INSTITUTE FOR EUROPEAN STUDIES

Metals for a Climate Neutral Europe

A 2050 Blueprint

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About the IES

The Institute for European Studies (IES) at the Vrije Universiteit Brussel (VUB) is an academic Jean Monnet Centre of Excellence and a policy think tank that focuses on the European Union in an international setting. The Institute advances academic education and research in various disciplines, and provides services to policy-makers, scholars, stakeholders and the general public.

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2. Introduction

2.1 Introduction to project, context and goal

This report was commissioned by Eurometaux, the European non-ferrous metals association. It represents the industry's vision on how it can contribute to achieving climate neutrality in Europe. The report profiles the non-ferrous metals ecosystem that the sector represents and its progress on climate mitigation and circularity. It also identifies the opportunities, challenges and constraints the sector faces in the transition to net-zero while determining a combination of key solutions that will help the non-ferrous metals, silicon and ferro-alloys sector to further reduce emissions, as well as address the necessary conditions for ensuring that the sector remains at the forefront of the energy and industrial transformation.

2.2 Scope

This report considers the base metals, silicon, ferro-alloys, precious metals, specialty metals and rare earth elements. With regard to energy use and greenhouse gas (GHG) emissions the report focusses on the base metals, silicon and ferro-alloys.

- **Base Metals**: Aluminium, copper, lead, nickel, tin, zinc (+ silicon & ferro-alloys)
- **Precious metals:** Gold, Silver, Platinum, Paladium, Ruthenium, Osmium, Iridium, Rhodium
- **Specialty metals:** Cobalt, Germanium, Gallium, Indium, Selenium, Antimony, Magnesium, Molybdenum, Cadmium, Beryllium, Bismuth, Chromium, Niobium, Vanadium, Hafnium, Lithium, Manganese, Rhenium, Tantalum, Tellurium, Titanium, Tungsten
- **Rare earth elements:** Neodymium, Dysprosium, Scandium, Cerium, Erbium, Europium, Gadolinium, Holmium, Lutetium, Ytterbium, Thulium, Lanthanum, Praseodymium, Samarium, Terbium and Yttrium

2.3 Methodology

The report starts by presenting a coordinated profile of the non-ferrous metals, silicon and ferro-alloys industry (chapter 3). This profiling aims to illuminate the delicate ecosystem that is the sector via a thorough assessment of metals interlinkages, production in Europe, trade patterns and the sector's high import reliance as well as the sector's close association to the broader economy. It also sheds light on China's growing profile and its impact on the EU non-ferrous industry. It then highlights the essential role of the non-ferrous metals, silicon and ferro-alloys industry in the low-carbon economy in their quality as enablers of the green economy.

Chapter 4 explains how the sector is a price taker on a global market where prices are set at the London Metals Exchange. The chapter first describes the workings of the LME and provides evidence of supply and demand impact on pricing of metals explaining how factors that influence the metal price at LME are outside the direct control of either producers or users.

Chapter 5 discusses the energy use and greenhouse as gas emissions from non-ferrous metals production as well as the options for further mitigation of GHG emissions as a contribution to the EU's goal to achieve climate neutrality by mid-century. The focus will be on base metals with highest over-all energy use (e.g. aluminium, copper, zinc, nickel, silicon, ferro-alloys). First a general overview is given of energy use in non-ferrous metals production and how it compares to other energy intensive industries, followed by a brief overview of over-all GHG emissions from non-ferrous metals production in the EU.

Next the primary and secondary production processes for aluminium, copper, zinc, nickel, silicon, ferro-manganese and ferro-silicon are presented together with energy use and (evolution) of GHG emissions. This is followed by a literature study on possible (new) GHG mitigation options for non-ferrous metal production. This includes techniques to reduce direct and indirect emissions in primary production but also addresses options that can improve use of secondary raw materials in non-ferrous metals production and technologies which the non-ferrous metals industry can apply to assist with reduction of GHG emissions in other sectors.

Chapter 6 discusses the most important challenges for non-ferrous metals industry from the perspective of a bellwether or frontrunner industry, in particular the high electro-intensity and vulnerability to rising electricity prices. Other challenges include trade related issues, and misalignment in the broader regulatory environment related to numerous environmental regulations to which non-ferrous metals industry is subjected to.

Chapter 7 brings the findings of previous chapters together to formulate a strategy that can enable a competitive transition to a climate neutral economy both for the non-ferrous metals sector as the value chains that will depend on metals. It looks at a set of five strategic actions: competitive carbon free electricity, climate friendly innovations and investments, nurturing future value chains, circularity and industrial symbiosis, assertive EU trade policies and strategic regulatory realignment.

The report is based on diverse sources and includes data from the non-ferrous metals, silicon and ferro-alloys sector as well as publicly available documents and data (e.g. industry reports, EU databases, European Commission studies, US and British Geological surveys, project websites and media articles). The research team also conducted interviews with experts from the various metal commodity associations and specific companies (see annex - list of contributors).

The metals ecosystem

3 The Metals Ecosystem

3.1. Introduction to non-ferrous metals

Non-ferrous metals are essentially building blocks of our society. Their value chains connect to vital infrastructure like buildings, transport, electronics; strategic sectors like defence; as well as almost every other economic sector such as food, jewellery and so on. They are particularly indispensable and irreplaceable in the production of low-carbon technologies. This means that the on-going transition to a climate neutral economy can be expected to be metals intensive.

The non-ferrous metals industry in Europe is worth EUR 120 billion employing around 500,000 persons directly and more than 2 million people indirectly. The sector consists of 931 facilities, including mining (54 facilities), primary and secondary production of metals (464) and further transformation (413). Metals production is present in most EU member states with a large presence in Italy (179 facilities), Germany (147 facilities), Spain (116 facilities), France (82 facilities), UK (53 facilities), and Poland (51 facilities) (Figure 1).[1]

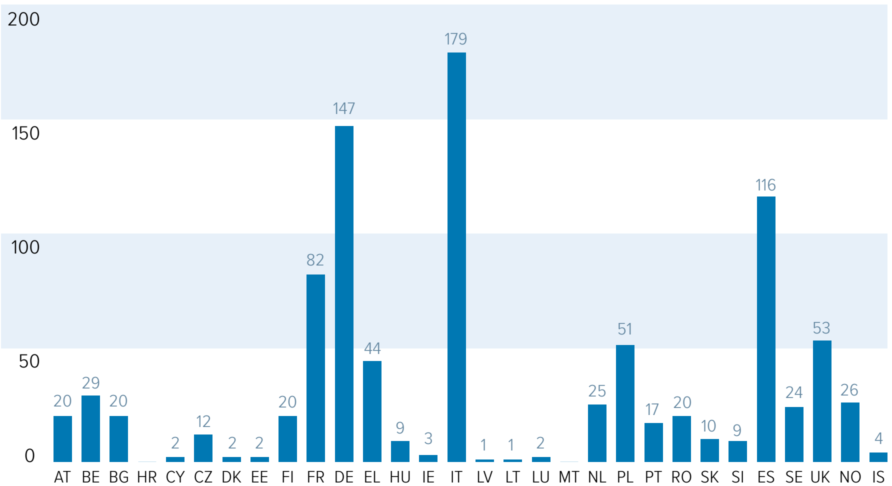


Figure 1: Distribution of the non-ferrous metals industry across Europe. Source: Eurometaux

3.1.1 The non-ferrous metals eco-system

The non-ferrous metals sector forms a fascinating eco-system over its value chain that connects one way or the other the base, precious, specialty and alloys production to each other. Most metal ores carry, next to the primary metals, various other metals in smaller concentrations. These latter are, when it is economically viable, extracted during the metallurgical process of the primary or 'carrier metal', including via recovery in slags or hydrometallurgical residues. All base metals (ores) are carrier metals for a wide range of other base-metals, precious and specialty metals (as shown in figure 2). Cobalt for instance, is as a key by-product of copper metallurgy (60% of cobalt production) and nickel metallurgy (40% of cobalt production).

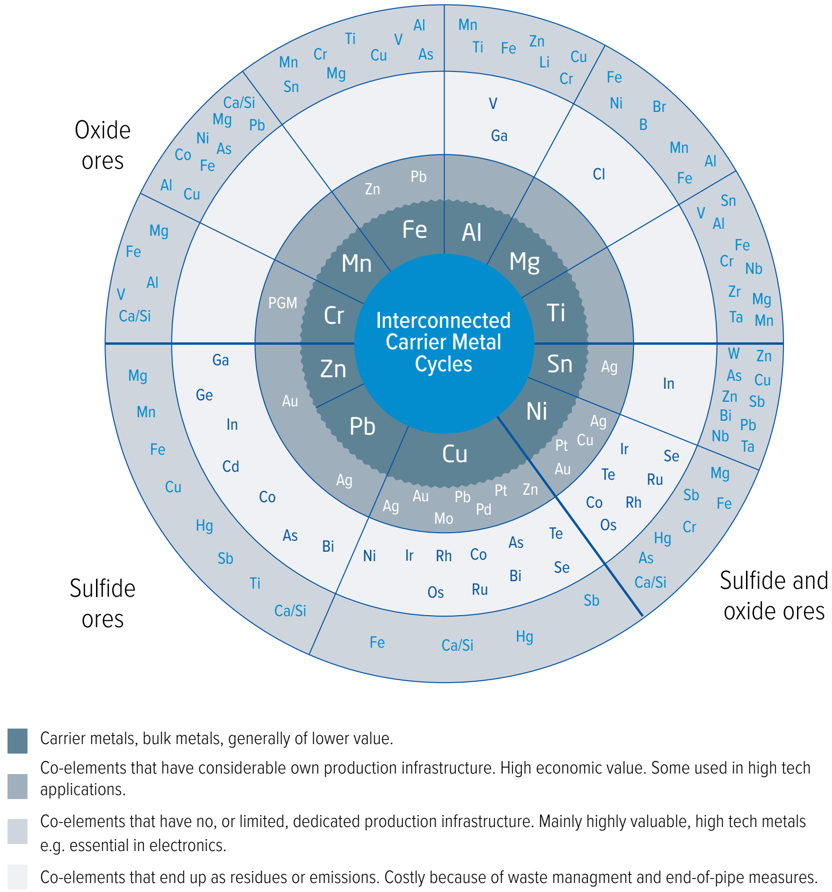


Figure 2: Non-ferrous metals sector interlinkages I Source: UNEP 2013[2]

1 Eurometaux

2 UNEP, 2013

But also, in secondary production the metals eco-system is clearly visible via the extraction of different metals in mixed waste streams or complex products consisting of different types of metals (e.g. batteries).

Finally, most non-ferrous metals can be and are alloyed with other non-ferrous metals, iron and silicon. Alloys bring about specific properties to metals that are essentials in down-stream applications (e.g. stainless steel).

Table 1 below shows the by-products attained in the production of non-ferrous base metals.

Primary Production	Aluminium	Copper	Nickel	Zinc	Lead
By-Products	Bauxite residue (red mud), Ga, waste gases	Sulphuric Acid, Au, Ag, Co, As, Bi, Mo, Se, Te, Platinum group metals (PGM)	PGM, Co, Cu, Au, sulphuric acid	Pb, Se, Te, In, Ge, Cu, Ni, Co, PGM, Au, Ag, Cd, Hg, sulphuric acid	Antimonial lead, Ag, Bi, Te, Se, In, waste gases

Table 1: Key non-ferrous base metals by-products

See Annex 1 for a detailed overview of the non-ferrous metals ecosystem.

Box 1: Flanders Metals Valley – example of non-ferrous metals ecosystem

Belgium's Flanders region, dubbed as Europe's epicenter of metals recycling and innovative production, is home to numerous key metals companies such as Aurubis, Metallo, Umicore Precious Metals Refining, Rezinal, Nyrstar and others, that not only produce significant volumes of nonferrous metal but also consistently explore new technology. These companies work closely together to maximise the value from their various input materials rendering the cooperation into a globally unparalled recycling model which results in the efficient recovery of over 20 metals. Agoria and its member companies can recycle around 17 metallic elements. Rezinal focuses on recycling zinc and alloys shipped in from some 35 countries. Nyrstar is also a zinc recycling specialist and its Balen plant is one of the world's largest zinc smelters in terms of production volumes. Galloo has pioneered ways to maximize the purity and value of mixed shredded before they go to a smelting facility. Metallo, Umicore and Rezinal already harvest metal from residue streams no matter how mixed or impure they may be. The Umicore Precious Metals Refining smelter in Hoboken, Belgium, recycles up to 17 different metals. Metallo is the leading producer of pure tin in Europe (less than 100 parts of lead per million).

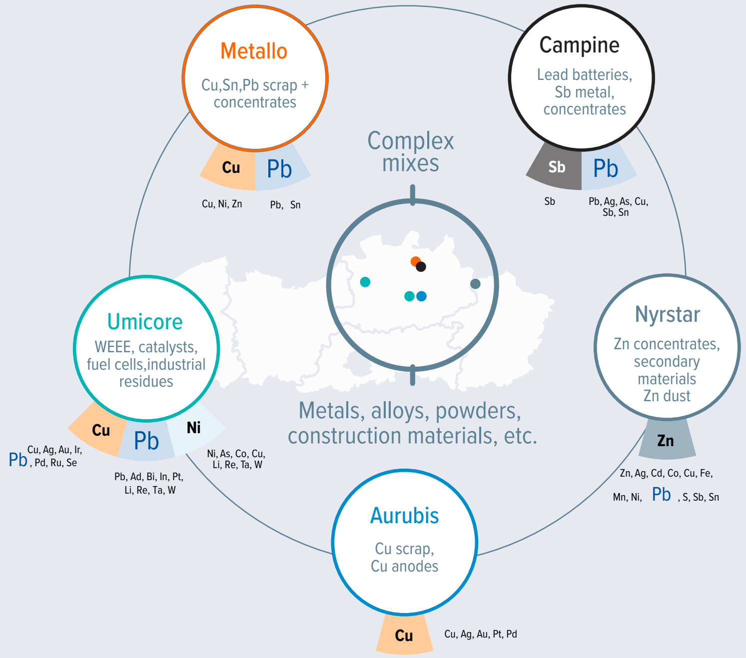


Figure 3: Flanders Metals Valley

3.1.2 Production of non-ferrous base metals in the EU

Within the EU, the total primary production of non-ferrous metals stood at 7.4 million tonnes (Mt) in 2016.

Aluminium is the most used non-ferrous metal by volume and the second most widely used metal after iron both in the EU and globally. The sector consists of more than 600 plants (most of these being small to medium sized enterprises) in 30 European countries, and provides indirect employment to more than 1 million persons with an annual turnover of around EUR 40 billion.[3] Primary production of aluminium stands at 2.2 Mt (2016) or just 4% of global total primary production. Secondary aluminium production in the EU however is higher at 3Mt as compared to 10.1 Mt global secondary production or 29.73%.

Copper is the second largest base metal sector in the EU after aluminium with around 500 companies in three sectors (mining, production and semi-fabrication) and an estimated

3 European Aluminium

turnover of about EUR 45 billion while employing around 50,000 people.[4] In 2016, primary copper production stood at 2.3 Mt or 13.1% of global total primary production. Secondary production in the EU, like aluminium, is significantly high as compared to global figures. In 2016, secondary copper production in the EU was a quarter of global figures: 0.73 Mt as compared to 2.8 Mt (or 25.82%).

Lead is a significantly large base metal sector and is usually found in and extracted in ore with zinc, copper and silver. The lead industry in Europe consists of 60 plants[5], employs 5400 persons[6] and has a turnover of EUR 3 billion.[7] Primary lead production in Europe stood at 436kt in 2016 or 9.37% of worldwide production. Secondary lead production in the EU is high: 1,351kt or 18.2% of world secondary production given high recycling rates in the EU[8] (65% EU27 in 2016).[9]

Zinc is the fourth-most used metal after iron, aluminum, and copper. The zinc industry in Europe is well established with 12 plants located regionally providing direct employment to around 5,000 people and indirect employment to more than 50,000 people with a turnover of EUR 5 billion approximately.[10] Primary zinc production[11] in the EU stood at 1,699 kt or 13.4% of global total primary production in 2016.[12] In the same year, secondary production of zinc[13] stood at 296 kt as compared to 1,563 kt global secondary production (18.94%).

Nickel represents a smaller metals industry in Europe with world class installations in Norway, Finland, the UK and France. It nonetheless employs 4700 persons with an annual output of EUR 9,2 billion. Primary nickel production in Europe (including Norway) amounted to 211 kt or 9.6% of global total primary production for 2018.[14] At 29.20%, secondary Nickel production in Europe is second only to the Aluminium sector: 200 kt secondary nickel is used in Europe as compared to 685 kt global secondary production.

3.1.3 Mining metal ores and raw materials in the EU

The extractive industry (mining) of non-ferrous metals sector in Europe is not a large sector given the paucity of ore reserves found in Europe.

For the main metal ores, EU mining has a small share in global ores production: 0.6% for bauxite (aluminium), 4.1% for copper ores, 3% for nickel ores, 5.44% for zinc ores and 1% for cobalt. Lead ores form the exception with the EU representing 9.7% of worldwide mining.[15]

4 European Copper Institute
5 ILZSG, 2017
6 ILA
7 CRU, 2019
8 ILZSG
9 https://ec.europa.eu/commission/sites/beta-political/files/swd-report-batteries-accumulators-april2019_en.pdf
10 EU Zinc Industry, 2011
11 Primary zinc production is not exclusively processing zinc ore concentrates. Some primary zinc smelters have close to 50% of secondary feed material.
12 IZLSG
13 Secondary production refers to re-melted zinc only.
14 INSG
15 Silver 7%, gold 0.6%, Tungsten 2.9, Lithium 0.175%, European Commission 2017a&b, Lead source: IZLSG

There is no extraction of antimony, beryllium, borates, magnesium, molybdenum, niobium, phosphorus, tantalum, titanium, vanadium and rare earths, for a variety of reasons (lack of discovery, lack of deposits, economic and societal factors or closures). The only raw materials for which an EU Member State is the main global producer is hafnium (France). There exists sufficient primary production of raw materials in the EU such feldspar, gypsum, hafnium, indium, kaolin clay, magnesite, silica sand, sulphur and tellurium.

Europe therefore relies heavily on metal ores and concentrates imports from other continents – almost 80% of its needs. The value chain of raw materials therefore shows a pronounced imbalance between the upstream steps (extraction / harvesting) and the down-stream steps (manufacturing and use). China is the dominant entity with 46 raw materials (of 77 assessed) being mainly extracted in China, followed by the USA with 9% production of raw materials assessed[16].

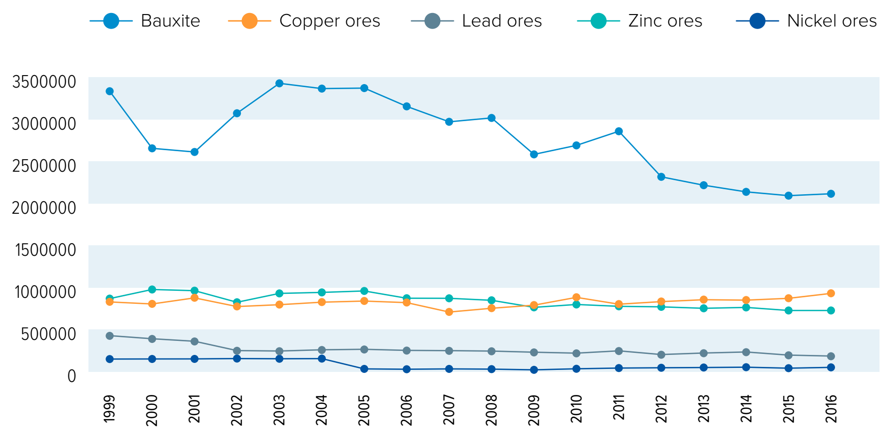


Figure 4: European Base Metal ore mining,Tonnes. Source: World-Mining-Data, C. Reichl, M. Schatz, G. Zsak, Volume: 31, Minerals Production, Vienna 2016

Rare Earths are currently not mined in the EU although several rare earth element deposits have been located (in Sweden, Denmark, Finland and Greece) and some are even being developed by mining companies.[17] The EU is 100% reliant on rare earth imports where China is the top producer – China's rare earth production went up 14.3% in just one year (from 105,000 tonnes in 2017 to 120,000 in 2018).[18]

16 Study on the review of the list of Critical Raw Materials: Criticality Assessments
17 EURARE 2017
18 McLead, 2019

3.2 EU Metals Production in a Global Context

3.2.1 EU production versus other large metals producers

The EU's primary production of non-ferrous metals in 2016 represented 3.71% of total global production (195.28 Mt)[19 20]. The EU still has an important share of primary production as a percentage of global production: 4% for aluminium, 13.1% for copper, 9.37% for lead, 9.6% for nickel, and 13.4% for zinc. For cobalt and silicon, the figure stands at 10.23% and 9% respectively.[21] EU's production share is particularly high as regards hafnium (41.67%), selenium (41.85%) and rhenium (16.47%). However, for a number of metals, EU production is less than 1% of global production[22].

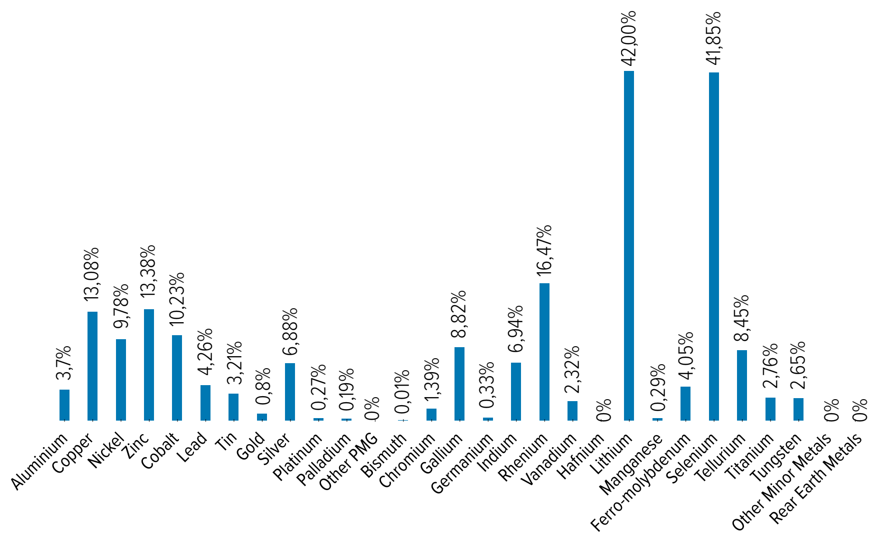


Figure 5: EU Primary Production as a % of World Production (tonnes), Base metals data 2016, Source: USGS, 2017, World Bureau of metals, ILZSG, Nickel Institute, Comtrade. I Other metals[23] average for 2010-2014 Source: European Commission 2017a, 2017b.

19 Data for primary base metals sourced from USGS Minerals Yearbook, World Bureau of metals, INSG 2017, ILZSG, Comtrade and the Nickel Institute, 2016 figures; data for all other metals sourced from European Commission (2017a&b), World production (tonnes) -average for 2010-2014. Figures without Silicon and Ferro-alloys included

20 With the exception of selenium (41.85% of world production average for 2010-2014), Hafnium (41.67% of world production average for 2010-2014) and Rhenium (16,47% of world production average for 2010-2014).

21 Figures for 2016. Lead figure source:ILZSG, Silicon figure source : European Commission, (2017b), Nickel figure for 2018 and includes Norway. Source: INSG. Other Sources: European Commission, (2017b)

22 Gold at 0.8%, Platinum at 0.27%, Palladium at 0,19%, Bismuth at 0,01%, Germanium at 0,33%, Manganese at 0,29%, Bauxite at 0,85%, and 0% for Iridium, Ruthenium, Rhodium, Beryllium, Niobium, Magnesium, Antimony, Tantalum, Scandium, Cerium, Dysprosium, Erbium, Europium, Gadolinium, Holmium, lutetium, ytterbium, thulium, Lanthanum, Neodymium, Praseodymium, Samarium, Terbium and Yttrium

23 Other PGM include Iridium, Ruthenium, Rhodium. Other minor metals include Niobium, Magnesium, Antimony, Tantalum, Beryllium

The global metals market is dominated heavily by China, followed by Russia, USA, Australia, Chile and South Africa (in order of frequency of appearance in Tables 2 & 3). The predominance of China as the top metals producing country for the largest number of metals/ores is clear. Not only does China top the list in almost every metals production but does so with a large margin. China is not only the largest nonferrous metals producer in the world but also the largest consumer of the base non-ferrous metals: copper, aluminum, zinc, lead, nickel and tin.

