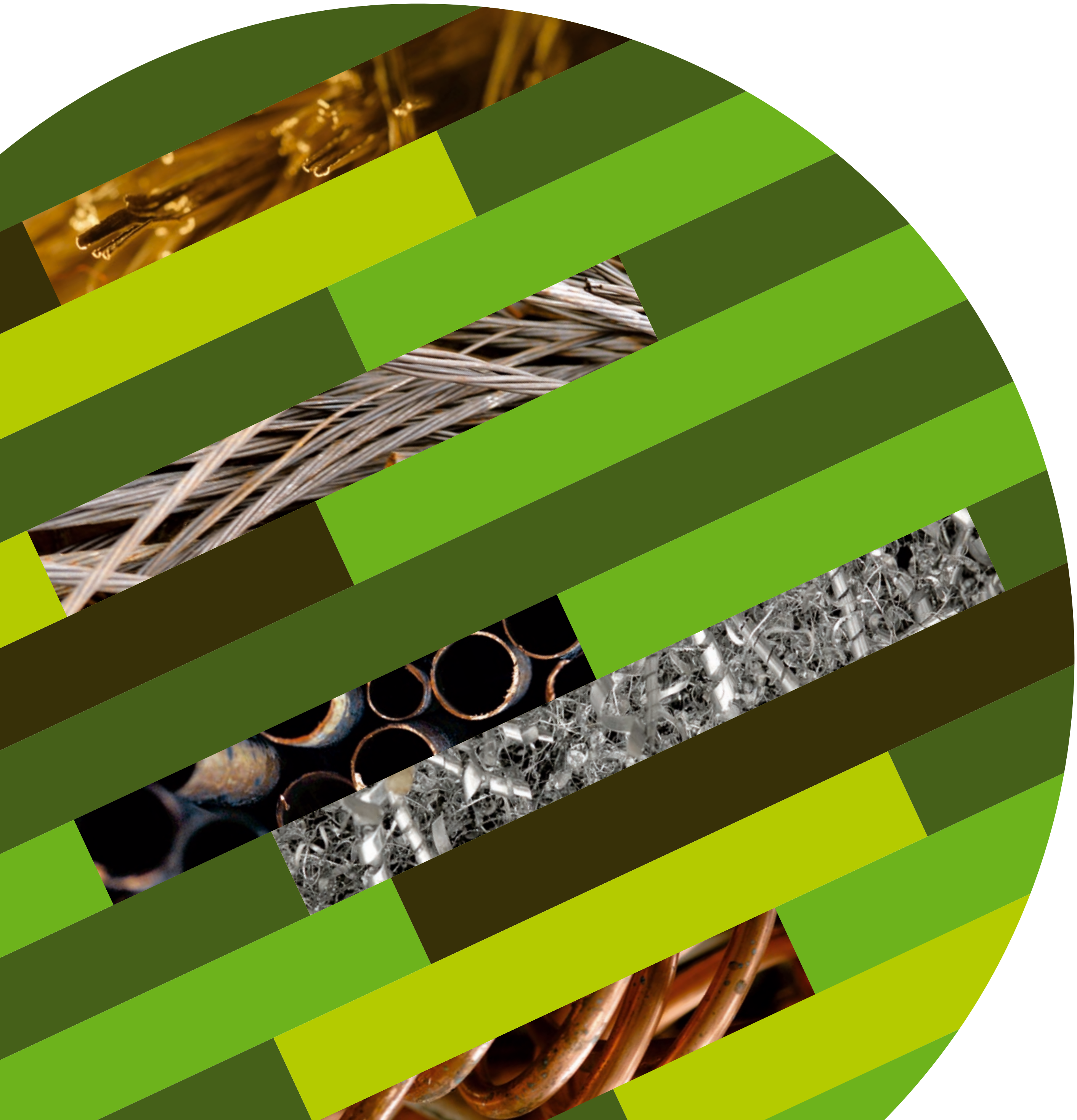
Report on the Environmental Benefits of Recycling

Bureau of International Recycling (BIR)

BIR



Report on the Environmental Benefits of Recycling

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Commissioned by the Bureau of International Recycling
Under the project leadership of Roger Brewster, Metal Interests Ltd.

October 2008

Contents

Foreword

The Imperial College remit was to use published literature data to estimate the carbon dioxide savings that could be made through the recycling of metals and paper. The key to the document produced was the need to avoid bias, and for this reason the concept of benchmark values was developed.

The benchmark values were based on the literature data and are intended to reflect what was achievable by both the primary and secondary metal industries. Given time, the Imperial group would have preferred to have used verifiable industry data provided for specific plants from different countries but, since this was not possible, sensitivity analyses on the benchmark data have been carried out. The sensitivity analysis data enable any individuals or groups to input any industry-specific data values that they might have for comparison with the benchmarks. We believe that the benchmark information is completely defensible and very conservative. Undoubtedly, sections of industry may claim greater savings based on their own databases, but there is a danger in over-stressing industry data which have not been independently verified and which in any case will differ from country to country depending upon the sophistication of both the energy supply and the metal production plant. The purpose of this report was to produce information on carbon dioxide savings that is defensible, and to provide a balanced comparison between primary and secondary production from delivery of ore or secondary material to a metal-producing plant. It is hoped that this report will be used by industry to assess their own situation in terms of secondary metal production and perhaps to provide information that can be independently verified to permit further more accurate calculations of carbon dioxide savings in specific cases.

Roger Brewster
Metals Interests Limited

Preface

In March 2008, Roger Brewster of Metal Interests Limited, UK, on behalf of the Bureau of International Recycling (BIR) in Brussels, commissioned Professor Sue Grimes of Imperial College and her team to carry out research and deliver a report on the *Environmental Benefits of Recycling*.

Imperial College was established in 1907 through the merger of the Royal College of Science, the City and Guilds College and the Royal School of Mines. In 2007, Imperial College celebrated its centenary and, coincident with this date, it withdrew its long-standing association with the University of London to become a university in its own right. Imperial College owns one of the largest estates in the UK university sector and resides in the heart of London with its main campus at South Kensington. The College has over 2,900 academic and research staff in total and more than 12,200 students, of whom approximately one third are postgraduates. The College has strong international links with students from over 110 countries.

Imperial is ranked fifth in the world and has world-renowned academic expertise across its four faculties of Natural Sciences, Engineering, Medicine and the Imperial College Business School. The College has a number of cross-faculty initiatives that bring together College-wide expertise to focus on grand challenge research themes; these include the Grantham Institute for Climate Change, the Energy Futures Laboratories and the Porter Institute for plant-based biofuels.
The College's academics have strong research groups delivering innovative solutions in all aspects of science, engineering, technology and business, and have taken a lead in guiding policy at national and international levels.

In 2005, the SITA Trust (the Trust body of SITA UK) and the Royal Academy of Engineering established a Chair in Waste Management at Imperial College. The holder of the post, Professor Sue Grimes (the first lady in the UK to be supported by the Royal Academy of Engineering to a professorship), is championing the creation of a centre for excellence in Sustainable Production and Resource Efficiency that brings together disparate Imperial research groups to provide a focus for collaborative research, in particular on key sustainability issues. The Centre draws on the College-wide expertise in material recovery, mineral wastes, materials science and material reprocessing, biological treatment of waste, waste electrical and electronic equipment, biofuels, incineration, energy from waste, carbon capture and sequestration, waste management decision-making tools, landfill science, agricultural waste, radioactive waste, and epidemiology.

Executive Summary

Energy requirement and carbon footprint values for the production of primary and secondary metals and paper have been obtained from a survey of the primary literature. The metals included in the survey are aluminium, copper, ferrous, lead, nickel, tin and zinc.

To avoid complications associated with the early stages of whole life cycles of these materials, benchmark energy requirements and carbon footprints are extracted from: ore or raw material delivered at the production plant for primary materials; and delivered at the secondary plant for secondary material. Benchmark data are reported per 100,000 tonnes of material produced to provide a means of direct comparison between primary and secondary production. These data are tabulated below for each material separately – as energy requirements and savings per 100,000 tonnes of production of material, and as carbon footprints and savings per 100,000 tonnes of production.

Energy Requirement and Savings in Terajoules (TJ/100,000t)

Material	Primary	Secondary	Saving/100,000 Tonnes
Aluminium	4700	240	4460
Copper	1690	630	1060
Ferrous	1400	1170	230
Lead	1000	13	987
Nickel	2064	186	1878
Tin	1820	20	1800
Zinc	2400	1800	600
Paper	3520	1880	1640

Carbon Footprint and Savings Expressed in Kilotonnes of CO_2 ($ktCO_2$)/100,000 Tonnes

Material	Primary	Secondary	Saving/100,000 Tonnes (% savings CO_2 in paretheses)	
Aluminium	383	29	354	(92%)
Copper	125	44	81	(65%)
Ferrous	167	70	97	(58%)
Lead	163	2	161	(99%)
Nickel	212	22	190	(90%)
Tin	218	3	215	(99%)
Zinc	236	56	180	(76%)
Paper	0.17	0.14	0.03	(18%)

The total estimated reduction in CO_2 emissions obtained from these data is approximately 500Mt CO_2 per annum.

The benchmark figures extracted from the primary literature in this work represent (i) data for situations that are said to be achievable and (ii) values that are the most acceptable and justifiable.

To deal with variations in the processes involved, sensitivity analyses are provided to show how the data can be handled to provide comparisons in any situation.

Understanding the Brief

The environmental benefits of recycling can be expressed in many ways, including savings in energy and in use of virgin materials. There appears however to have been very little attempt to express these benefits in terms of carbon footprint and particularly in savings in carbon dioxide equivalent emissions which would have implications in terms of both the environment and carbon emission.

The brief given by Metal Interests Limited on behalf of BIR is 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. In the first instance, the materials to be considered in the study are seven metals – aluminium, copper, ferrous metals, lead, nickel, tin and zinc – and paper.

The overall aim of the project is to provide verifiable data on the influence of recycling on carbon emissions. Ideally, the project should be carried out under two key phases.

The first phase (Phase I) would involve two steps:

(i) to provide information to the Global Emissions Study of CO_2 for recyclables with preliminary information from available sources. This should provide a preliminary comparison between the use of primary and recycled materials for paper and metals;

(ii) to extend the study to provide additional information from primary scientific sources to verify the preliminary data, and provide new data where appropriate and to produce a report containing verifiable quantitative data.

Since the timescale did not permit detailed optimisation of the data, it is recommended that in the second phase (Phase II) consideration be given to further quantification and verification of the data using individual secondary material recovery operations throughout the world. This is considered necessary to ensure that the collective data presented by trade associations and other bodies can be defended, and to allow the secondary materials industries to be certain of carbon savings achieved prior to second use of their materials by manufacturing industries.

Phase I, the subject of this report, will be the results of a detailed survey of the primary literature on energy consumption in primary and secondary material recovery.

Methodology

This report contains the results of a detailed survey to obtain information on energy consumption in primary and secondary material recovery and the carbon emissions associated with these processes. The information obtained is used in calculations to assess the environmental benefits of recycled materials expressed in both energy terms and as a carbon footprint.

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.

The methodology used involved:

(i) A detailed survey of the primary literature to extract the data available on energy consumption and associated carbon emissions.
(ii) The use of energy data and associated carbon emissions, extracted to highlight differences between primary and secondary production of seven metals - aluminium, copper, ferrous metals, lead, nickel, tin and zinc - and of paper. The assumptions made in all information provided are identified and the units used in the calculations are expressed as MegaJoules per kilogram of product for energy and tonnes of CO_2 per tonne of product for carbon emissions.
(iii) 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.
(iv) A summary table comparing the energy consumption and carbon footprint of primary and secondary production of aluminium, copper, ferrous metals, lead, nickel, tin and zinc, and of paper, is compiled per 100,000 tonnes of production. For all materials, the life cycle boundaries are set to compare the production of (a) primary material from raw material delivered to the primary production plant to final product, and (b) secondary materials delivered to the recycling plant to final product.
(v) Sensitivity analyses are carried out on the data obtained using the benchmark values in the summary table to show how these data can be handled to deal with variations in input such as the details of the energy sources used, the energy/fuel mix for different countries, and the energy efficiency of specific recovery plants.

