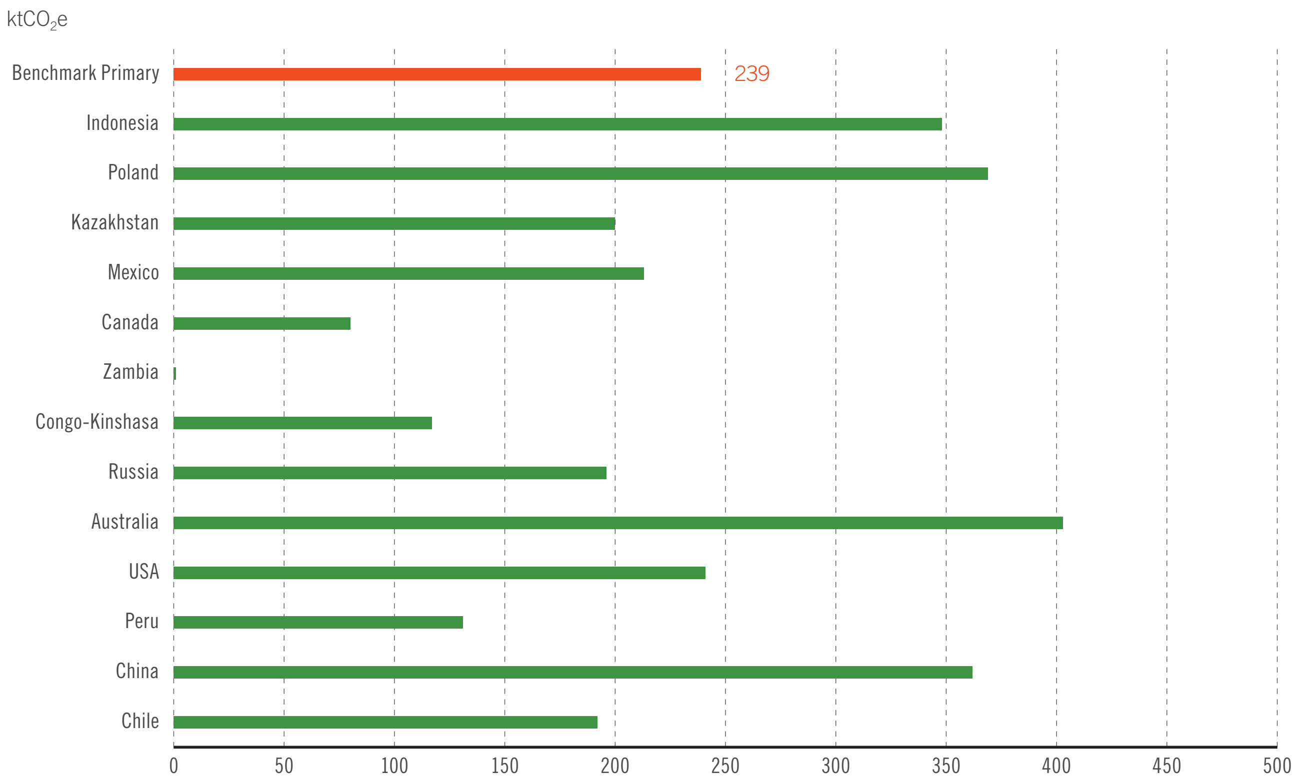
The estimated primary production of copper in 2013 was 17.9M tonnes, with almost 90% mined in the largest producing countries, as listed in the table. Corresponding $CO_2$ emissions per kWh from electricity generation are included.

**Largest Copper Mine Producers and Production in 2013**

| Country | Copper Mine Production (Mt)[a] | $CO_2$ Emissions $kgCO_2e/kWh$[b] |
|---|---|---|
| Chile | 5.70 | 0.408 |
| China | 1.65 | 0.771 |
| Peru | 1.30 | 0.280 |
| USA | 1.22 | 0.514 |
| Australia | 0.99 | 0.859 |
| Russia | 0.93 | 0.417 |
| Congo-Kinshasa (incl DRC) | 0.90 | 0.250 |
| Zambia | 0.83 | 0.003 |
| Canada | 0.63 | 0.171 |
| Mexico | 0.48 | 0.454 |
| Kazakhstan | 0.44 | 0.427 |
| Poland | 0.43 | 0.787 |
| Indonesia | 0.38 | 0.741 |
| **Total** | **15.88** | **6.082** |

[a] U.S. Geological Survey, Mineral Commodity Summaries, February 2014;
[b] IEA Statistics 2013 $CO_2$ Emissions from Fuel Combustion

**$CO_2$ Emissions per 100,000 tonnes of Primary Copper Production in Selected Countries**



The production of 100,000 tonnes of primary copper following the pyrometallurgical route can be compared for different countries on the basis of electricity emission factors.

To do this, it is assumed that all countries initially have the same specific energy requirement (based on the benchmark primary and secondary data of 1690TJ per 100,000 tonnes and 630TJ per 100,000 tonnes respectively), and takes no account of variation in process efficiencies at country level.

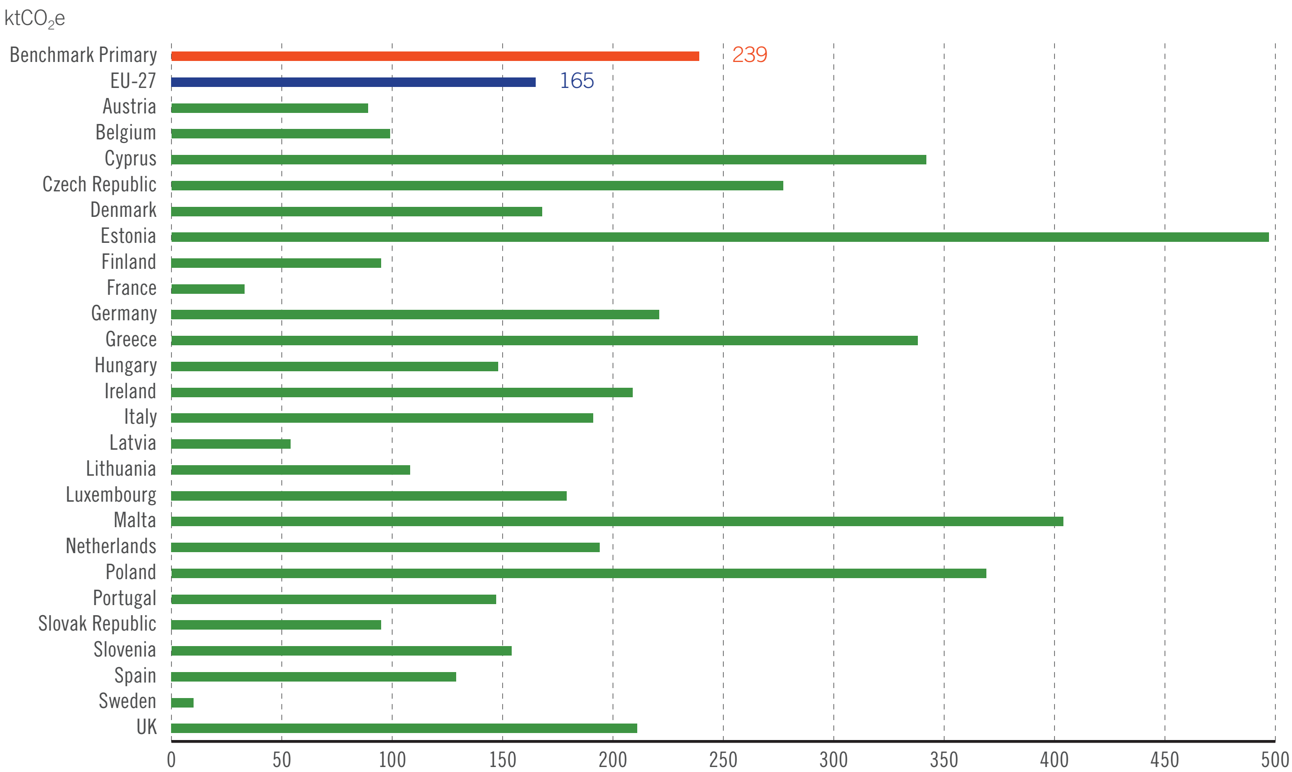
Assuming that the energy requirement can be based on electricity emission factors, the profile on p. 32 shows the calculated emissions of $CO_2$ per 100,000 tonnes of primary copper production from ore concentrate compared with the benchmark value of 239kt$CO_2$, using the energy conversion factor of 0.50935kg$CO_2$e/kWh.