Name	Top Metal Producer	Country Rank 1-3		
Primary Aluminium	Top Metal Producers	China 55%	Russia 6%	Canada 5%
	EU Import Partners	Norway 21%	Russia 20%	Iceland 14%
Copper	Top Metal Producers - Smelting	China 37%	EU 10%	Chile 9%
	Top Metal Producers - Refining	China 37%	EU/Chile 11%	Japan 7%
	EU Import Partners	Chile 26%	Peru 23%	Brazil 11%
Nickel	Top Metal Producers	China 28%	Japan 10%	Russia 9%
	EU Import Partners	Russia 32%	Norway 13%	Australia 10%
Zinc	Top Metal Producers - Smelting	China 45%	South Korea 7%	Canada 5%
	EU Import Partners[24]	Peru 31%	Namibia 28%	Russia 27%
Lead	Top Metal Producers	China 42%	USA 9%	South Korea 8%
	EU Import Partners	Australia 11%	Macedonia 11%	Peru 9%
Tin	Top Metal Producers	China 51%	Indonesia 19%	Malaysia 8%
Refined Tin	EU Import Partners	Indonesia 35%	Peru 24%	Malaysia 9%
Selenium (refined)	Top Global Mining Countries	Japan 29%	Germany 25%	Belgium 8%
	EU Import Partners	Brazil 26%	Russia 14%	Japan 12%
Tellurium (refined)	Top Metal Producers - Refined	China 61%	USA 11%	Russia 9%
	EU Import Partners	Ukraine 30%	China 15%	Russia 6%
Titanium (mined)	Top Global Mining Countries	Canada 21%	Australia 15%	South Africa 12%
	EU Import Partners	Norway 25%	Canada 21%	South Africa 17%
Tungsten (mined)	Top Global Mining Countries	China 79%	EU 7%	Canada/Vietnam/ Russia 3%
	EU Import Partners	Russia 84%	Bolivia/Vietnam 5%	USA 1%

Table 2: Top 3 metals producing countries and top 3 EU import partners. Source: JRC 2017, BGS 2016 (Zinc – import of refined zinc. Source: Comtrade)

24 Comtrade

Name	Top Mining Country	Country Rank 1-3		
Bauxite	Top Global Mining Countries	Australia 29%	China 18%	Brazil 13%
	EU Import Partners	Guinea 72%	Brazil 12%	Sierra Leone 8%
Copper	Top Global Mining Countries	Chile 32%	China 9%	Peru 8%
	EU Import Partners	Chile 26%	Peru 23%	Brazil 11%
Nickel	Top Global Mining Countries	Indonesia	Philippines	New Caledonia/Russia
	EU Import Partners	Guatemala 85.7%	Canada 12.4%	South Africa 3%
Zinc	Top Global Mining Countries	China 35%	Australia12%	Peru 10%
	EU Import Partners	Australia 33%	Peru 23%	USA 17%
Lead	Top Global Mining Countries	China 49%	Australia 14%	USA 7%
	EU Import Partners	Australia 11%	Macedonia 11%	Peru 9%
Tin	Top Global Mining Countries	China 45%	Indonesia 19%	Malaysia 10%
	EU Import Partners	Bolivia 23.8%%	Malaysia 16.7%	USA 16.5%
Cobalt Oxides, hydroxides, chlorides, mattes, intermediate products, unwrought metal and powders	Top Metal Producers	China 45%	EU 18%	Canada 6%
	EU Import Partners	DRC 49%	USA/Norway 8%	Russia 7%
Gold	Top Global Mining Countries	China 14%	Australia 9%	Russia / USA 8%
	EU Import Partners	South Africa 26%	Other 9%	
Silver	Top Global Mining Countries	Mexico 21%	Peru/China 14%	Australia 7%
	EU Import Partners	Peru 51%	Mexico 17%	Argentina 9%
Platinum	Top Global Mining Countries	South Africa 72%	Russia 12%	Zimbabwe 8%
	EU Import Partners	USA 37%	Switzerland 8%	Japan 6%
Bismuth	Top Global Mining Countries	China 57%	Mexico 22%	Japan 16%
	EU Import Partners	China 84%	Peru/SA/USA 3%	Japan/Canada 2%
Chromium	Top Global Mining Countries	South Africa 48%	Kazakhstan 21%	Turkey 13%
Ferrochromium	EU Import Partners	South Africa 60%	Russia/Zimbabwe 8%	Kazakhstan 4%
Rhenium	Top Global Mining Countries	Chile 43%	USA 19%	Poland 16%
	EU Import Partners	Iran/South Korea/Uzbekistan 6%		
Lithium	Top Global Mining Countries	Chile 44%	Australia 32%	Argentina 11%
Lithium compounds	EU Import Partners	Chile 77%	USA 10%	China 6%
Manganese	Top Global Mining Countries	China 9%	South Africa 20%	Australia 14%
Ores & Concentrates	EU Import Partners	South Africa 33%	Brazil 31%	Gabon 26%
Molybdenum (mined)	Top Global Mining Countries	China 42%	USA 23%	Chile 15%;
	EU Import Partners	USA 57%	Chile 15%	Peru 14%
Antimony	Top Global Mining Countries	China 73%	Tajikistan 10%	Russia 4%
Unwrought metal	EU Import Partners	China 90%	Vietnam 4%	Kyrgyzstan 2%

Table 3: Top 3 metals-ores producing countries and top 3 EU import partners. Figures for 2016, Source: European Commission, 2017 a&b, BGS, Tin Source: Resource Trade Earth, Nickel Mining (2019) Source: Da Silva, 2019

Despite the predominance of China, the EU has diverse import partners with the top countries being Russia and Peru (8 metals each) and USA (7 metals), Norway and China (4 metals each). One of the reasons is that not only has China put in place export restrictions but has also imposed export taxes (see Box 2 and Chapter 7.3 for more details).[25][26] Although the EU has maintained supply security and its dependence on China is not as yet dire, in the near future the situation could turn drastically different. It is important to note that the EU does not have a free trade agreement framework in place with any of its top trading partners which could provide not only greater supply security but also a reliable political and economic framework.[27]

3.2.2 The EU's import reliance and metals trade balance

The EU has a large import dependency[28] as concerns base metal ores - 84% for aluminium (bauxite)[29], 82% for copper, 78% for tin, 71% for zinc (concentrate), 59% for copper, 48% for cobalt – with the exception of lead at 18%.[30] For silicon and ferro-alloys, imports contribute 73% of total consumption.[31] In the case of other non-ferrous metals ores, the import dependency is high, most palpable for the platinum group of metals (EU production[32] of platinum – 0.5 tonnes, palladium – 0.4 tonnes), beryllium, bismuth (EU production 0.8 tonnes) , niobium, magnesium, molybdenum (EU production ferro-molybdenum - 11,000 tonnes), antimony (although the EU does produce antimony trioxide in Belgium, France, Spain and Italy), tantalum, and rare earths where the EU production is close to 0. Needless to say, the EU is not a significant exporter or ores and primary metals. In fact, the EU has 100% import reliance for the vast majority of non-ferrous metal ores. Europe's 100% import reliance for several critical raw materials means that it is entirely dependent on third countries.

25 European Commission, 2017a&b
26 It is worth noting that China is by far the largest EU import partner of downstream aluminium products.
27 The EU has recently reached accord on a long-standing free trade agreement negotiation with the MERCOSUR group of countries which has not yet entered into force.
28 Import dependency, a metric derivable from EW-MFA, denotes the share of physical imports in the direct material input of a given economy (the DMI comprises domestic extraction and physical imports).
29 The import dependency specifically for primary aluminium is lower than 84%.
30 Sector Data
31 Wyns, Khandekar & Robson., 2018
32 Primary

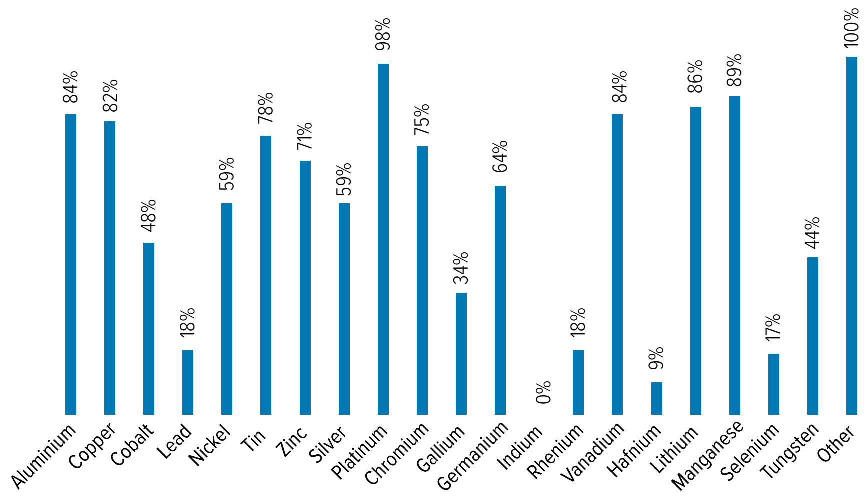


Figure 6: EU Non-Ferrous Metal Ores Import Reliance[33] Source: European Commission, 2018

The EU also has an important negative trade balance when it comes to imports and exports of metals. Non-ferrous metals imports into the EU heavily outweigh exports and have steadily increased in the past nearly two decades from 9.9 Mt in 2000 to 12.5 Mt in 2017. But exports also increased over the same period (3.8 Mt in 2000 to 6.2 Mt in 2017)[34]. Imports showed a relative decline immediately after the EU and international financial crisis, with the biggest dip occurring in 2009) although they have once again assumed pre-crisis levels (except copper, nickel, specialty metals). Exports too dropped in 2009 and picked up immediately after until 2014 but have since stayed below the high reached in 2014. For some sectors however, exports remain below 2000 levels – zinc and specialty metals. EU non-ferrous metals exports principally go to China, US, Switzerland, Turkey and India (2016 figures)[35].

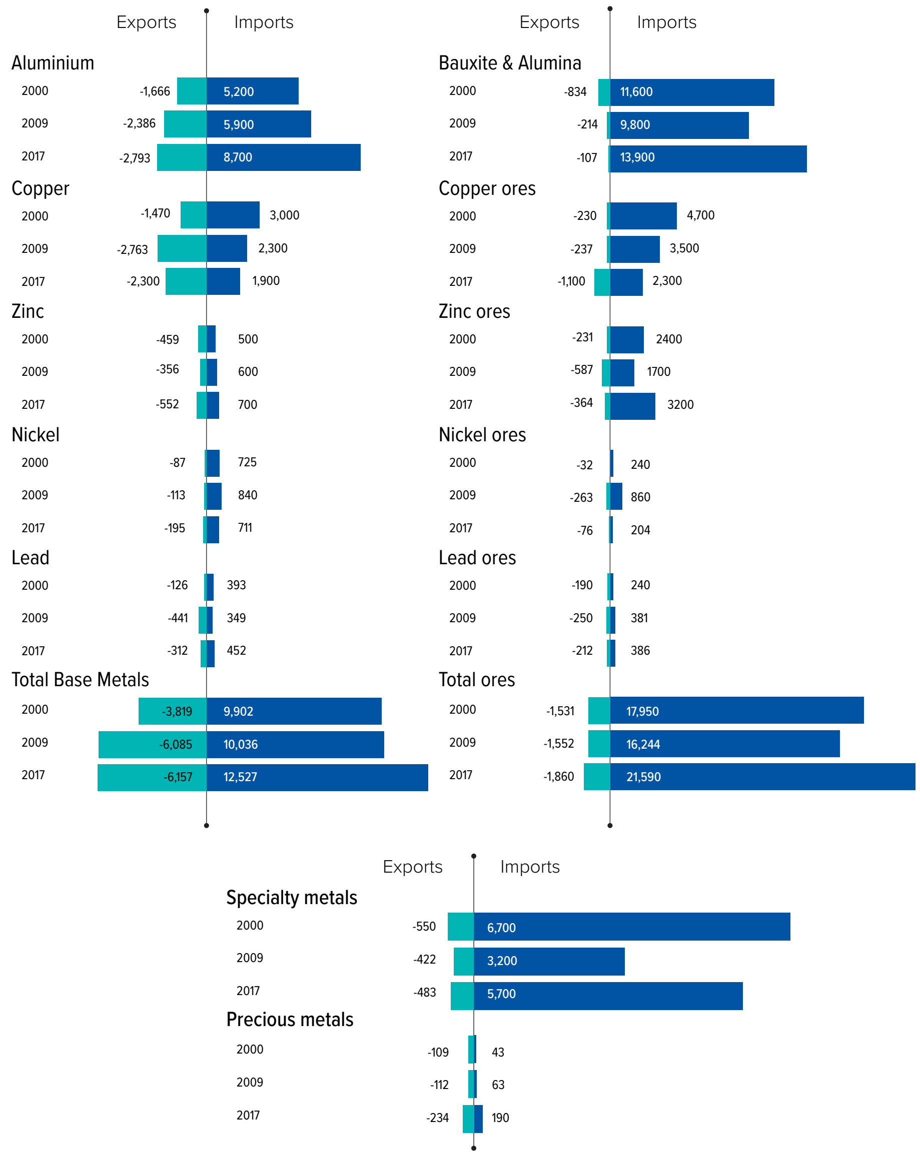


Figure 7: EU Non-ferrous metals trade (Ktonnes) timeseries, Source: Resource Trade Earth[36]

33 Other includes the Platinum group of metals, rare others and minor metals: Magnesium, Niobium, Molybednum, Antimony, Tantalum, Tellurium and Titanium. There is a meaningful import reliance for gold but it cannot be calculated because of the complexity of trade flows of gold in diverse forms and uncertainties in reported trade data. Zinc – figure for concentrates. For Refined Zinc – 10% (with Norway – 3%).

34 Resource Trade Earth

35 Ibidem

36 Includes products, ores and concentrates, waste and scrap, refined, unwrought, ash and residues, unwrought alloys, master alloys, other alloys, dust, powder non-monetary.

The same trend can be observed in the terms of base metal ores. Total imports of non-ferrous metal ores saw a dip after the crisis (from 17.9 Mt in 2000 to 16.2 Mt in 2009) but have since increased to 21.6 Mt in 2017. Total exports remained stable following the crisis and have also resumed pre-crisis levels (1.5 Mt in 2000 and 2009 to 1.9 Mt in 2017). Exports however declined significantly for bauxite, while imports of copper and nickel ores have still not resumed pre-crisis levels. In the case of lead, the import-export gap is not as extreme as with other metals and ores due to a high percentage of secondary production (65% EU27 recycling rate -between 90-100% for 21 EU member states in 2016).[37]

There is also an important trade of waste and scrap, primarily as concerns copper and aluminium (discussed in section 3.4 on circularity). Overall, the EU exports 2.065 Mt waste and scrap against 0.913 Mt imports of the same.

BOX 2: China's market domination

China is the world's top overall producer of non-ferrous metals and also the largest consumer of non-ferrous metals. Between 2008-2016, China's share of global base metals production has skyrocketed: from 34% to 54% in the case of aluminium[38], from 20% to 35% in the case of copper[39], from 37% to 42% in the case of lead,[40] from 15% to 30% in the case of nickel, from 33% to 46% in the case of zinc. As concerns cobalt the figure rose from 25% to 48 (68% in 2018 if refined production is considered)[41] and from only 4Mt in 2000 to 32.9Mt in 2017 in ferro-alloys production.[42] China accounts for about 80% of global magnesium mining and processing (1.4 million tons primary production capacity of 1.65 million tons globally)[43] and 40% of international refined lead production and consumption (the share of secondary lead in China's domestic market supply stood at 33% in 2015, projected to reach 45% in 2020).[44] In 2016, Chinese companies produced an estimated 71,000 tons of tungsten (by metal content) or about 80 percent of global output even though the country is home to only half of global tungsten deposits.[45]

China's production of non-ferrous metals first peaked in 2002 when the country's economy experienced a growth spurt. It continued its trajectory after a small dip in 2008 given the global financial crisis had a significantly less severe impact on Asia (Figure 8). In August 2018, China's production of 10 major non-ferrous metals (copper, aluminum, lead, zinc, nickel, tin, antimony, mercury, magnesium and titanium) expanded 5.7% year-on-year.[46]

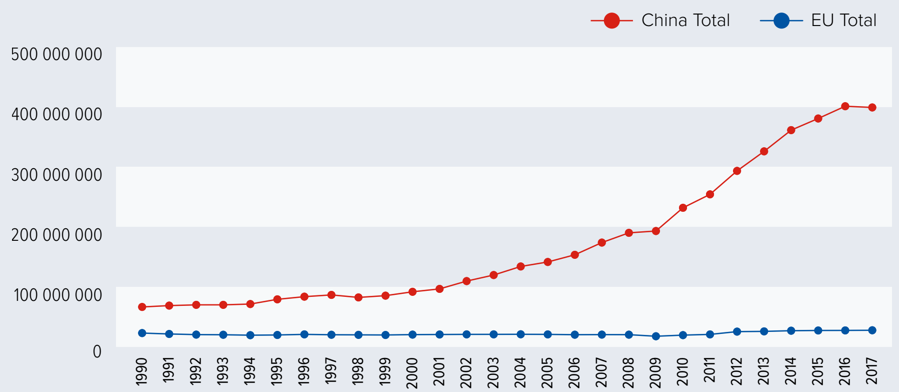


Figure 8: China and EU production of base metals [47] time series (metric tonnes) I Source: BGS

China's domination of the non-ferrous metals industry has not ensued as a natural corollary of national development; rather because of a conscious mission-oriented industrial development policy - the sector has long been identified as "strategic importance to the Chinese economy and its further development".[48 49] The Chinese non-ferrous metals sector is also characterized by a number of state-owned enterprises who are primed to become national champions. These have for many years been the key beneficiaries of government subsidy disbursements (65 enterprises have received a total of 4000 individual subsidy transactions since 2011).[50] This will be discussed further in Chapter 7.3.

Chinese dominance is critical especially as concerns rare earth metals: 36.7% of the world's known rare earths reserves are found in China and the country produces 70.6% of the total global rare earth production. Were China to restrict the export of rare earth metals, it would severely handicap western economies. For example, China currently applies export taxes and quotas for antimony. EU imports of unwrought antimony from China decreased from 23,000 tonnes in 2010 to 17,000 tonnes in 2014 likely due to restriction of Chinese supply in 2010 and 2011, due to mine closures and export quotas. Such restrictions also impact large scale investment projects, which due to long business cycles cannot react rapidly enough to short term changes or market manipulations by established suppliers.

37 European Commission, 2019a
38 China's share in global aluminium production was around 10% at the time of China's accession to the WTO In 2001. World Aluminium Statistics
39 China is home to seven of the 20 largest copper smelters in the world and nine of the world's 20 largest copper refineries.
40 Timeframe – 2008 to 2018, Source USGS, 2008, IZLSG
41 Taube, 2017, pp.130-133
42 AEGIS Europe, 2019
43 International Magnesium Association, 2017, Taube, 2017, pp.130-133.
44 ILZSG, USGS, 2017, Taube, 2017, pp. 124-129.
45 Quanxun, 2017, Xiuxia, 2017, Taube, 2017, pp. 145-151.
46 China Daily, 2018

47 Primary Aluminium, Cobalt (Refined), Copper (Refined), Copper (Smelter), Ferro-alloys, Lead (Refined), Nickel (Smelter/Refined), Tin (Smelter), Zinc (Refined)
48 Taube, 2017
49 The non-ferrous sector is a key element of a number of government planning initiatives such as the Strategic Emerging Industry Initiative (launched in 2009), the Made in China 2025 Plan (launched in 2015) as well as a broad range of other high level programmes, policies and tools provide detailed directions for all aspects of non-ferrous metal sector development.
50 Taube, 2017

3.3 Non-ferrous metals of strategic importance for essential EU value chains

3.3.1 Main downstream applications (sectors) of non-ferrous metals

Non-ferrous metals are of strategic importance to Europe's current value chains, critical to each other's value chains and at the forefront of low-carbon solutions.

Non-ferrous metals, silicon and ferro-alloys are the building blocks of vital infrastructure – buildings, transportation, electronics, energy generation and transmission, and connectivity – and strategic sectors like defence. Their value chains also form fundamental and strategic links with other energy intensive industries. For the base metals sector, the most important end sectors are buildings and construction, transport, and other energy intensive sectors. Aluminium, nickel, copper and zinc link to the buildings and construction sector as well as the transport and automotive sectors. Copper, tin and zinc feed into the broader industry sector while tin links to the packaging and chemicals sector. Zinc for instance protects steel from corrosion and abrasion and enhances the longevity of steel structures. Nickel is added to stainless steel to enhance corrosion resistance. Copper is not only used to create formidable alloys with nickel and zinc but is also used for instance in energy infrastructure and equipment and with gold to create jewellery. Cobalt is essential for super-alloys, batteries, magnets, electronics, etc.

Silicon and ferro-alloys feed into the steel, ceramics, cement, chemicals, fabricated metal products, other non-ferrous metals, and rubber and plastics sectors. Silica Fume, the by-product of the production of silicon and ferrosilicon improves the sustainability of buildings and contributes to reducing their carbon footprint. Ferro-alloys are mainly used as master alloys in the iron, foundry and steel industry to improve their tensile strength, wear and corrosion resistance which hence help prolong the lifetime of steel-based infrastructure and vehicles. Precious metals have a range of applications from transport to industrial sectors, metallurgy, aerospace, and green energy technologies amidst others. Minor metals feed into sectors like cement, steel, chemicals, plastics, green energy technologies and others. While rare earth metals are crucial for energy storage, lighting, magnets, optical sectors amongst others. The value chains to other energy intensive industries are pronounced even in the case of recycling. For example, zinc takes back steel mill dusts for zinc recycling. Metal recyclers like e.g. hydrometallurgical recycling of metals from sludges from all kinds of industrial waste-water treatment plants.

Figures 9-12 below depicts the complex value chains between non-ferrous metals ecosystem and the broad range of end sectors.

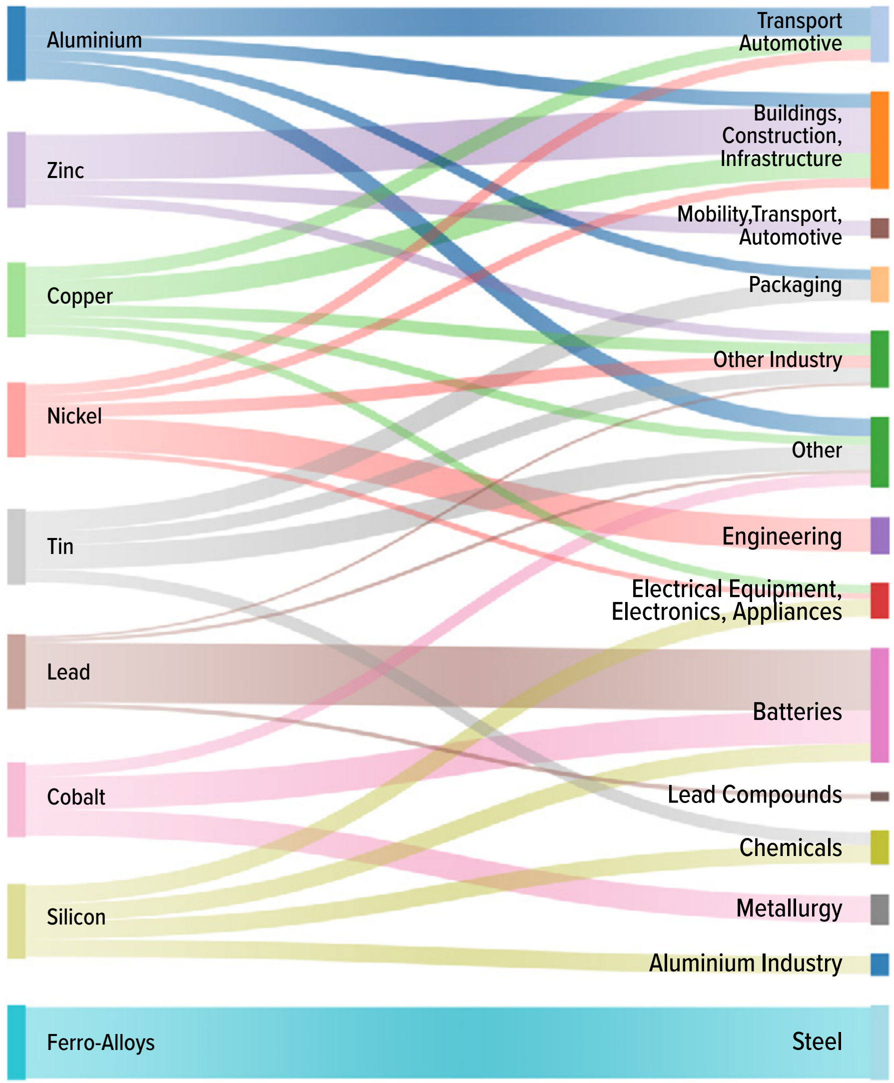


Figure 9: End Sectors of Base Metals [51]

51 Other Industry: Lead - Rolled and Extruded Products; Nickel - Metal products; Tin - Industrial Solders; Zinc - Consumer Goods Ferro-Alloys: FeCr - Stainless steel, chrome steel, nickel-chromium alloys, SiMn - steel with wear resistance, Aluminium-manganese alloys; FeSi - special steels, heat resistant steels, electrical steel; FeMo - steel use for high-speed tools and machine parts