This report sets out in the section 'Primary and Secondary Metals Production' (p.7) the data gathered for each metal. The energy data obtained are expressed in flow diagrams and all references to the primary literature are given. For the purposes of comparing primary and secondary production, however, the results for energy consumption and carbon footprint are those for the following processes: (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. This choice of life cycle boundaries avoids the complications associated with differences in mining and beneficiation of ores and in the collection and transport of scrap to a recycling process.

The data for primary and recycled paper are compared in the section 'Primary and Secondary Paper Production' (p.30).

Sensitivity analyses are provided on page 35 to show how data can be handled to provide comparisons and deal with any variations in processes. Conclusions (p42) drawn from Phase I of the study are presented.

Primary and Secondary Metals Production

The metals are discussed in the order: aluminium, copper, ferrous metals, lead, nickel, tin and zinc.

Primary and Secondary Aluminium Production

In 2006, the tonnages of primary and secondary aluminium produced were approximately 34 and 16Mt respectively, so that about one third of aluminium demand is satisfied from secondary production.

The difference between primary and secondary production is illustrated in the following figure.

Primary and Secondary Production of Aluminium

Primary Production

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 because about 3.2 tonnes of mud are produced per tonne of aluminium produced, the comparison between primary and secondary aluminium production made in this report 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 2050ºC for the ore concentrate to about 960ºC.

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. The process results in the production of between 2 and 4% dross.

Secondary Production

All secondary aluminium arisings are treated by refiners or remelters. Remelters accept only new scrap metal or efficiently sorted old scrap whose composition is relatively 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.

Energy Requirement and Carbon Footprint Tables for Aluminium

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

Energy Requirements of Production of Primary Aluminium

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

(c.e. – refers to conversion efficiency)

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) are in the following table along with the assumptions made on the fuel used.

Energy Requirements of the Hall Héroult Process

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
Cambridge	55	Hydro efficiency 95%
Cambridge	160	Coal efficiency 35%
Cambridge	50	100% efficient
Choate and Green	56	US average

For the purpose of comparison of the energy requirements and associated carbon emissions for primary aluminium production with data for secondary aluminium production, we have assumed that the benchmark process would involve an electricity benchmark figure of about 47MJ/kg.

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

Carbon Footprint for Primary Production of Aluminium

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

Carbon Footprint for the Hall Héroult Process

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

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 as-received concentrate.

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

The energy requirement data for secondary aluminium production are reported in the following table as mean values for melting and casting and benchmark values for melting and casting. The carbon footprint data included in the table on the following page have been calculated on the basis of these energy requirement data, using the carbon emission factor for the UK.

Energy Requirement of Secondary Processes for the Production of Aluminium from Scrap

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

Carbon Footprint for the Secondary Processes for the Production of Aluminium from Scrap

Process	CO_2 Emissions (tCO_2/t)	Benchmark (tCO_2/tAl)
Remelting	0.54	0.25
Casting	0.06	0.04

Summary

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:	**383kt CO_2**
Carbon footprint for secondary production:	**29kt CO_2**

Sensitivity analyses on these data are given on page 35 of this report to illustrate the effects of deviations from benchmark conditions.

Primary and Secondary Copper Production

According to the US Geological Survey, world copper production in 2007 was 15.6Mt. The percentage of copper recovered from scrap as a percentage of total copper produced has been reported to vary with geographical location within the range 19-45%.

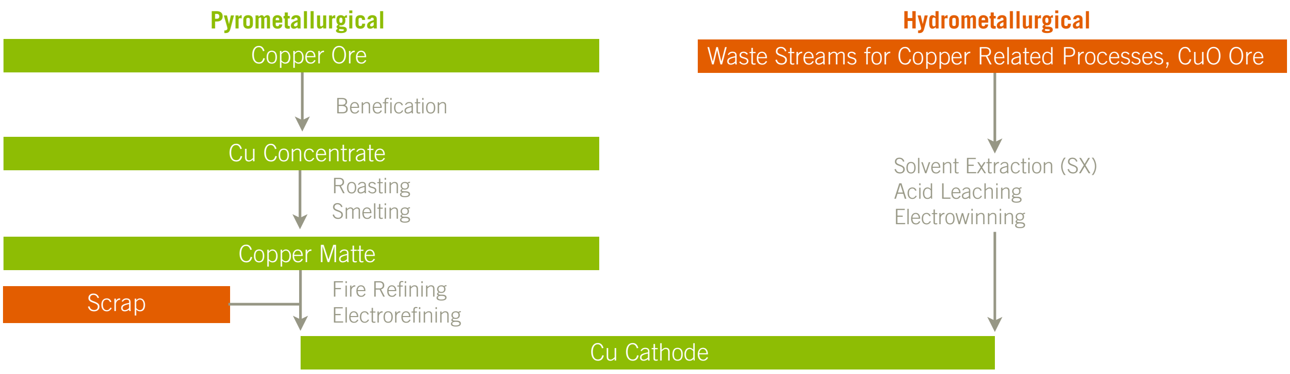
Primary Production

The major route in 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 30-50% 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.

Schematic of Copper Production



Secondary Production

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. The following figure for example is a flow chart of secondary pyrometallurgical copper production.

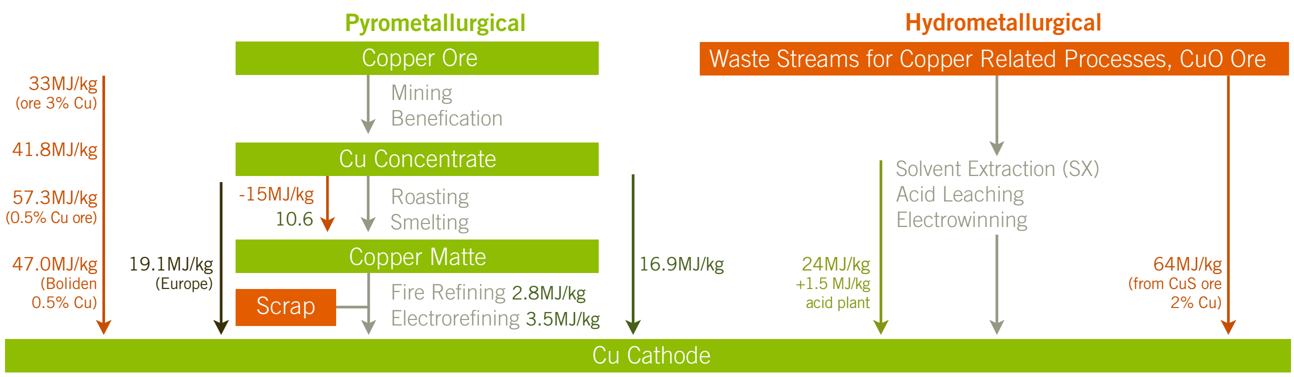
Secondary Copper Production By Pyrometallurgy

Energy Requirement and Carbon Footprint Tables for Copper

There are literature reports suggesting that the energy requirement for secondary copper production is between 35 and 85% that for primary production – the higher value is that reported by the Institute of Scrap Recycling Industries, and this would lead to an estimated 7.3MJ/kg energy saving.

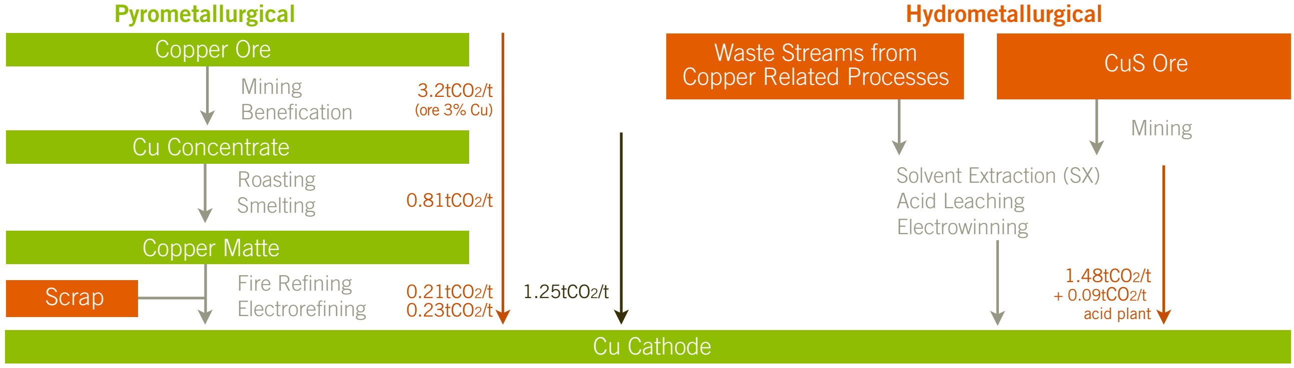
The data for energy required for primary copper production via pyrometallurgical and hydrometallurgical routes are given in The following figure, and the figure also shows the point in the energy requirement diagram at which scrap copper would enter the pyrometallurgical process. These are the data on which comparisons between primary and secondary production have to be based. The data quoted on the extreme left of the figure are for energy calculations based on different ore grades and by different authors.

Energy Requirements for Copper Production



The carbon footprint data for copper production from these data are presented in the following figure.

Carbon Footprint for Copper Production



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

Benchmark Energy Requirements for Copper Production

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

Summary

Using the benchmark data for primary and secondary copper production from delivered ore concentrate and scrap respectively, 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

Sensitivity analyses on these data are given on page 35 of this report to illustrate the effects of deviations from benchmark conditions.

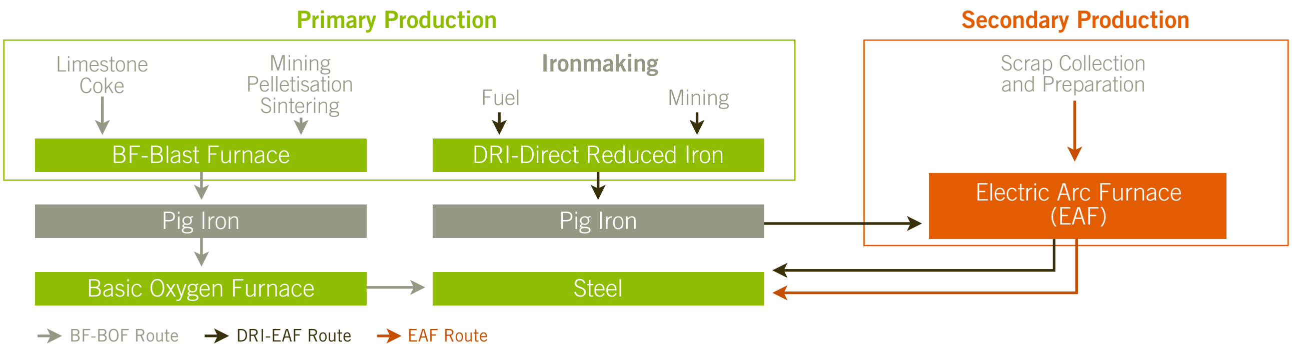
Primary and Secondary Ferrous Production

Primary Production

In 2006, world production of steel was 1,245Mt in which scrap consumption amounted to approximately 440Mt.

A schematic representation of iron recovery and steel manufacture is in the following figure. 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).

Iron Recovery and Steel Manufacture



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 furnace (EAF). 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 (EAF) 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 1600ºC. 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.

Secondary Production

Electric arc furnaces (EAF) 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.

Energy Requirements and Carbon Footprint Tables for Steel Production

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

The energy requirements reported for the whole life cycle of steel production from ore to metal via the BF/BOF route and for the conversion of ore concentrate to steel by this route, are presented in the following two tables.