The data are based on the most recent reported figures from the IEA (averaged for the period 2009-2011) published in 2013 for $CO_2$ emissions per kWh from electricity generation, by country, and have been applied to the benchmark primary energy requirement of 1690TJ, normalised to provide direct comparison. From this comparison profile, four producer countries, for example, exceed by more than 10% the benchmark value of 239kt$CO_2$, with primary production in Australia (at 403kt$CO_2$) some 69% higher than the benchmark.

A similar profile (not shown) is obtained for $CO_2$ emissions for secondary copper production from scrap, normalising the data against the benchmark secondary energy requirement of 630TJ and again taking no account of changes in process efficiencies at country level. On this basis, comparison with the secondary benchmark value of 89kt$CO_2$ indicates a $CO_2$ emission level for secondary production in Australia that exceeds the benchmark value by 150kt$CO_2$.

The profile below shows a sensitivity analysis that takes account of the differences in the electricity-based energy conversion factors for different countries across the EU and shows how the $CO_2$ emissions would change (for copper) if the conversion factors for other countries were used rather than the conversion value of 0.50935kg$CO_2$e/kWh used in the study.

## Variation in Primary Carbon Footprint Data for Copper (based on Conversion Factors for EU-27 Countries)




Source: IEA $CO_2$ Emissions from Fuel Combustion Highlights 2013

Hypothetically, looking at the same profile across Europe, with the EU-27 average at 165kt$CO_2$, there are six countries that would exceed the benchmark value of 239kt$CO_2$, with Estonia generating an emission level of 497kt$CO_2$, some 108% higher. Sweden, on the other hand, records the lowest level of emissions at 10kt$CO_2$, 96% lower than the benchmark value.

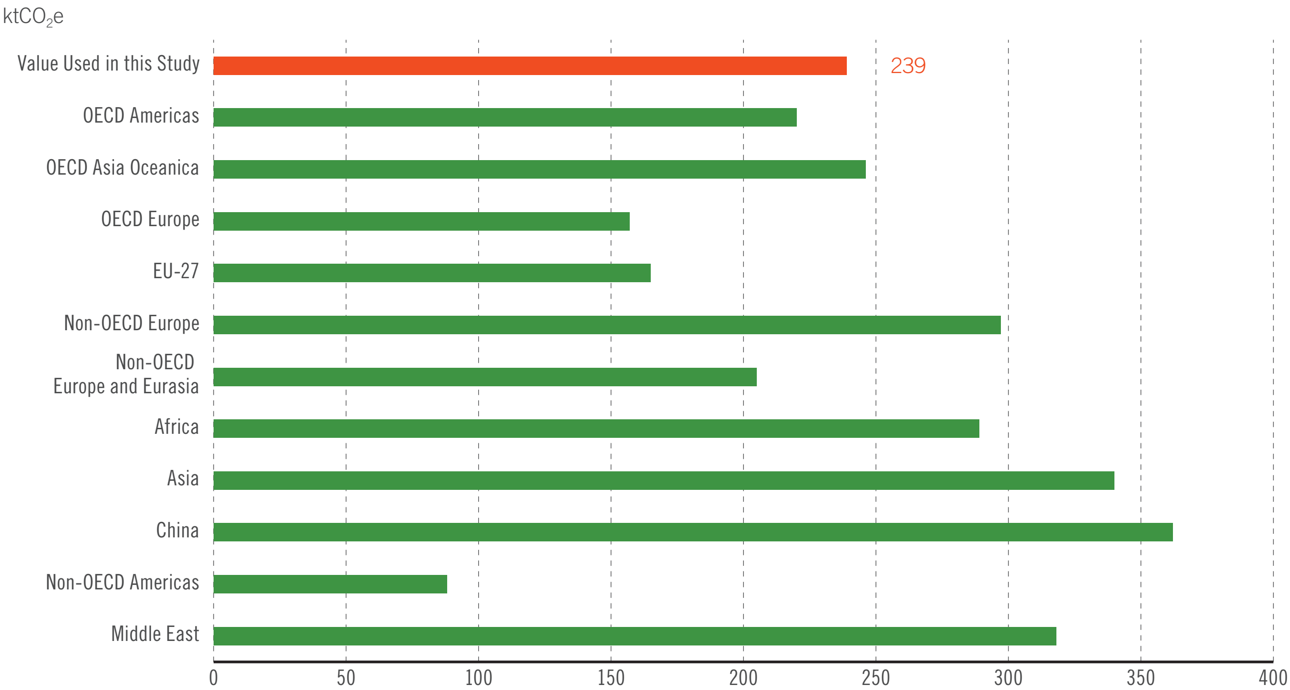
It can be seen from the profile that the calculated UK value of 211kt$CO_2$ is less than the benchmark of 239kt$CO_2$. The UK value is calculated using the IEA's most recent data for $CO_2$ emissions per kWh from electricity generation for all countries (published in 2013), a figure which is close to that reported in the UK DECC GHG Conversion Factors for 2011 (DECC, 2013), but less than the value used to calculate the benchmark equivalent which is taken from the UK DECC GHG Conversion Factors for 2012 (DECC, 2014), 0.50935kg$CO_2$e/kWh.

Interpreting the IEA figures for electricity emission factors (expressed as $CO_2$ emissions per kWh), by region, for 2009-2011, and normalising the data against the primary benchmark of 239kt$CO_2$, the profile below shows that five would exceed this level by more than 10%, with China, a major producing country generating an emission level of 362kt$CO_2$, some 50% higher, with the Non-OECD Americas region, on the other hand, recording the lowest comparative level of emissions at 88kt$CO_2$, or 63% lower than the benchmark value.

Regional differences in contributions to global emissions, however, do conceal even larger differences among individual countries as shown in the following table.

| **Region** | **Calculated kt$CO_2$e** |
|---|---|
| OECD Europe | 157 |
| *Estonia* | *497* |
| Non-OECD Europe and Eurasia | 297 |
| *Kosovo* | *576* |
| Africa | 289 |
| *Botswana* | *839* |
| Non-OECD Americas | 88 |
| *Cuba* | *475* |
| **Benchmark** | **239** |

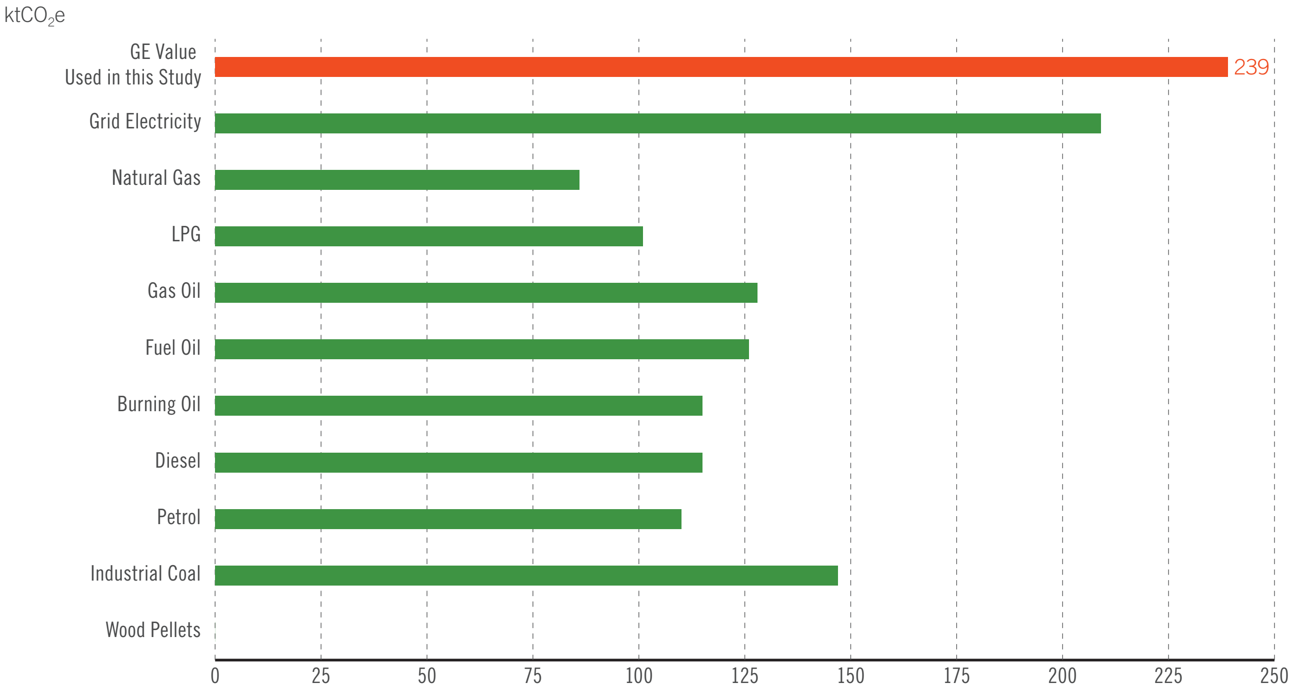
## Variation in Primary Carbon Footprint Data for Copper (based on Conversion Factors for World Regions)




Source: IEA $CO_2$ Emissions from Fuel Combustion Highlights 2013

Using the comparative most recent energy conversion factors for electricity generation, by fuel type, cited earlier in this section, the data can be normalised against the primary benchmark of 239kt$CO_2$. The resulting profile below shows the impact of a change in energy conversion factor for grid electricity [from 0.44548kg$CO_2$e/kWh (reported for 2011) to 0.50935kg$CO_2$e/kWh (reported for 2012)], on $CO_2$ emissions – 209kt$CO_2$ and 239kt$CO_2$ respectively.