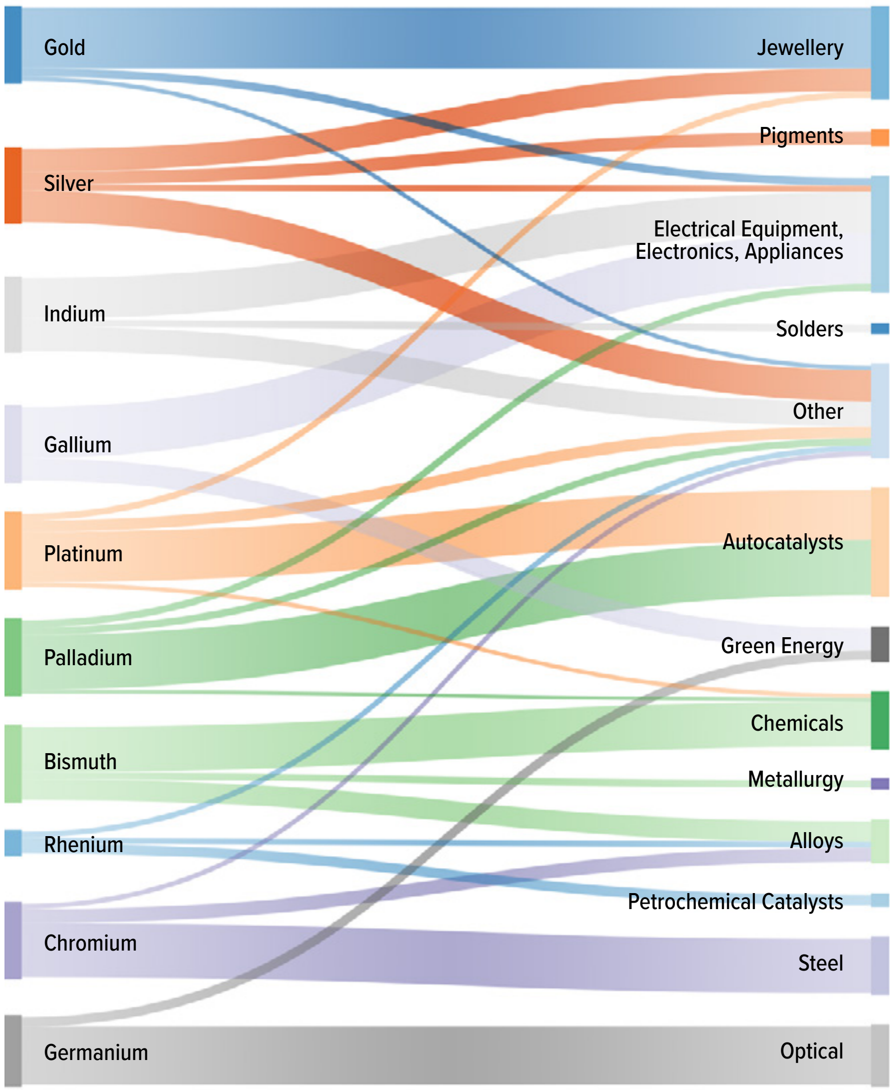


Figure 10: End Sectors of Precious Metals

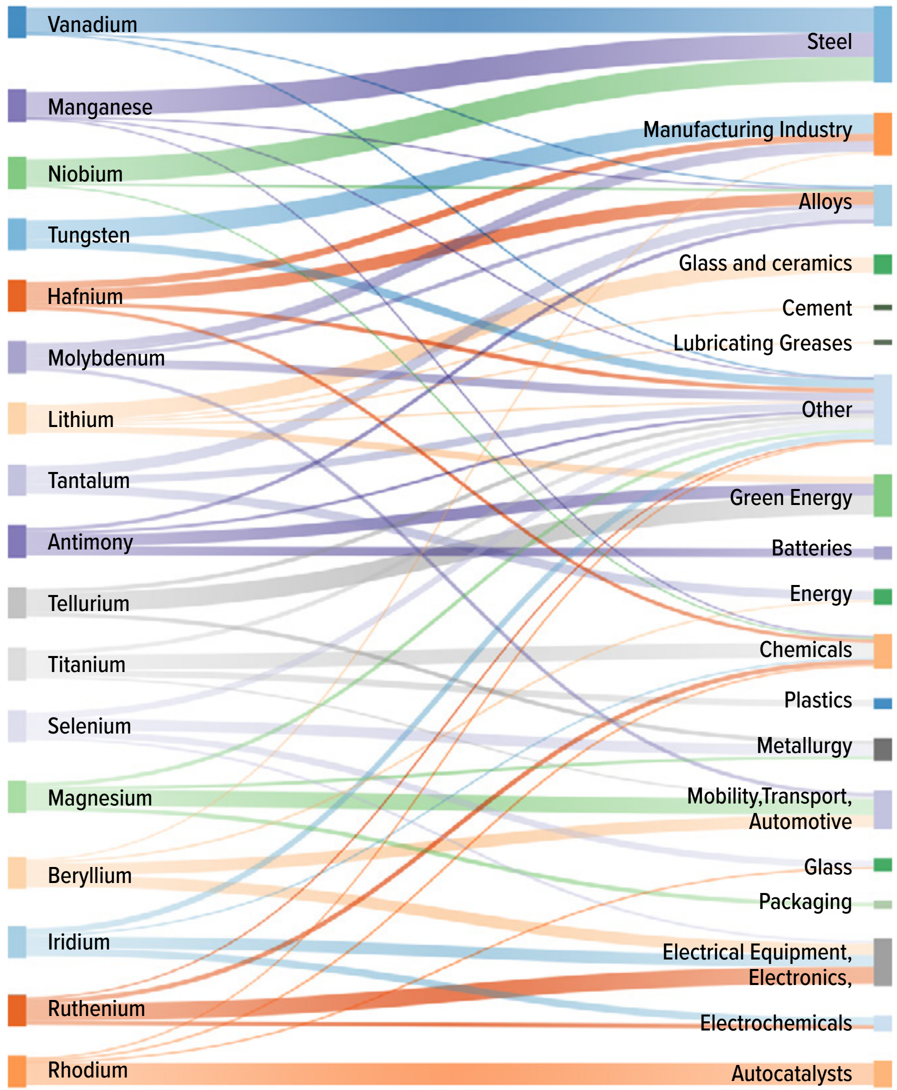


Figure 11: End Sectors of Speciality Metals [52]

52 Vanadium – Steel includes high-strength low-alloy steel (HSLA), Tantalum – Alloys includes Sputtering Targets, Magnesium – Metallurgy includes Desulfurization agent

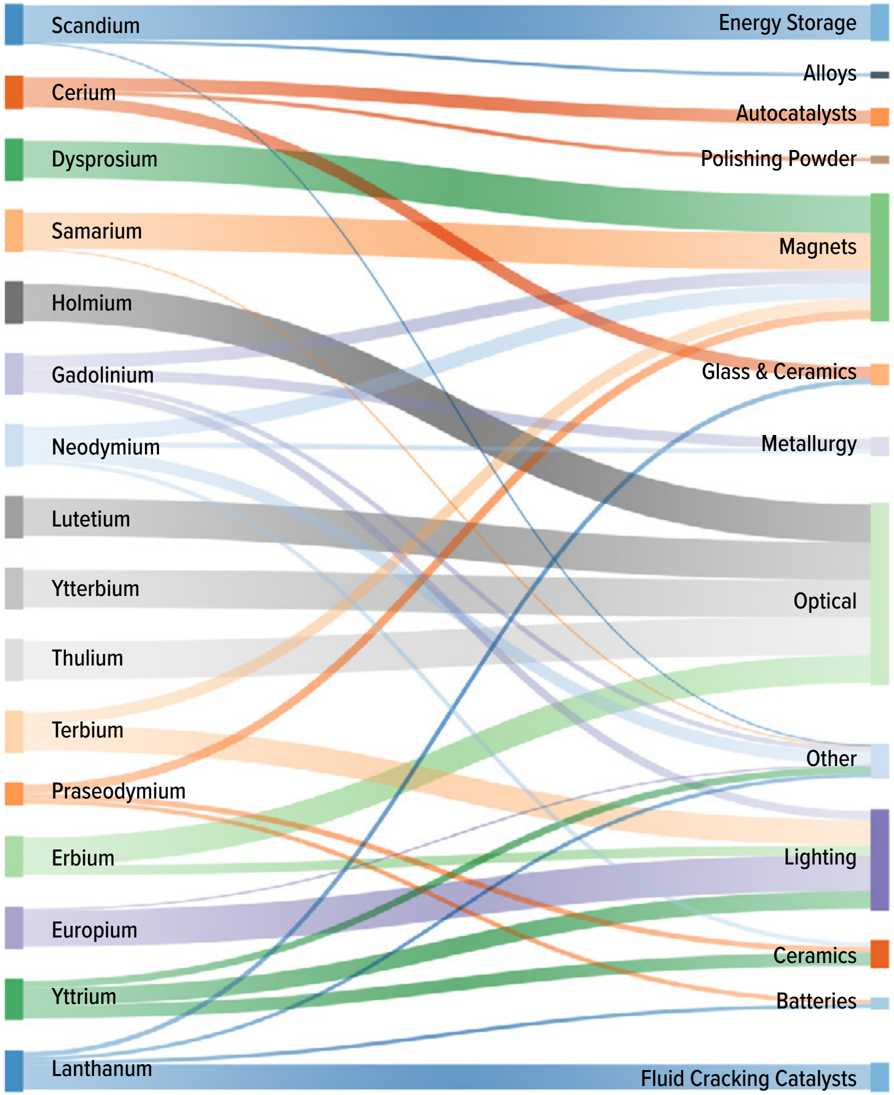


Figure 12: End Sectors of Rare Earth Metals

3.3.2 Non-ferrous metals are essential in all value chains for climate neutrality

The critical transition to a carbon neutral Europe will be achievable only with sufficient amounts of non-ferrous metals. Non-ferrous metals are the building blocks of all the currently known low-carbon solutions for a decarbonised economy: transport system (hybrid, electric and fuel cell vehicles) renewable energy (solar PVs, wind turbines, thermal systems, etc.), battery storage, environmentally- friendly power distribution network with smart digital networks, 21st century low-carbon and longer lasting infrastructure, 100% recyclable packaging, energy and resource efficient modern communications and IT devices, and so on. It is estimated, that the low-carbon transition will require much more non-ferrous metals. Global demand as a result can be expected to almost triple from 7 Gt to 19 Gt per year by 2060.[53] Metals such as aluminium, cobalt, copper, lead, zinc and nickel as well as lithium are all going to be needed in significantly higher quantities to deliver on climate mitigation goals. These would respond in particular to the growth of technologies needed for the clean energy shift, e.g. wind, solar, hydrogen, and electricity systems. By 2050, demand for metals in world's wind energy production will have increased by 300% compared to today, for solar energy this will be an increase of more than 200% and for battery energy storage (including for transportation) 1000% more metals[54].[55]

Global demand for primary aluminium is expected to increase by a further 50% by 2050 with Europe requiring almost 9 Mt of primary aluminium each year in the coming decades[56] translating into a 55%, 28% and 25% growth respectively in the transport, construction and packaging sectors as compared to 2017 demand. In the last 25 years, the demand for copper has doubled and is projected to rise 43% in the next 15 years alone.[57] According to the European Copper Institute, 22Mt of copper will be needed for the transition to a climate-neutral European economy in 2050.[58] Globally, the annual cobalt consumption is expected to reach about 220,000 tonnes in 2025, increasing to 390,000 tonnes in 2030. In the EU, overall cobalt demand may amount on average to 53,500 tonnes in the next 6 years and 108,000 tonnes by 2030[59].

Aluminium is a super-conductor of heat and electricity, enabling energy-efficient systems for electrical transmission and is also extensively used in renewable energy technologies like solar or wind power as well as for electro-mobility solutions, given its use for charging

53 OECD, 2018
54 Such aluminium, cobalt, lead, lithium, manganese and nickel
55 World Bank, 2017
56 CRU Group, 2018
57 McKinsey Global Institute; Copper Institute
58 European Copper Institute, International Copper Alliance
59 JRC, 2018b

stations, wires and cables. For the buildings sector, aluminium improves overall energy performance, notably via windows, curtain walls and ventilated facades. Tailor-made aluminium alloys can also be created. Furthermore, aluminium offers highly efficient packaging that uses very little material and that often has a lower environmental footprint than its contents. In addition, it provides an efficient barrier that helps reducing food waste. Finally, aluminium's lightweight properties (1/3 density compared to steel) enabled cars produced in Europe in 2019 to prevent 50 million tons of unwanted CO_2 in vehicle emissions during their lifetime.[60]

Copper will be a crucial metal for the energy transition. By 2027, more than 100,000 tonnes of copper will be needed to build 40 million charging points for electric vehicles coming on the market.[61] Solar panels will require 3000 kg Cu / MW, wind turbines would demand 3500 kg Cu / MW, and efficient grids, interconnectors, subsea grid would need + 400 Kt Cu over next decade[62]. Copper demand will also grow exponentially in a number of end-use sectors.[63] Copper will therefore play an important role in GHG mitigation. For every Kg of Copper used in a motor, 3 less tons of CO_2 are produced, and for every Kg of Copper used in a transformer, 0.5 less tons of CO_2 are produced. A tonne of copper in electrical systems could deliver a lifetime savings of 100-7500 tonnes of CO_2.[64]

Zinc will contribute in different ways to the transition to a climate neutral economy. Given that zinc prolongs the lifetime of steel constructions and vehicles, there is lesser consumption of primary raw materials, lower energy consumption and reduced CO_2 emissions. A galvanized steel structure of 500 t actually saves ~ 57 Tonnes CO_2 emissions compared with an "equivalent" painted system.[65] Both zinc and platinum are used in fuel cells for grid storage and micro-grid generation. Zinc-based energy storage systems such as primary zinc-carbon and alkaline batteries, zinc-air and zinc-silver "button cell" batteries would be of critical importance too. Large zinc-based energy storage systems ensure a constant energy supply from non-constant energy sources (wind and solar). Moreover, Zinc helps protect transmission towers, offshore windmill towers and carrier constructions for solar panels from corrosion, thus ensuring their reliable functioning over a long period of time.

Ferro-alloys and Silicon also help prolong the lifetime of steel-based infrastructure and vehicles thereby reducing primary material consumption, energy and emissions. Silicon is also used in lithium-ion batteries (anodes), photovoltaic (PV) thin cells, and wind turbine generators among the most relevant green tech applications.

60 According to the [insert source here], Cars produced in Europe in 2019 contain on average [insert data] kg of aluminium. Every kilogram of aluminium in a car has the potential to reduce the vehicle weight by 1 kg. [insert data] kg of aluminium in a car reduces the CO_2 emissions by 14 g/km.
61 International Copper Association
62 According to the European Copper Institute (2014), By 2050, copper alone could help reduce EU carbon emissions by 25% or around 1,100 million tonnes per year.
63 Lithium batteries (+ 600 kg Cu / MWh), building with automation (+10% Cu), home with automation (+22 kg Cu), Electric vehicle (+30 kg Cu), Heat pump (+8 kg Cu)
64 International Copper Association
65 International Zinc Association, 2012

Cobalt compounds will be crucial for rechargeable batteries[66] that are already powering hybrid and electric vehicles (EVs), and other batteries[67] for portable applications, as well as for energy storage in stationary applications. In addition, cobalt provides durability to alloys and magnets required for green energy (wind turbines). Cobalt compounds are key materials in production of catalysts which are used worldwide to produce clean transportation fuels. Thereby cobalt enables compliance with the EC's fuel quality, as well as attainment of clean air and climate change/low carbon initiatives.[68]

Rare earths are crucial in not only metallurgy (metal refining and metal alloying), catalysts in the automotive and the petrochemical industry, colouring of glass/ceramics, phosphors (LEDs, compact fluorescent lamps, flat panel displays), lasers, rechargeable solid state batteries (Ni-MH), and fibre optics; but also vital for emerging technologies such as solid state fuel cells, superconductors, magnetic cooling, hydrogen storage and high-performance permanent magnets (used in a variety of high-tech applications ranging from wind-turbines and hybrid cars to HD drives and cell phone speakers and microphones).

This essential role of non-ferrous metals in low-carbon applications also highlights the importance of maintaining and fostering base metals production on which recovery/production of strategic minor metals depends. In other words, putting base metals industry at risk would entail placing strategical metals production at risk as well.

Box 3: EU Battery Alliance

Recognising the shift to electric-based transport, power and industrial applications, the European Commission launched the European Battery Alliance in October 2017. Battery production is a strategic imperative for the clean energy transition, circular economy and industrial competitiveness which represents an annual market value estimated at €250 billion from 2025 onwards. The EU's battery alliance therefore represents a strategic endeavour to create a competitive completely domestic battery value chain in Europe with sustainable battery cells at its core.

The EBA250 is a project-driven community which brings together more than 250 industrial and innovation actors, from mining to recycling, with the common objective to build a strong and competitive European battery industry. This includes a number of EU non-ferrous metals companies and their associations who participate directly. The Battery Alliance is guided by a strategic action plan which includes a comprehensive set of concrete measures to develop an innovative, sustainable and competitive battery 'ecosystem' in Europe.

66 Lithium cobalt oxide batteries, nickel manganese cobalt batteries, nickel cobalt aluminium oxide batteries
67 Nickel cadmium, Nickel-metal hydride batteries.
68 Cobalt Institute, 2019a

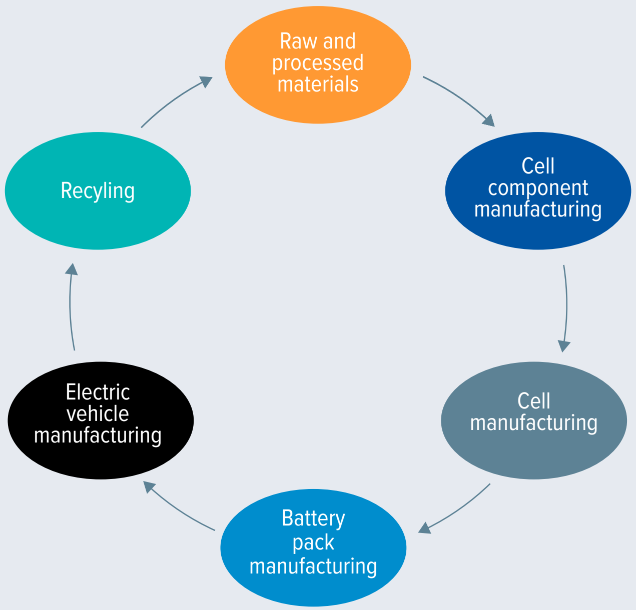


Figure 13: EU Battery Alliance Action Plan [69]

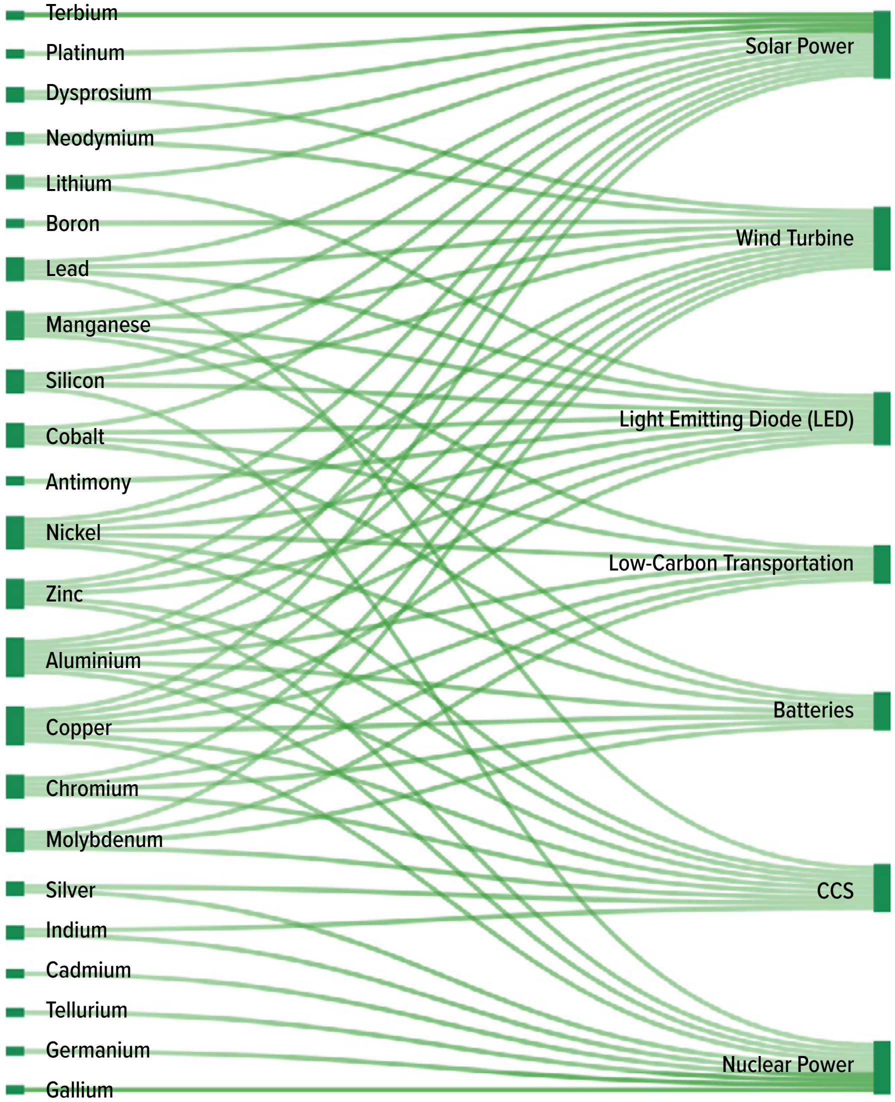


Figure 14: Metals Green Value Chain

69 European Battery Alliance

3.4 Non-ferrous metals in the EU: a frontrunner in the circular economy

Metals are inherently permanent materials which do not lose their properties after recycling and can be recycled endlessly. Strategically, metals recycling is an essential route for Europe to develop a secure domestic supply of the non-ferrous metals (alongside existing levels of primary production) required for its climate transition, possibly without relying on more imports of primary metals from regions with higher carbon footprints[70].

Embracing the circular economy can also enhance production, revenue growth through reducing costs and increasing employment in society through new business models.[71] In general, metals recycling processes require less energy on a lifecycle basis than extraction and primary production operations. This is particularly relevant for recycling of pure metals waste streams.

3.4.1 The EU has high metals recovery and recycling rates for metals

The EU is a world leader when it comes to recovering metals from pre-consumer scrap (from industrial production processes) and post-consumer scrap. Europe's metals recycling industry has a position of real global leadership, with state-of-the-art recycling facilities able to recover over 20 metals from scrap, end-of-life products and industrial by-products. Sections of the industry are closely integrated, with companies working together to extract maximal value from different types of waste. Several hundreds of firms recycle non-ferrous metals in Europe.

Recycling rates from pre-consumer scrap are very high due to the relatively large volumes linked to a business to business collection infrastructure. This scrap can be easily recycled because of its high purity. Pre-consumer scrap also allows for recycling of several special metals that cannot be recovered from their end-use applications due to their use in very low quantities yet.[72]

The end of life metals recovery rates are extremely high in the construction and buildings with over 95% of metals recovered. Over 90% of metals in end-of-life vehicles is recovered in Europe when using the appropriate facilities. For lead batteries this is over 99%. For packaging it is over 60%. A number of key low-carbon technologies, including wind turbines and electric vehicle batteries, too have been designed to heed high end-of-life recycling rates. Given their long lifetime in use, high end-of-life volumes are not yet available.

Application	End-of-life metals recovery rate	Metals recycled
Buildings/construction	>95%	Aluminium, copper, nickel, lead, zinc (+ steel alloying elements)
Automotive	>90% (of metals from cars recycled properly in Europe)	Aluminium, copper, zinc, gold, e-mobility battery metals (nickel, cobalt, lithium)
Engineering	>95%	Nickel, cobalt, other metals contained in super alloys
Lead batteries	>99% (of batteries recycled properly in Europe)	Lead
Packaging	>60%	Aluminium
Electronics waste	<35%	Copper, gold, silver, palladium

Table 4: End-of-life recovery rates by end-sectors and metals recycled. Source: Eurometaux

Recycling rates for some consumer applications such as electronics waste are lower. Only 35% of Europe's electronics waste is collected and recycled through the proper channels, resulting in a loss of valuable materials[73] and complex products such as electronics waste require more energy to recycle compared with simple products.

The recovery rates for metals commonly alloyed with steel (chromium, titanium, manganese, cobalt etc.) are mostly above 50%. For precious metals there are different recovery rates (gold – 20%, silver – 55%, platinum – 11%, palladium – 9%, iridium – 14% rhodium – 9%, ruthenium – 11%)[74]A further 7 metals have recovery rates between 1 and 25% (molybdenum, magnesium, iridium, tungsten, cadmium, antimony, mercury).[75] The remaining 35 metals have end-of-life recovery rates of less than 1%. These are all minor metals used in very small volumes, where recycling is technically or economically unfeasible.

Not only is the metals recovery rate high in Europe, the use of recovered metals in base metals production is high. They contribute a noteworthy percentage of Europe's total base metals supply - for example, 43% (or 1.7 Mt) of Europe's copper demand is already met from recycled material.[76] For zinc and nickel, the figures stand at 30% (1.05 Mt) and 33% (0.7 Mt) respectively.[77] These figures are higher than the reported secondary production, because the latter often does not include the scrap recovered in primary and secondary production processes.

70 Material Economics (2018) recognises that existing primary production and recycling must work together :'The gradual decarbonisation of the aluminium supply in the EU can go hand in hand with efforts to improve the circularity of European aluminium use. By both decarbonising supply, and reducing the need for (imported) primary metal to serve demand, the EU can act on two complementary fronts to bring aluminium in line with low-carbon objectives' (pg.112)
71 Wyns, Khandekar & Robson, 2018
72 For example, Germanium is mainly recycled from the production processes of industries like fibre optics, solar cells, LEDs and infrared optics. Slags or final slags, as by-products from the production of non-ferrous metals, ferro-alloys and silicon are largely used in (road) construction applications, according to European or international standards.