Energy Requirements for Steel Production from Ore via the BF/BOF Route

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

Energy Requirements for Steel Production from Ore Concentrate via the BF/BOF Route

BF-BOF Only	
	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 via the BF/BOF Route

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

Table continues on page 16 →

Carbon Footprint for Steel Production via the BF/BOF Route *(Continued from Page 15)*

BF-BOF Route	
Source	Carbon Footprint (tCO_2/t Steel)
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)

The reported energy requirements for the DRI step of the steel production process, and for the DRI + EAF steps combined, along with assumptions made on the energy source used, are represented in the following two tables. The data for the carbon footprints associated with the energy source used are presented separately in the table below.

Energy Requirements for Steel Production for the DRI Step Only

DRI Only	
	Energy Requirement (MJ/kg Steel)
Gielen and Moriguchi	10
Phylipsen et al	10.93

Energy Requirements for Steel Production for the DRI + EAF Steps

DRI + EAF		
	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

Carbon Footprint for Steel Production for the DRI + EAF Steps

DRI + EAF		
	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)	

The energy requirements and carbon footprints for the electric arc furnace route for production of steel from secondary sources are in the following two tables.

Energy Requirements for Steel Production from Scrap in an Electric Arc Furnace

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 in an Electric Arc Furnace

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)

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 in in the following table.

Benchmark Energy Requirements for Steel Production

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

Summary

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:

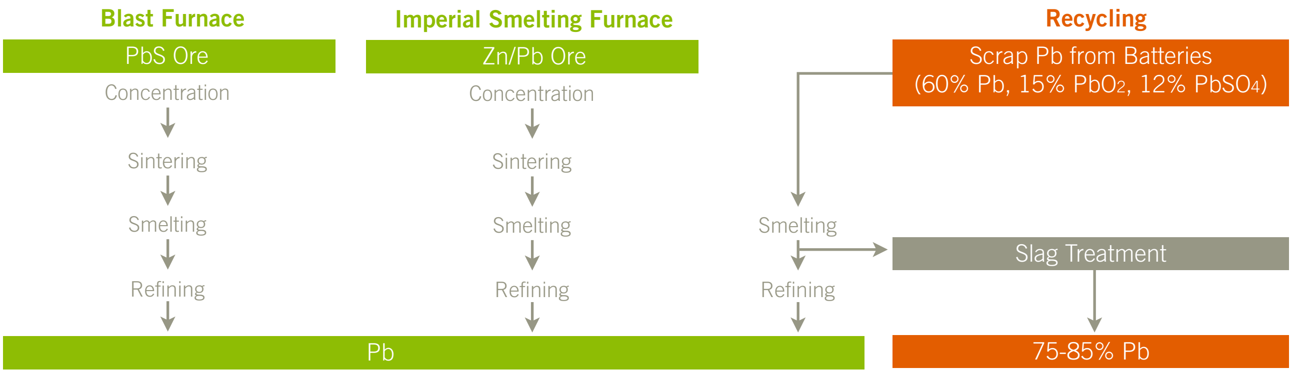
Carbon footprint for primary production BF-BOF route: 167kt CO_2
Carbon footprint for primary production DRI + EAF route: 70kt CO_2
Carbon footprint for secondary production EAF route: 70kt CO_2

Sensitivity analyses on these data are given on page 35 of this report to illustrate the effects of deviations from benchmark conditions.

Primary and Secondary Lead Production

The annual production of lead is about 6.2M tonnes with approximately half of that originating from ore. The schematic diagram of the production of primary lead and lead from scrap is in the following figure.

Schematic of Primary Lead Production



Primary Production

Lead sulfide ores usually contain less than 10% of the metal by weight and are concentrated to around 70% before processing. The main method of lead recovery from ores is a blast furnace process that involves three main steps: sintering, smelting and refining. Lead is also recovered in the Imperial smelting furnace process that is designed to recover both lead and zinc from ores. The energy demand for the Imperial smelting process is higher than that for the blast furnace process for lead but is used because it has a significantly lower energy demand for zinc production than alternative processes.

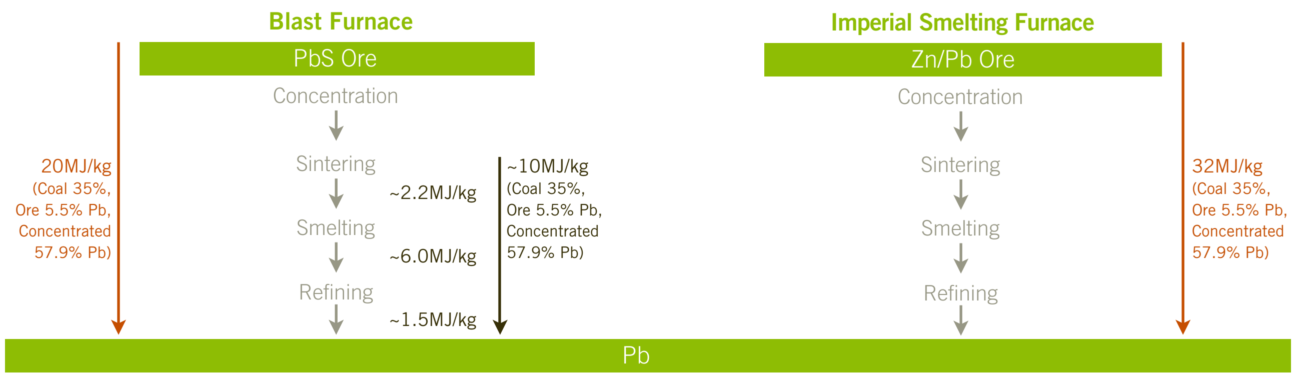
Secondary Production

Lead is easily recycled via pyrometallurgical routes and can be recycled many times without any deterioration or degradation of its properties. A very high proportion of scrap lead comes from spent vehicle batteries. Secondary lead from this source is usually smelted at 1260°C in a rotary reverberatory furnace to produce a slag with a high lead content, along with lead metal for refining. The slag can then be heated in a blast furnace at 1000°C with coke to produce lead (purity 75-85%) and a slag with a low lead content.

Energy Requirement and Carbon Footprint Tables for Lead

The energy requirements for the production of lead from primary sources by the blast furnace and Imperial smelting furnace routes are in the following figure.

Energy Requirements for the Production of Lead from Primary Sources



Primary Production

In 2002, it was reported that 20MJ/kg of energy are required to produce 1kg of lead in the blast furnace process while the Imperial smelting furnace process requires 32MJ/kg for the whole life cycle including mining and concentration, assuming 98.3% and 95% recoveries in the blast furnace and Imperial smelting furnace respectively. The energy requirements excluding the mining and mineral processes obtained from several different sources are reported to be 2.4MJ/kg Pb for the blast furnace route and 2.71MJ/kg Pb for the Imperial smelting furnace route.

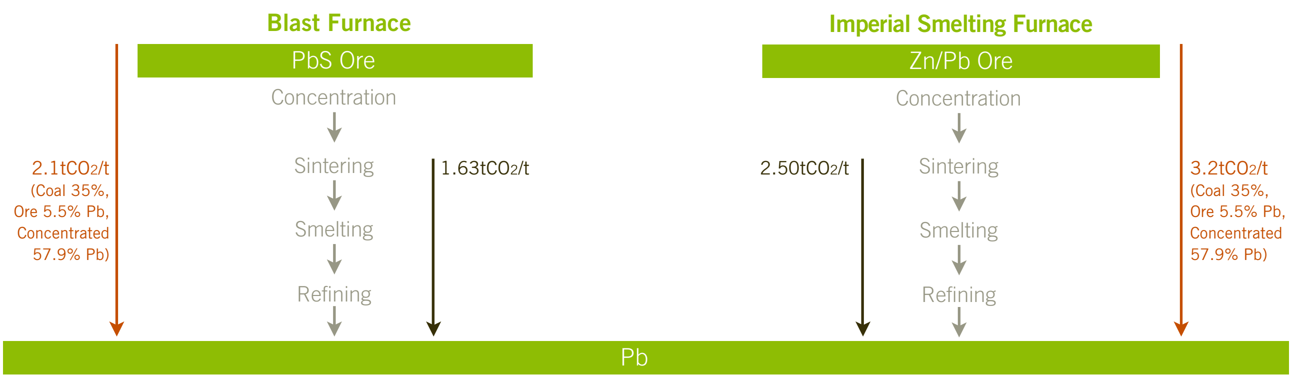
Secondary Production

The literature contains reports that claim secondary production of lead results in a 60-65% energy saving compared to primary production. Using these data, Norgate estimates a general energy demand of 9.1MJ/kg for secondary lead production.

Life cycle analysis of the secondary process has been conducted, including the processes of disaggregation and remanufacturing that would be carried out at a reprocessing facility. From the data, energy consumption at a reprocessing plant was estimated at a total of 0.40MJ/kg Pb.

The energy chosen as a benchmark for secondary production is that of calculated theoretical melting energies with 50% furnace efficiency.

Carbon Footprint for Lead Production



Carbon footprint data for production of lead calculated by Norgate are given in the previous figure. In 2001, Robertson produced a life cycle analysis of primary lead production based on data from two plants in Australia, one of which is the third largest producer of lead in the world. His calculations for emissions yielded a total value of 4.202tCO_2e/t Pb; this value is greater than that obtained by Norgate but it is not absolutely clear how Robertson's data were derived and what assumptions were made.

The benchmark energy requirements for the production of lead metal from primary ore concentrate and for secondary lead from scrap are in in the following table.

Benchmark Energy Requirements for Lead Production

Lead Recovery Method	Energy Requirement (MJ/kg Pb)	Carbon Footprint (tCO_2/t Pb)
Primary	10	1.63
Secondary Assuming 50% Furnace Efficiency	0.129*	0.015**

*Theoretical minimum energy requirement to melt lead assuming furnace efficiency of 50%
**Based on electricity consumption (UK average emission factor)

Summary

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

Energy requirement for primary production of lead: 1000TJ
Energy requirement for secondary production of lead: 12.9TJ

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

Carbon footprint for primary production of lead: 163kt CO_2
Carbon footprint for secondary production of lead: 1.5kt CO_2

Sensitivity analyses on these data are given on page 35 of this report to illustrate the effects of deviations from benchmark conditions.

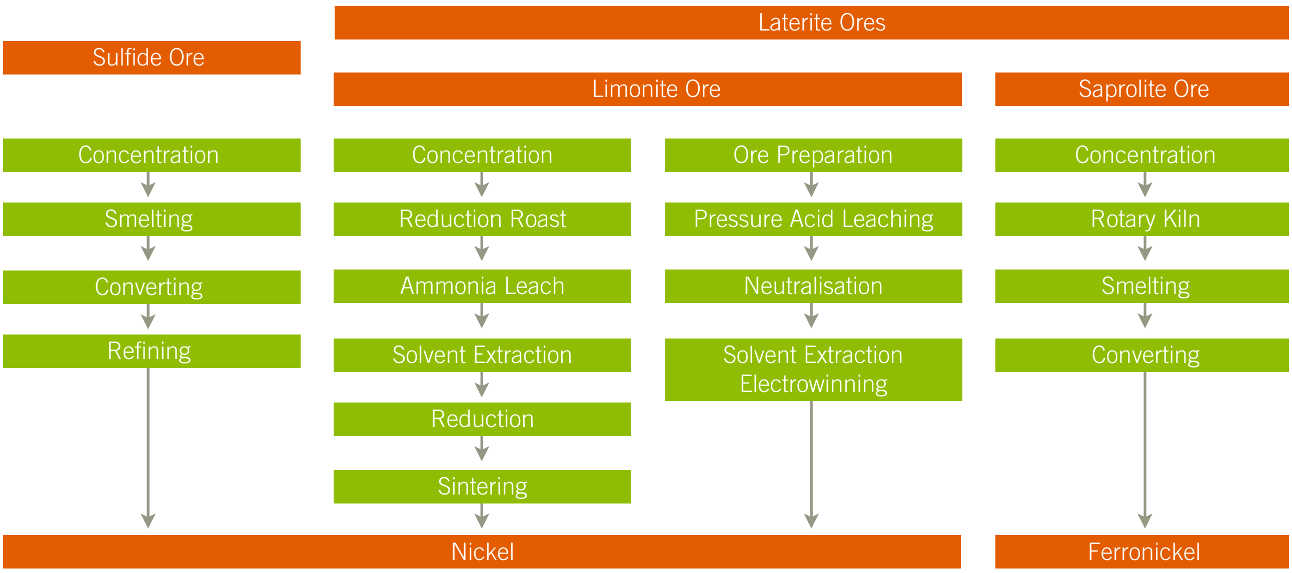
Primary and Secondary Nickel Production

The International Nickel Study Group quotes a global primary production figure of 1.44Mt for nickel in 2007, and it has been estimated that 0.35M tonnes of nickel is recycled from about 4.5Mt of scrap every year.