**Variation in Primary Carbon Footprint Data for Copper (based on Conversion Factors for Different Energy Sources)**




## Summary

The benchmark energy and carbon emissions data for primary production represent the most efficient production processes available with the lowest energy consumption in situations where the best possible energy mixes are used anywhere in the world. To take account of operations that depart from the ideal benchmark conditions for the production of the BIR-nominated commodities, sensitivity analyses have been carried out on the data to show how differences in process parameters would be reflected in the overall energy saving and carbon footprint results.

The impact of variations in energy conversion factors, energy source, fuel mix and country emission levels have been described. Although illustrated for copper as the example commodity, using its benchmark primary and secondary data, the impact of these and other variations such as process efficiencies can be studied for any commodity using benchmark or real industry data.

# Analysis and Interpretation of Industry-Acquired Data for Single- and Mixed-Stream Processes

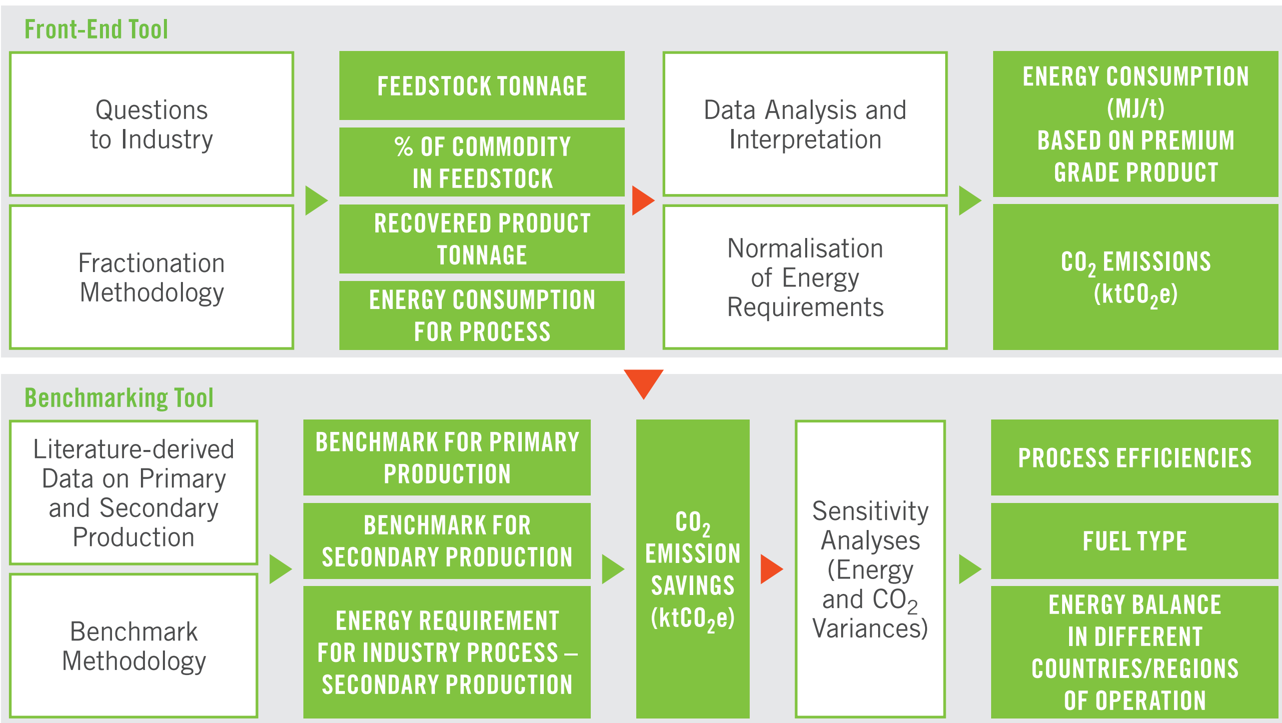
## Introduction

To realise the full potential and value of applying the benchmark methodology, developed as part of the 2008 BIR study, relies on industry engagement such that the energy requirements and carbon footprints can be determined based on industry-acquired data. In this section, data provided from industry have allowed calculations of energy requirements and carbon dioxide emissions for both single-stream processes for each of the BIR-nominated commodities, and separately for mixed-metal streams containing all three target metals. As agreed with BIR, the sources of these industry data remain anonymous and unattributed.

Using the data provided by industry, the energy requirement for the recovery of 100,000 tonnes of each commodity is calculated based on the methodologies developed and applied in this study (illustrated in the schematic below) and compared with the benchmark values (essentially the best achievable) for its primary and secondary production derived from the desk-based research carried out in the 2008 BIR study.

Conversion of these energy requirements to the corresponding $CO_2$ emissions for the industry-acquired data used, for illustrative purposes, the most recently reported value of the energy conversion factor for UK Grid electricity generated (excluding imports), namely, 0.50935kg$CO_2$e/kWh (taken from the UK DECC GHG Conversion Factors for 2012, published in June 2014 (DECC, 2014)). Sensitivity analyses on these data are carried out to illustrate the effects of deviations from benchmark conditions. To permit direct in-region comparison to be made, the 2008 benchmark data have been recalculated using the 0.50935kg$CO_2$e/kWh energy conversion factor.

***For the purposes of interpretation, values obtained directly from industry are referred to as "industry-acquired" but any values reported based on calculations in this work are referred to as "industry-derived".***



## Single-Stream Process

For single-stream processes, industry data have been provided that have allowed the determination of energy requirements and $CO_2$ emissions (using the "Front-end" tool) for the recovery of a fully-refined product for each commodity. Moreover, sensitivity analyses can be used on the industry-acquired data for each commodity, for individual process plants and regions, to illustrate how differences in operating conditions and process parameters can influence the overall energy savings and carbon footprint results.

### Aluminium

The data on energy and carbon dioxide emissions savings are presented for aluminium delivered as a fully-refined product. The calculated energy requirement for the recovery of 100,000 tonnes of aluminium is compared with the benchmark values for primary and secondary production, as shown below.

| | |
|---|---|
| **Energy requirement for primary production:** | **4700TJ** |
| **Energy requirement for secondary production:** | **240TJ** |
| **Energy requirement for the process (industry-derived):** | **266TJ** |

These data are shown diagrammatically for the commodity to illustrate the comparisons (see below).

Using the energy data and applying the energy conversion factor of 0.50935kg$CO_2$e/kWh, the carbon footprints ($CO_2$ emissions) for primary and secondary processes of aluminium, on the same basis, are:

| | |
|---|---|
| **Carbon footprint for primary production:** | **665kt$CO_2$** |
| **Carbon footprint for secondary production:** | **34kt$CO_2$** |
| **Carbon footprint for the process (industry-derived):** | **38kt$CO_2$** |

***The benchmark energy and carbon footprint savings achieved by industry against the primary benchmark for aluminium production in a region where the conversion factor, 0.50935kg$CO_2$e/kWh, is appropriate, would be 4434TJ/100,000t in energy and 627kt$CO_2$e/100,000t in $CO_2$ emissions, respectively.***

### Copper

The data on energy and carbon dioxide emissions savings are presented for copper delivered as a fully-refined product. The calculated energy requirement for the recovery of 100,000 tonnes of copper is compared with the benchmark values for primary and secondary production, as shown below:

| | |
|---|---|
| **Energy requirement for primary production:** | **1690TJ** |
| **Energy requirement for secondary production:** | **630TJ** |
| **Energy requirement for the process (industry-derived):** | **657TJ** |

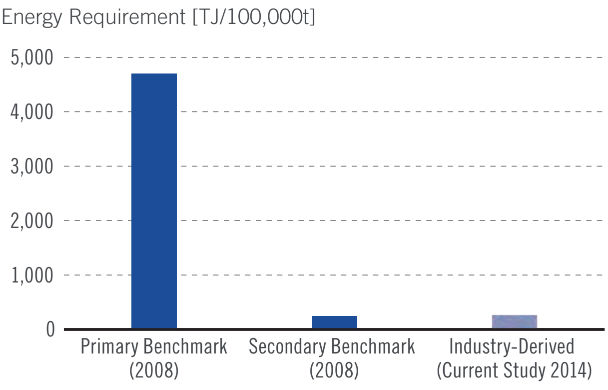
These data are shown diagrammatically for the commodity to illustrate the comparisons (see below).