73 Huisman et. al., 2015
74 Deloitte, 2015
75 Recycling rates for Mercury and Cadmium are low because of imbalances between offer and demand for applications. Much of these collected metals are stabilized and safely stored because of little demand.
76 European Copper Institute
77 International Zinc Association, 2019, Nickel Institute

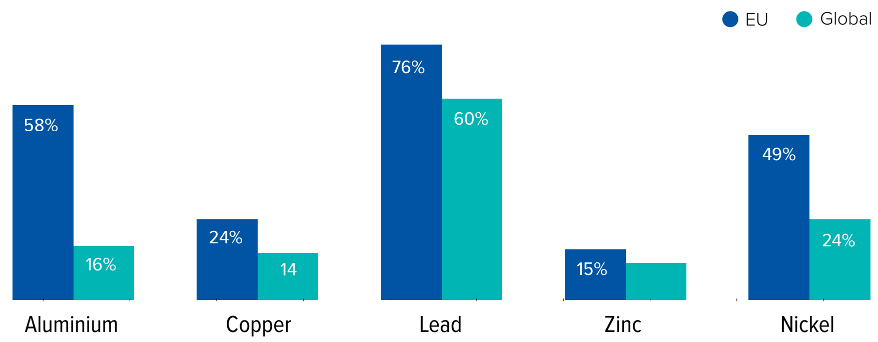


Figure 15: % of EU secondary in total EU production of base metals (Aluminium, Copper, Nickel, Zinc) compared to % global secondary production in total global production.

Production	Aluminium	Copper	Lead	Nickel	Zinc	Cobalt
World secondary production (2016)	10,103.39	2,812kt	7407kt	685 kt	878kt	<1%[78]
EU secondary production (% of global secondary production)	3,004kt (30%)	726kt (25%)	1351 kt (18%)	200 kt (18%)	296kt (34%)[79]	4.3 Kt (32%)

Table 5: World and EU Secondary Production 2016 (Kt) I Source: World Bureau of Metals

Europe is a net exporter for almost all types of base non-ferrous metals scrap. In 2017, total waste and scrap (copper, nickel, aluminium, lead and zinc) imports by the EU in 2016 stood at 0.91 Mt while exports stood at 2,07 Mt resulting in a trade balance of -1.15Mt (see Figure 16).[80] However, in the case of lead, Europe imports more lead waste and scrap than it exports. Asia is the major destination market for metals scrap – in particular China, although flows have started to be diverted to other countries in the wake of a waste ban imposed by a number of Asian countries. Approximately 9.45 million tonnes of waste from electrical and electronic equipment (WEEE) are generated each year in Europe. Only 3.3 million tons of WEEE are reported as collected and recycled. While 15% of Europe's electronics waste, equivalent to 750,000 tonnes is exported each year (mostly to Africa and Asia)[81]. This includes 17,000 containers of illegally exported e-waste annually from Europe.[82] About 4 million end-of-life vehicles or a third of all vehicles are deregistered without a certificate of destruction each year.[83] Roughly 0.5 Mt of EU aluminium scrap is estimated to exported as a result.

78 NR – not reported globally
79 Tonnages refer to remelted zinc only: metallic zinc from zinc sheets, zinc foundry scrap and galvanizing plant dross. Much larger amounts of zinc are recycled than only the ones that are recovered by remelting scrap metal. About 350kt zinc is annually recovered in the EU from EAF dust
80 UN Comtrade, 2017
81 Huisman et. al., 2015
82 IMPEL, 2018
83 European Commission, 2017c

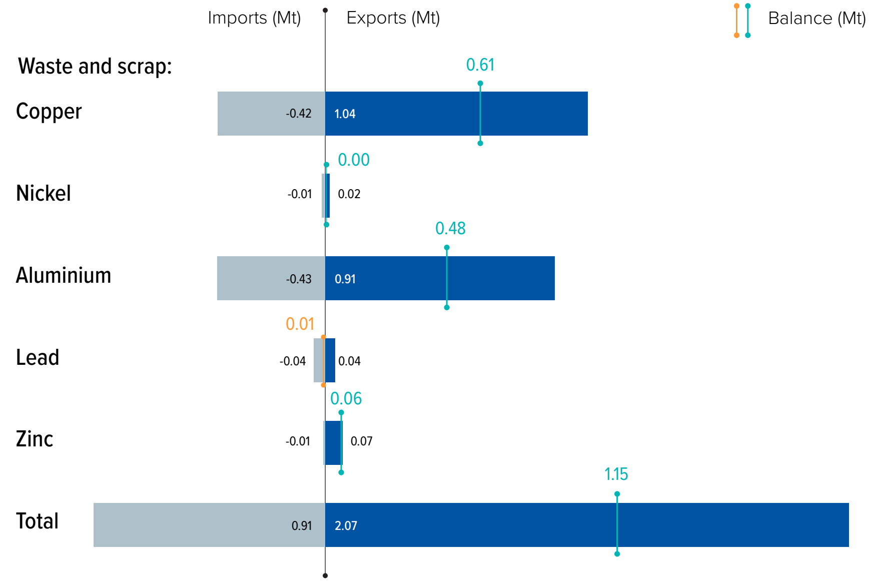


Figure 16: EU Scrap Trade, Source: Comtrade

3.4.2 Potential for higher levels of metals circularity in the EU

To achieve higher levels of metals recovery and recycling three main target stream jump out. First, as shown above, one of the important elements will be to stem exports of scrap, in particular of scrap that will most likely not be recycled or recycled under bad conditions. This includes improving EU infrastructure for non-ferrous metals scrap and investing in recycling infrastructure for emerging low-carbon applications (e.g. solar panels and electric vehicle batteries). Secondly, there can also be improvements to the end-of-life recycling of vehicles, seeking to apply high dismantling and recovery standards across the EU. Thirdly, higher recovery and recycling rates of WEEE form a major challenge. The complexity of WEEE often leads to higher energy use and CO_2 emissions in recycling (sometimes even higher than primary metals production). Improved WEEE recovery will require investments in better collection, sorting and treatment facilities. Furthermore, technological innovation will play an important role in achieving high recovery rates in an efficient manner from WEEE (see also chapter 6 on technologies).

These three streams (i.e. end-of-life vehicles, WEEE and scrap exports) are estimated to be those with the highest future potential, together with increasing recovery of metals from green applications, but recycling rates can be further improved via a number of ways.

For instance, through advanced sorting processes across Member States. For example, aluminium scrap flows can be better sorted, preferably by specific product and by alloy family. In addition, there will be greater demand for product-to-product recycling. Extra investment in innovative sorting technologies (x-ray, laser, robot, etc.,) will be essential. But also higher levels of metals recovery from primary production slags and sludges can lead to higher metals productivity vis a vis the raw materials inputs.

Finally, higher quantities of metals are already used in low-carbon technologies such as electric vehicle batteries, solar panels and wind turbines. Currently, the ratio between these applications reaching their end-of-life and annually entering the market is very low (e.g. lower than 1% for solar panels[84]). This ratio will shift significantly after 2030 (e.g. reaching 40% for solar panels). It is important that Europe makes early investments into its recycling industry for these applications, which is currently in its infancy. This is currently happening through the EU Battery Alliance and related initiatives (See Box 3).

3.4.3 The impact of a growing metals in-use stock on secondary production

Metals can remain in use for a long time. This implies there is a large metals in-use stock in society. In use stocks are relatively higher in Europe as an industrialised economy given per capita in-use stocks in more-developed countries typically exceed those in less-developed countries by factors of five to ten.[85] Currently, in-use stock[86] for EU-28 are estimated to be about 132 Mt for aluminium (around 260 kg per capita, 2013), 73 Mt for copper (around 140 kg per capita), Nickel (5 Mt) and 5.3 Mt for silicon.[87]

Aluminium		Copper		Nickel	
Transport	31.5%	Electrical and electronic products	28.6%	Engineering	37%
Building and construction	36.5%	Building and construction	48.8%	Transport	19%
Industrial machinery and equipment	5.7%	Industrial machinery and equipment	13.4%	Consumer durables	19%
Consumer durables	6.3%	Transportation equipment	5.6%	Building and construction	18%
Electrical engineering	15.6%	Consumer and general goods	3.6%	Other	8%
Packaging and cans	2.2%				
Others	1.9%				
Dissipative uses	0.3%				

Table 6: Distribution of Stocks, Source: JRC, 2018a, Nickel Institute, 2012

84 Solar Power Europe
85 UNEP, 2010
86 "In-use stock" is the amount (mass) of a given material in the anthroposphere, as the result of the shift in metal stocks from the lithosphere to the anthroposphere
87 JRC, 2018a

Distribution of metals in-use stock is concentrated in buildings and construction, transport and electrical and electronic products.

Given that the EU metals stock is increasing, including with expected growth in demand due to the greening of the economy it is expected that recycling volumes for all metals are expected to increase between now and 2050, as more of Europe's in-use stock becomes available and the overall recycling infrastructure improves. Europe's aluminium annual recycling volumes are projected to rise from 4.5 Mt in 2015 to 9 Mt in 2050.[88] For copper scrap the global amount available for recycling annually is projected to increase from 12.5 Mt to 43 Mt in 2060[89], for the EU this will be an annual amount of around 7.5 Mt scrap in 2060.[90]

3.4.4 Conclusions

The circular Economy will be an important part of the non-ferrous metals industry's development towards 2050 not only complementing the industry's efforts to further lower the CO_2 footprint of European primary production but also to lower import dependency and improve security of supply for strategic metals.

However, there are important elements to be taken into consideration. For instance, recycling pure metal scrap leads to significant energy savings. However, the more recycling takes place and the purity of recycled metal decreases, the process incurs greater energy requirements and costs. Recycling metals from more complex waste and from used products with sometimes low metals content too presents technological and economical challenges, and in some cases the achievement of high metal yields from complex products can be energy-intensives. In the case of alloys, if one specific metals alloy is recycled to another alloy this does not mean recycling the original alloy to the same alloy again is not possible, but it might not be economic, the market may demand different alloys instead, producing the same alloy could be associated with a higher carbon footprint etc. At times, the industry therefore engages in targeted recycling which is optimized for various factors. As such, recycling will not be the panacea and must be seen in complement to other measures.

While the shift to more secondary production may not match future demand requirements, a meaningful integration of low-carbon and circular economy policy agendas will help to maximise the benefits from the transition.

88 European Aluminium, 2018a
89 with China contributing 41% and the EU & America 16%
90 OECD, 2018

Non-ferrous metals, a bellwe
challenges for non-ferrous metals production on the pathway to eu clin

Price takers in a global market

4 Price takers in a global market

The ‘reference price’ for non-ferrous metals like aluminium, copper, nickel, lead, zinc and cobalt is set at metals exchanges.[91] There exist a large number of metals exchanges around the world which set the prices for different types of non-ferrous metals. The most prominent of these are the London Metals Exchange (LME), the New York Mercantile Commodity Exchange (COMEX), Hong Kong Mercantile Exchange (HKMEx), and the Shanghai Futures Exchange (SHFE). Nonetheless, the LME remains the predominant player. Even though China is the largest producer and consumer of non-ferrous metals, the high volumes traded on the SHFE follow, rather than lead, the physical reference price which retains its home at the LME.[92] There is, moreover, no indication that the SHFE is pulling volume from the LME with the additional trading at night.[93]

The LME connects physical and financial market participants to create liquidity in a global market. These participants buy and sell LME futures and options to transfer (hedge) and take on (invest in) price risk and in that process discover globally relevant prices. Participants on the LME include:

- Metal producers such as miners, smelters and refiners
- Metal consumers such as industrial manufacturers
- Merchants and physical traders
- Banks, financial funds and commodity trading advisers
- Proprietary traders
- Brokers and clearing institutions

The number of transactions on the LME platform is 25 to 50 times higher than physical transactions. This high number of transactions happens because buyers and sellers of physical metal use the LME to gain protection from movements in prices. Their hedging requirements are ultimately set according to their production or purchasing programmes, but they can also be opportunistic and use the LME to lock in sales when prices are high, or purchases when prices are low. A miner, smelter or fabricator could sell an LME contract at a forward date to lock in the revenue to be earned from a future physical sale. A merchant could do the same to protect inventory. This is called a short hedge. Meanwhile, an industrial participant could buy a contract at a forward date (a long hedge) to fix their future raw material costs. They have a lot of future dates to choose from – contracts on the LME can trade up to ten years in the future, depending on the metal. The higher number of transactions is also related to large number of financial trading of metals positions, mostly done by institutional investors.

91 Despite the fact that LME prices do not apply to the ferro-alloys and silicon, they are also exchanged on a global level with globally set prices.
92 LME, 2017
93 Klein & Todorova, 2018

For physical transactions, the agreed price is always set with references to the LME price. The LME settlement price is a reflection of market expectations based on demand, offer and metal stocks. As the LME accounts for the vast majority of the non-ferrous metals trading on terminal markets, its settlement prices have become the reference prices of the global industry. These prices are used even for metals that are not traded on the LME (e.g. OTC) such as fabricated products, and also form an important element in the pricing ores and concentrates.

The LME traded metals price is influenced by various factors. Important elements are balance between offer and demand, metal stock in LME warehouses and smelters and trader warehouses. Market expectations are influenced daily by information such as strikes at a mining/refining plants, an unexpected shutdown due to technical complications, an announced delay of a new planned mining or refining capacity, new metal applications, or press releases on growth expectations in metal applications, etc. Important trading activities on futures and options can also have secondary effects on the LME price. t

Evidence of supply and demand impact on the pricing of metals can be seen in the graphics below which show the LME prices for aluminium, copper, zinc and nickel between January 2007 and January 2019. This clearly shows the V-shaped impact of the economic crisis between 2008 and 2010. Latest price evolutions show a sideways movement, partially due to (over)production in China. This is particular the case for nickel where over the past years important production capacity for nickel pig iron came online.[94]

A wide variety of factors that influence the metal price at LME are outside the direct control of either producers or users, who have to accept the prevailing price as a given. A distinguishing characteristic of metals is that no single company can fix the price of its own products independently of what happens in the rest of the market. One ton of metal of a standard quality from any individual plant can be replaced by material of a similar quality from another.

Furthermore, producers of non-ferrous metals have limited options to respond to changing LME prices in the short term. In this regard price setting in global metals markets is very different from electricity markets, which are more local or regional. In the power market, the last or marginal unit put on the market sets the price. With metals producers, the situation is quite different. Metals producers are not able to change production on an hourly basis, contrary to power producers. Indeed, both curtailment and restart of a primary non-ferrous metals production site such as a primary aluminium, zinc or copper smelter is both very costly and very time-consuming. Restarting can take up to several months. So, when a smelter is fully or partially idle, it tends to be so for a longer period. Given these

94 Nickel institute

factors, it can often make more economic sense to operate a smelter with cash loss in the hope of a future increase in the LME price instead of idling part of the production. Sustained depression of international metals prices combined with limited changes in production costs can however lead to closures. In Europe this was the case during the 2007 economic crisis, which since saw the closure of around 1000 kt primary aluminium production capacity.[95]

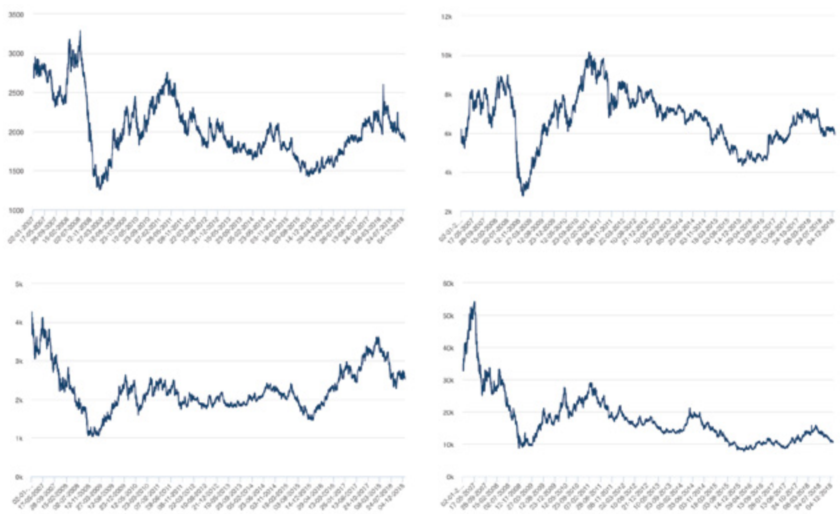


Figure 17: Evolution of LME prices for Aluminium (top left), Copper (top right), Zinc (bottom left) and Nickel (bottom right) Source: LME

BOX 4: The smelting business model and LME pricing

The zinc, copper, lead and precious metal smelters business model is tightly linked with the LME metals pricing. Smelters pay mining companies the price of metals contained in the ores as set by the LME and not the price of the ores themselves (as is the case in steel production).

A typical contract between a smelter and mining company sells ores at a price that is the LME metals price multiplied by the concentration of metal in the ore (e.g. 55%) and the amount expected to be extracted (e.g. 85% of the metal present in the ores). To this, a treatment charge is added.

From the smelter perspective it is hence essential to achieve a high extraction rate (e.g. 95%). The difference between the contracted and actual extraction gives the so-called ‘free metal’. Furthermore, the smelter can get revenues from the sales of by-products (e.g. sulphuric acid) and other metals recovered (unless these are part of the contract with the mining company too).

(Source: Nyrstar)

95 Eurometaux, LME, 2018

Non-ferrous metals: production processes, energy use and greenhouse gas emissions

5 Non-Ferrous metals: production processes, energy use and greenhouse gas emissions

This chapter will discuss the energy use and GHG emissions from non-ferrous metals production as well as the options for further mitigation of GHG emissions as a contribution to the EU's goal of achieving climate neutrality by mid-century. A comparison is also drawn of energy use in non-ferrous metals production against other energy intensive industries. The focus will be on base metals with highest over-all energy use (e.g. aluminium, copper, zinc, nickel, silicon, ferro-alloys).

5.1 Non-ferrous metals production: electro-intensive production processes

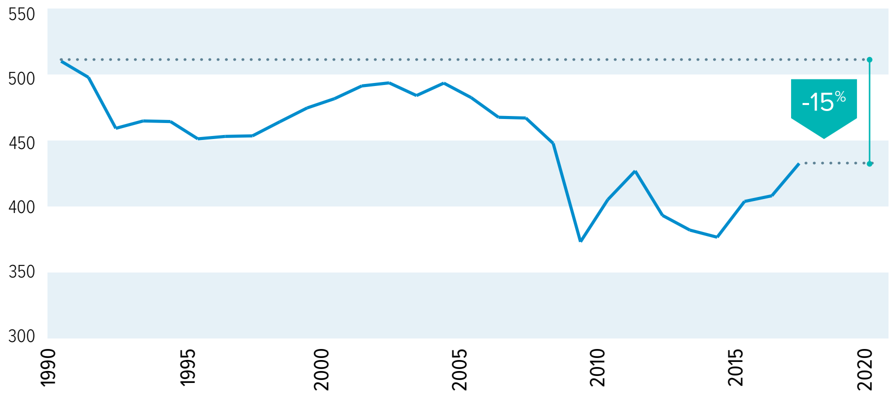


Figure 18: Evolution of final energy use in the non-ferrous metals industry (PJ) (Source: Eurostat EU energy balances 2018 edition)

Total energy use in 2017 by the non-ferrous metals industry was 432 Petajoule (PJ) - 15% less than 1990 (510 PJ) levels. There was an important fuel shift over the same period with the use of solid fuels and oil products shifting from respectively 11% and 12% of final energy use in 1990 to 3% each in 2017. The share of natural gas share increased from 17% to 35% over the same period. Electricity is by far the most important energy carrier for the non-ferrous metals industry with a share of 58% of final energy use (both in 1990 and 2017). Total electricity consumption stood at almost 69 TWh in 2017. [96]

96 Eurostat, 2018. For non-ferrous metals, this includes the final energy use from NACE Rev. 2 Group 24.4; and NACE Rev. 2 Classes 24.53 and 24.54. Final energy consumption covers the consumption by the non-ferrous metals industry. This refers to fuel quantities consumed by the industrial undertaking in support of its primary activities. For heat only or CHP plants, only the quantities of fuels consumed for the production of heat by auto-producers are applicable. Quantities of fuels consumed for the production of heat that is sold, for the production of electricity, and the quantities of coke transformed into blast-furnace gas are reported under the energy transformation sector.

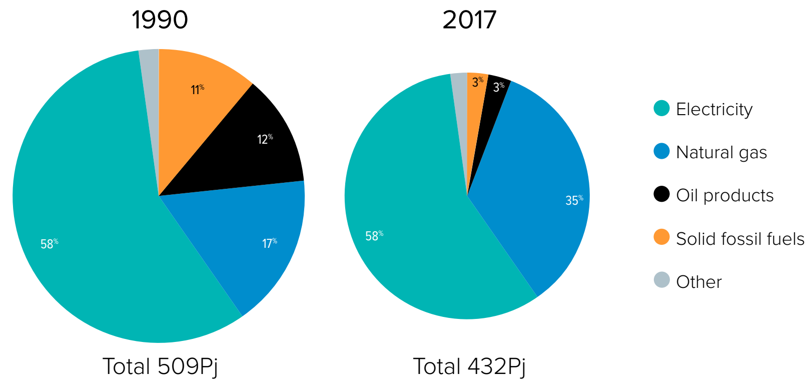


Figure 19: Fuel shift between 1990 and 2017 in the non-ferrous metals industry final energy use (Source: Eurostat EU energy balances 2018 edition)

While the non-ferrous industry is not the largest consumer of electricity compared to other energy intensive industries (Iron & steel: 114 TWh, Chemicals: 184 TWh, non-metallic minerals: 70 TWh, 2017 figures) it has the highest share of electricity use amongst the energy intensive industries at 58% of final energy use in 2017. This is significantly higher than tha iron and steel (35%), chemicals (30%) and non-metallic minerals (18%) industries.

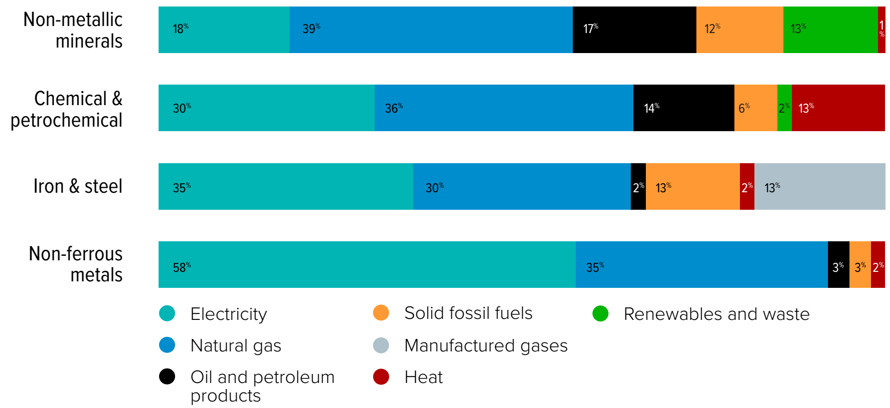


Figure 20: Relative shares of energy carriers in the final energy use of select energy intensive industries (2017) (Source: Eurostat, 2018)

Therefore, electricity costs will affect the non-ferrous metals industry production costs to a larger extent as compared to other energy intensive industries in general.[97] This will be further elaborated in chapter 7.

The non-ferrous industry has made significant efforts to reduce its GHG emissions since 1990. Between 1990 and 2015, the non-ferrous metals industry reduced its CO_2-eq emissions (direct and indirect) 61%. Direct emissions fell 64.5% while indirect emissions reduced 56% over the same period.[98] The latter is partially due to the significant reduction in the GHG intensity of the EU power grid from 0.524 t/MWh to 0.314 t/MWh between 1990 and 2015 or a reduction of 40%.

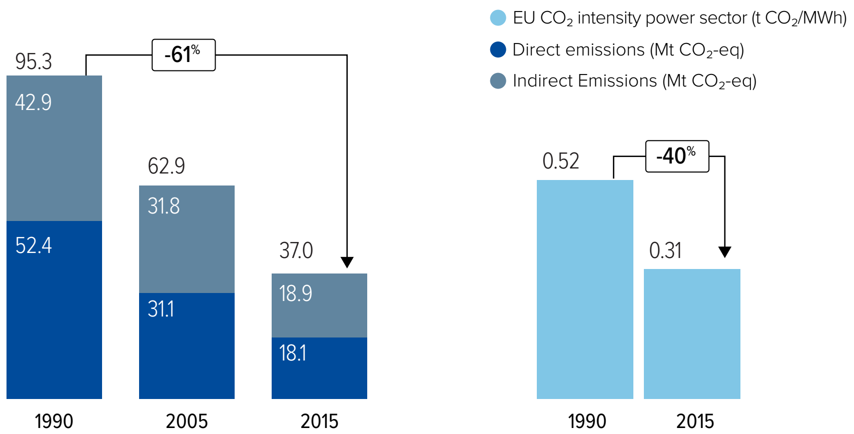


Figure 21: (left) GHG emissions (Mt-CO_2 - eq) of the non-ferrous metals industry (Sources: EEA (direct process emissions), Eurostat (direct emissions related to energy use) and EEA (indirect emissions using EU average CO_2 intensity of power production)[99] (right) Evolution of CO_2 intensity of the EU power production (t CO_2/MWh) (Source: EEA)[100]

In 2015 indirect emission represented 51% of total GHG emissions while direct emissions stood at 49%, for the non-ferrous metals industry.