Primary Production

There are two types of nickel ore that are treated in different ways. The common ores are nickel sulfides (containing about 2% Ni) and these are processed pyrometallurgically. Laterite oxide ores (containing approximately 1% Ni) are treated hydrometallurgically to produce nickel metal, or pyrometallurgically to produce ferronickel. The following figure is a schematic showing the primary production routes.

Schematic for Primary Production of Nickel



The pyrometallurigical process involves concentration of the sulfide ore followed by smelting to produce a matte which is converted to nickel metal and refined by routes such as the Sherritt-Gordon process. Final nickel refining is often carried out by an electrowinning process.

Laterite ores with nickel concentrations greater than 1.7% (saprolite ores) are processed pyrometallurgically in a rotary kiln and an electric furnace to obtain ferronickel. Laterite ores with less than 1.5% nickel (limonite ores) are processed via a hydrometallurgical leaching route with the metal generally being recovered electrolytically.

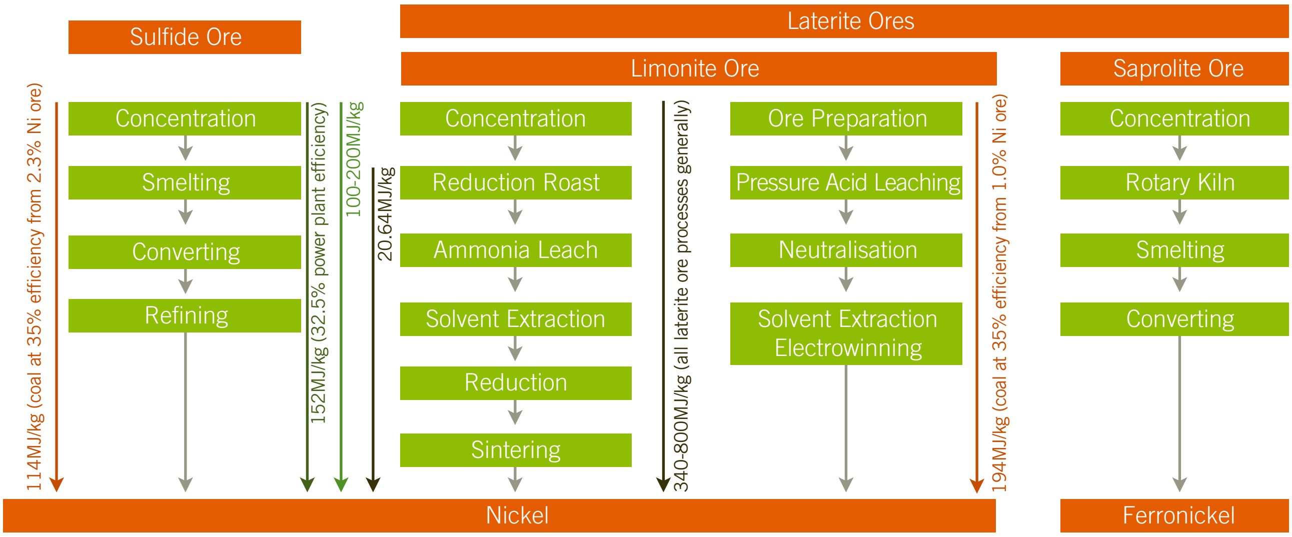
Secondary Production

Nickel is recycled in different ways depending on its original application. Nickel alloys are often recycled as the same alloys, for example the nickel in stainless steel, where about 40% of the nickel used in the production of stainless steel originates from post-consumer stainless steel scrap. Other secondary nickel arisings tend to be recycled by primary nickel smelters.

Energy Requirement and Carbon Footprint Tables for Nickel

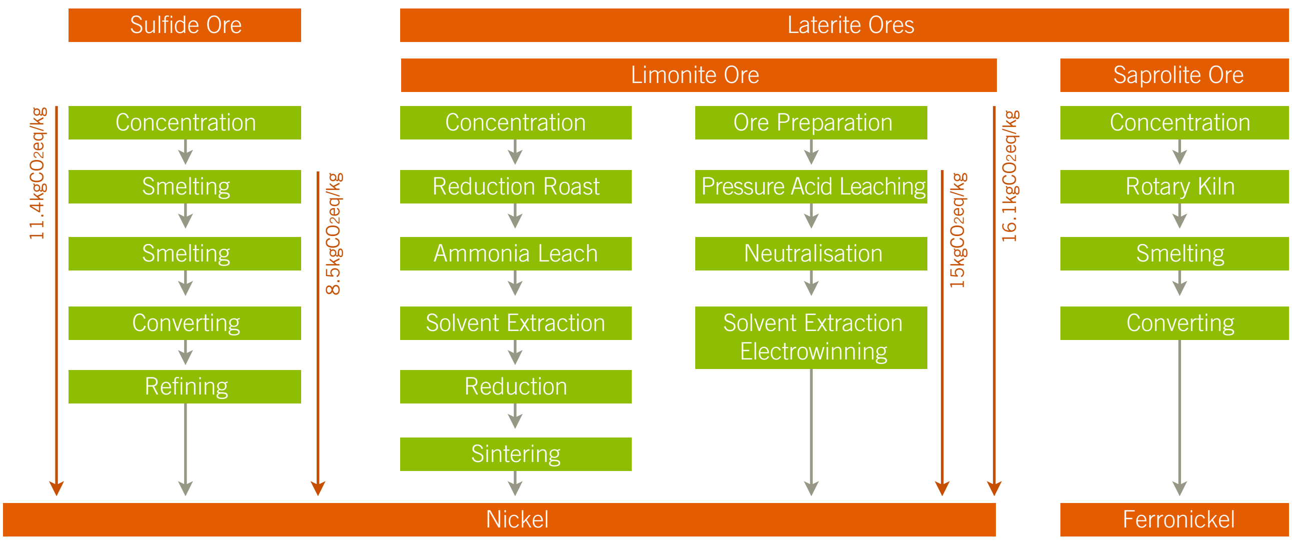
The energy requirement and carbon footprint data reported in the literature are in the following two figures. The data in the figures are based on publications by Norgate, Kellogg, Chapman and Roberts for the whole life cycle of nickel production from mining to metal, and are expressed as gross energy requirement (GER) in MJ/kg and carbon footprint in kg CO_2eq/kg Ni.

Energy Requirement for Production of Nickel



The Norgate data for the whole life cycle – from mining a sulfide ore containing nickel to the recovery of nickel by flash furnace smelting with Sherritt-Gordon refining to recover 78% of the nickel and assuming a 35% energy efficiency – give a GER equal to 114MJ/kg and a carbon footprint of 11.4kgCO_2eq/kg Ni. The smelting and refining processes alone are reported to require 2900kWh/t of electricity, producing a carbon footprint of 8.5kgCO_2eq/kg Ni.

Carbon Footprint for Production of Nickel



Norgate's data for the whole life cycle of a 1% laterite ore – with nickel recovery by pressure acid leaching followed by solvent extraction and electrowinning to recover 92% of the nickel assuming a 35% energy efficiency – give a GER value of 194MJ/kg and a carbon footprint of 16.1kgCO_2eq/kg Ni. The pressure leach and solvent extraction/electrowinning stages of the hydrometallurgical process are reported to require 7651kWh/t of electricity, giving a carbon footprint of 15kgCO_2eq/kg Ni.

A study of the effects of ore concentration on GER and carbon footprint suggested that lowering the ore grade from 2.4% to 0.3% Ni resulted in an increase in GER from 130MJ/kg to 370MJ/kg and in carbon footprint from about 18kgCO_2eq/kg Ni to 85kgCO_2eq/kg Ni.

Chapman and Roberts report GER values for the whole life cycle of 100-200MJ/kg for processing sulfide ores and 340-800 MJ/kg for processing laterite ores. Kellogg's energy requirement value is 152MJ/kg to recover nickel from processing to mining nickel ingot, assuming 32.5% energy efficiency.

On the basis of an assumption of 90% energy savings for secondary nickel production and based on the European average for hydrometallurgical and pyrometallurgical use, Norgate estimates a 15.4-15.8MJ/kg energy requirement for secondary nickel recovery.

Taylor has reported that recycling of nickel-based superalloys into a superalloy ingot requires only 14% of the primary "material fuel equivalent", including transportation, sorting and processing.

The benchmark energy requirements for the production of nickel metal from primary ore concentrate and for secondary nickel metal from scrap and secondary sources are in the following table.

Benchmark Energy Requirements for Nickel Production

Nickel Recovery Method	Energy Requirement (MJ/kg Ni)	Carbon Footprint (tCO_2/t Ni)
Primary Production of Nickel	20.64	2.12
Secondary Production from Scrap	1.86*	0.22**

*Theoretical minimum requirement to melt assuming furnace efficiency of 50%
**Based on melting recovery using UK average electricity emission factor to estimate CO_2 emissions

Summary

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

Energy requirement for primary production of nickel: 2064TJ
Energy requirement for secondary melting of nickel: 186TJ

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

Carbon footprint for primary production of nickel: 212kt CO_2
Carbon footprint for secondary melting of nickel: 22kt CO_2

Sensitivity analyses on these data are given on page 35 of this report to illustrate the effects of deviations from benchmark conditions.

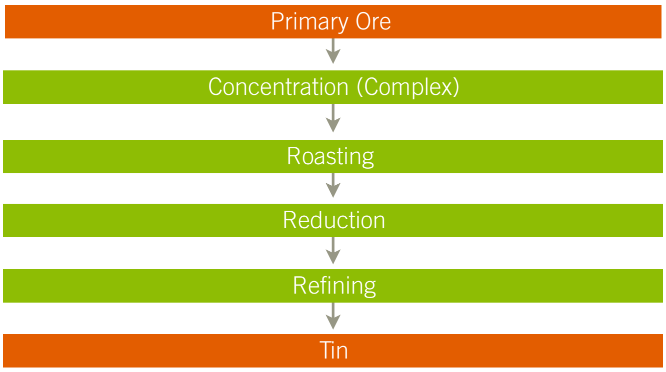
Primary and Secondary Tin Production

In 2007, approximately 300,000 tonnes of tin was recovered from ore worldwide, and an additional amount of approximately 50,000 tonnes was produced from scrap and other secondary sources.

Primary Production

The main ore of tin is cassiterite. The ores need to be concentrated prior to smelting in the presence of carbon to obtain the metal that can be subsequently refined by pyrorefining or electrolytic refining to produce metal of high purity. The following figure is a schematic of the processes involved in the recovery of tin from cassiterite ores.

A Schematic of the Processes Involved in Primary Production of Tin



Secondary Production

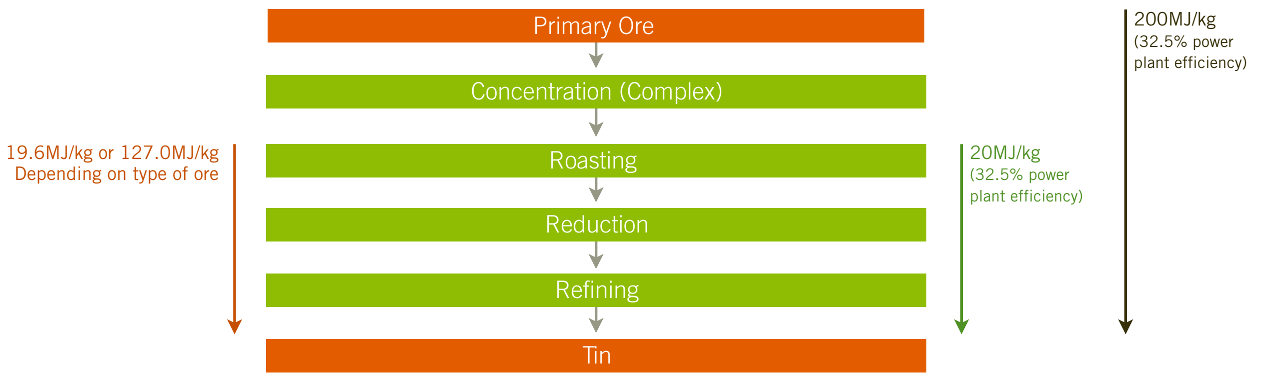
Tin can be recovered from secondary sources via pyrometallurgical treatment by melting the scrap and purifying the metal obtained by similar refining processes to that used in primary production. Tin can also be recovered from secondary sources by hydrometallurgical routes in which either alkali or acid leach solutions can be used, with final recovery usually involving electrowinning of the tin from leach solutions.