Using the energy data and applying the energy conversion factor of 0.50935kg$CO_2$e/kWh, the carbon footprints ($CO_2$ emissions) for primary and secondary processes of copper, on the same basis, are:

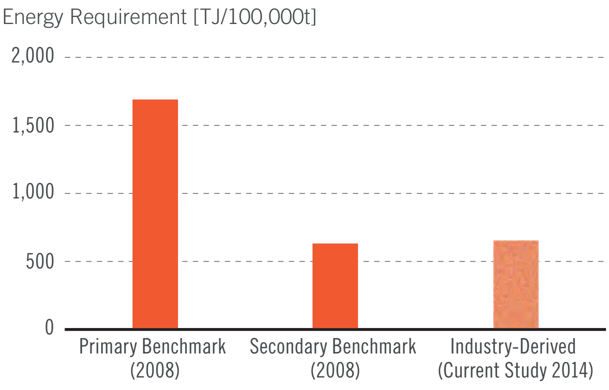
| | |
|---|---|
| **Carbon footprint for primary production:** | **239kt$CO_2$** |
| **Carbon footprint for secondary production:** | **89kt$CO_2$** |
| **Carbon footprint for the process (industry-derived):** | **93kt$CO_2$** |

***The benchmark energy and carbon footprint savings achieved by industry against the primary benchmark for copper production via the pyrometallurgical route, in a region where the conversion factor, 0.50935kg$CO_2$e/kWh, is appropriate, are 1033TJ/100,000t in energy and 146kt$CO_2$e/100,000t in $CO_2$ emissions, respectively.***

### Aluminium




### Copper



### Ferrous

The data on energy and carbon dioxide emissions savings are presented for ferrous delivered as a fully-refined product. The calculated energy requirement for the recovery of 100,000 tonnes of ferrous is compared with the benchmark values for primary and secondary production, as shown below:

| | |
|---|---|
| **Energy requirement for primary production:** | **1400TJ** |
| **Energy requirement for secondary production:** | **1170TJ** |
| **Energy requirement for the process (industry-derived):** | **1194TJ** |

These data are shown diagrammatically for the commodity to illustrate the comparisons (see below).

Using the energy data and applying the energy conversion factor of 0.50935kg$CO_2$e/kWh, the carbon footprints ($CO_2$ emissions) for primary and secondary processes of ferrous, on the same basis, are:

| | |
|---|---|
| **Carbon footprint for primary production:** | **198kt$CO_2$** |
| **Carbon footprint for secondary production:** | **166kt$CO_2$** |
| **Carbon footprint for the process (industry-derived):** | **169kt$CO_2$** |

***The benchmark energy and carbon footprint savings achieved by industry against the primary benchmark for ferrous production via the BF-BOF route in a region where the conversion factor, 0.50935kg$CO_2$e/kWh, is appropriate, are 206TJ/100,000t in energy and 29kt$CO_2$e/100,000t in $CO_2$ emissions, respectively.***

### Paper

The data on energy and carbon dioxide emissions savings are presented for paper delivered as a fully-refined product. The calculated energy requirement for the recovery of 100,000 tonnes of paper is compared with the benchmark values for primary and secondary production, as shown below:

| | |
|---|---|
| **Energy requirement for primary production:** | **3520TJ** |
| **Energy requirement for secondary production:** | **1880TJ** |
| **Energy requirement for the process (industry-derived):** | **1541TJ** |

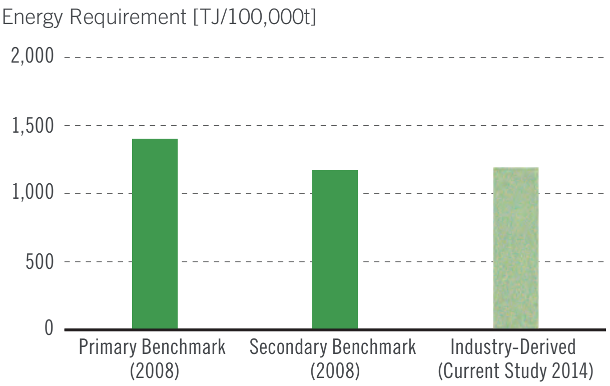
These data are shown diagrammatically for the commodity to illustrate the comparisons (see below).

Using the energy data and applying the energy conversion factor of 0.50935kg$CO_2$e/kWh, the carbon footprints ($CO_2$ emissions) for primary and secondary processes of paper, on the same basis, are:

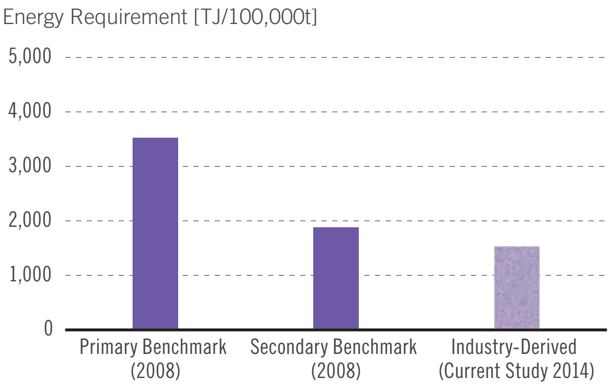
| | |
|---|---|
| **Carbon footprint for primary production:** | **498kt$CO_2$** |
| **Carbon footprint for secondary production:** | **266kt$CO_2$** |
| **Carbon footprint for the process (industry-derived):** | **218kt$CO_2$** |

***The benchmark energy and carbon footprint savings achieved by industry against the primary benchmark for paper production in a region where the conversion factor, 0.50935kg$CO_2$e/kWh, is appropriate, are 1979TJ/100,000t in energy and 280kt$CO_2$e/100,000t in $CO_2$ emissions, respectively.***

### Ferrous




### Paper



### Sensitivity Analysis of Industry-Derived Data

Sensitivity analysis can be applied to industry-acquired data for individual process plants and regions to take account of differences in operating conditions and illustrate the effects of deviations from benchmark conditions.

The data in the tables below show how overall variations, expressed as a percentage deviation from the industry-derived data, would affect the energy savings (and $CO_2$ emissions) achieved in specific plant processes. It should be noted for aluminium, copper and paper that even if the savings in energy consumption are doubled, there are still substantial savings in energy consumption (and associated $CO_2$ emissions using the energy conversion factor of 0.50935kg$CO_2$e/kWh (DECC, 2014)) arising from the recovery of these secondary materials.

In the case of ferrous materials, however, overall inefficiencies of 20% or more (assuming that the primary benchmark situation can be achieved in every case) do eliminate the savings across the production plant, although it is likely that if the differences in the energy required to deliver ore to the plant and secondary material to the plant are considered, this would still favour secondary production.

For each of the BIR-nominated commodities, aluminium, copper, ferrous and paper, the sensitivity analyses, expressed as a general percentage variation of industry-derived secondary data for the material (from the current study) and the secondary benchmark data (from the 2008 study), are compared with the single benchmark value for primary production (also derived in the 2008 study).

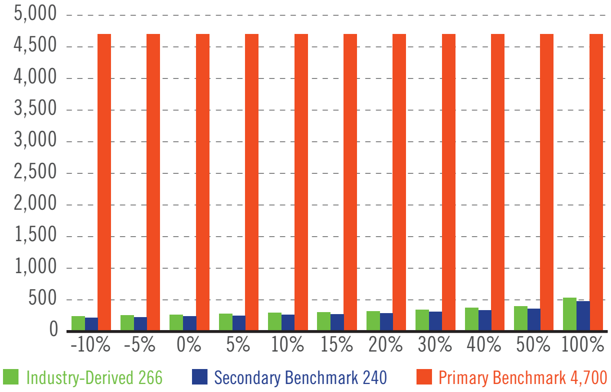
| Material | Primary | Secondary Industry-Derived | Industry-Derived Secondary Energy Requirement Data (expressed as TJ/100,000t) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | -10% | -5% | 0% | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 100% |
| **Aluminium** | **4700** | **266** | 239 | 253 | 266 | 279 | 293 | 306 | 319 | 346 | 372 | 399 | 532 |
| **Copper** | **1690** | **657** | 591 | 624 | 657 | 690 | 723 | 756 | 788 | 854 | 920 | 986 | 1314 |
| **Ferrous** | **1400** | **1194** | 1075 | 1134 | 1194 | 1254 | 1313 | 1373 | **1433** | **1552** | **1672** | **1791** | **2388** |
| **Paper** | **3520** | **1541** | 1387 | 1464 | 1541 | 1618 | 1695 | 1772 | 1849 | 2003 | 2157 | 2312 | 3082 |

| Material | Primary | Secondary Industry-Derived* | Industry-Derived Secondary $CO_2$ Emissions Data (expressed as kt$CO_2$e/100,000t) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | -10% | -5% | 0% | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 100% |
| **Aluminium** | **665** | **38** | 34 | 36 | 38 | 40 | 41 | 43 | 45 | 49 | 53 | 57 | 75 |
| **Copper** | **239** | **93** | 84 | 88 | 93 | 98 | 102 | 107 | 112 | 121 | 130 | 139 | 186 |
| **Ferrous** | **198** | **169** | 152 | 161 | 169 | 177 | 186 | 194 | **203** | **220** | **237** | **253** | **338** |
| **Paper** | **498** | **218** | 196 | 207 | 218 | 229 | 240 | 251 | 262 | 283 | 305 | 327 | 436 |