97 Some chemical and steel processes are highly electro-intensive too e.g. chlorine production and electric arc steel production.
98 This is an estimation based on multiple data-sources. For the indirect emissions the electricity consumption from the Eurostat EU energy balances, 2018 edition was used. This was multiplied with the average EU emission factor for power generation from the European Environmental Agency (EEA) (see footnotes below). The direct emissions are the sum of process emissions as reported by EU member states to the UNFCCC and the EU's GHG monitoring mechanism (IPCC sectors: 2.C.2 to 2.C.7 (i.e. ferro-alloys, aluminium, magnesium, lead, zinc and other (non-ferrous) metals)) (see: EEA, 2019) and the emissions from energy use as reported by Eurostat in the energy statistical datasheets for the EU-28 countries (august 2018 update) (see: EU Open Data Panel, 2018). It is possible that a small overlap between emissions accounted in the electricity use (indirect emissions) and from the other energy use exists e.g. for heat from CHP and auto-generation.
99 ibidem
100 EEA, The CO_2 emission intensity (g CO_2/kWh) is calculated as the ratio of CO_2 emissions from public electricity production (as a share of CO_2 emissions from public electricity and heat production related to electricity production), and gross electricity production. The average was calculated using national emissions data report to the UNFCCC and to the EU's GHG monitoring mechanism. EEA, 2018.

The following sections explore in more detail the energy use and the evolution of GHG emissions of a selection of metals (aluminium, copper, zinc, nickel ferro-alloys and silicon[101]) of which the production contributes a significant share of the overall energy use and GHG emissions of the non-ferrous metals industry. This will offer better insights into the evolution of GHG emissions of the non-ferrous metals industry and help build the perspective of further mitigation options.

5.2 Aluminium

The primary production of aluminium involves three processes after the extraction of bauxite ore:

- purification of bauxite or to aluminium oxide (alumina)
- synthesis of cryolite and aluminium fluoride for the electrolytic reduction process
- electrolytic reduction of alumina to aluminium

Primary aluminium is produced from bauxite that is converted into alumina (aluminium oxide). Around 100 tonnes of bauxite produces 40 to 50 tonnes of alumina, which can then produce 20 to 25 tonnes of primary aluminium. Most of the bauxite is mined outside Europe, but there are several alumina production facilities within Europe.[102]

In the refining process of bauxite (Bayer's process) bauxite ore is first crushed and dissolved in hot sodium hydroxide. The iron and other oxides are removed as insoluble 'red mud'. The solution is then precipitated and goes through a calcination process to produce a dry white powder, alumina.[103]

Manufacturing of primary aluminium utilizes a carbon anode in the smelting (Hall-Héroult) process. The carbon is consumed during the electrolytic process therefore a constant supply is required for the smelting process. Carbon anodes are produced by heating up of coke or tar pitch.[104]

The Hall-Héroult process is the primary process for commercial aluminium production. The process takes place in an electrolytic cell or pot, consisting of two electrodes, anode and cathode. Alumina is dissolved into a cryolite bath and serves as an electrolyte for the process. High amounts of electrical current are passed through the molten bath and reduces alumina to form liquid aluminium at the bottom of the cell or pot. Molten aluminium is dens-

101 A detailed description of evolution of lead emissions is not included. In 2017 the specific emissions of lead production were: 1.82 t CO_2-eq/t primary lead production (1.16 t CO_2-eq/t lead indirect emissions (63%) and 0.66 t CO_2-eq/t direct emissions (37%)). For secondary lead production the specific emissions in 2017 were 0.98 t CO_2-eq/t lead (0.62 t CO_2-eq/t lead indirect (63%) and 0.36 t CO_2-eq/t direct (37%) (2015)). Total EU28 GHG emissions from lead production in 2017 were 2.1 Mt CO_2-eq (0.8 Mt CO_2-eq primary and 1.3 Mt CO_2-eq secondary). Source: LCA Pb production ILA 2018
102 JRC, 2017a
103 ICF, 2015
104 ibidem

er than cryolite and collects on the cell bottom. The metal is generally cast as ingots, which are at least 99% pure with small amounts of iron and silicon being the main impurities.[105]

Carbon is consumed in the anode process, much of it reacting with the liberated oxygen. The anode blocks must thus be renewed regularly. Typically, a cell has twenty anode blocks, one being replaced each day in a twenty-day cycle (to replace all of the blocks at once would result in too much cooling of the cell), with the block size being designed to give an operating life of 20-21 days.[106]

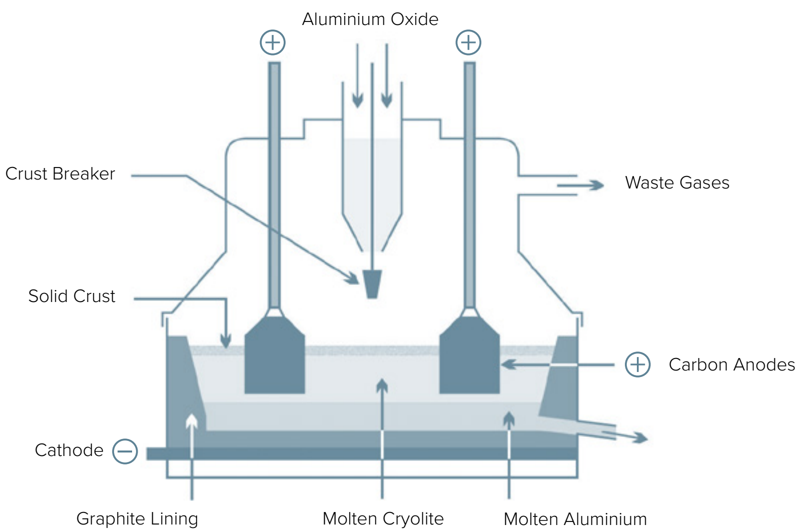


Figure 22: Primary production of aluminium – electrolysis cell (source: CIES, N.D.,)

Downstream treatment of aluminium includes rolling mills, extruders and casters.

Secondary aluminium production involves using recovered or recycled aluminium from waste streams as raw material to produce aluminium. Secondary aluminium production uses far less energy than primary aluminium production due to the lower heating temperature. The process starts with the sorting and pre-treatment of the scrap feedstock according to their quality and characteristics. Various furnace types are available for the melting process, including reverberatory and induction furnaces and emerging technologies such as rotary arc and plasma furnaces. The choice of furnace depends on the characteristics of the scrap feedstock.[107] Recycling 1 kg of aluminium saves up to 8 kg of bauxite ore and 4 kg of other chemical products.[108] Primary production of aluminium is a highly electro-intensive process with 14-16 MWh electricity use per tonne primary aluminium produced. This process requires a steady, uninterrupted supply of baseload electricity. For secondary aluminium the electricity use per tonne aluminium produced is 0.12-0.34 MWh/t.[109] Aluminium is a key material for the circular economy, with an enormous decarbonization potential stemming from its circular properties: Aluminium has been recycled from the beginning of its industrial production 125 years ago and, as a result, today about 75 percent of all aluminium ever produced remains in use. Around half of the aluminium produced in Europe originates from recycled materials, with recycling levels of 90-95 percent for end-of-life vehicles and building parts and close to 75 percent for beverage cans.[110]

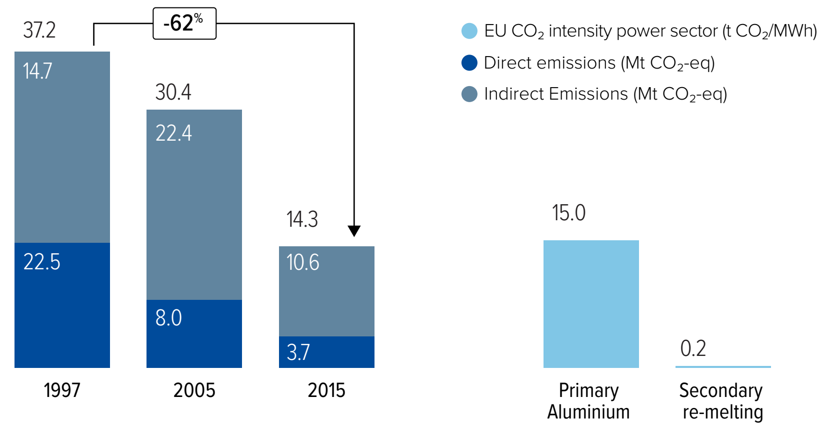


Figure 23: (left) Evolution of GHG emissions from EU28 aluminium production (Mt CO2-eq) (Sources: European Aluminium and EEA)[111][112] (right) Average electricity use in primary and secondary aluminium production (MWh/t Al) (Source: Ecofys et al., 2009)

Between 1997 and 2015 the total GHG emissions from aluminium production in the EU fell 62%. Direct emissions were reduced by 75% over same period. This is due to PFC emissions being almost eliminated - from 22.8 to 0.4 Mt or down by 98% 1990-2015[113] due to better process management (avoiding flaring in aluminium cell pots) and flue gas treatment.

105 CIES, N.D.,
106 ibidem

107 ICF, 2015
108 CIES, N.D.,
109 Ecofys et al., 2009a
110 European Aluminium
111 The data for direct emissions are the process emissions as reported by EU member states to the UNFCCC and the EU's GHG monitoring mechanism (IPCC sector: 2.C.3) (see: EEA, 2019). Data source indirect emissions EU 28: European Aluminium.
112 In the EFTA the emissions from aluminium production were 3.34 Mt CO2-eq in 2015 a 9% reduction compared to emissions in 1997 (3.67 Mt CO2-eq). These represented almost only direct emissions, given the extreme high share of hydro-electricity in EFTA. Source: European Aluminium.
113 PFC emissions as reported by EU member states to the UNFCCC and the EU's GHG monitoring mechanism (IPCC sector: 2.C.3) (see: see: EEA, 2019) Most emission reductions of PFC took place before 1997 with only 4% further reduction of PFC emissions between 1997 and 2015.

Emissions from anode consumption decreased 19% between 1997 and 2015.[114] In particular indirect emissions fell 53% (1997-2015) due to this decline in production capacity, efficiency improvements and the decarbonisation of the EU power grid.

Between 1997 to 2005, indirect emissions appeared to be "stable". However, indirect emissions per ton decreased almost 30% because of the decarbonisation of the grid and energy efficiency improvements. Despite the decrease, in the same period, the total EU primary production increased around 23% because of the positive economic upturn and growing demand, which overall re-balanced the total emissions for the period.[115]

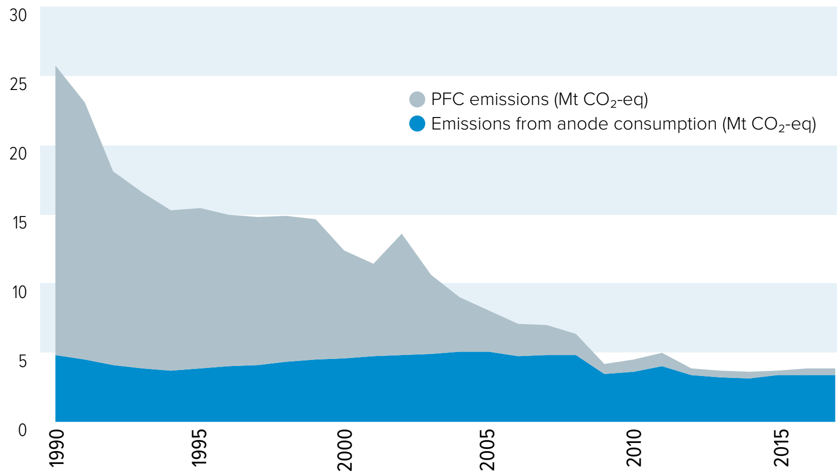


Figure 24: Evolution of aluminium process emissions (PFC and CO_2 emissions from anode consumption. CO_2-eq) (Source: EEA, 2019)

There are two factors which explain the large drop of emissions between 2005 to 2015. First, there have been continuous improvements in overall process efficiency. Second, an important element in the overall reduction in GHG emissions is due to a 35% reduction of primary capacity in the EU since 2007[116] (compared to 2006 production levels[117]). These closures followed the economic crisis which depressed global aluminium prices and exposed EU primary aluminium production to international competitors with lower production costs, in particular, electricity prices. This means that part of the EU's primary production was replaced by more imports, given the growing demand, and secondary production.

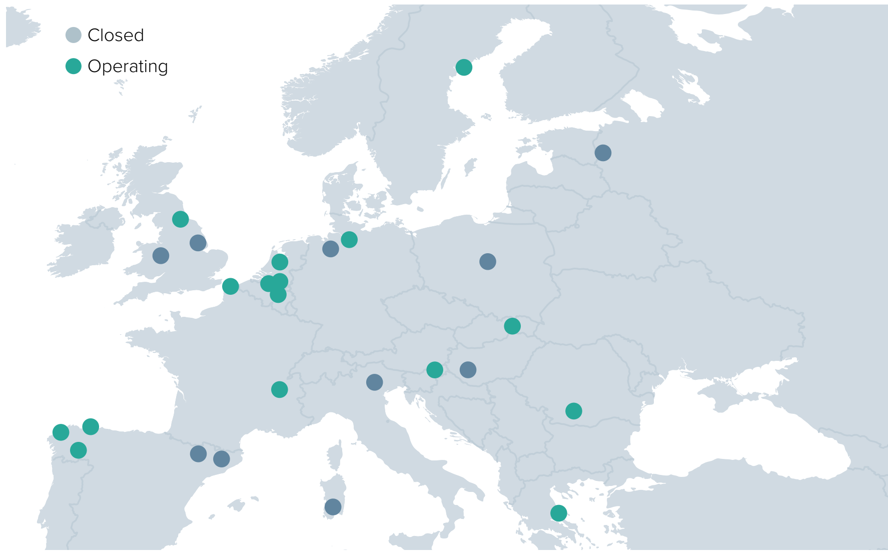


Figure 25: Since 2002, 10 out of 26 aluminium smelting facilities closed in the EU (source: European Aluminium)

5.3 Copper

The primary production of copper takes place in three stages:
a) concentration of the ores
b) conversion of the sulfides and other copper compounds to copper
c) refining of copper

There are 2 main routes in production of copper[118]; the pyro-metallurgical and the hydro-metallurgical (leaching) route. Worldwide, approximately 80% of primary copper is produced through pyrometallurgy process and the remaining 20% with hydro-metallurgy process. The hydro-metallurgical route is particularly suitable for ores which are difficult to concentrate by conventional means.[119]

In the pyrometallurgical route the mined and powdered copper ore is mixed with oil and agitated with water in a large tank to which detergent has been added. Compressed air is forced through the mixture, and the lightweight particles of copper sulfide are carried to the top and float on the froth. Heavier clays and other silicates settle to the bottom of

114 CO_2 process emissions as reported by EU member states to the UNFCCC and the EU's GHG monitoring mechanism (IPCC sector: 2.C.3)
115 European Aluminium
116 European Aluminium
117 BGS

118 A third and efficiency way of copper production uses bacteria and acidified water on copper-mining wastes (with low copper content). The bacterial processes lead to the solution of copper into water, where the copper can be recovered. In the US a significant amount of copper is produced in this way. (CIES, N.D.,)
119 CIES, N.D.,

the tank. This residue is known as ‘gangue’. The copper-rich froth is skimmed off.[120] After this the concentrated (sulfide) ores are roasted via an exothermal process (requiring little energy inputs), to remove impurities. The drying and smelting process is typically carried out simultaneously in a single furnace to produce melt that can be separated into matte (copper sulphide typically containing 60 – 65% copper) and a slag rich in iron and silica. The matte produced in the smelting furnace is then grinded before being fed into the conversion process. The conversion process converts matte into blister copper (typically 98.5% copper) by oxidising the copper sulphide with an air/oxygen mixture. The blister copper then goes into a furnace where sulphur is oxidised in a short oxidation period and finally cast into anodes. The cast anodes are then placed into an electrolyte bath which separate other metals to produce high purity (99.99%) copper (cathodes).[121]

The slags produced from primary smelting and converting stages are still rich in copper and are subject to a number of slag treatment processes. The most used slag treatment/cleaning processes are electrified e.g. electric furnace or slag flotation.[122] The slag fuming process is a specific process that may need measures to further reduce carbon emissions.

Approximately 1.5 MWh electricity is used to produce a tonne of copper in the EU[123], with total energy use standing around 12 GJ/t or 3.3 MWh/t copper. Hence a little less than half of the energy use in copper production comes from electricity. Modernised smelter-refiners are even more electrified and use higher current densities during electrolysis, resulting in higher electricity consumption. In the primary copper matte production process (roasting and smelting) direct CO_2 emissions result from fossil fuel and coke input as well as from the carbon, which is dissolved in the concentrates. During the following copper anode production (converting) direct CO_2 emissions occur due to fossil fuel input. No direct CO_2 emissions stem from the electrolysis process as electricity is used.[124]

The hydro-metallurgical (leaching) process offers an alternative to mining and is carried out with much lower temperatures, therefore eliminating the production of sulfur dioxide emission, but produces effluent which must be treated. In this process, known as SX-EW (solvent extraction/electrowinning), crushed ores are mixed with a leaching solution, typically sulfuric acid, which dissolves the copper and leaves a residue of precious metals. The leach solution then undergoes a purification process to remove dissolved iron and other impurities, and concentrates copper in smaller volumes by the solvent extraction process. The stripped solution, containing mainly copper sulphate, is then sent to the electro-winning stage. Electro- winning consists of the recovery of copper metal from the stripped solution (electrolyte) in a unique electro-winning cell. When a current is passed, copper is then deposited at the cathode forming copper cathode.[125] Advantages of these leaching processes are:

- Much less energy is used than in traditional mining but much higher electricity is used in electrowinning stage
- No waste gases are emitted
- Low capital investment
- Ability to be operated economically on a small scale.

The process can be used on ores with as little as 0.1% copper – for this reason, leaching extraction is growing in importance. It is estimated that SX-EW (almost non-existent before 1960) will represent 21% of total global copper refined production in 2019.[126] Because this process is ideally carried out near mining operations, it is rarely (< 3%) used in the EU.

Secondary copper is produced using recycled copper as the main basic material through a pyro-metallurgical process. Production of secondary copper depends heavily on the copper content of secondary raw material and its size distribution. It follows a similar process as of production of primary copper in removing impurities and copper recovery. Scrap quality has a high impact on the energy consumption and direct emissions of secondary copper furnaces, i.e. production of secondary copper from low quality scrap is more energy and CO_2-intensive than from high quality scrap. Secondary copper smelting leads to direct CO_2 emissions due to fossil fuel input. Recycling of electronic scrap in particular leads to high CO_2 emissions, since electronic scrap contains a high share of carbon leading to additional process emissions (up to 60% of direct emissions).[127] Counter-intuitively, secondary copper production can be more energy intensive compared to primary production which is very efficient due to exothermal processes. It does however come with a lower environmental footprint from a life-cycle perspective.

The recycling of copper is the most comprehensive among the non-ferrous metals. Copper metal scrap can be in the form of:

- copper scrap, such as fabrication rejects, wire scrap, plumbing scrap, apparatus, electrical systems or products from cable processing;
- alloy scrap, such as brass, gunmetal, bronze, in the form of radiators, fittings, machine parts, turnings or shredder metals;
- copper-iron scrap like electric motors or parts thereof, plated scrap, circuit elements and switchboard units, telephone scrap, transformers and shredder materials.

120 idem
121 ICF, 2015
122 JRC, 2017a
123 2013 data, JRC, 2016. Average electricity use: 1.1 MWh/t anode + 0.4 MWh/t cathode, average total energy use: 9.57 GJ/t anode + 2.43 GJ/t cathode.
124 Ecofys, et al., 2009b
125 ICF, 2015 and CIES, N.D.,
126 European Copper Institute, (N.D.,)
127 Ecofys, et al., 2009b

Another large group of copper-containing materials is composed of oxidised materials, including drosses, ashes, slags, scales, ball mill fines, catalysts as well as materials resulting from pollution control systems. The copper content of scrap varies from 1% to nearly 100%. The associated metals that have to be removed are mainly zinc, lead, tin, iron, nickel and aluminium as well as certain amounts of precious metals.[128]

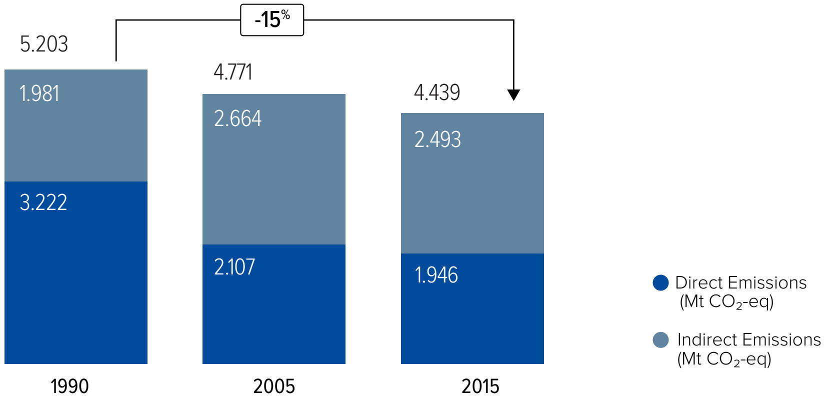


Figure 26: Evolution of direct and indirect emissions from copper production in the EU 28 (Mt CO_2-eq) (Source: European Copper Institute)

European copper production is heterogeneous and different companies have different levels of vertical integration, composition of raw materials and processes to extract and refine all the valuable elements by primary and secondary smelting routes.

Between 1990 and 2015 the emissions from copper production in the EU decreased 15%. Direct emissions fell 40% but indirect emissions went up 25%. However, over the same period (1990-2015) copper production increased 40% (from 1.94 Mt in 1990 to 2.73 Mt in 2015). Hence the CO_2 intensity of copper production reduced significantly from 2.67 t CO_2/t copper in 1990 to 1.62 t CO_2/t copper in 2015 or a reduction of 40%. These shifts can be explained by important efficiency gains in copper production (60% reduction in energy use per tonne of copper since 1990[129]), in particular the shift to flash-smelting. This process requires a lot of oxygen and hence higher levels of electricity use for the production of oxygen, which explains the increase in indirect emissions. Further efficiency gains came from new and modernised furnaces, renovated electrical equipment, efficient drying technologies, (residual) heat recovery systems and energy management systems.[130]

128 JRC, 2017a
129 European Copper Institute
130 Ibidem

5.4 Zinc

Nearly all mineral zinc concentrates processed in the primary zinc refining process are sulphides, which also usually contain other metals such as lead, copper, nickel, iron, cadmium and other precious and rare metals such as silver, gold, indium, cobalt and germanium. The most commonly occurring ores are sphalerite, also known as zinc blende (ZnS), and another variety of sphalerite called marmatite which contains significant quantities of iron sulfides.

There are two main processes: the electrolytic process and the thermal process. Over 90% of the world's production comes from the electrolytic process.

The electrolytic process has four stages:

- concentration of the ore at the mining site
- roasting of the ore with air
- conversion of zinc oxide to zinc sulfate
- electrolysis of zinc sulfate solution

The ore is mined, crushed, ball-milled and then concentrated by froth floatation. This removes unwanted components, including lead compounds and waste rock.[131]

Primary zinc is produced from zinc mineral concentrates via either the RLE (Roasting – Leaching – Electrolysis) or the ISF (Imperial Smelting Furnace) route.

In the RLE route calcine (ZnO) is produced from zinc concentrates in a roasting process and a zinc sulphate solution (ZnSO4) obtained following a leaching and purification step. Some plants operate a direct leach process on a part of the flow, which allows to by-pass the roasting step. Zinc sulphide ore roasting usually takes place in a fluidised bed furnace at around 1000° C, with air being blown in through a perforated bottom. The most important reaction is the conversion of zinc sulfide to zinc oxide.[132] The oxidized zinc is dissolved in acid and other metals are separated as by-product from this zinc flow. Pure zinc metal is finally recovered by electrolysis where zinc is deposited at the cathodes. The zinc deposit on the cathodes is stripped off, molten and cast into ingots. The metal is at least 99.95% pure. It is possible to make very high purity zinc (99.995% pure) by adjusting electrolysis conditions such as temperature and current density. Metal of this purity is required for diecasting alloys containing aluminium, magnesium and copper.[133] A pyrometallurgical process after

131 Several new methods have now been developed that dispense with the roasting stage, obtaining zinc sulfate directly from concentrated zinc sulfide ore. They generally use much more extreme conditions and are suitable for lower-grade ores. One process developed in Canada, and capable of recovering 99% of the zinc in the ore, uses pressures in excess of 10 atmospheres and a temperature of ca 150°C. The presence of iron in the ore concentrate is important in this method, as it is in part responsible for the conversion of zinc sulfide to zinc sulfate. Very high zinc extraction rates (up to 99%) from low-grade ores (as low as only 5% zinc) can also be achieved using bacterial action. The bacteria used thrive at temperatures up to ca 45°C, and produce weak zinc solutions that are concentrated for electrolysis using solvent extraction. CIES, N.D.,
132 CIES, N.D.,
133 Ibidem

the RLE route can recover the lost zinc, lead, silver, indium, germanium from the residues. It is waste material and needs energy and reducing agent to make pure slag and metal fume for metals recovery.

In the ISF process, zinc concentrate is agglomerated by sintering and then directly lead into the Imperial Smelting Furnace together with coke. Coke acts as energy source and reducing agent.

In the RLE as well as in the ISF process secondary raw materials such as zinc oxide or EAF dusts can be added. By-products of these processes include sulphuric acid, lead, precious metals, cadmium, copper, indium, germanium, nickel and cobalt.