Energy Requirement and Carbon Footprint Tables for Tin

The energy requirement for the whole life cycle production of tin from mining the ore to refined metal from a low-grade ore has been reported as 200MJ/kg. The energy requirements for the smelting and refining stages only have been recorded as 19.6MJ/kg from alluvial ores and 127MJ/kg from hard rock ores, and a value of 20MJ/kg has been calculated for these stages based on a 32.5% energy efficiency.

The energy requirements reported for the production of primary tin are given in the following figure.

Energy Requirements for Primary Tin Production



The benchmark energy requirements for the production of tin metal from primary tin ore concentrate and for secondary tin metal from scrap and secondary sources are in the following table.

Benchmark Energy Requirements for Tin Production

Tin Recovery Method	Energy Requirement (MJ/kg Sn)	Carbon Footprint (tCO_2/t Sn)
Primary production of tin	18.2*	2.18***
Secondary production of tin from scrap	0.2**	0.024****

*Based on data shown but recalculated at 35% plant efficiency
**Theoretical minimum requirement to melt assuming furnace efficiency of 50%
*** Based on emissions of 0.12kgCO_2/MJ, as found in processes with similar chemistry
****Based on melting recovery using UK average electricity emission factor to estimate CO_2 emissions

Summary

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

Energy requirement for primary production of tin: **1820TJ**
Energy requirement for secondary production of tin: **20TJ**

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

Carbon footprint for primary production of tin: **218kt CO_2**
Carbon footprint for secondary production of tin: **2.4kt CO_2**

Sensitivity analyses on these data are given on page 35 of this report to illustrate the effects of deviations from benchmark conditions.

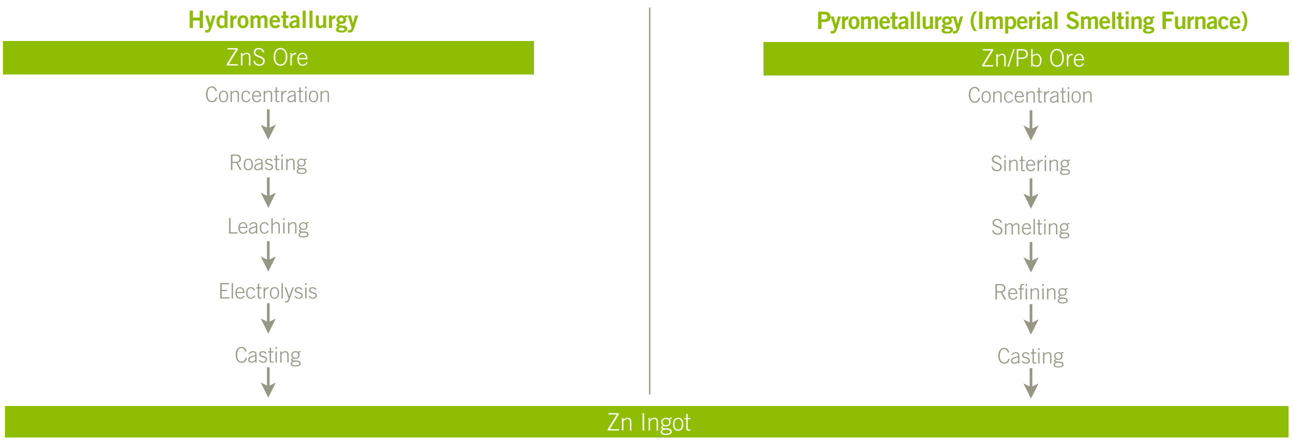
Primary and Secondary Zinc Production

The estimated worldwide production of zinc metal in 2007 was 11.4Mt. Of the total production of smelter zinc (10.6Mt), 4.97Mt are categorised as either primary or secondary, and the remaining 5.63Mt (53%) are not differentiated. Production from secondary is estimated at 7.5% of the differentiated 4.97Mt.

Primary Production

Zinc is produced from zinc sulfide ores containing between 2 and 30% zinc, which are concentrated by froth flotation. Primary zinc metal can be recovered from ore concentrates by both pyrometallurgical and hydrometallurgical processes as shown in the schematic diagram in the following figure.

Schematic for Zinc Production



In the hydrometallurgical process, ore concentrate is roasted to convert the sulfide to zinc oxide which is then leached out in sulfuric acid to give a leach solution that can be purified before recovering zinc by electrowinning.

The pyrometallurgical process makes use of a sulfide ore concentrate that is high in lead and zinc, and recovers both metals simultaneously. This process has three main steps: (i) sintering in which the sulfide ore is converted to zinc oxide, (ii) smelting in the presence of carbon to reduce the oxide to zinc metal, and (iii) distillation in which the zinc is evaporated off as zinc vapour and cooled to obtain the zinc metal.

Secondary Production

The routes for secondary processing of zinc depend upon the types of zinc-containing secondary material being recycled, and in some cases the primary feed may include some secondary material as shown in the life cycle diagram in the following figure.

Life Cycle Diagram Illustrating Zinc Flows

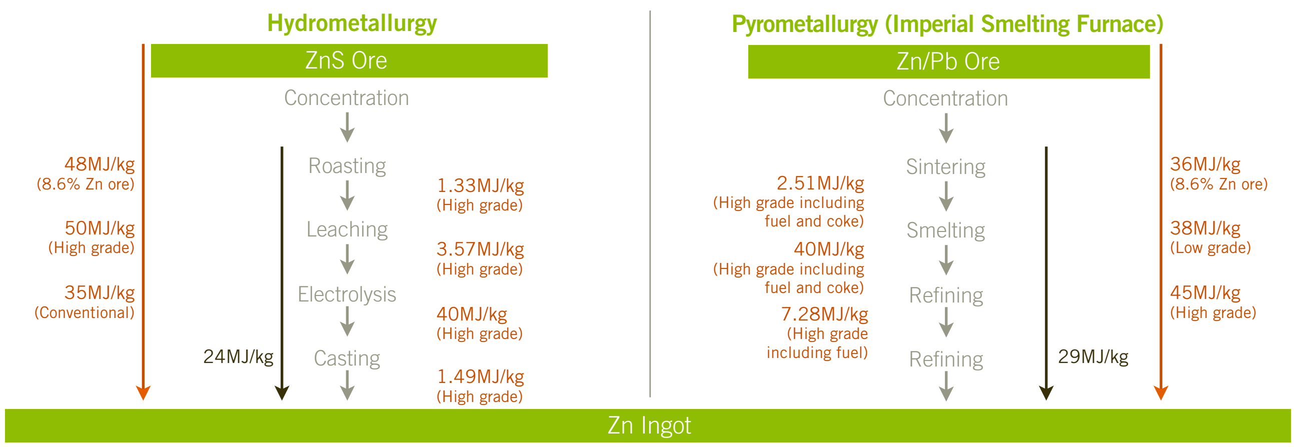
Clean and mixed scrap can be treated by sweating whereby the scrap is heated at 360-420°C to melt zinc for recovery, leaving other impurities such as copper, aluminium and iron in a solid slag. Zinc alloy scrap can also be recovered by a similar process to recover the metal as the alloy and zinc oxide residues can be converted to zinc by dissolving them in sulfuric acid and recovering the metal by electrowinning.

Energy Requirement and Carbon Footprint Tables for Zinc

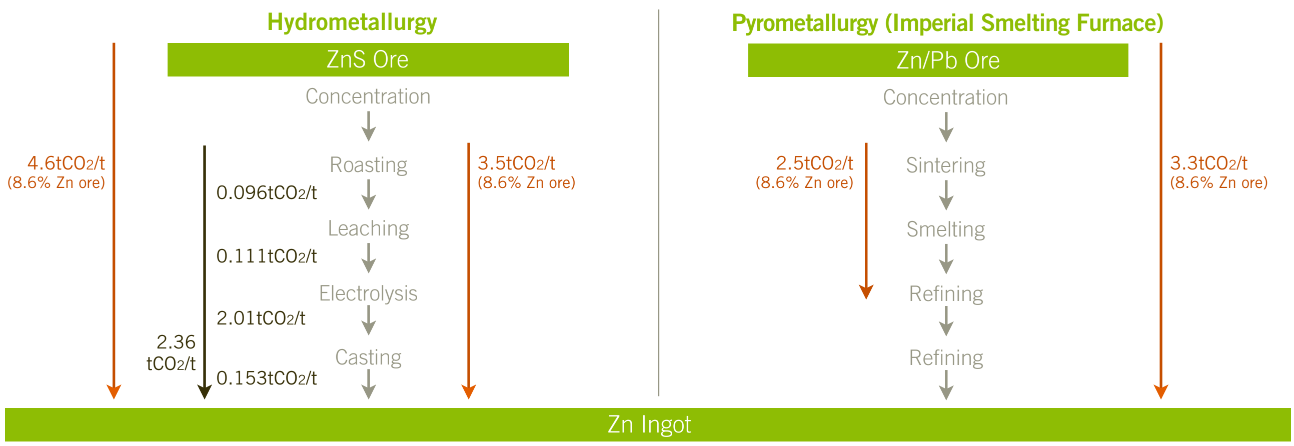
The literature values for the energy requirements and carbon footprints for the production of primary zinc by different routes are given in the following two figures respectively.

Two values have been reported for the energy savings made when secondary production is used instead of primary viz. 75% by Norgate (apparently based on a position paper on recycling by EuroMetaux) and 60% by Gaballah (based on US Institute of Scrap Recycling Industries data from 1993). From these assumptions, Norgate estimated the total energy consumption to recover secondary zinc as 13.7MJ/kg Zn. In 1982, Kellogg stated that secondary processing requires about 5-40% of the energy required for primary processing. None of these data, however, seem to be based on fundamental energy data measurements.

Energy Requirements for the Primary Production of Zinc



Carbon Footprint for the Primary Production of Zinc



The energy data and carbon footprint data that have been reported for zinc recovery from flue dust are in the following two tables.

Energy Requirements for Processes Associated with the Recovery of Zinc from Scrap

Secondary Processing of Zinc Flue Dust			
Process	Energy Requirement (MJ/kg Zn)	% Electricity	Additional
Dezincing	54		
Waelz-Kiln Process	18	93	1.2tcoke/t Zn
EZINEX	35	82	
DC-furnace	27	96	0.27tcoke/t Zn

Carbon Footprint Data for Processes Associated with the Recovery of Zinc from Scrap

Secondary Processing of Zinc Flue Dust	
Process	Carbon Footprint (tCO_2/t Zn)
Dezincing	4.6
Waelz-Kiln Process	
EZINEX	0.7-1.4
DC-furnace	

The benchmark energy requirements for the production of zinc metal from primary zinc ore concentrate and for secondary zinc metal from scrap and secondary sources are in the following table. Although an energy value of 16.4MJ/kg has been reported in Europe for the primary production of zinc via a combination of hydrometallurgical and pyrometallurgical routes, in this work we have used the value of 24MJ/kg as this is more defendable.