* Based on DECC's GHG Conversion Factors - June 2014

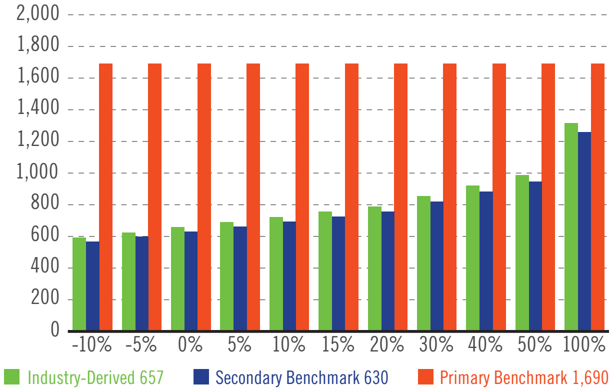
## Aluminium

Energy Requirement [TJ/100,000t]



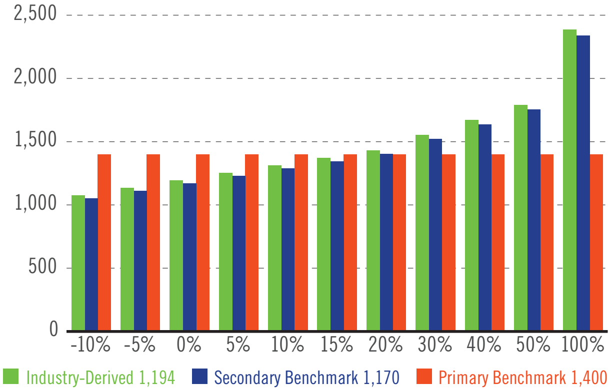

## Copper

Energy Requirement [TJ/100,000t]



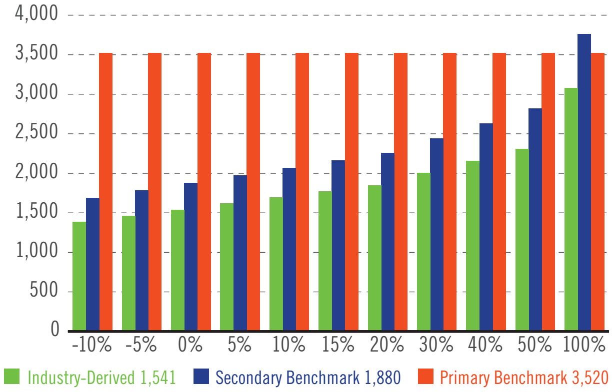

## Ferrous

Energy Requirement [TJ/100,000t]




## Paper

Energy Requirement [TJ/100,000t]




## Copper

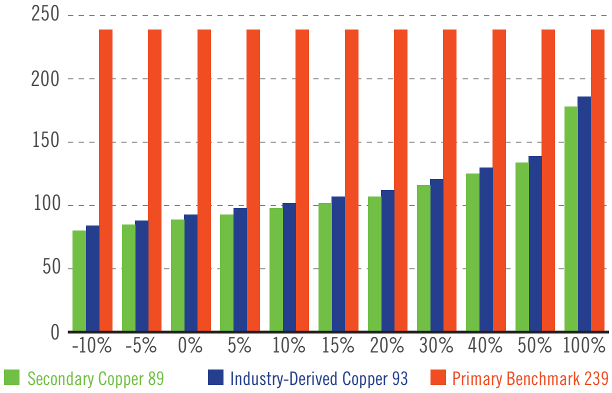
| Primary | Secondary | Secondary Industry-Derived | Secondary Recovery Data – Carbon Footprint (expressed as $ktCO_2e$/100,000t) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | -10% | -5% | 0% | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 100% |
| **239** | **89*** | | 80 | 85 | 89 | 93 | 98 | 102 | 107 | 116 | 125 | 134 | 178 |
| **239** | | **93*** | 84 | 88 | 93 | 98 | 102 | 107 | 112 | 121 | 130 | 139 | 186 |

* Based on DECC's GHG Conversion Factors - June 2014

The table above shows how variations would arise in carbon footprint data for secondary production, drawn from literature data, and separately, acquired from industry if a given process deviated from the primary benchmark data. The sensitivity analysis, shown here for copper as an example, is calculated across the same range; for the metal, deviations by plus 100% from the benchmark still lead to the prediction of carbon dioxide savings from both secondary processes.

## Copper: Sensitivity Analysis

$ktCO_2$/100,000t



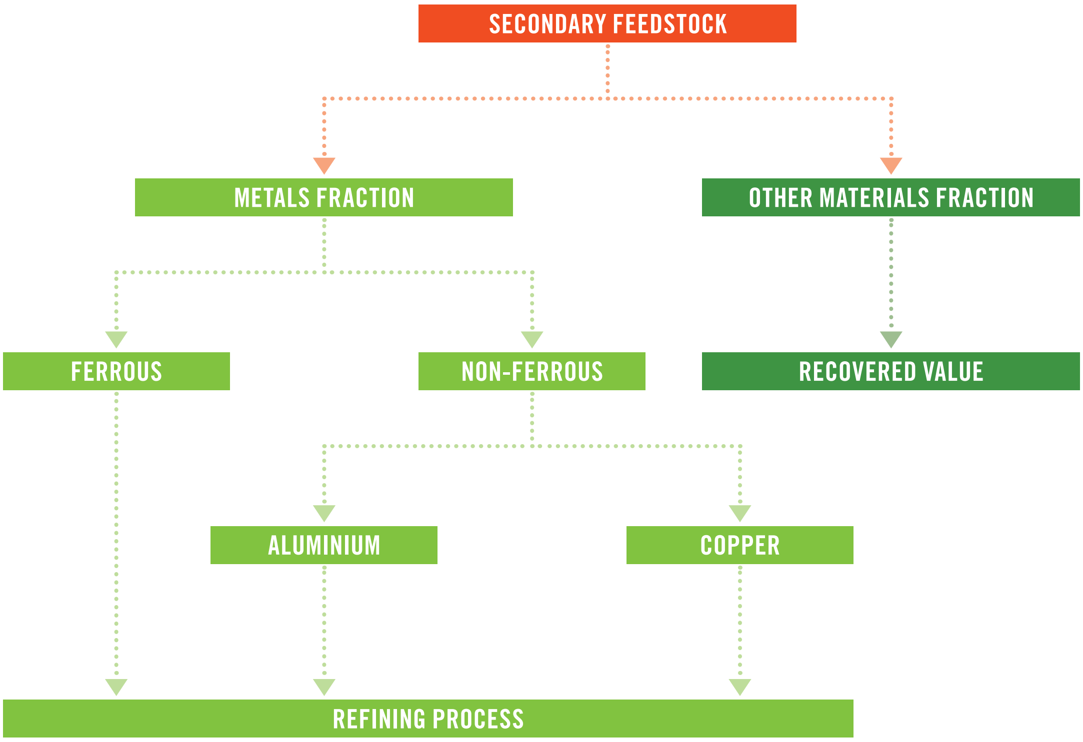
## Mixed-Stream Process

In the same way, for mixed-stream processes, industry data have been provided that have allowed the determination of energy requirements and $CO_2$ emissions for the recovery of a "saleable" product for further refinement to a fully-refined product, according to the fractionation flowchart methodology below.

In situations where data have been provided for a mixed waste stream comprising both metal and non-metal fractions, applying the "Front-end" tool it is possible to determine the energy requirements for the recovery of the commodity metal fractions assuming that: (i) the non-metal "other materials" fraction is producing a return and not going to waste and therefore has no negative energy cost, and (ii) some or all of that non-metal fraction does go to waste and therefore the energy can be allocated to recovery of each of the commodity materials.