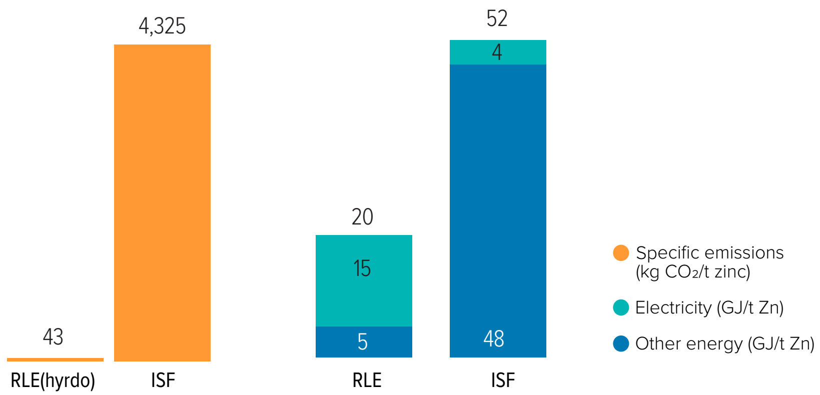


Figure 27: (left) Direct emissions of Zinc production (source: Ecofys, 2009b), (right) energy use per tonne of zinc (Source: Brook Hunt a Wood Mackenzie Company)

The figures above illustrate important differences between both the CO_2 intensity (direct emissions) and energy use of RLE and ISF technologies. Direct emissions of ISF are a factor 100 higher compared to RLE with hydrometallurgical treatment of leaching residues.[134] Energy use of ISF is more than 2.5 times higher compared to RLE per tonne of zinc produced. The RLE process is much more electro-intensive with 4.17 MWh electricity needed to produce one tonne of zinc.[135]

With regard to secondary production, over 40% of the zinc used annually originates from recycled metal.[136] Much of this comes from zinc-coated steel (e.g. zink used in roofing). This is placed in the EAF being used to recycle steel. Zinc is relatively volatile and leaves the furnace with other gases. It is collected on cooling as zinc dust (EAF dust). Today, this dust is highly contaminated with iron. Therefore, this dust is first processed in Waelz kilns to separate it from iron. Iron come out as a slag for construction and roads while zinc comes out as an oxide. This zinc oxide is further refined by zinc smelters in the process described above.[137]

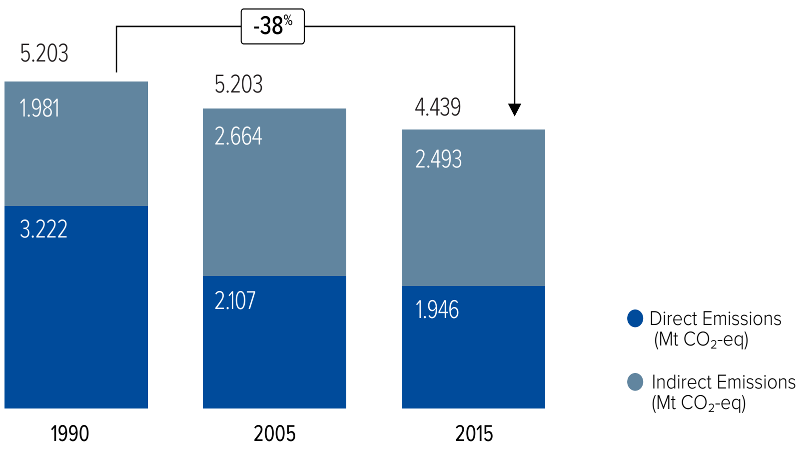


Figure 28: CO_2-eq emissions from Zinc production (Mt CO_2-eq) in the EU and Norway (Source: International Zinc Assocation)

Between 1990 and 2015 the GHGs from zinc production in the EU28 and Norway fell 38%. Major reductions in direct emissions (62%) came about due to the shift from the coke intensive pyrometallurgical ISF process towards the more energy efficient electrolytic RLE process. In 1990, there were 22 zinc refineries in the countries of the EU27 plus Norway producing zinc metal using three technologies:

- 6 plants with a pyrometallurgical Imperial Smelting Furnace (ISF) technology
- 14 plants with Roasting-Leaching-Electrolysis process (RLE), full hydro
- 2 plants with RLE process, combined hydro and pyro processes.

After 2000, a number of plants were closed down, mainly smelters using the ISF technology. The major reason for the closure of plants using the ISF technology was their comparatively higher energy consumption leading to much higher production costs. The ten zinc refineries which closed, used to produce up to 740 kt zinc metal per year. More than half of that production loss has been compensated by production increases in the remaining RLE plants.[138]

134 Ecofys, et al., 2009b
135 Brook Hunt, a Wood Mackenzie company
136 Secondary production includes recycling in zinc smelters and in the brass industry, the zinc compound industry and re-melting.

137 CIES, N.D.,
138 International Zinc Association, 2012

In 2015, there was 1 ISF plant left in the EU providing only 3% of the EU production[139], down from 18% in 2004. Presently, most zinc[140] is produced using the RLE, full hydro process, accounting for 93% of the total production. The RLE, full hydro process has the lowest energy consumption and 94% of the consumed energy is electricity – with 84% of electricity consumed used in the electrolysis stage of the zinc refining process. Today, electricity represents 85% of all energy used in the production of zinc.[141]

Further emission reductions in zinc production will not be straightforward given that secondary raw materials in smelter feeds are increasing, which can lead to higher CO_2 emissions.

5.5 Nickel

Nickel is primarily extracted from nickel sulphide ores, which contain about 1-3.5% nickel content, and the iron-containing lateritic ores limonite and garnierite, which contain about 1-2% nickel content.

Sulphide ores can be separated using froth flotation and pyrometallurgical processes to create nickel matte and nickel oxide. These intermediate products, which usually contain 40-70% nickel, are then further processed, often using the Sherritt-Gordon Process.

Lateritic ores are usually treated with hydrometallurgical processes. Lateritic ores also have a high moisture content (35-40%) that requires drying in a rotary kiln furnace. High pressure acid leaching (HPAL) is one of the most common treatment processes of lateritic nickel ores. The high temperature (around 250°C) acid pressure leaching of nickeliferous laterite ore has been commercially in use since the 1950's. The acid pressure leach solution is treated using hydrogen sulphide to produce a high-grade sulphide containing at least 50% nickel. This mixed sulphide is then pressure leached to give a high purity concentrated nickel-cobalt solution, suitable for solvent extraction to separate the valuable metals.

The Mond (or Carbonyl) Process is a method to treat nickel oxide sinter. In this process, the nickel oxide sinter is treated with hydrogen and fed into a volatilization kiln. Here it meets carbon monoxide at about 60°C to form nickel carbonyl gas. The nickel carbonyl gas decomposes on the surface of pre-heated nickel pellets that flow through a heat chamber until they reach the desired size. At higher temperatures, this process can be used to form nickel powder.[142]

139 This last ISF plant has a process that enables to process feedstock which cannot be treated by regular zinc smelters such as mixed zinc-lead mineral concentrates with elevated Pb content and complex waste streams. Since there is worldwide little processing capacity for these materials, there is a bigger margin to operate the process.
140 In 2010, zinc production was 2098 kt and this production was achieved in 12 plants: 1 plant with ISF technology, 10 plants with RLE process, full hydro, 1 plant with RLE process, combined hydro and pyro
141 International Zinc Association
142 Bell, 2019

The use of electrical cells equipped with inert cathodes is the most common technology for nickel refining. Electrowinning, in which nickel is removed from solution in cells equipped with inert anodes, is the more common refining process. Sulfuric acid solutions or, less commonly, chloride electrolytes are used.[143]

With regard to secondary production, nickel scrap can be used in melting processes as addition to refined nickel. Moreover, efficient recycling of nickel takes place in the stainless-steel industry, which is the major first use of nickel. In 2010, around 43% of all nickel used in EU came mainly from stainless steel scrap (process scrap, end of life products, …).[144]

Some nickel mining activities in Europe take place in Finland; smelting and refining in Finland, France, Norway and the UK where nickel mine products and intermediates (mainly from outside the EU) are converted into nickel metal. Nickel production in Europe is diverse with production in Norway and Finland being very electro-intensive. Sites in France and the UK are much smaller and less electro-intensive. The conversion of nickel into first-use products (e.g. stainless steel, nickel alloys, foundries, plating) and-end use products (e.g. tubes and pipes, metal goods, electrical and electronic equipment) takes place in other industries.

Most of the nickel produced in Europe is high purity (nickel class I; nickel content >99%). Other nickel products such as ferro-nickel and nickel pig iron are mostly produced outside of Europe, with most nickel pig iron being produced in China. Ferronickel and nickel pig iron have a lower nickel content ranging from 4-15% (nickel pig iron) to 30% (ferronickel). The specific GHG emissions differ significantly with class I nickel production at 7.8 kg CO_2/kg nickel, 32.8 kg CO_2/kg nickel in ferro nickel, and between 70 kg and 98 CO_2/kg nickel in blast furnace and electric arc furnace nickel pig iron production respectively.[145]

Nickel refining is highly electro-intensive at 5-5.5 MWh/t nickel product. But also, processes related to the flash-furnace, can consume high levels of electricity up to 2.6-2.8 MWh/t nickel, 75% of which is related to slag treatment.[146] On average the energy use for nickel producers in Europe is 70-80% electricity and 20-30% natural gas.[147]

Between 2011 and 2016, the emissions from Nickel production remained stable (from 346 kt CO_2-eq in 2011 to 349 kt CO_2-eq in 2016 in the EU28 and Norway). The CO_2 intensity was reduced by 5% over the same period (from 1.91 to 1.84). Given the electro-intensity of nickel refining, the indirect emissions represent at around 85% by far the highest share of overall CO_2 emissions.[148]

143 World Bank, 1998
144 Nickel Institute, 2012
145 Nickel Institute
146 Data from Harvjavalta refinery and Harvjavalta Flash furnace. USGS, 2011
147 Nickel Institute
148 Ibidem

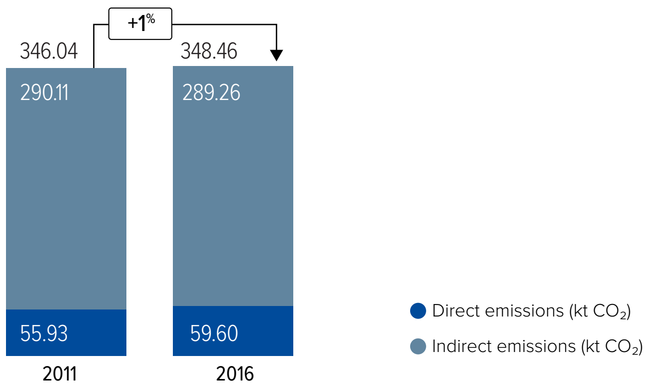


Figure 29: CO_2-eq emissions in Nickel production (EU28 + Norway) (Source: Nickel Institute)

5.6 Silicon, Ferro-Silicon and Ferro-Manganese

Ferro-alloys and silicon are principally produced in submerged EAF (electric arc furnaces). The process is the carbothermic reduction of oxidic ores or concentrates, in which carbon in the form of coke (metallurgical coke), coal or charcoal is normally used as a reducing agent.[149] In the EAF, passing current through graphite electrodes suspended in a cup-shaped (refractory-lined steel shell) accomplishes heating. Carbon reduction of the metallic oxides occurs as both coke and graphite electrodes are consumed. The carbon in the electrodes reacts with the oxygen from the metal oxides to form CO_2, while the ores are reduced to molten base metals which then combine in the solution. In silicon production, one of the important by-products of this process is silica fume which can be used in the construction industry.

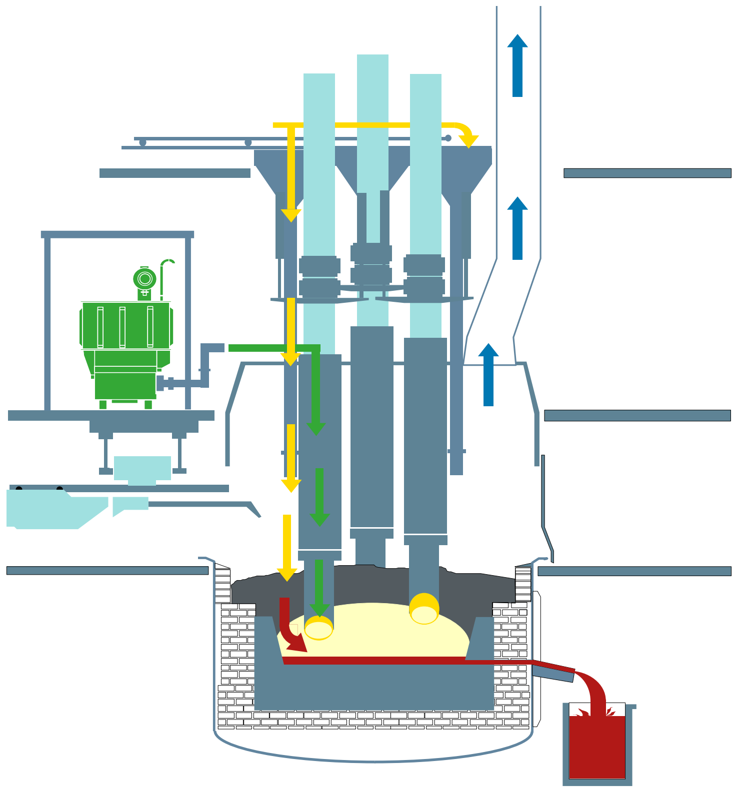


Figure 30: Submerged electric arc furnace (source: Elkem)

Product quality requirements impose major constraints in the choice of raw materials such as coal and cokes. Natural gas cannot be used as a reducing agent as smelting needs elementary carbon. The energy consumption per ton of metal differs greatly from one ferro-alloy to another. The production of ferro-alloys is a highly energy-consuming process because high temperatures are needed for the reduction of metal oxides and smelting. Factors affecting energy consumption are, among others, the quality of raw materials (such as ores, quartz and reducing agents) and their pre-treatment before smelting, the utilisation of energy reaction, as well as the heat content of the processes.

Ferro-alloy and silicon production are energy- and in particular electro-intensive process-

149 Raw material inputs also include raw materials (ores), reductants (coke, silicon-bases ferro-alloys, aluminium), iron additions (iron ore or steel scrap), and fluxes (lime, magnesia, dolomite, limestone, fluorspar, etc.)

es. Silicon production requires 12.4 MWh electricity per tonne, Ferro-silicon 8.7 MWh/t and Ferro-Manganese 3 MWh/t.[150]

Ferro-alloys and silicon production results in both combustion (generating heat) and process emissions (carbothermic reduction of metal oxides) which are the major source of carbon dioxide (CO_2). The direct emissions of silicon and ferro-alloys production are the result of the metallurgic reduction process. It is estimated that total CO_2 emissions from silicon in the EU were 1.6 Mt in 2013 and 0.4 and 1.5 Mt for respectively Ferro-manganese and Ferro-silicon.[151]

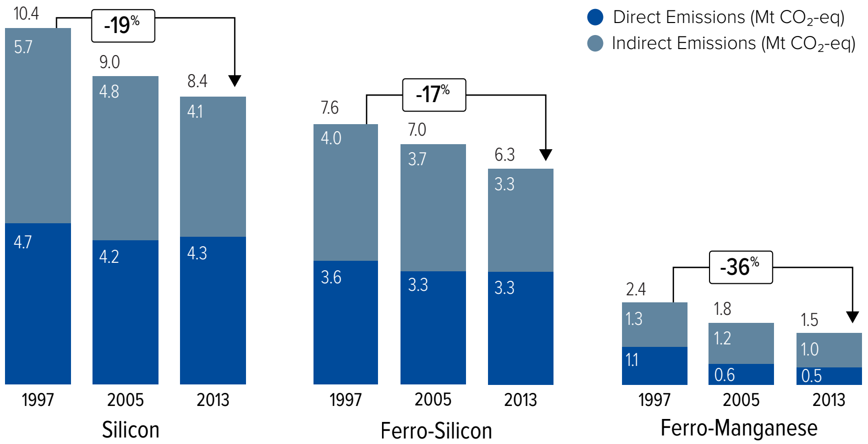


Figure 31: Specific direct and indirect CO_2 emissions for Silicon (left), Ferro-Silicon (middle) and Ferro-Manganese (right) (source: Euroalliages) (EU+EFTA)

Specific CO_2 emissions for silicon production reduced 19% between 1997 and 2013, 17% for Ferro-silicon and 36% for Ferro-Manganese. Over the past years, consolidation took place over these sectors together with plant closures of less efficient installations. Furthermore, significant investments to improve energy efficiency have been made.[152]

150 Based on data provided by Euroalliages
151 Calculation based on specific emissions data by Euroalliages, EU production data in British geological survey and EEA data on carbon intensity of EU power production in 2013.
152 Euroalliages

GHG mitigation technologies towards climate neutrality in non-ferrous metals production

6. GHG Mitigation Technologies towards climate neutrality in non-ferrous metals production

6.1 Introduction

While the non-ferrous metals industry has seen important GHG reductions since 1990 due to the (almost) elimination of PFC emissions, efficiency improvements and fuel switch to electricity and natural gas, there is a wide range of possible technological options to achieve GHG reductions in line with climate neutrality by 2050. However, many of these options are not (yet) mature or commercially interesting and depend on evolutions outside of the non-ferrous metals industry.

The options under consideration here are based on Wyns, Khandekar, & Robson (2018), new literature and information from sectors and companies. These include:

- Decarbonisation of the EU power sector
- Energy efficiency
- New processes in primary aluminium production
- Further electrification
- Hydrogen as a smelting reducing agent
- Bio-based carbon as a smelting reducing agent
- Carbon capture and utilisation and/or storage (CC(U)S)
- Enhanced metals recovery from secondary raw materials (mining residues, slag, sludges and scrap recovery)
- Sector coupling: demand response and waste heat usage outside of non-ferrous metals production

For each of the above-mentioned options, the possible application to specific types of metals production is considered together with the current state of technology and (current) constraints regarding economic viability or other elements that need to be addressed for wide-scale application in the industry.

6.2 Decarbonisation of the EU power sector

Due to the high level of electricity use, decarbonisation of EU power production will be the most important factor in the decarbonisation of non-ferrous metal production. Assuming that indirect emissions will hence be reduced to zero and direct emissions stay at same level as in 2015, this alone would imply a GHG reduction of 81% compared to 1990 levels.

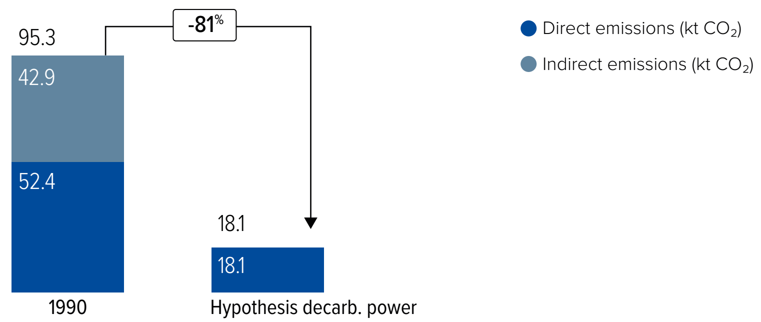


Figure 32: Emission reductions (hypothetical) of the EU non-ferrous metals industry if decarbonisation of the EU power sector occurs (using 2015 emissions)

The possible impact of power sector decarbonisation on the total emission of aluminium, copper, zinc, nickel, silicon, ferro-silicon and ferro-manganese is shown below. For all these metals, reducing emissions in the power sector to zero would be the single biggest action towards deep emission reductions.

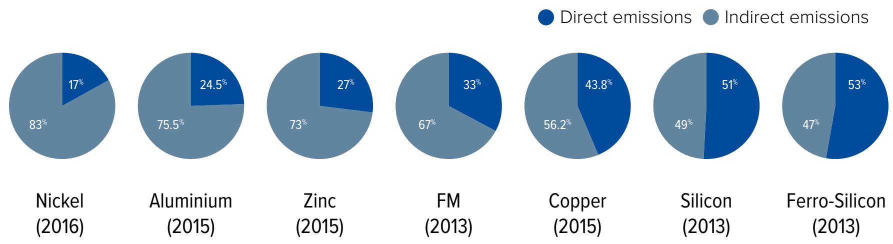


Figure 33: Direct vs indirect emissions (%) - based on emissions data

However, the transition to a power system that fully runs on renewables together with non-CO_2 emitting balancing and (seasonal) storage will be complex and challenging for electro-intensive consumers. This includes possible passing through of cost related to the support for renewable energy production, balancing, storage, capacity markets and indirect CO_2 costs. These elements will be further discussed in chapter 7. Chapter 8 will show how the metals industry can help facilitate the transition of the EU power system.

6.3 Energy efficiency

While most metal production processes have been optimised for years or even decades (e.g. the Hall-Heroult process), there still remains potential for further (relatively) small efficiency improvements in metals production. An assessment by ICF for DG ENER[153] showed an economic potential (2 to 5 years payback time) of reduction in final energy consumption for non-ferrous metals between 12-12.7% compared to BAU energy consumption in 2050 (ref. 2013).[154] The technical potential is considered to be larger with savings up to 21%.

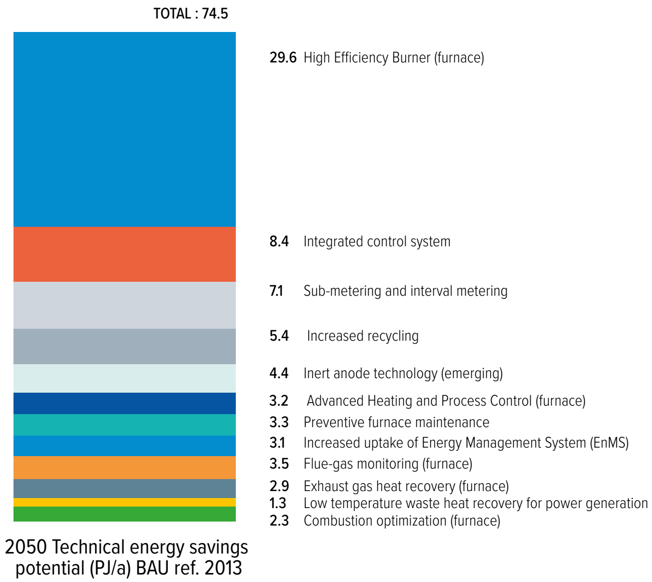


Figure 34: Main energy savings options (representing a total of 70% of the technical potential) in the non-ferrous metals industry, Source: ICF 2015

The figure above shows the main energy savings options (representing a total of 70% of the technical potential) in the non-ferrous metals industry as identified by ICF. Important options include better, smarter and integrated control systems, increased efficiency of burners and increased heat recovery.

Achieving the deeper technical energy savings potential will require (sometimes) capital-intensive investments e.g. replacements of major parts of existing production processes. In some cases, the payback of investments in some existing technologies are far from attaining companies' typical financial criteria. At the same time (high) capital-intensive investments can be required for new low-CO_2 technologies, including the replacement of existing processes. Because most of the metals producers have long investment cycles, it is therefore possible that investments in capital-intensive energy savings measures might be forsaken in favour of changing to radically new production processes such as the ones presented in the next sections.

153 ICF, 2015
154 BAU with 2013 final energy consumption as reference point and overall reduction in energy consumption of 0.5% per year following the trend of the period 1990-2012.

BOX 5: Glencore Nikkelwerk – energy savings

Glencore's Nikkelverk refinery in Norway has successfully implemented a portfolio of new energy management technologies which will save over 30 GWh energy annually. These include initiatives based on pressurised air, steam, ventilation, reusing waste heat and process improvements. Glencore has installed new tanks, electrical contacts and energy-efficient anodes to reduce its energy consumption. Waste heat from their sulphuric acid plant is now being used to replace electrically generated steam. The refinery is working to replace any remaining older anodes with efficient alternatives. This will save a further 17 GWh per year.[155]

BOX 6: Energy efficiency innovation in copper production

In copper smelting, further innovation in flash smelting, the oxygen flash technique, is a more efficient method of smelting copper compared to current best available technologies. In this process, a fine mix of copper ore, sand and limestone is injected by compressed oxygenated air, prompting immediate endothermic combustion at 1100°C, without using any other fuels. It also eliminates the converter stage, as the metal has been already converted to blister copper in the flash furnace.[156]

6.4 New processes in primary aluminium production (incl. copper electrolysis)

Primary aluminium production has seen large efficiency gains since it was first introduced. Further efficiency improvements become more difficult, but there still exists potential for improvements.

155 Glencore and Eurometaux
156 Fraunhofer ISI, 2019

Higher efficiency of primary aluminium electrolysis process

Lowering the temperature of primary aluminium production (from 950˚C closer to the melting point of 680˚C) while maintaining stable operation can bring about important energy savings.

Theoretically, reducing the temperature to around melting point should decrease electricity use by 1.0-1.5 MWh/t, although in reality savings are likely to be around 0.7 MWh/t (5%). Also, energy from the superheated metal is generally used to re-melt pre-loaded scrap in the casting house, benefitting from its “free” energy.[157] The chloride process developed by Alcoa between 1960-1980, based on the chlorination of refined aluminium oxide, does take place at such lower temperatures. In practice, the chloride process has not been able to compete with the Hall-Héroult process, and little information is available on industrial experience with the method. The chloride process is adversely affected by raw materials impurities; a number of unfortunate side reactions can occur, and gaseous chlorine compounds are generally toxic.[158][159]

The application of dynamic (AC) magnetic field in electrolysis cells can enable smaller electrode separation and hence reduce energy losses. Energy savings can be between 5-20%. TRL stands at 3-4. This technology is likely not compatible with use of inert and wetted anodes (see below).[160]

The physical design of anodes can be also altered to improve energy efficiency of the Hall-Héroult cells. For example, sloped and perforated anodes make electrolysis more efficient by allowing better circulation within the electrolyte bath, while vertical electrode cells save energy by reducing heat loss and improving electrical conductivity.[161] This new design of anodes will however also require a different type of cathode.