Benchmark Energy Requirements for Zinc Production

Zinc Recovery Method	Energy Requirement (MJ/kg Zn)	Carbon Footprint (tCO_2/t Zn)
Primary production of zinc	24	2.36
Secondary production from scrap	18	1.4
Secondary zinc vaporisation	4.7*	0.56**

*Theoretical minimum with 50% furnace efficiency
**UK average electricity emission factor to estimate CO_2 emissions

Summary

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

Energy requirement for primary production of zinc: 2400TJ
Energy requirement for secondary production of zinc: 1800TJ
Energy requirement for secondary vaporisation of zinc: 470TJ

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

Carbon footprint for primary production of zinc: 236kt CO_2
Carbon footprint for secondary production of zinc: 140kt CO_2
Carbon footprint for secondary vaporisation of zinc: 56kt CO_2

Sensitivity analyses on these data are given on page 35 of this report to illustrate the effects of deviations from benchmark conditions.

Primary and Secondary Paper Production

Approximately 365 million tonnes of paper and paperboard are produced globally per annum, with about 46% from secondary sources.

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

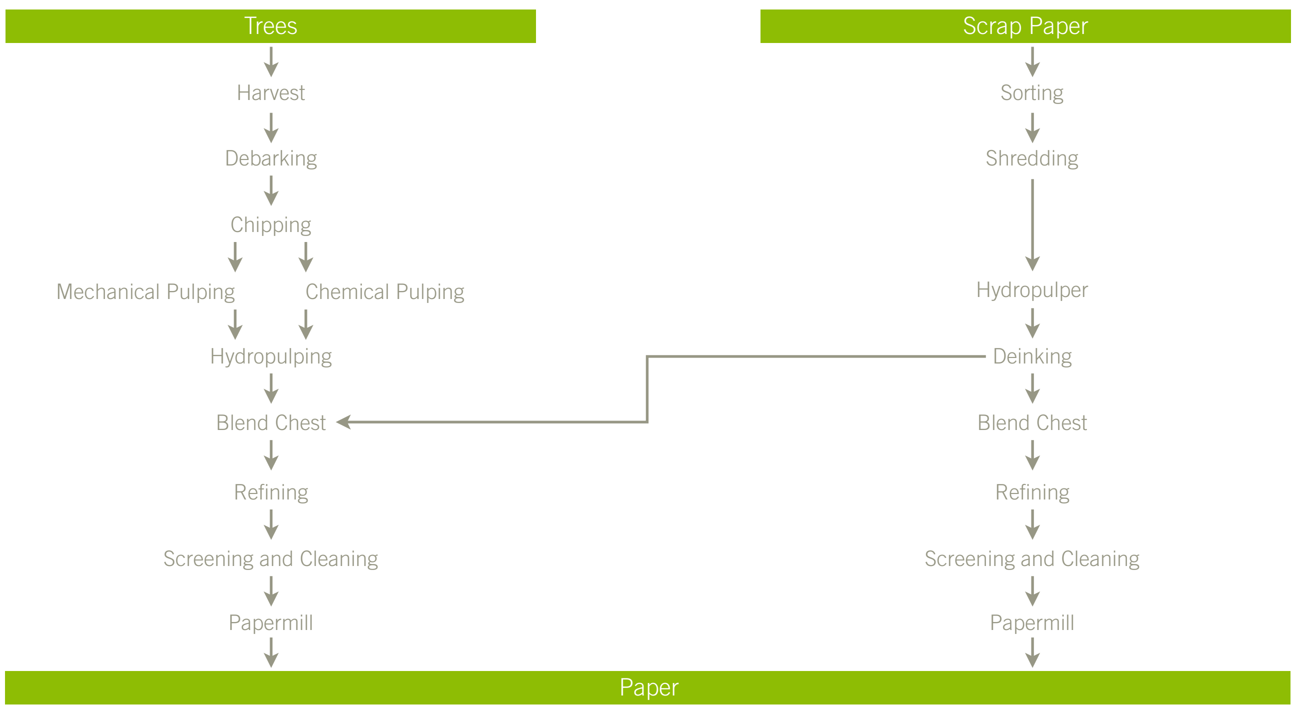
Primary and Secondary Production of Paper

The primary and secondary production of paper is illustrated schematically in the figure below.

Primary Production

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 added 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.

Schematic for the Primary and Secondary Production of Paper



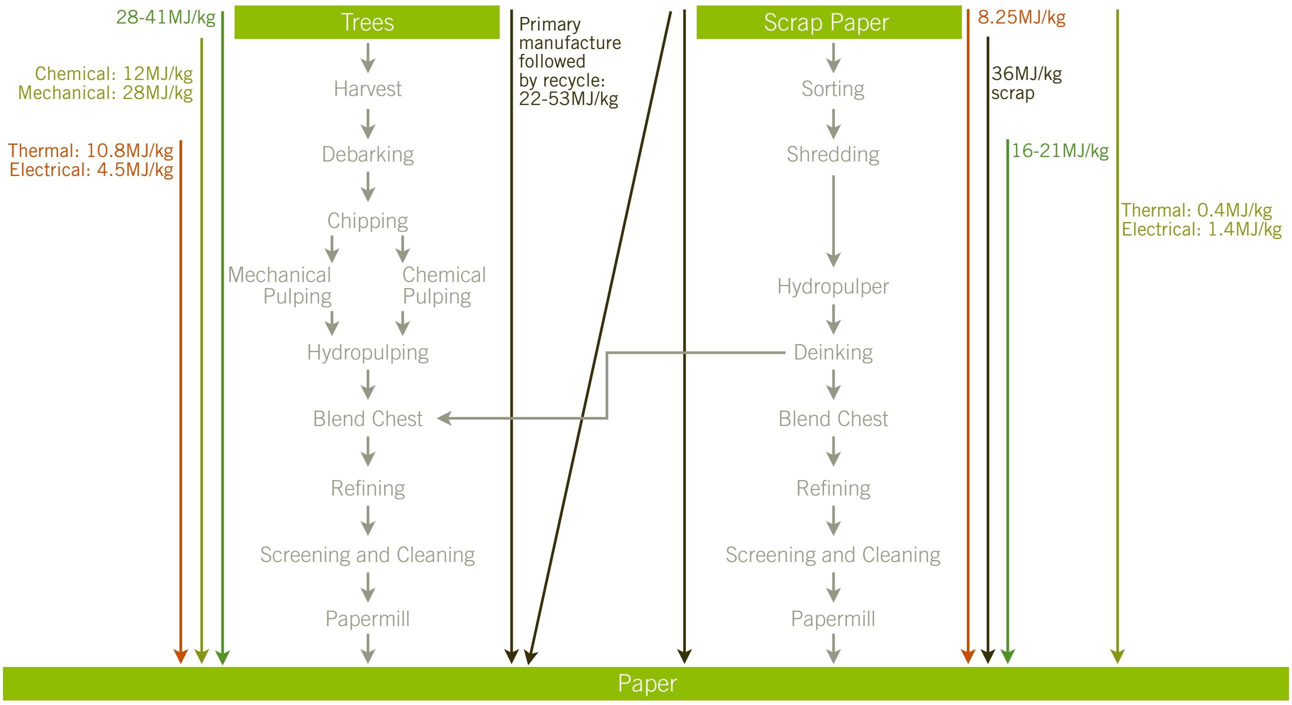
Secondary Production

Waste paper from various sources is sorted, shredded, pulped with water and cleaned to remove impurities such as wire, plastic, paperclips 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.

Energy Requirements and Carbon Footprint for Paper Production

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 22-53MJ/kg, excluding transportation.

Reported Energy Requirements in Primary and Secondary Paper Manufacture



A review in 2007 of high-quality Life Cycle Analyses that compared disposal options for paper concluded that recycling is a better option than landfill or incineration in terms of energy demand.

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 12MJ/kg for chemical processing and 28MJ/kg 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.

An updated 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 in the three scenarios from tree felling and waste paper collection to landfill consequences and incinerator ash disposal. For ease of comparison 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.

Energy Use and CO_2 Emissions for Paper Production

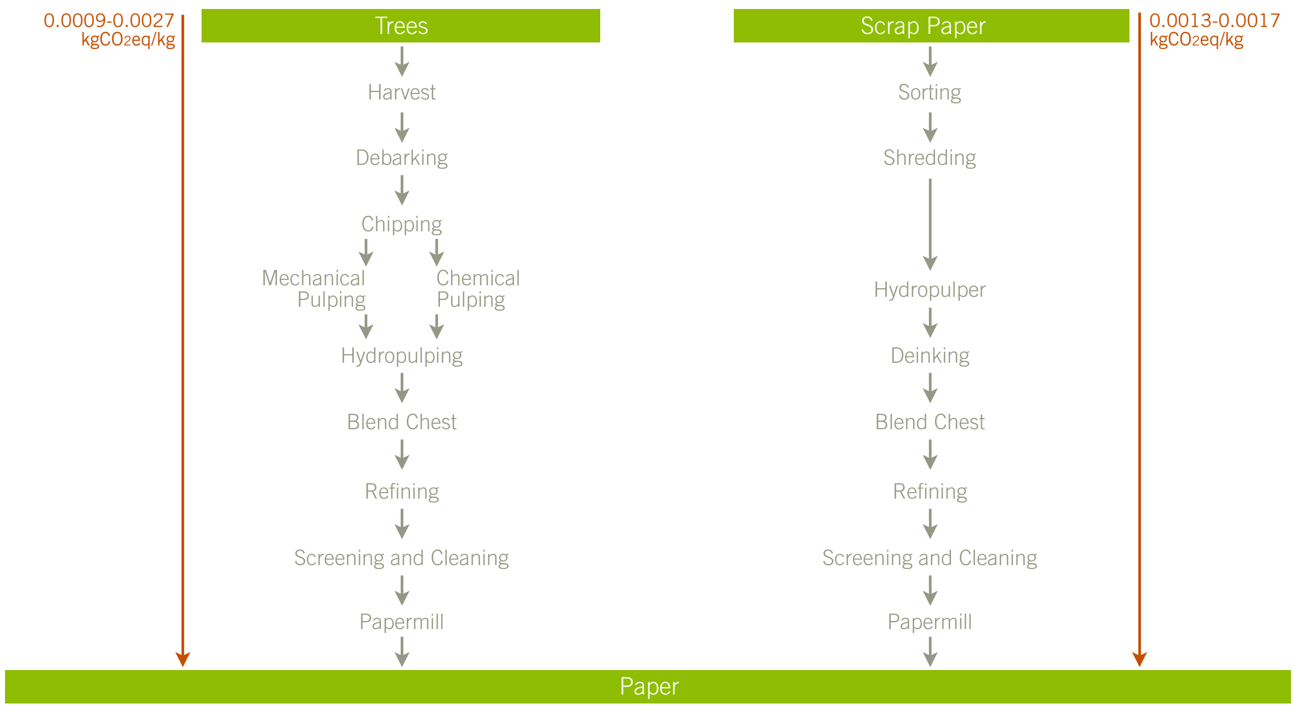
	UNITS	Newsprint	Corrugated Containers	Office Paper	CUK Paperboard	SBS Paperboard
Virgin Manufacture						
Total Energy	MJ/kg paper managed	39	28	40	28	41
Purchased Energy	MJ/kg paper managed	36	15	19	14	19
Fossil Fuel Energy	MJ/kg paper managed	26	13	14	12	14
Recycled Manufacture						
Total Energy	MJ/kg 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_2eqt/t paper	0.0023	0.0014	0.0014	0.0009	0.0027
Recycle	CO_2eqt/t paper	0.0013	0.0013	0.0017	0.0013	0.0014

The data in the table above, 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.

Values have been calculated by the Ecobilan Group for the energy requirement and CO_2 emissions for recycling paper but are reported per tonne of waste paper treated rather than per tonne of paper produced.

The carbon footprints (in the following figure) for the whole life cycle of primary and secondary paper manufacture and the numerical values obtained from the literature on energy use and carbon footprint are given in the following table.