Using the data provided by industry and applying the 2-step formula of the "Front-end" tool developed as part of this study, the energy usage through the plant per commodity fraction recovered **($E_{(1...n)}$)** from the mixed-stream process is calculated.

### Fractionation Flowchart Methodology for Mixed Metal Process




### Step 1

**Energy usage through plant in MJ per commodity fraction recovered:**

$$E_{(1...n)} = D_{(1...n)} \times (\Sigma(C_{1...}C_n) + cf^0)$$

### Step 2

**Energy in TJ/100,000t of product:**

$$F_{(1...n)} = (E_{(1...n)} \div B_{(1...n)}) \div 10$$

**$CO_2$ emissions per 100,000t of product:**

$$G_{(1...n)} = F_{(1...n)} \times cf^1 \times cf^2 \times cf^3$$

Following step 1, these data can be expressed in terms of energy consumption **($F_{(1...n)}$)** and corresponding $CO_2$ emissions **($G_{(1...n)}$)** for the recovery of 100,000 tonnes of each commodity product, using the formulae set out in step 2:

The energy requirements for the recovery of aluminium, copper and ferrous metals from a mixed-stream process are calculated and shown in the following table. Applying the energy conversion factor of 0.50935kg$CO_2$e/kWh (reference **cf**[1] in the equation above), the associated $CO_2$ emissions for aluminium, copper and ferrous have been determined assuming all of the energy is used to produce saleable products of recovered aluminium, recovered copper and recovered ferrous.

| Material | Energy Requirements for Secondary Production (TJ/100,000t) | $CO_2$ Emissions for Secondary Production* (kt$CO_2$e/100,000t) |
|---|---|---|
| Aluminium | 27 | 33 |
| Copper | 27 | 34 |
| Ferrous | 24 | 30 |

* Based on DECC's GHG Conversion Factors - June 2014

The energy values shown above could increase to 266, 657 and 1194 for aluminium, copper and ferrous respectively (in line with the calculated industry-derived values summarised for these metals reported on pages 37 and 38) if the operation was treating materials to a stage that needed then to go to refinement (e.g. to a smelter) and the refinement could be carried out at the same site. But if the material had to be transported offsite, the energy requirements could increase beyond these values to take account of the additional energy costs associated with transport.

Whilst it is unlikely that industry will not be able to recover value from the residual non-targeted material, consideration can be given to the reallocation of the energy, attributed to this fraction, to recover more of the target material(s). To take account of situations where less than 100% recovery of useful material is achieved from a mixed-stream process, sensitivity analysis on the data can be applied.

Use of the "Front-end" tool can be extended to allow calculation of the potential for redeploying the energy attributed to the non-target fraction (up to 100%) to recovery of further value from the commodity material(s). Considering the mixed stream of aluminium, ferrous and copper, with energy requirements of 27, 27 and 24TJ per 100,000 tonnes respectively as recovered product, and other non-target material, the following formula permits calculation of the reallocated energy **$[F^R{}_{(1\ldots n)}]$** to one or more commodity materials. Using ferrous metal as an example, the reallocated energy, **$F^R{}_{(Fe)}$**, for the ferrous commodity is calculated as:

**Reallocated Energy in TJ/100,000t of product:**

$$F^R{}_{(Fe)} = (E_{(Fe)} + (E_{(Fe)} \times D_{(Other)}) \div B_{(Fe)}) \div 10$$

where

1 **$D_{(Other)}$** is the non-target waste fraction;

2 **$B_{(Fe)}$** is the percentage of the ferrous fraction in the target fraction of a mixed stream; and

3 **$E_{(Fe)}$** is the energy usage through the plant in MJ per ferrous fraction recovered.

The total allocation of the energy, both baseline and reallocated residual energy, for ferrous is shown in the table below.

The data show the extent to which additional energy can be channelled towards recovery of ferrous product with a maximum level of 30TJ per 100,000 tonnes assuming 25% of the energy is not associated with the recovery of the target commodity metals.

**Total Allocation of Energy for Ferrous Metal (TJ/100,000t)**

| | | 0% | 5% | 10% | 15% | 20% | 30% | 40% | 50% | 90% | 100% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Baseline Energy | | 24 | 25 | 26 | 28 | **29** | **31** | 34 | 36 | 46 | 48 |
| Reallocation of Additional Energy | 100% | **30** | 32 | 33 | 35 | 37 | | | | | |
| | 75% | 29 | **30** | 32 | 33 | 35 | | | | | |
| | 50% | 27 | 29 | **30** | 31 | 33 | | | | | |
| | 25% | 26 | 27 | 28 | **29** | **31** | | | | | |

## Summary

Where operations are handling either single- or multi-commodity materials at a plant, use of the novel "Front-end" tool, developed in the work, allows determination of energy requirements and $CO_2$ emissions for the recovery of a fully-refined product for each commodity from a single-stream process; and recovery of a "saleable" product for further refinement to a fully-refined product from mixed-stream processes. Data used in these calculations were provided by industry, the sources of which remain anonymous and unattributed.

In mixed-stream processes from which value can be derived from more than one commodity stream, where account needs to be taken of the energy apportioned to each metal and non-metal fraction, fractionation and attribution of energy data in the process have been applied to determine the energy and $CO_2$ emissions for each recovered commodity product, and, where there is less than 100% recovery of useful material, the tool can be extended to attribute that energy back into further recovery of the commodity product(s).

Sensitivity analyses have been applied to the benchmark and industry-acquired data for each commodity, for individual process plants and regions, to take account of differences in operating conditions and process parameters and to show any such deviation would be reflected in the overall energy saving and carbon footprint results.

Furthermore, there are two ways in which the results from the current study can be compared with those from the 2008 study as set out below:

**Regional Comparison:** A comparison of the industry-derived data (from secondary production) with the benchmark primary energy data from the 2008 study assuming that the primary production can be carried out in the same region as the secondary production.

The benchmark primary energy data from the 2008 study can be converted to $CO_2$ emissions data using the same conversion factor used for the industry-derived data which effectively gives a comparison between primary production and the industry-acquired secondary process energy and $CO_2$ emissions savings data assuming that primary production could be achieved in a region where this conversion factor is appropriate. These results, which are comparable to those derived in the literature-based 2008 study, can be extended to processes carried out in any region or country by use of the relevant conversion factor.

The energy requirements for single-stream processes for the recovery of aluminium, copper, ferrous or paper are compared with the benchmark values (essentially the best achievable) for primary production from the desk-based research carried out in the 2008 study, as shown in the table below. The energy savings achieved against the primary benchmark, using the industry-acquired data, are 4434, 1033, 206 and 1979 TJ/100,000t for each commodity respectively.

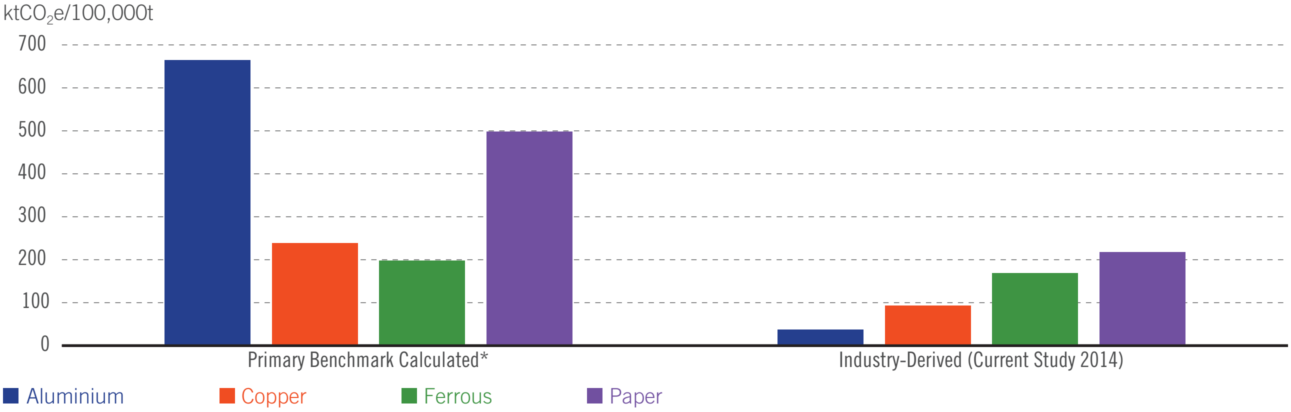
Using the energy data and applying the energy conversion factor, for the UK, of 0.50935kg$CO_2$e/kWh, the carbon footprints ($CO_2$ emissions) for primary and industry-derived processes for aluminium, copper, ferrous and paper are presented in the table and graph on p. 44. The corresponding savings in $CO_2$ emissions achieved against the primary benchmark, using the industry-acquired data, are 627, 146, 29 and 280kt$CO_2$e/100,000t for each commodity respectively.