BOX 7: Norsk Hydro’s Karmoy Technology plant

During the last decade, researchers in Norks Hydro’s technology centres have developed a new generation of electrolysis technology. This aims to reduce both industry energy consumption and emissions. It is now being tested in a full-scale production plant. The pilot was designed with an annual production capacity of approximately 75,000 tonnes. It consists of 48 cells running on the HAL4e technology (12.3 kWh/kg) and 12 cells using the HAL4e Ultra technology (11.5-11.8 kWh/kg). This technology will use 15 percent less energy for aluminium production than the global average, providing the lowest CO_2 footprint in the world. The pilot aims to set a new benchmark for emissions, reducing direct CO_2 emissions to 1.40-1.45kg CO_2 equivalents per kg aluminium or 0.8kg per kilo of aluminium below the current world average. The true innovation of HAL4e is the unique combination of low energy consumption, high current density (i.e. high productivity), low CAPEX (i.e. compact footprint) and low emissions. There has been a strong focus to include as many digital and Industry 4.0 aspects in the pilot as possible, mainly focusing on automation, real-time connectivity and an enhanced control platform.

Total costs are estimated at €442 million, consisting of net project costs of €277 million and around €164 million in support from Norwegian government enterprise Enova. This grant was essential in making the pilot possible given that industrial scale testing of new technologies is both capital and risk intensive.[162]

Figure 35: Norsk Hydro primary aluminium production (source: Norsk Hydro)

Inert (non-carbon) anodes

Inert anodes are seen as the holy grail in the production of primary aluminium. These inert anodes would replace the energy-intensive production of carbon anodes and would eliminate the production of (direct) CO_2 emissions due to the consumption of the anode during the aluminium production process. In theory, these inert anodes would come with important other benefits. This includes (in theory) reductions in the cost of production and replacement of the consumable carbon anodes, overall lower capital costs vis-à-vis carbon

157 Ibidem
158 Øye B., 2019
159 The chloride process also has inert anodes, but the carbochlorination process can produce high CO_2 concentrations in the process gas, making it easier to implement CO_2 capture and storage. Øye B., 2019
160 Fraunhofer ISI, 2019
161 IEA, 2018

162 European Aluminium, 2018b, Norsk Hydro and Vatne, 2018

anodes (-10 to -30%), improved plant efficiency by eliminating the need to regularly replace the anodes, elimination of PFC emissions and oxygen production that can be valorised as possible by-product. Energy savings of 3 to 4% compared to existing electrolysis processes are expected, however still uncertain.[163] Inert anodes have not reached the demonstration stage and their TRL is estimated at 5.[164] [165]

Wettable (inert e.g. titanium diboride (TiB2) composite) cathodes improve energy efficiency (-20% energy use) by means of providing a geometrical stable cathode surface. They would also extend the life of cells and reducing the amount of toxic waste.[166]

Multipolar cells (with inert anodes) would improve the existing process by allowing multiple anode- cathode pairs in same cell (compared to only one horizontal cathode now). This would make energy savings of around 40% possible through lower operating temperatures (around 700˚C), higher current densities, better control of heat losses and improved circulation of the electrolyte. [167] It is not known if multipolar cells can be applied to the current Hall-Heroult process with fluoride-based electrolytes. In the chloride process, mentioned before, they have been used at industrial scale.

BOX 8: Elysis – Alcoa/Rio Tinto

Currently the frontrunner in developing inert anodes-based aluminium production is Elysis a partnership of two major aluminium producers - Alcoa and Rio Tinto. Elysis was established in 2018. The Canadian Government and the Quebec Government, through participation of Investissement Quebec, each are investing $60 million (CAD) in Elysis. Technology company Apple, an important consumer of aluminium, has helped facilitate the collaboration between Alcoa and Rio Tinto on the carbon-free smelting process and, in addition to investing $13 million (CAD), has agreed to provide the project with technical support.

The technology was successfully demonstrated and has been producing metal at the Alcoa Technical Center, near Pittsburgh in the United States, since 2009. In the second half of 2020, Elysis will open a research and development center in Saguenay, Quebec, to further scale-up the process. This research center will be housing the next generation cells with the objective to demonstrate the technology at commercial scale. The goal is to bring it to commercial size by 2024.[168]

The application of inert anodes in EU primary aluminium production would reduce most of its direct emissions.[169] This technology would have the single biggest impact to further GHG reductions in the aluminium and non-ferrous metals production by reducing over-all non-ferrous direct emissions by more than 20% compared to 2015 levels. Furthermore, most inert anode technologies promise important energy savings, in particular lower electricity consumption. However, this must still be proven in practice given one of the challenges with inert technology is higher electricity consumption as thermodynamic cell voltage is considerably higher than for the classic Hall-Héroult process.

Next to efficiency improvements in the electrolysis process and shift to inert anodes, there are also other, more radical process innovations being investigated for primary aluminium production.

One such radical shift would be low (close to room) temperature electrolysis using ionic liquids would could replace the current Hall-Héroult process and lead to important energy savings (30% to 85%) due to lower temperatures and higher bauxite-to-alumina conversion.[170] This process is still only at the R&D phase and the process has several substantial difficulties to overcome. TRL is hence still low at 1-2 and it is more likely this process will not be useful for large scale aluminium production and rather be applied to electroplating processes.[171]

The electrolysis process could also be replaced by the carbo-thermic reduction of alumina. In this process (not dissimilar to current hot iron production), alumina reacts with carbon at high temperatures (>2000 ˚C) to form aluminium and CO. It would be 20-30% more efficient compared to electrolysis-based aluminium production and have lower (50%) capital costs. The technology has been tested up to pilot scale by Alcoa and Elkem, but further development has stalled (TRL 4-5).[172][173] Furthermore, the technology would still emit substantial amounts of CO_2 which will have to be mitigated through e.g. CCS, leading to additional capital and operational costs.

It is, in theory also possible to produce aluminium from kaolin which is an alumina-silicate clay, currently used in the production of some ceramics products. Europe (but also China) has large resources of kaolin clay, but alumina-silicate concentration can be low in some places.[174] The chlorination and electrolytic reduction of kaolin would replace the current Bayer (alumina production) and Hall-Héroult processes. The overall process would be 12-

163 Inert anodes exhibit higher theoretical levels of energy consumption than carbon anodes (9.16 kWh/kg Al). This is because inert anodes cannot utilise the chemical energy stored in carbon. See: Solheim, 2018, pp. 1253-1260.
164 Fraunhofer ISI, 2019
165 A research project (AGRAL) under the EU SILC II programme did advance in finding materials and processes suitable for replacing carbon anodes. The project was not followed up with further industrial testing or piloting. Cordis, 2019
166 IEA, 2018, , Fraunhofer ISI, 2019, And ARPA-E, 2017
167 Fraunhofer ISI, 2019
168 Elysis

169 3.7 Mt CO_2-eq reductions due to avoided CO_2 emissions in consumption of carbon anodes and PFC emissions (Source: EEA, 2019 - 2015 emissions data) and around 0.7 Mt CO_2 from the production of carbon anodes (Ecofys, 2009a - references corrected for 2015 production).
170 Given that it can be used in the recovery of aluminium from bauxite residue. Tam, et al., 2016, Recovery of aluminium from bauxite residue dissolution and electrowinning of aluminium using pyrrolidinium ionic liquid.
171 Fraunhofer ISI, 2019
172 Ibidem
173 Bruno, M. J., 2014
174 European Commission, 2017a, Flavier et al., 2018

46% more efficient and would use smaller cells with the ability to retain temperature and would allow aluminium producers to take better advantage of electricity demand response systems.[175] The process is still at the early development stages (TRL 2-4[176]).

Primary copper production via electrolysis

Finally, a process similar to the Hall-Héroult process could also be applied to copper production from sulphate-based minerals through a route[177] which selectively separates pure copper and other metallic elements from sulphur-based minerals, using molten electrolysis. The process is broadly similar to the aluminium H-H cell. The research found a method of forming liquid copper metal and sulphur from an electrolyte composed of barium sulphide, lanthanum sulphide, and copper sulphide. Electrolysis decomposed sulphur-rich minerals into pure sulphur and extracted three different metals at high purity: copper, molybdenum, and rhenium. This one-step process greatly simplifies metal production. It yields >99.9% pure copper, which is equivalent to the best current copper production methods but without having to undergo multiple (energy-intense and polluting) process stages. Furthermore, it is more energy efficient (50% energy savings compared to pyrometallurgical route) and eliminates toxic by-products such as sulphur dioxide. Research is still at early stages and TRL is estimated to be 2-3.[178]

6.5 Further electrification of processes

While non-ferrous metals production is already very electro-intensive, there still exists potential for further shifts to replace fossils fuels with electricity. In zinc EU production, this shift has been outspoken over the past 20 years. It is conceivable that in the EU, some smelting processes and in particular recycling and metals recovery processes could see a shift over the next decades to the more electro-intensive (and energy-efficient) hydrometallurgical leaching or bio-leaching processes. This is also due to the decreasing metals concentrations in ores following increased global demand and more difficult-to-recycle waste streams which might make the pyrometallurgical route more energy intensive and less competitive.[179]

But also, in some[180] pyrometallurgical smelting routes, higher levels of electricity use can be possible by replacing fossil fuels with other electricity-based heating technologies (e.g. induction heating).[181] In the nickel industry, various sources of fossil fuels are used in the production of technical/industrial gases which might be replaced by electricity (longer-term). Electric heating can also be considered as a replacement to the fossil fuel used for heating in auxiliary processes (e.g. boilers and heating).

Finally, in secondary production and more downstream applications, electricity might be a viable replacement for some processes using e.g. natural gas as energy source being replaced by induction heating. For higher levels of electrification to be viable, it will be relevant that these new processes improve efficiency of existing (fossil fuel-based) processes as to off-set possible higher costs of electricity vis-à-vis e.g. natural gas.

6.6 Hydrogen as smelting reducing agent

Hydrogen can be considered as a replacement to coke as the reductant in some pyrometallurgical processes of non-ferrous metals or as a reducing agent in the copper fire refining process. Hydrogen produced via electrolysis has the benefit of having oxygen as a by-product, which can also be used in some of the smelting processes (e.g. copper smelting). This can improve the business case of using electrolysis-based hydrogen as a reducing agent.

In silicon production research is ongoing to reduce fine grain quartz sand (d 50<35µm) in a plasma reactor by means of a suitable reduction agent to produce high-purity solar cell quality silicon metal in a one step process (instead of the metallurgical followed by the chemical processes). The reduction agent or agents can comprise gases and solid particles and is/are typically chosen among hydrocarbon gases, particularly methane, natural gas, hydrogen or a combination of these gases.[182]

It should be underlined that using hydrogen instead of carbon as reducing agent - like in steel – is not applicable in all cases as the reduction process to transform a metal oxide into a metallic form are governed by laws of thermo-dynamics. The more G (Gibbs constant) is high, the more difficult is the reaction. Constants Gibbs & equilibrium K are favourable for reduction by hydrogen of iron ore and are very unfavourable for chromium/manganese/silicon ores as the energy to accomplish the reaction is much higher than to keep it in equilibrium.[183]

As with the electrification of processes, to be viable is will be relevant that hydrogen costs are competitive with carbon-based feedstocks. Furthermore, hydrogen production itself will need to be CO_2 free. This is possible through e.g. CCS applied to methane steam reforming processes or by producing hydrogen via electrolysis.

175 Fraunhofer ISI, 2019
176 Ibidem updated by additional input aluminium technology expert
177 Paiste, 2018, Stillman, H., 2018
178 Fraunhofer ISI, 2019
179 See Biomore project: European Commission, N.D.,a and Teck – Aurubis, N.D.,
180 For primary copper production this would not apply given that these processes are already exothermal.
181 ICF, 2015
182 Euroalliages
183 Sabat et. al.,, 2014

On the other hand, due to the relative lower demand for hydrogen (compared to e.g. steel and chemicals) it might be interesting to look for synergies with other (larger) industries that are investigating or investing in the use of hydrogen for production of basic materials. For instance, the Hybrit[184] direct iron ore reduction project currently being prepared for piloting at SSAB in Sweden or iron smelting processes explored by other steelmakers can be a possible example of technology synergy between steels and metals.

6.7 Bio-based fuels and other fuel switching

Fuel switching can lead to lower CO_2 emissions. For example, shifts from liquid fuels to gas, or the use of biogas may be used where possible.[185] There is potential for low-carbon fuels to replace fossil fuels in copper production and other smelting and re-melting of metals, once economically competitive and available in sufficient quality.

The switch to natural gas for ferro-alloy manufacturing can lower emissions compared to solid carbonaceous materials such as coal and metallurgical coke. This possibility is also investigated due to the possible shortage of high-quality fossil carbon materials and charcoal in the future. In Silicon (and ferro-alloys) production furnaces can operate with a relatively high biocarbon content. Some installations already use some biocarbon, but there remain bottlenecks (i.e. technology, cost and impact on land-use and biodiversity).[186]

The company Elkem has initiated a research programme called Carbon Neutral Metal Production (CNMP). The concept of CNMP is to produce charcoal in the same production facility (like ferrosilicon or silicon plants), connecting this to an energy recovery unit, to produce electricity from the excess heat. The local conditions are favourable with green hydropower, local wood-chips production and significant forests. This project required collaboration between different industries in a cluster as one company alone cannot set this up. Significant research, cooperation and funding are required, as well as a holistic approach utilising all side streams (fines, pyro-gas, condensate): wood chips production and drying, novel pyrolysis process transforming these chips into charcoal and off-gas, used of the off-gas e.g. by heat transfer and the charcoal by nearby consumers.[187]

Given the high temperatures needed to make copper, biofuels are not currently seen as good candidates as replacement of thermal energy sources. With the development of new biofuels for jet fuel, this limitation may be overcome in the following years.[188] Use of synthetic fuels can be an option for use in copper smelters, but these must be cost-competitive.

Bio-based fuels can become an important mitigation option in upstream (e.g. alumina) and downstream heating processes, especially when electrification of heating is not viable.

184 http://www.hybritdevelopment.com
185 ICF, 2015
186 Euroalliages
187 Ibidem.,
188 Fraunhofer ISI, 2019

6.8 Carbon Capture and Utilisation or Storage CC(U)S

Carbon capture and storage does not seem like an economically viable option for metals producers on their own, due to the high capital cost vis-à-vis the relatively low emissions compared to e.g. integrated steel plants, cement production or basic chemicals. There might however be the opportunity for some metals producers to apply CC(U)S if they have a favourable location (e.g. in the vicinity of steel, cement or chemicals producer) to make use of (forthcoming) existing CO_2 transport and storage infrastructure. New carbon capture-ready iron ore smelting technologies such as HIsarna, currently piloted at Tata Steel in Ijmuiden[189], show that CCS in theory can be used in non-ferrous metals smelting processes, in particular for carbothermic processes.

Metals smelting processes which operate in a high oxygen environment might see flue gases with high CO_2 concentration (after cleaning) and consider the use of CCS. CCS could also be applied to capture the CO_2 emissions from embedded carbon in concentrates and secondary raw materials and from the treatment of slag and leaching residues. However, the investment costs might be high vis-à-vis the total amount of emissions captured.

The most interesting application of CCS would be in silicon and ferro-alloys carbo-thermic reduction processes due to the high carbon-monoxide concentration in flue gases. CCS in combination with use of bio-based carbon could even make silicon and ferroalloys production CO_2 negative, for its direct emissions.

Absorption-based CCS can (in theory) be applied to primary aluminium production (TRL 3-4). Because the CO_2 concentration in off-gases from aluminium electrolysis is dilute (4%)[190], costs for capturing are estimated to be around EUR 100/t CO_2 (including additional energy use).[191] Furthermore, if inert anodes would become available, CCS in primary aluminium production would become redundant given the expected lower operational costs of inert anodes.[192]

CCS could also be applied in power-plants or CHP plants operated by non-ferrous metals producers. However, it would make electricity production significantly more expensive and hence uncompetitive.

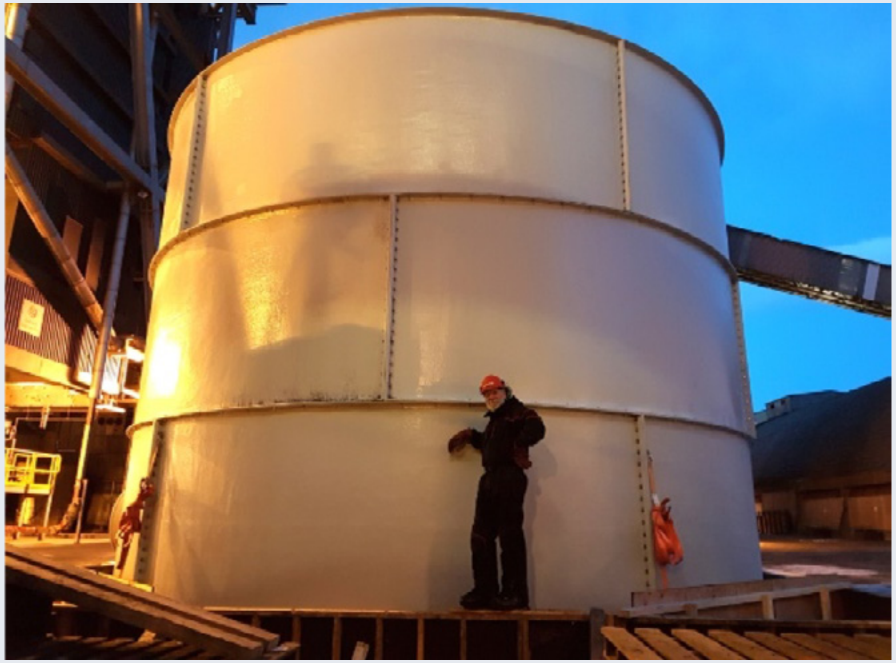
Some carbon capture and utilisation (CCU) technologies can be applied in non-ferrous metals and silicon production with concentrated CO_2 streams. This already takes place at a small scale in Finnfjord's Norway ferrosilicon production plant[193] which uses recovered CO_2 to farm algae and subsequently produce biofuels. As is the case with CCS, the non-ferrous

189 Tata Hisarna, N.D.,
190 JRC, 2015
191 Fraunhofer ISI, 2019
192 JRC, 2015
193 ICCU, N.D.,

metals industry could benefit from innovations that are pioneered at larger process installations in other industries. For instance, the Steelanol[194] project by Arcelormittal, which uses a bacteria-based process to turn blast furnace gas into ethanol, could possibly find applications in some non-ferrous metals smelting processes and in ferro-alloys or silicon production.

Box 9: An Organic Rankine Cycle project in the ferro-alloy Industry – Finnfjord

The project concept includes the production of diatom biomass by sequestration of CO_2 and nitrogen oxide from factory fumes and differs from other conventional initiatives with respect to the choice of organisms, photobioreactor type, illumination, cultivation technology and processing. The main product is fish feed, but bioprospecting and other applications are included. The production initiative is integrated in the production line of the ferrosilicon factory Finnfjord located in Norway. The ground-breaking feature is the integration of the "mineral world" and the "organic world" within the same industrial compound by linking the "mineral" and the "organic" value chains with the conversion of CO_2 to fish fodder or fuel.[195]



194 Steelanol
195 Euroalliages

6.9 Enhanced metals recovery from secondary raw materials (mining residues, slag, sludges and scrap recovery)

While non-ferrous metals production already processes a significant amount of secondary raw materials (e.g. metal scrap), there still exists a significant potential to increase the recovery of metals from e.g. low-grade ores, sludges and slags from metals production and post-consumer metals scrap. Enabling higher recovery of metals from these streams will reduce or limit Europe's import dependence for metals. Furthermore, better treatment of waste streams (which are often landfilled) can reduce the risk of hazardous materials entering the environment.

By-products from red mud (bauxite residue from alumina production)

The current bauxite residue (red mud) production level in the EU is 6.8 Mt per year; while the cumulative stock- piled level is a staggering >250 million tonnes (dry matter). Out of the 6.8 Mt of bauxite residue produced annually in Europe, currently only a very small part (0.015%) is re-used as a raw material for clinker cement.[196]

Much more value can, in theory, be extracted from bauxite residue. For instance, out of the annual red mud production, iron ore products could be produced, representing a possible 18% increase of domestic EU iron ore production. Further large volumes of materials from red mud include mineral wool, aluminate cement, geopolymer and slag cement, amounting to 2-3 million tonnes possible recovery per year in the EU. Last but not least, bauxite residue also contains valuable metals such as rare-earth elements[197], in minor but non-negligible concentration. Therefore stockpiled and annually produced bauxite residue can be considered an important low grade resource for extracting critical metals like rare-earth elements, metals with high economic importance for Europe e.g. titanium and vanadium and base metals such as aluminium and iron (as mentioned above).[198] Extracting the rare-earth elements from the aluminium of Greece's annual bauxite residue production alone can, in theory meet the needs of approximately 10% of the European rare-earth elements demand[199], implying that recovery of rare-earth elements from total bauxite residue in the EU could cover most of European demand.

A novel EAF technology, Advanced Mineral Recovery Technology (AMRT), can smelt red mud (the waste product from alumina production (Bayer process)) without any pre-treatment, producing pig iron and viscous slag suitable for industrial mineral wool. In total, the new proposed process for complete bauxite exploitation (for alumina, pig iron and mineral wool production) could increase the exergy efficiency from 3% in the conventional Bayer

196 EU MSCA-ETN REDMUD, 2018
197 E.g. Scandium, Yttrium, Lanthanum and Neodymium
198 Rivera et. al., 2019
199 EU MSCA-ETN REDMUD, 2018

Process to 9-13 %. It's TRL is estimated to be 7.[200] More importantly, the process converts a hazardous waste into two viable co-products, also preventing accidental discharge into the environment (e.g. rivers/ marine or ground water). This technology would also offer a solution for cleaning-up legacy red-mud.[201]

Other technologies in development to treat red mud with the goal to extract valuable materials and metals include[202]:

- Leaching of rare earth elements from red mud (TRL 5)
- Recovery of titanium dioxide and aluminium oxide through microwave roasting of bauxite residue and inorganic cement binder production (TRL 4)
- Scandium extraction from bauxite residue (TRL 7)
- Inorganic polymers from bauxite residue (TRL 6)
- Production of iron alloy (TRL 6)

Enhanced metals recovery from low grade ores, (landfilled) sludges and slags

Next to the recovery of valuable metals and other products from bauxite residue, waste streams from other non-ferrous mining and production can result in large quantities of additional metals production in the EU. The combination of enhanced metals recovery from low-grade ores (e.g. laterite), fine grained landfilled sludges, iron rich sludges from metals production (e.g. Jarosite sludge from zinc production[203]) and fayalitic slag (mostly from primary and secondary copper production) can bring about the following additional annual metals production in the EU[204]:

- +129,000 t Zinc
- +49,000 t lead
- +38,000 t nickel
- +36,000 t chromium
- +27,000 t copper
- +1,400 t cobalt (13% of current EU demand)
- +225 t antimony (28% of current EU demand)), +78 t gallium (29% of current EU demand), +58 t indium (77% of current EU demand) and +31 t germanium (15% of current EU demand)

200 Ibidem (EN EX AL project, FP7/2010-2014 estimates TRL 7)
201 Fraunhofer ISI, 2019
202 EU MSCA-ETN REDMUD, 2018
203 Jarosite contains for example: Fe ~15 wt-%, Zn 2-3 wt-%, Pb 3 wt-% Ag, In, Ga, Ge in ppm levels and Au less than 1 ppm.
204 The sources considered here are: Polish laterite, Greek laterite, Fe-Ni slag, landfilled Cr-rich sludge, Jarosite, landfilled Zn-rich sludge, Goethite, fayalitic slag, steel sludge and automotive shredder residue. METGROW+, N.D.,

The total estimate market value of these taround EUR 2.9 Bn per year.

With current technologies and new pyrometallurgical methods, the recovery of additional metals from residues requires energy intensive smelting and fuming processes. Furthermore, these processes will have to avoid direct (and indirect) CO_2 emissions.[205] Indirect emissions can be avoided by using more carbon-free electricity. In addition, process emissions will be released in the fuming of metals from the waste streams due to the use of reducing agents such as coal. The slag obtained after fuming can be used in other industries (e.g. as construction material), in particular if environmentally hazardous substances such as arsenic have been removed. This would limit or avoid landfilling. Avoiding or reducing CO_2 emissions in fuming and smelting processes would require technologies and techniques as mentioned before. For instance, the use of bio-based fuels and/or reducing agents, hydrogen and/or CC(U)S. However, investment costs can be large and higher operational expenditure might hamper large-scale application.

Other new technologies that can help bring about a higher recovery rate of the above-mentioned metals from low-grade ore and waste streams include[206]

- Atmospheric acid leaching (TRL 3-4, TRL 2 for ferro-nickel slag)[207]
- Heap leaching (TRL 3-4, TRL 2-3 for ferro-nickel slag)[208]
- Autotrophic bioleaching (TRL 2-3)[209]
- Heterotrophic bioleaching (TRL 2)[210]
- Solvometallurgical leaching (TRL 2-4)[211]
- Ionometallurgical exctraction (TRL 3-4)[212]
- Plasma-pyro technology (TRL 3-4)[213]

Most of the above-mentioned technological option are still at low TRL and will require further research and investments to allow up-scaling to pilot and demonstration stages.