Carbon Footprint Measurements



Energy Use and Carbon Footprint Data for Primary and Secondary Paper Production

Measure	Units	Value
Thermal + Electrical Energy	MJ/kg	10.8 + 4.5
Primary Paper Production + Recycle	MJ/kg	22-53
Primary Paper Production + Incineration	MJ/kg	11-40
Closed Recycle Scheme with Nearby Papermill	*MJ/kg*	*8.25*
100% Primary Pulp – Chemical Process	MJ/kg	12
100% Primary Pulp – Mechanical Process		28
100% Paper Recycling Rate (Energy per Ton of **Total** Paper Production)		
Chemical Primary Processing	MJ/kg	4
Chemical Secondary Processing	*MJ/kg*	*13*
Mechanical Primary Processing	MJ/kg	5
Mechanical Secondary Processing	MJ/kg	17
Primary Manufacture (Total Energy)	MJ/kg	28-41
Recycled Manufacture (Total Energy)		*16-21*
Specific Energy Consumption – Primary	MJ/kg	8.7-16.9
Primary Energy Used in Secondary Production (In Terms of Waste Paper Treated)	*MJ/kg*	*36.2*
Primary Energy to Produce a Clean Fibre Pulp from Wastepaper	*MJ/kg*	*3.9*
Overall Energy to Produce 1 Tonne Recycled Paper	*MJ/kg*	*16.3*

Table continues on page 34 →

Energy Use and Carbon Footprint Data for Primary and Secondary Paper Production *(Continued from Page 33)*

Measure	Units	Value
GHG Emissions Primary Production *Secondary Production*	 tCO_2eq/t *tCO_2eq/t*	 0.0009-0.0027 *0.0013-0.0017*
CO_2 Emissions (In Terms of Waste Paper Treated) Secondary Production	*tCO_2/t*	*1.4*
GHG's over 20 years (In Terms of Waste Paper Treated) Secondary Production	*tCO_2eq/t*	*1.4*

Text written in italics signifies the secondary process.

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

Benchmark Energy Requirements for Paper Production

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

Summary

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: 0.17ktCO_2
Carbon footprint for secondary production: 0.14ktCO_2

Sensitivity analyses on these data are given on page 35 of this report to illustrate the effects of deviations from benchmark conditions.

Sensitivity Analyses

The benchmark figures extracted from the primary literature in this work represent data for situations that are said to be achievable. To account for any variations arising from differences in processes, however, 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 carried out on any input parameter but the following are given as examples of variation in:
(i) secondary production energy requirement data compared with the primary benchmark;
(ii) primary production energy requirement data from the benchmark;
(iii) carbon footprint data for secondary recovery compared with the primary benchmark;
(iv) carbon footprint data for primary production from the primary benchmark;
(v) energy and carbon footprint data expressed for different countries or regions depending on their fuel/energy balance.

Variation in Secondary Energy Requirement compared with Primary

The data in in the following table show how variations would arise in energy requirement data if a given process deviated from the benchmark data process. Variations are calculated for deviations of -10, -5, +5, +10, +15, +20, +30, +40, +50, +90 and +100%. The data presented in the three tables after the following table, are calculated for deviations of -10, -5, +5, +10, +15, +20, +30, +40, +50 and +100%.

For aluminium, copper, lead, nickel and tin, even if a given process deviates by 100% from the benchmark, an energy saving would still be predicted (figure on the following page). However, for ferrous, zinc and paper, deviations of less than 100% would result in the prediction of an energy balance in favour of primary production.

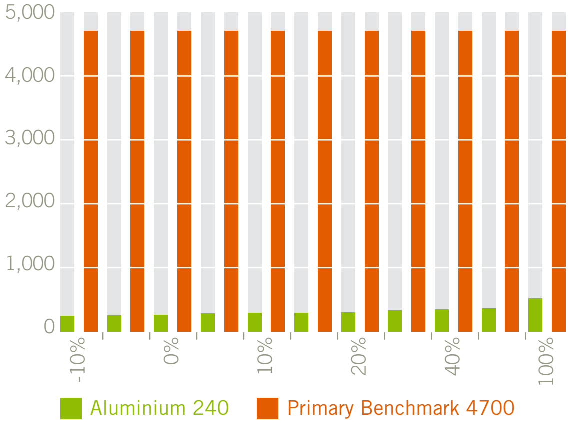
Variation in Primary Energy Data from Benchmark Values

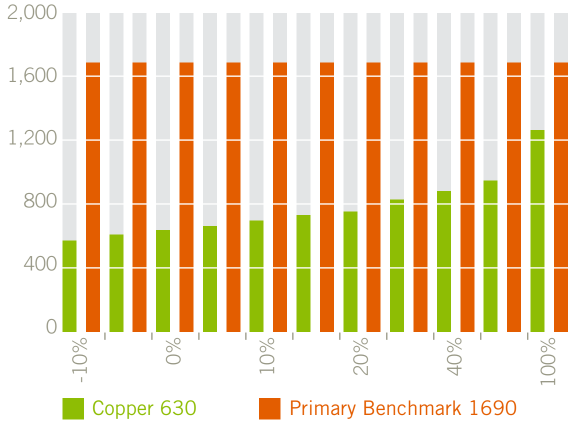
The sensitivity analyses on the primary energy data are expressed in the same way and show the variation in energy requirement with deviations from the primary benchmark data (table on p.37) that would have to be compared with the energy requirement for secondary production in given situations.

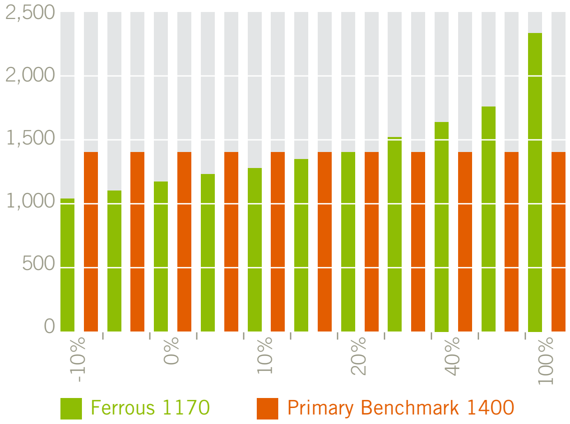
Sensitivity Analysis for Secondary Energy Requirement Data vs. Primary Benchmark Data (Expressed in TJ/kg)

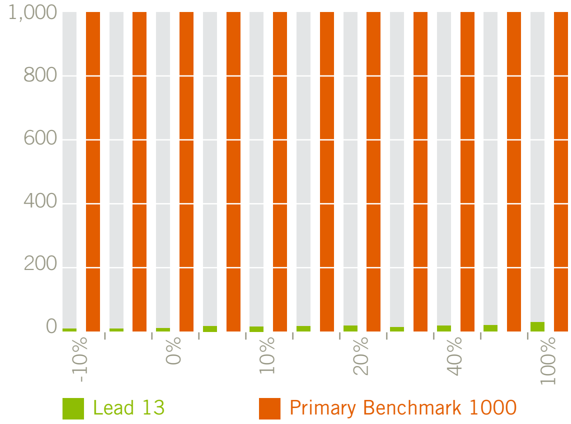
Material	Primary	Secondary	Sensitivity Analysis of Secondary Recovery Data											
			-10%	-5%	0%	5%	10%	15%	20%	30%	40%	50%	90%	100%
Aluminium	4700	240	216	228	240	252	264	276	288	312	336	360	456	480
Copper	1690	630	567	599	630	662	693	725	756	819	882	945	1197	1260
Ferrous	1400	1170	1053	1112	1170	1229	1287	1346	1404	1521	1638	1755	2223	2340
Lead	1000	13	12	12	13	14	14	15	16	17	18	20	25	26
Nickel	2064	186	167	177	186	195	205	214	223	242	260	279	353	372
Tin	1820	20	18	19	20	21	22	23	24	26	28	30	38	40
Zinc	2400	1800	1620	1710	1800	1890	1980	2070	2160	2340	2520	2700	3420	3600
Paper	3520	1880	1692	1786	1880	1974	2068	2162	2256	2444	2632	2820	3572	3760

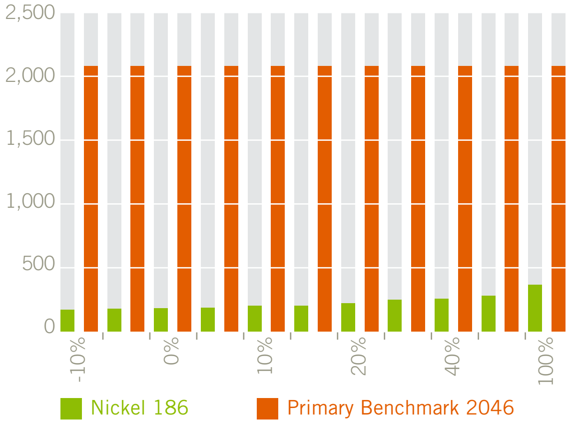
Diagrammatic Representation of Changes in Secondary Energy Requirements vs Primary Benchmark Data

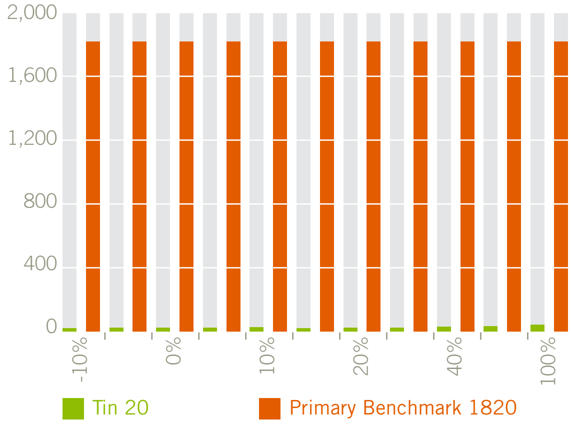


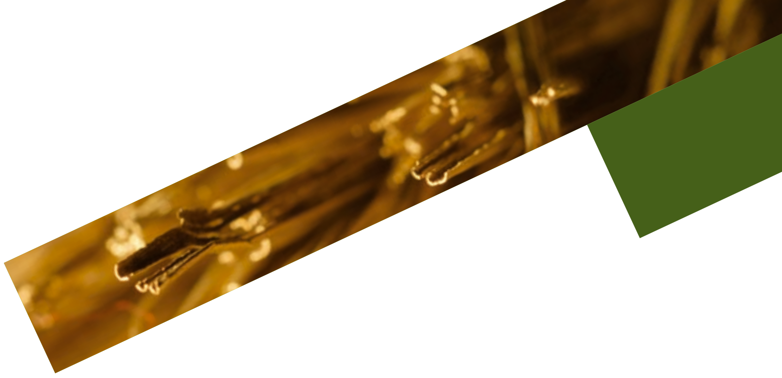


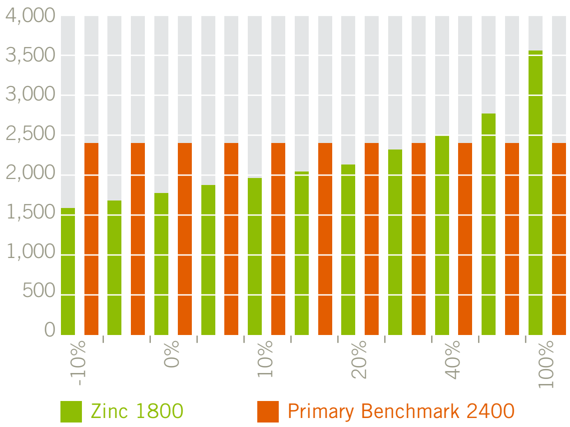


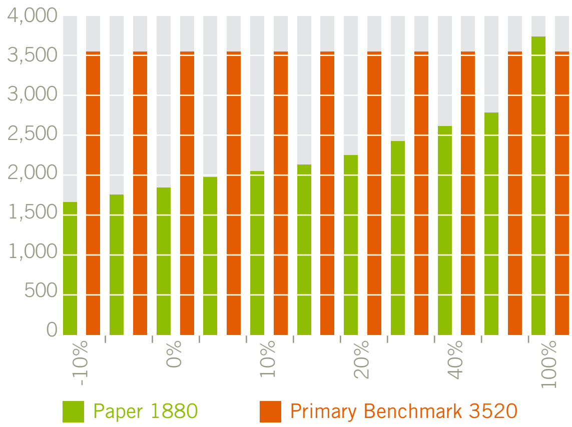












Sensitivity Analysis for Primary Energy Requirement Data vs. Primary Benchmark Data (Expressed in TJ/kg)