| Material | Energy Requirements | | Savings (achieved by industry against Primary Benchmark) (TJ/100,000t) |
|---|---|---|---|
| | Primary Benchmark (TJ) | Industry-Derived (TJ) | |
| Aluminium | 4700 | 266 | 4434 |
| Copper | 1690 | 657 | 1033 |
| Ferrous | 1400 | 1194 | 206 |
| Paper | 3520 | 1541 | 1979 |

| Carbon Footprint ($CO_2$ emissions) for Primary and Industry-derived Processes | | | |
|---|---|---|---|
| **Material** | **Calculated $CO_2$ Emissions* from Primary Energy Benchmark ($ktCO_2e$/100,000t)** | **Industry-Derived $CO_2$ Emissions* ($ktCO_2e$/100,000t)** | **Savings (achieved by industry against Primary Benchmark) ($ktCO_2e$/100,000t)** |
| Aluminium | 665 | 38 | 627 |
| Copper | 239 | 93 | 146 |
| Ferrous | 198 | 169 | 29 |
| Paper | 498 | 218 | 280 |

* Based on the same Conversion Factor (DECC's GHG Conversion Factors - June 2014)

### Carbon Footprint ($CO_2$ emissions) for Primary and Industry-derived Processes




Based on DECC's GHG Conversion Factors – June 2014

**Best Available Worldwide Comparison:**
A comparison of the industry-derived data (from secondary production) with the benchmark primary data from the 2008 study representing the most efficient production processes available with the lowest energy consumption in situations where the best possible energy mixes are used anywhere in the world.

In the 2008 report, highlight calculations of total $CO_2$ savings arising from the benchmark primary data for annual worldwide secondary material production were made. In the current study, energy savings obtained for the production of 100,000t of secondary aluminium, copper and ferrous metals, using the industry-acquired data, were compared with primary production benchmark data from the 2008 study and converted to $CO_2$ emissions savings for the most recent worldwide annual secondary production tonnages for each commodity metal studied in the current work, with total estimated savings in annual $CO_2$ emissions arising from the secondary production of the metals, shown in the table below, in comparison with primary production, of 572Mt.

| Material | Energy Savings (achieved by industry against Primary Benchmark) (TJ/100,000t) | Annual Worldwide Secondary Production* (Mt) | Estimated Savings in Annual $CO_2$ Emissions (Mt) |
|---|---|---|---|
| Aluminium | 4434 | 18 | 63.3 |
| Copper | 1033 | 6 | 4.8 |
| Ferrous | 206 | 580 | 503.9 |
| Total Estimated Savings in Annual $CO_2$ Emissions for the Production of the Secondary Metals Studied [Current Study] | | | **572.0** |

* Annual worldwide secondary production (Mt) as quoted in 2014 for Aluminium and in 2013 for Copper and Ferrous

# Conclusion and Summary Highlights

## Conclusion

The benefits of the 2008 research have been widely acknowledged in the recycling industry worldwide, and, for the recycling industries, the value of expressing environmental benefits in terms of $CO_2$ emissions savings is becoming increasingly necessary. It is in this context that the current study is carried out:

***"… to update the findings of the 2008 study, applying the methodology developed, to more recent data on four of the original commodities, namely, aluminium, copper, ferrous metals and paper".***

The 2008 desk-based research involved a detailed review of available scientific and technical literature on seven metals – aluminium, copper, ferrous metals, lead, nickel, tin and zinc – and of paper. The study introduced the concept and application of a benchmark methodology to determine the best available and most justifiable energy use and carbon emissions data for primary production processes, and used best estimates from the literature of benchmark data for energy and carbon footprint calculations for both primary and secondary production. For primary production, the benchmark data represented the most efficient production processes available with the lowest energy consumption per tonne of metal produced in situations where the best possible energy mixes were used. The conversion factors used to express the primary production energy data as benchmark carbon emission data were also based on those for the best possible energy mixes. Benchmark data were, thus, defined as those data that represented material production situations that were achievable and gave values that were most acceptable and justifiable as the best achievable, acknowledging that these would not be achieved in all primary production processes. The calculations of benchmark values for secondary production in the 2008 study were similarly derived from literature-based data.

The benchmark data were used to highlight the advantages (environmental impacts) of secondary production over primary production and were reported per 100,000 tonnes of material produced to provide a means of direct comparison between primary and secondary production and expressed as $CO_2$ savings per 100,000 tonnes of production. To avoid complications associated with the early stages of the whole lifecycles of these materials, benchmark energy requirements and carbon footprints were taken from ore or raw material delivered at the production plant for primary material, and delivered at the secondary plant for secondary material. Sensitivity analyses were then developed and used to show how the benchmark results can be used to deal with variations in different production processes, for example, variations in efficiency, and fuel and energy balances.

Building on the acknowledged benefits of the 2008 research, it is clear that realising the full potential and value of applying the benchmark methodology relies on industry engagement so that the energy requirements and carbon footprints are determined on industry-acquired data (i.e. "real" data). In the current study, use has been made of industry-acquired data to obtain energy and carbon emission results from real situations. As with the 2008 study, sensitivity analyses have been used in this work to enable the data presented to be extended to other operations to take account of differences in, for example, plant and operation efficiencies, energy mix and other country/region-specific data to permit realistic and reasonable comparisons to be made in any situation with any set of variable factors.

As part of the current study, a novel "Front-end" tool has been developed for "normalisation" of industry-acquired data (in terms of energy requirements and associated $CO_2$ emissions), as input to the methodology used. To optimise the value of the output from the analysis, the nature and type of information required from industry about its recycling operations formed the basis of a questionnaire to industry to assist BIR in the acquisition of information from members and other stakeholders. A fractionation flowchart methodology was developed to take account of the information sought in situations where operations are handling either single- or multi-commodity materials at a plant, or are operating globally. The "Front-end" tool uses a two-step formula to determine the energy requirements and associated $CO_2$ emissions based on industry-acquired data.

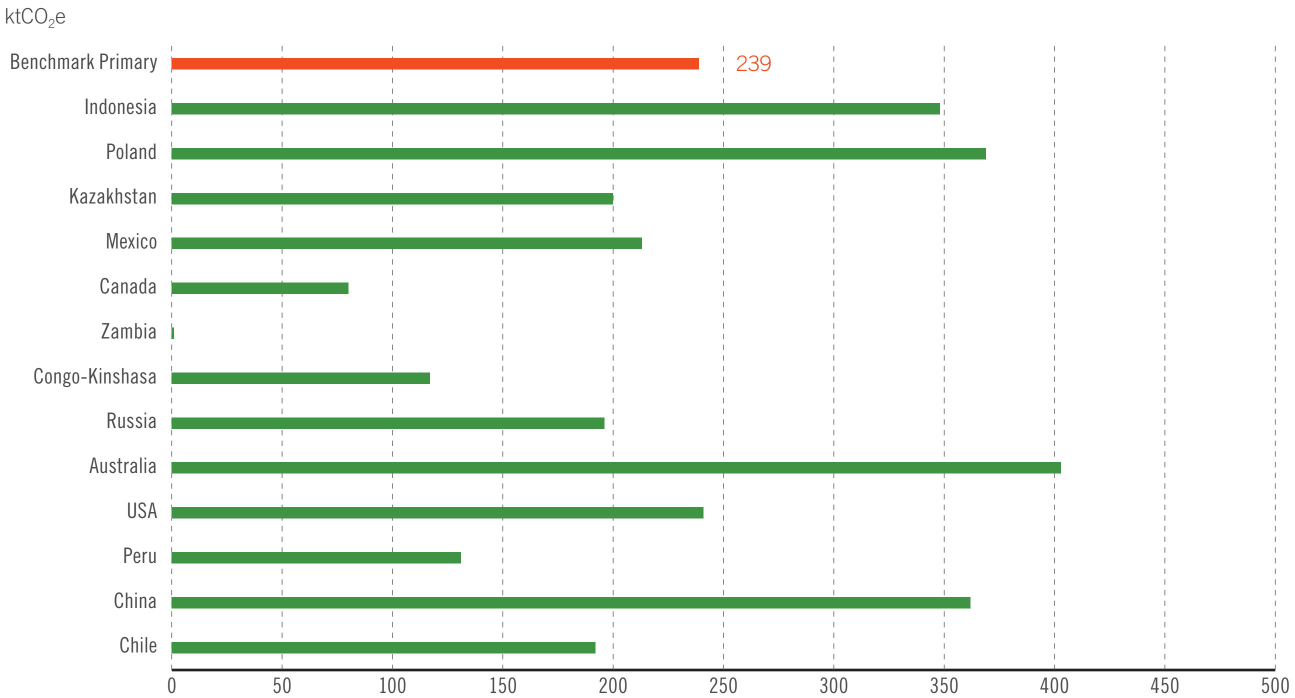
As part of the update of carbon emission data for the commodities of interest, using industry-derived data, an investigation of the impact of variations in energy conversion factors and energy source/fuel mixes on the benchmark data has been carried out. These factors not only change with region but also with time. For example, the energy conversion factor for UK Grid electricity generated changed from 0.70991kg$CO_2$e/kWh in 1990 to the latest reported value of 0.50935kg$CO_2$e/kWh in 2012.