Material	Primary	Sensitivity Analysis of Primary Data										
		-10%	-5%	0%	5%	10%	15%	20%	30%	40%	50%	100%
Aluminium	4700	4,230	4,465	4,700	4,935	5,170	5,405	5,640	6,110	6,580	7,050	9,400
Copper	1690	1,521	1,606	1,690	1,775	1,859	1,944	2,028	2,197	2,366	2,535	3,380
Ferrous	1400	1,260	1,330	1,400	1,470	1,540	1,610	1,680	1,820	1,960	2,100	2,800
Lead	1000	900	950	1,000	1,050	1,100	1,150	1,200	1,300	1,400	1,500	2,000
Nickel	2064	1,858	1,961	2,064	2,167	2,270	2,374	2,477	2,683	2,890	3,096	4,128
Tin	1820	1,638	1,729	1,820	1,911	2,002	2,093	2,184	2,366	2,548	2,730	3,640
Zinc	2400	2,160	2,280	2400	2,520	2,640	2,760	2,880	3,120	3,360	3,600	4,800
Paper	3520	3,168	3,344	3,520	3,696	3,872	4,048	4,224	4,576	4,928	5,280	7,040

Variation in Carbon Footprint for Secondary Production Compared with Primary Production

The data in the second table on page 38 show how variations would arise in carbon footprint data if a given process deviated from the benchmark data process. The sensitivity analysis is calculated across the same range; for all of the metals studied, deviations by plus 100% from the benchmark still lead to the prediction of carbon dioxide savings from the secondary process, but for paper production deviations of greater than 30% would lead to a prediction of a carbon footprint in favour of primary production.

Variation in Carbon Footprint Data for Primary Production from the Benchmark Data

The sensitivity analyses on primary carbon footprint data are expressed in the same way and show the variation in CO_2 emissions with deviations from the primary benchmark data (third table on p.38) that would have to be compared with the carbon footprint for secondary production in given situations.

Variation in Energy by Country

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. The following table shows the emission factors for different fuels averaged for the following 14 European countries (Europe-14): Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden and the UK.

CO_2 Emission Factors in kg/GJ, Average for Europe-14

State	Type of Fuel	CO_2 Emissions Factor in (kg/GJ)
Gas	Natural Gas	56.3
Liquid	Natural Gas Liquids	63.8
Liquid	Crude Oil	73.6
Liquid	Orimulsion*	80.7
Solid	Anthracite	98.7
Solid	Bituminous Coal	94.8
Solid	Sub-bituminous Coal	96.7
Solid	Lignite	105.5
Solid	Peat	106.8

* Orimulsion is a bitumen based fuel from Venezuela.

The data in the table above are averaged over the 14 European countries but they also vary with the source of extraction. For example, although the average factor for bituminous coal in Europe-14 is 94.8, the UK average is 83.3 and for Canada the factor is 80.3kgCO_2/GJ.

Sensitivity Analysis for Secondary Carbon Footprint Data vs Primary Benchmark Data (Expressed in kTCO_2/t)

Material	Primary	Secondary	Sensitivity Analysis of Secondary CO_2 Data										
			-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
Lead	163	2	2	2	2	2	2	2	2	3	3	3	4
Nickel	212	22	20	21	22	23	24	25	26	29	31	33	44
Tin	218	3	3	3	3	3	3	3	4	4	4	5	6
Zinc	236	56	50	53	56	59	62	64	67	73	78	84	112
Paper	0.17	0.14	0.13	0.13	0.14	0.15	0.15	0.16	0.17	0.18	0.20	0.21	0.28

Sensitivity Analysis for Primary Carbon Footprint Data vs. Primary Benchmark Data (Expressed in kTCO_2/t)

Material	Primary	Sensitivity Analysis of Primary CO_2 Data										
		-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
Lead	163	147	155	163	171	179	187	196	212	228	245	326
Nickel	212	191	201	212	223	233	244	254	276	297	318	424
Tin	218	196	207	218	229	240	251	262	283	305	327	436
Zinc	236	212	224	236	248	260	271	283	307	330	354	472
Paper	0.17	0.15	0.16	0.17	0.18	0.19	0.20	0.20	0.22	0.24	0.26	0.34

Many primary and secondary production processes for metals rely on electricity as a source of energy, and the data in the following table show the benchmark CO_2 emissions in the generation of electricity from different energy sources. A US Department of Energy report provides information on the electricity emission factors worldwide between 1999 and 2002, averaged by region, and these are recorded in the table at the bottom of this page.

Benchmark CO_2 Emissions in Generation of Electricity from Different Energy Sources

Minimum Emissions for Production of Electricity from Different Sources ($kgCO_2/GJ$)	
Coal	238.9
Oil	190.6
Natural Gas	127.8
Biomass	8.6
Solar PV	8.3
Hydro	4.4
Wind	4.2
Nuclear	2.5

Electricity Emission Factor by Region

Region	Electricity Emission Factor ($kgCO_2/GJ$)
Non-OECD Asia	224.8
Middle East	206.3
Africa	189.7
U.S.	187.8
Mexico	164.8
Non-OECD Europe and Eurasia	142.5
OECD Asia	142.0
OECD Europe	107.4
Canada	62.0
Central and South America	56.7

The data provided in this section show that there are large variations in carbon footprints arising from the differences in the sources of energy available between regions. For the purposes of this report, copper has been used as an example.

The estimated primary production of copper in 2007 was 15.6M tonnes. The following table shows the mine production of copper in the largest producing countries.

Largest Copper Mine Producers and Production in 2007

Country	Copper Mine Production (Mt)
Chile	5.70
Peru	1.20
U.S.	1.19
China	0.92
Australia	0.86
Indonesia	0.78
Russia	0.73
Canada	0.58
Zambia	0.53
Poland	0.47
Kazakhstan	0.46
Mexico	0.40
Total	13.82

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 (the benchmark data taken from table on page 13 and presented in the table below). Assuming that the energy requirement can be based on electricity emission factors, the emissions of CO_2 per 100,000 tonnes of primary copper production compared with the benchmark value of 125 for different countries are given in the table below.

Benchmark Energy Requirements for Primary and Secondary Copper Production

Copper Recovery Method	Energy Requirement (MJ/kg Cu)
Pyrometallurgy from Ore Concentrate	16.9
Secondary Production from Scrap	6.3

CO_2 Emissions per 100,000 Tonnes of Copper Production in Selected Countries

Country	Electricity Emission Factor ($kgCO_2$/GJ)	Emissions in $ktCO_2$ (100,000 tonnes Cu)
Kazakhstan	359.2	607
Australia	256.8	434
China	233.1	394
Poland	202.7	343
Indonesia	200.5	339
U.S.	187.8	317
Mexico	164.8	279
Russia	97.5	165
Chile	92.4	156
Benchmark		125
Canada	62.0	105
Peru	41.1	70
Zambia	1.9	3

The data for production of 100,000 tonnes of secondary copper are given along with the benchmark figure in the following table.

CO_2 Emissions per 100,000 Tonnes of Secondary Copper Production in Selected Countries

Country	Electricity Emission Factor ($kgCO_2$/GJ)	Emissions in $ktCO_2$ (100,000 tonnes 2^{ary} Cu)
India	277.4	175
Australia	256.8	162
South Africa	253.0	159
China	233.1	147
Poland	202.7	128
Indonesia	200.5	126
U.S.	187.8	118
Islamic Republic of Iran	166.2	105
Mexico	164.8	104
Germany	149.7	94
United Kingdom	132.0	83
Japan	116.0	73
Russia	97.5	61
Venezuela	69.7	44
Benchmark		44
Canada	62.0	39
Brazil	25.8	16

Using the benchmark data from this work, the total savings in CO_2 from production of secondary material rather than primary are estimated as approximately 500Mt CO_2 (see table below).

Estimated Savings in CO_2 Emissions

Material	Secondary Production (Mt)	Emission by Primary Production (Mt CO_2)	Emission by Secondary Production (Mt CO_2)	Savings (Mt CO_2)
Aluminium	16	61.3	4.6	56.6
Copper	6	7.5	2.6	4.9
Ferrous	440	734.8	308.0	426.8
Lead	3	4.9	0.1	4.8
Nickel	0.35	0.7	0.1	0.6
Tin	0.05	0.1	<0.1	0.1
Zinc	1	2.4	0.6	1.8
Paper	168	28.6	23.5	5.1
Total	628	840	340	501

Conclusion

Values of the energy requirements and carbon footprints have been obtained from a survey of the primary literature for the production of primary and secondary metals and paper. The metals included in the survey are aluminium, copper, ferrous, lead, nickel, tin and zinc.

To avoid complications associated with the early stages of the whole life cycles of these materials, benchmark energy requirements and carbon footprints for primary materials are extracted from ore or raw material delivered at the production plant, and for secondary material delivered at the secondary plant. Benchmark data are reported per 100,000 tonnes of material produced to provide a means of direct comparison between primary and secondary production. These data are tabulated in the following two tables for each material separately, as energy requirements and savings per 100,000 tonnes of production of material, and as carbon footprints and savings per 100,000 tonnes of production of material.

Energy Requirement and Savings in Terajoules (TJ/100,000t)

Material	Primary	Secondary	Saving/100,000 Tonnes
Aluminium	4700	240	4460
Copper	1690	630	1360
Ferrous	1400	1170	230
Lead	1000	13	987
Nickel	2064	186	1878
Tin	1820	20	1800
Zinc	2400	1800	600
Paper	3520	1880	1640

Carbon Footprint and Savings Expressed in Kilotonnes of CO_2 ($ktCO_2$)/100,000 Tonnes

Material	Primary	Secondary	Saving/100,000 Tonnes
Aluminium	383	29	354
Copper	125	44	81
Ferrous	167	70	97
Lead	163	2	161
Nickel	212	22	190
Tin	218	3	215
Zinc	236	56	180
Paper	0.17	0.14	0.03

Using these data, the total saving in annual carbon dioxide emissions for the production of the secondary materials that are the subject of this report is calculated to be approximately 500Mt. The savings for the individual materials are listed in the following table.

Estimated Annual Savings in CO_2 Emissions

Material	Secondary Production (Mt)	Emission by Primary Production (Mt CO_2)	Emission by Secondary Production (Mt CO_2)	Savings/100 000tonnes (% savings CO_2 in parentheses)	
Aluminium	16	61.3	4.6	56.6	(92%)
Copper	6	7.5	2.6	4.9	(65%)
Ferrous	440	734.8	308.0	426.8	(58%)
Lead	3	4.9	0.1	4.8	(99%)
Nickel	0.35	0.7	0.1	0.6	(90%)
Tin	0.05	0.1	<0.1	0.1	(99%)
Zinc	1	2.4	0.6	1.8	(76%)
Paper	168	0.286	0.235	0.05	(18%)
Total	634	812	316	496	

The benchmark figures extracted from the primary literature in this work represent (i) data for situations that are said to be achievable and (ii) values that are the most acceptable and justifiable. To account for any variations arising from differences in processes, however, 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 carried out on any input parameter but the following are given as examples:

(i) the variation in secondary production energy requirement data compared with the primary benchmark;
(ii) the variation in primary production energy requirement data from the benchmark;
(iii) the variation in the carbon footprint data for secondary recovery compared with the primary benchmark;
(iv) the variation in the carbon footprint data for primary production from the primary benchmark;
(v) the variation in energy and carbon footprint data expressed for different countries or regions depending on their fuel/energy balance.

Except for variations by country and region, variations have been calculated for deviations of -10, -5, +5, +10, +15, +20, +30, +40, +50, +90 and +100%, or -10, -5, +5, +10, +15, +20, +30, +40, +50 and +100%. This provides a rapid method of comparing data from real production processes with the benchmark values used in this work.

The concept of benchmarking is 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.

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