Initial calculations in this study make use of the most recently published electricity conversion factors (taken from UK DECC GHG Conversion Factors (DECC, 2014)) to convert energy data to carbon emissions. To obtain a comparison of the results with the possible primary production for the same region (e.g. the UK), the electricity conversion factor of 0.50935kg$CO_2$e/kWh has also been applied to the 2008 benchmark data for primary production. All data and graphical and schematic representations being derived from these calculations are reported here for the first time.

Another potential variation in energy use between countries or regions depends upon the nature of the energy source, ranging from efficient hydroelectric production of electricity to the use of low-grade coals. To look at the influence of energy source/fuel mix on benchmark data, copper has been used as an example. The production of 100,000 tonnes of primary copper following the pyrometallurgical route can be compared, for example, for different countries on the basis of electricity emission factors. To do this, it is assumed that all countries initially have the same specific energy requirement (based on the benchmark primary and secondary data of 1690TJ per 100,000 tonnes and 630TJ per 100,000 tonnes respectively), and takes no account of variation in process efficiencies at country level.

Assuming that the energy requirement can be based on electricity emission factors, the following profile shows the calculated emissions of $CO_2$ per 100,000 tonnes of primary copper production from ore concentrate compared with the benchmark value of 239kt$CO_2$, using the energy conversion factor of 0.50935kg$CO_2$e/kWh.

**$CO_2$ Emissions per 100,000 tonnes of Primary Copper Production in Selected Countries**



The data are based on the most recent reported figures from the IEA (averaged for the period 2009-2011) published in 2013 for $CO_2$ emissions per kWh from electricity generation, by country, and have been applied to the benchmark primary energy requirement of 1690TJ, normalised to provide direct comparison.

Other profiles reported in the current work show how sensitivity analyses can take account of differences in the electricity-based energy conversion factors for different countries across the EU and global regions and show how the $CO_2$ emissions would change if the conversion factors for other countries were used rather than the conversion value of 0.50935kg$CO_2$e/kWh used in the study.

Data provided from industry (which remain anonymised) have allowed calculations of energy requirements and carbon dioxide emissions for both single-stream processes for each of the BIR-nominated commodities, and separately, for mixed-metal streams containing all three target metals. Using these data, the energy requirement for the recovery of 100,000 tonnes of each commodity has been calculated based on the methodology developed and compared with the benchmark values (essentially the best achievable) for its primary and secondary production derived from the desk-based research carried out in the 2008 BIR study.

For the single-stream process, the industry data provided allow for the determination of energy requirements and $CO_2$ emissions for the recovery of a fully-refined product for each commodity. Sensitivity analyses have been applied to the benchmark and industry-acquired data for each commodity, for individual process plants and regions, to take account of differences in operating conditions and process parameters and to show any such deviation would be reflected in the overall energy saving and carbon footprint results. For mixed-stream processes, the industry data provided allow the determination of energy requirements and $CO_2$ emissions for the recovery of a "saleable" product for further refinement to a fully-refined product. The calculated energy requirements and $CO_2$ emissions for secondary production from this mixed stream for aluminium, copper and ferrous are 27, 27 and 24 TJ per 100,000 tonnes and 33, 34 and 30 kt$CO_2$e per 100,000 tonnes respectively. In situations where industry is handling mixed streams from which value can be derived from more than one commodity stream, account needs to be taken of the energy apportioned to each metal and non-metal fraction. In this regard, use has been made of the "Front-end" tool, developed in this work, to systematically attribute energy data in the process and determine the energy and $CO_2$ emissions for each recovered commodity product. In situations where there is less than 100% recovery of useful material, the tool can be extended to attribute that energy back into further recovery of the commodity product(s).

## Summary Highlights

The summary highlights from the current study are:

1 Realising the full potential and value of applying the benchmark methodology relies on industry engagement such that the energy requirements and carbon footprints are determined on industry-acquired data (i.e. "real" data). Of further benefit is the ability to apply sensitivity analyses on these data to take account of differences in, for example, plant and operation efficiencies, energy mix and other country/region-specific data to provide a basis for realistic and reasonable comparison;

2 Using the methodology developed and applied in this work, variations in energy conversion factors, energy source, fuel mix and country emission levels, and other variations such as process efficiencies, do impact the $CO_2$ emissions, as illustrated for copper, for any commodity, exploiting either benchmark or real industry data;

3 Where operations are handling either single- or multi-commodity materials at a plant, or are operating globally, use of the novel "Front-end" tool developed in the work allows determination of energy requirements and $CO_2$ emissions for the recovery of a fully-refined product for each commodity from a single-stream process; and recovery of a "saleable" product for further refinement to a fully-refined product from mixed-stream processes. In mixed-stream processes from which value can be derived from more than one commodity stream, fractionation and attribution of energy data in the process have been applied to determine the energy and

$CO_2$ emissions for each recovered commodity product, and, where there is less than 100% recovery of useful material, the tool can be extended to attribute that energy back into further recovery of the commodity product(s);

4 Using the same conversion factor as that used for the industry-derived data for converting the benchmark primary energy data from the 2008 study to $CO_2$ emissions data allows comparison of the industry-derived data (from secondary production) with the benchmark primary energy data, assuming that primary production can be carried out in the same region where this conversion factor is appropriate *[Regional Comparison].*

   The calculated energy savings achieved, against the primary benchmark, are 4434, 1033, 206 and 1979 TJ/100,000t for aluminium, copper, ferrous and paper respectively, with corresponding savings in $CO_2$ emissions (using the electricity conversion factor, for the UK, of 0.50935kg$CO_2$e/kWh) of 627, 146, 29 and 280kt$CO_2$e/100,000t for each commodity respectively. These results, which are comparable to those derived in the literature-based 2008 study, can be extended to processes carried out in any region or country by use of the relevant conversion factor; and

5 With the benchmark primary data from the 2008 study representing the most efficient production processes available with the lowest energy consumption in situations where the best possible energy mixes are used anywhere in the world, comparison of the industry-derived data with the benchmark primary data can be made using updated figures of total savings in annual $CO_2$ emissions for worldwide secondary production *[Best Available Worldwide Comparison]*.

   The BIR-nominated metals (aluminium, copper and ferrous metals) studied in the current work, represented 98% of the total estimated annual savings in $CO_2$ emissions (equivalent to 488.3Mt/100,000t) that would result from worldwide secondary production of the materials contained in the 2008 report. Using the most recent worldwide secondary production tonnages for these metals, **the estimated savings in annual $CO_2$ emissions arising from the secondary production of aluminium, copper and ferrous metals, in comparison with primary production, are 572Mt.**

Furthermore, the methodologies described in this report can be used to obtain energy and carbon emissions data with a view to calculating the potential $CO_2$ savings that can be achieved for:

1 Recycling operations of any BIR member for any of the nominated commodities described in this work – aluminium, copper, ferrous metals and paper;

2 Other ferrous-based commodities [stainless steel and its alloys – containing chromium, molybdenum, nickel, titanium, tungsten and vanadium] of importance to BIR and its members; and

3 Any other material of interest to any BIR member, on a case-by-case basis, in the industry's secondary recovery processes.

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# Annex

## Questions Prepared for BIR to put to Members

1. What metals/materials do you recover in the plant?
2. What is the tonnage of feedstock through the plant per day?
3. What is the typical percentage of aluminium, copper and ferrous metals in the feedstock? Or paper?
4. What is the total energy consumption through the plant per day? [If possible provide an estimate of the energy sources e.g. oil, gas, electricity, etc]
5. What is the tonnage of recovered metal at the end of the process?
6. Does the recovered metal require further refinement after it leaves the plant?
7. If you recover more than one metal, provide an estimate of the fraction of energy usage that you believe is attributable to the recovery of aluminium, copper or ferrous metal fractions.
8. It would be helpful if you could indicate which of the following regions you operate in: (a) Europe; (b) North America; (c) South America; (d) Africa; (e) Asia; (f) Australasia.

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