205 Salminen J. and Olaussen S., 2018
206 Metgrow+, 2018
207 Atmospheric acid leaching refers to hydrometallurgical processes that utilize non-pressurized, stirred reactor applications with temperatures <100°C. For application to laterite ores and ferro-nickel slag
208 Heap leaching is a controlled process whereby a complex or low-grade ore is stacked in short lifts, usually crushed and often agglomerated on a carefully prepared containment system (the leach pad) and irrigated in a controlled manner with a solution to extract the optimum amount of metal from the material. For application to laterite ores, ferro-nickel slag, landfilled chromium-rich sludge, jarosite, landfilled zinc-rich sludge and Goethite
209 Autotrophic oxidative and reductive bioleaching refers to bio-hydrometallurgical methods, which rely on bacterial activity to oxidize/reduce different sulfur and iron species. This results in production of leaching agent (sulfuric acid), oxidant (ferric iron), or reduction of iron enabling enhanced leaching of certain oxidized minerals. For application to laterite ores, Jarosite, landfilled zinc-rich sludges, goethite, fayalitic slags
210 Heterotrophic bioleaching involves the production of diverse biogenic lixiviants via microbial (yeast, fungi and bacteria) respiration using organic carbon. For application to landfilled chromium-rich sludge, jarosite, landfilled zinc-rich sludge, fayalitic slag, steel sludge and automotive shredder residue
211 Solvometallurgical leaching consists of applying organic liquids (solvents, extractants, organic acids, modifiers, ...) to extract metals from a solid source. The aim is to reduce the volume of the aqueous phase (<50 %) compared to conventional leaching. For application to laterite ores, jarosite, landfilled chromium and zinc-rich sludge, Ggoethite and steel sludge.
212 Solvent leaching using Deep Eutectic Solvents (DESs), which are eutectic mixtures of Lewis or Brønsted acids and bases. For application to laterite ores, Jarosite, landfilled zinc-rich sludge, fayalitic slag and steel sludge.
213 A pyrometallurgical route to pre-concentrate different type of materials. For application to jarosite, landfilled zinc-rich sludge, goethite and fayalitic slag.

Furthermore, it will be an R&D challenge to get higher metal extraction rates for some processes and achieve high levels of selective recovery.

Recovery of metals from waste electrical and electronic equipment (WEEE)

Waste from electrical and electronic equipment (WEEE) contains considerable quantities of valuable metals such as base metals (e.g. copper), precious metals and rare earth elements. Current state of the art of WEEE recycling is limited to pyrometallurgical, and to a smaller extent, hydrometallurgical approaches. Currently, a number of smelting facilities, historically primary ore smelters, also process WEEE for metal recovery. Pyrometallurgical metal recovery from WEEE happens through incinerating the waste material in furnaces.[214] This process can be followed by (copper) leaching and electrowinning.[215] The pyrometallurgical process is capital-intensive and is CO_2-intensive due to the high carbon content of some of the waste.

Emissions from burning of the WEEE in the process to recover metals can be reduced through the use of pyrolytic processes (i.e. heating in the absence of oxygen).[216] This results in pyrolytic gas, oil and solid carbon residues. The pyrolytic gas (and oil) can be used as fuel in the process so no or limited additional fuels would be required. The solid carbon residue can be used as additive to construction materials or used as a reducing agent in pyrometallurgical processes.

A full hydrometallurgical process in which shredded WEEE is not incinerated but dissolved in an acidic solution followed by metal recovery through electro-disposition can have a lower energy and CO_2 footprint. Research at Imperial College London has demonstrated the feasibility of removing a high percentage of both the hazardous and valuable metals from electronic scrap, at low cost.[217]

Finally, advances in bio-leaching (bacterial-based leaching of metals) could further reduce the costs of recovering gold, silver, copper and platinum from printed circuit boards found in electrical and electronic waste. A new two-stage bioleaching process is currently being researched in the EU. This new solution is expected to reduce energy consumption and processing costs in comparison to other treatment processes (pyrometallurgy, hydrometallurgy, one-step bioleaching). It will also make use of available waste from other industries (food and animal feed) as an additional nutrient-booster for microorganisms.[218] The goal is to come to a 50% reduction in metal recovery costs as compared to hydrometallurgical processes (and 35-40% compared to one-step bioleaching) and to 75-100% of metal recovered, including a fourfold increasing in the amount of gold recovered. The process would also emit 8% less CO_2 as compared to hydrometallurgical processes.

214 Isildar, A., 2018
215 Umicore
216 Ecocarbon
217 Cheng, et al.. N.D.,. Estimated electrical energy cost of recovering metals from solution is about 250 GBP per tonne of scrap with a metal value of over 2000 GBP per tonne of scrap.
218 The LIFE BIOTAWEE project (running from July 2018 to December 2020)

Improved sorting and recovery of scrap

Metals scrap comes in a variety of different grades and quality (as well as impurities), which act as a major cost barrier. Economic scrap collection and sorting is key. Physical sorting of scrap metal is more economical than melt refining technology.

The most recent new technologies for economic aluminium[219] sorting include eddy current, sink-float, and more recently sensor-based sorting as well as, colour etching then sorting and laser induced breakdown spectroscopy (LIBS). Currently, the latter option appears to be the most promising high volume/ high speed process; it is currently at demonstration stage. Specifically, for end-of-life-vehicles, in today's modern plants, 95% of the aluminium in an end-of-life-vehicle is successfully and profitably reused or recycled into new aluminium products substituting primary aluminium.[220] [221]

Other research and development initiatives for higher and better-quality scrap recovery include adjustable magnetic fields and X-rays. The University of Utah is developing a light metal sorting system that can distinguish multiple grades of scrap metal using an adjustable and varying magnetic field. Current sorting technologies based on permanent magnets can only separate light metals from iron-based metals and tend to be inefficient and expensive. The new sorting technology uses an adjustable magnetic field rather than a permanent magnet to automate scrap sorting, which could offer increased accuracy, less energy consumption, lower CO_2 emissions, and reduced costs. Due to the flexibility of this design, the system could be set to sort for any one metal at a time rather than being limited to sorting for a specific metal. Similarly, a US company[222] is developing a sorting technology that uses X-rays to distinguish between high-value metal alloys found in the scrap of many shapes and sizes. Existing identification technologies rely on manual sorting of light metals, which can be inaccurate and slow. The system will rapidly sort scrap metal passed over a conveyer belt, making it possible to lower metals waste while simultaneously increasing the quality of recycled metal alloys. By analyzing the light emitted from X-rayed metal pieces, the probe is able to identify alloy compositions for automated sorting. Automating this process would significantly reduce the costs associated with recycling light metal scrap.[223]

219 Secondary aluminium production uses far less energy than primary aluminium production process (the electricity use per tonne aluminium produced is 0.12-0.34 MWh/t compared to around 14-16 MWh for primary, which is around 5% of the energy use from primary production. Around half of the aluminium produced in Europe originates from recycled materials, with recycling levels of 90-95 percent for end-of-life vehicles and building parts and over 73 percent for beverage cans. For all these reasons, aluminium is a key material for the Circular Economy, with an enormous decarbonization potential stemming from its circular properties. Source: European Aluminium
220 European Aluminium, 2019
221 Fraunhofer ISI, 2019
222 UHV Technologies
223 ARPA-E, N.D.,a and ARPA-E, N.D.,b

Distributed ledger technology (blockchain) to improve traceability

Distributed ledger technologies such as blockchain might find their way into metals production, specifically with the goal to improve traceability and hence recovery of metals during the production and lifecycle. In theory, this technology would allow the tracking of metals during their production process, their application in intermediate and final products and at the scrapping phase.[224] Distributed ledger technology can also be an instrument that allows adding verified environmental performance indicators' information to metals used in the value chain. This would allow customers of non-ferrous metals to have verified and reliable information on e.g. the GHG intensity of the metals used. It can hence become a valuable instrument in case performance standards are introduced on the materials used in final products (e.g. cars). Such robust and verifiable standards might also allow the introduction of for example a 'green' premium at metals exchanges.

6.10 Sector coupling: demand response and waste heat usage outside of non-ferrous metals production

Finally, there are important actions that could be (further) taken by non-ferrous metals producers that do not impact the direct or indirect emissions of metals production but assist other sectors to reduce energy use and/or GHG emissions.

Demand response – ancillary grid services

Many electro-intensive metals producers already participate in ancillary services to the power grid (e.g. grid stabilisation and peak attenuation), by e.g. allowing for (temporary) interruption of power supply or participation in demand response. Competitive services are already being provided in countries including France, Belgium, Netherlands and Germany. With higher levels of variable (renewable) energy to be produced in the EU, it is expected that these ancillary markets will become more important. Non-ferrous metal production has a significant potential to offer higher levels of demand response to the European power market. This is in particular the case for primary aluminium, zinc and copper production.

A key enabling technology to apply demand response on large scale is automated process management systems.

Next to the technology challenge of ensuring that processes keep running smoothly under reduced loads, the main issue is that viable business models are created for non-ferrous metals producers to allow for maximum participation in ancillary markets and are not penalised (via TSO grid fees) if their load profile becomes more variable.

224 This technology is being pioneered in steel production through the 'SteelTrace' platform. SteelTrace is a blockchain based platform for all companies, from steel production to installer to end client, that enables traceability of steel quality via the first true digital certificate. The SteelTrace platform enables data storage in an unchangeable format, exchange of ownership of certificate instead of sending copies, traceable ownership to the original source and data storage so that machines can understand the certificates content.

BOX 10: TRIMET virtual battery pilot

A €36 million investment by TRIMET into a 'showcase' pilot plant is demonstrating this potential. TRIMET Aluminium allows one of its pot-rooms in its Essen plant to operate as an energy storage or 'virtual battery'. Its output can vary by +/- 25 percent, based on a nominal load of 90 MW, providing a virtual storage capacity of approximately 2,100 megawatt hours (MWh). This is comparable to a medium-sized pumped-storage power plant. By balancing grid fluctuations, this power-storing capability allows variable renewable energy sources, including wind and solar energy, to be fed into the German power grid. To ensure flexible control of its electrolysis cells, TRIMET Aluminium has developed a process technology that maintains a constant energy balance within the cell, even with a fluctuating energy supply. Fully implemented, the three TRIMET smelters in Germany (located in North Rhine-Westphalia and Hamburg) could increase the country's pumped storage capacity - currently 40 gigawatt hours (GWh) - by nearly 40 percent.[225]

225 European Aluminium, 2018b

BOX 11: Zinc smelter virtual battery[226]

The electrolysis section of zinc smelters can be switched down to a holding pattern at short notice. This service is currently commercialized as emergency switch-off capacity. European zinc smelters are typically bottlenecked on their electrolysis plants, as a result any reduction in power means a reduction in production. Therefore, the zinc smelters incur high costs when decreasing power since the production of zinc is lost. By investing in additional cell house and intermediate storage capacity this service can be supplied at a very low operational cost and without zinc capacity loss. The Investment lies in line with investments for pumped-storage power plant.[227]

Specific investments depend on specific plant set-up, availability of surplus power supply to the plant and desired up-time/down-time profile. A 300kt/y zinc smelter could thus provide a flexibility of up to 80 MW power and around 3500 MWh energy storage. Technologically this is feasible with current technology. As an example: the Nyrstar Budel smelter has from November 2008 till July 2009 voluntarily reduced production and during that period has run on an off-peak regime where the smelter operated at full power during weekends and nights and a holding power the rest of the time to mitigate to some extent the lost income from reduced production.[228]

Waste heat to other sectors

While waste heat recovery is important to improve the energy-efficiency of metals production itself, there is (limited) potential for low-temperature heat which has no direct application in metals production to be used by other sectors (e.g. buildings). This will only be possible if nearby demand is present. Furthermore, investments in e.g. district heating require significant capital costs which will have to be carried by other sectors. Finally, long-term and transparent contracts will need to be established to create a viable business model for non-ferrous metals producers.

226 Nyrstar
227 Reference for pumped power station from Nikolaides and Poullikas, 2017
228 Nyrstar, 2009

BOX 12: Aurubis Hamburg district heating

In 201,8 Aurubis started with the delivery of industrial waste heat to the energy supply in the Hamburg district of Hafencity East. The partnership between Aurubis and the district sees industrial waste heat from the copper plant in Hamburg providing energy-efficient district heating to Hafencity East. For this purpose, Aurubis extracts heat that is formed when sulfur dioxide – a by-product of copper smelting – is converted to sulfuric acid. This industrial waste heat is nearly free of CO_2 and utilising it will, over time, reduce CO_2 emissions by more than 20,000 t per year. About half of this reduction results from the replacement of natural gas used to produce steam on the Aurubis plant premises, while the other half is saved by delivering the waste heat to the district. Aurubis will deliver the heat to its plant boundaries. Enercity, a local energy provider, will collect the heat, secure it and transport it further to the area that will use it.[229]

229 Aurubis, 2017

BOX 13: Boliden sectoral symbiosis in Western Finland

Boliden is capturing excess heat and supplying it to district heating networsk in large quantities. The Kokkola Industrial Park (KIP) in western Finland is one of best examples in Europe of how industrial synergies developed since the 1960s contribute to a circular economy – originally based on meeting practical needs and reducing costs. The companies located in the KIP are intrinsically linked with one another, with many synergies based on material and resource flows in closed systems. Excess heat and steam from the Boliden Kokkola zinc smelter are used to generate municipal district heating and electricity. Sulphuric acid produced at Boliden's sulphuric acid plant is used as a raw material by other companies in the KIP. Boliden sells the steam it produces in the zinc roasting process to the municipal energy company that generates electricity from the steam. In 2017, 320,000 MWh of steam from Boliden was used to produce electricity, district heating and low-pressure steam for industrial partners in KIP and local households. In 2017, around 125,000 MWh of heat from the sulphuric acid plant was delivered to the municipal heating plant, which is enough to heat approximately 6,000 homes as well as some buildings in the industrial park.[230]

230 Boliden, N.D.,

6.11 Other technology breakthroughs enabled by NFM

Metals will continue to play an important role in other technologies (e.g. batteries, CCU) that will be crucial for achieving a climate neutral economy. Some examples of metals related innovations in other technologies are given below.

Molten metal batteries

Liquid metal batteries were born from the practice of electrochemical aluminium smelting (electricity in, aluminium from oxide out), but operating in reverse. Electrons come from the lighter metal on top, where the corresponding ions are travelling downwards through the electrolyte in order to recombine with the electrons at the boundary of the heavier liquid metal at the bottom. For the rest, no mixing takes places and the three layers remain separate. During discharge the top layer gets thinner and bottom layer thicker, during charging this process reverses. Degrading of the system is nearly absent.[231]

Thermally regenerative batteries

Copper could be used in new fashions to reduce the global energy footprint. Large amounts of low-grade waste heat (<130°C) are currently released during many industrial, geothermal and solar-based processes. Thermally regenerative batteries (TRBs) can convert this waste heat into electrical power. Thermally regenerative ammonia-based batteries (TRABs) as well as acetonitrile-based batteries, based on copper electrodes, have been developed to produce electrical current from the formation of copper-ammonia or copper-acetonitrile complex, using waste heat to regenerate the process.[232, 233]

The new TRAB technology can be applied to convert low-grade waste heat, which cannot be used for any other application, into power. The process increases the efficiency of the manufacturing industry and reduces its carbon emissions.

It is estimated that in Europe alone, TRAB technology could generate about 6 TWh of electricity per annum. This is comparable to the electricity generated by solar panels in Europe in 2010 or almost 10% of the electricity use of the non-ferrous metals sector in 2017.

Metals based flow batteries

Redox flow batteries (RFBs) are a type of electrochemical energy storage device. This means they store electrical energy in chemical form and subsequently dispense this energy in electrical form via a spontaneous reverse redox reaction of dissolved ions in positive and negative electrolytes. These electrolytes are collected in external tanks and pumped into a power module for charge and discharge. The concept is modular and highly scalable.

231 Ambri
232 Fraunhofer ISI, 2019
233 CUBES

Aalto University is developing an RFB based on the electrochemistry of copper. This battery would be more cost-effective and scalable than state-of-the-art vanadium RFBs. The initial feasibility of the concept has been demonstrated, and the basic principles patented in Finland by Aalto University. Laboratory-scale multicell prototype stacks were designed and operated in a nationally funded project in 2016. Electrochemical efficiency of 70% has been achieved in prototype systems that have been operated for over 1000 hours. Cost projections indicate the possibility of reaching a price of EUR 150/kWh at relatively low production volumes of below 1 GWh/year.[234]

A similar innovation is pursued via zinc-based air flow batteries. The fuel for the system is zinc and air. Because the air component of the fuel is obtained from the atmosphere and does not need to be stored within the system, the solution is very compact. The power (kW) and energy (kWh) can be scaled separately to service different applications. Zinc as an anode fuel has an advantage over other metals due to its unique set of attributes, which include a low equilibrium potential with respect to hydrogen, electrochemical reversibility, stability in aqueous electrolytes, high specific energy, high volumetric energy density, abundance, low cost, environmental compatibility, and ease of storage and handling.[235]

New, less cobalt intense chemistry for Lithium Ion batteries (NMC811)

Nickel Manganese Cobalt (NMC) cathodes have become mainstream inside Lithium ion batteries (e.g. used in most electric vehicles). Industry has been improving NMC technology by steadily increasing the nickel content in each cathode generation (e.g. NMC 433 (40% Ni, 30% Mn, 30% Co), NMC 532, or the most recent NMC 622). The cells have higher capacity and lower weight, which means the battery packs store more energy and have better driving range.[236] The next generation of cathodes will be NMC 811, a cathode composition with 80% nickel, 10% manganese, and 10% cobalt and is expected to be introduced over the next years.[237]

Metal Organic Frameworks (MOFs) – advanced catalysis with metals

Metal-organic frameworks (MOFs) are highly crystalline porous architectures built up of inorganic metal nodes connected via organic building units. The enormous variability in both the organic and the inorganic moiety makes these hybrid structures highly tuneable towards a large number of applications. For example, mixed-metal MOFs can be used as gas adsorbing and separating materials. This technology can become highly relevant for carbon capture and utilization (CCU) as it shows promise in producing cost-efficient fuels from CO_2.[238]

234 Ibidem
235 Zin8 energy solutions
236 Researchinterfaces, 2018
237 Arcus, .C., 2018
238 Energy Post – Stanford University, 2019 and Service. R.F., 2019

6.12 Conclusions

There is a theoretical potential for the non-ferrous metals industry as a whole to reduce (direct + indirect) GHG emissions beyond 90% compared to 1990 levels.

The most important mitigation will come from the decarbonisation of EU power production, which alone would reduce total emissions from non-ferrous metals production by 81% compared to 1990. Further innovations such as the use of inert anodes in aluminium production, electrification of smelters (e.g. move to hydrometallurgical and electrified pyrometallurgical processes), fuel-shifts to lower emitting or bio-based inputs, the use of non-carbon reducing agents in smelting, higher efficiency in furnaces and better process management systems (including digitisation) can lead to further important GHG reductions.

Important innovations will also be required in order to allow for efficient and climate friendly recovery (incl. of metals in residues) and recycling of metals given that more and more difficult-to-recycle secondary materials will have to be processed in the future.

Non-ferrous metals innovations will also help other sectors to decarbonise faster e.g. by using waste heat from metals production or by higher levels of power demand response.

However, there are important conditions for the above-mentioned transitions to take place:

- Decarbonisation of EU power production happens outside of the non-ferrous metals industry and can have a negative impact on the competitiveness of metals production through e.g. pass through of additional cost associated with deployment of higher levels of renewables and storage. Non-ferrous metals on the other hand can facilitate the transition to higher levels of variable renewable energy by maximising their load flexibility in production. This will require a market environment that allows such business models to be profitable and must avoid additional grid fees for producers that offer (more) variable loads.
- Major breakthroughs in primary aluminium production (e.g. inert anodes) can have significant impact on emissions and energy use in aluminium production (and by extension for the whole NFM sector). Important R&D is also taking place outside of Europe. Due to the important potential it is important to further focus and extend R&D and support for pilot and demonstration of these technologies in Europe.
- Some technologies are promising but not yet commercial or applied at industrial scale. In particular, the use of inert anodes in primary aluminium production, CC(U)S and hydrogen as a reducing agent. It will require dedicated and long-term R&D investments. Scaling up R&D to pilot and demonstration plants is both capital- and risk-intensive. Therefore, specific innovation support (e.g. Enova, EU ETS innovation fund) will be required to enable upscaling of R&D.

- Furthermore, cooperation with other sectors will be necessary in order to make some options available for the metals industry (e.g. hydrogen, CCS). Through cooperation with other larger industries the non-ferrous metals industry would be able to benefit from economies of scale and infrastructure for these technologies.
- It is not clear if all new technologies will be economically competitive, for instance, the use of hydrogen or electrification of heating processes might at present not be competitive with e.g. the use of natural gas or other carbon carriers as reducing agents.
- Large CAPEX will be required for major investments in new processes. To enable companies to make these investments, a positive investment climate will be required to ensure that companies see (long-term) value in making these investments.
- Location will an important factor in the deployment of certain options, in particular for access to new input materials (e.g. biomass) or for symbiosis with other companies and sectors. Hence, the application of some technology option will depend on the location of the plant.
- Last but not least, there is a very large potential for enhanced recovery of base metals, rare earth metals and other by-products from primary and secondary production, waste streams and post-consumer scrap. Enabling this recovery could reduce Europe's import dependency significantly. However, the technologies used for enhanced recovery must both be economical and not lead to emissions of GHGs. Advances in hydrometallurgy show promise of both - economical extraction with low CO_2 footprint.

Technology options	Description - impact	Enabling conditions	Relevance
Decarbonisation EU power	Large impact for non-ferrous metals industry. Can bring total (direct + indirect) emissions down by 81% ref. 1990.	This evolution will happen outside of non-ferrous metals industry. Transition to low-carbon electricity will have to go with affordable and secure electricity. Non-ferrous metals can help by higher levels of demand response/ancillary grid services.	All metals +++
Energy efficiency	Important energy savings are possible mostly related to digitisation and automated process management and efficiency in furnaces.	Not all energy savings technologies are compatible with new breakthrough technologies. Favourable investment climate required for continuous investments.	All metals +++
Anode technology aluminium	Innovation in electrolysis process can bring further efficiency gains of up to 20%. Inert anode technology can eliminate direct emissions while reducing energy use.	Major R&D effort needed, including support for pilot and demonstration. Investments can be capital intensive but likely with lower operational costs.	Al +++
Further Electrification	Further electrification of pyrometallurgical processes and/or shift to hydrometallurgical processes in some smelting processes. Electrification (heat) in downstream processes.	High temperature electrification might not yet be mature or too expensive compared to natural gas-based heating. Shift to hydrometallurgical processes can be limited and will most likely be applied in secondary and waste streams	Cu, Zn, Pb, Ni Al (& downstream all metals) +++
Fuel shift - bio-based	Fuel shift from fuels/coal to gas has occurred in non-ferrous metals industry where possible. Further shifts to natural gas and bio-feed are possible. Can be relevant for recovery of metals from smelting slag or leaching residues	Fuel shift must be economically viable and bio-based fuels must meet required quality.	Cu, Ni, Pb, Zn (ISF), Ferro-alloys, Si +++
Non-carbon reducing agents/ hydrogen	Can be relevant for some pyro smelting processes (e.g. copper). Limited application of H_2 in ferro-alloys. Can be relevant for recovery of metals from smelting slag or leaching residues	Will depend on economic development of H_2 production by other sectors and available infrastructure. Smelters already requiring a lot of O_2 might have better business case for use of H_2 via electrolysis, which has O_2 as a by-product.	Cu, Zn (ISF), Pb, Si ++
CC(U)S	Due to relative low level of GHG emissions compared to e.g. steel, chemicals and cement not priority for non-ferrous metals but can be linked to other sectors when technology is ready. Can become important for silicon and alloys production.	Will depend on capture, transport and storage technology and infrastructure developed by other larger industries.	Ferro-alloys, Si, Zn (ISF), Cu ++
Higher metals recovery (residues, slag and scrap)	New technologies (mostly hydrometallurgical but also new pyro) can enable recovery of high amount of metals (incl. precious and rare) from waste and secondary streams. Important potential for improvements. Greenhouse gas impact can be limited (over-all) but important environmental and economic co-benefits possible.	Further R&D support needed including scaling up to pilot and demonstration stage. Can be regulatory conflict with regulations on waste and hazardous materials.	Cu, Zn, Ferro-alloys, Ni, Pb Alunina +++
Sector coupling: demand response and waste heat	Important potential by non-ferrous metals for increased demand response services. Waste heat recovery by e.g. buildings sector can help reduce emissions there	Market conditions need to be favourable. More variable load profiles cannot be punished with higher grid tariffs.	Al, Cu, Zn, Ni, Pb, Si, Ferro-alloys +++

Table 7: Summary of technology options for GHG reductions in the non-ferrous metals industry

+++ Important technology options often with significant mitigation potential
++ Options with possible significant mitigation potential but can be difficult for the non-ferrous metals industry to apply on its own, e.g. requiring cooperation with other larger industries

Non-ferrous metals, a bellwether industry: challenges for non-ferrous metals production on the pathway to EU climate neutrality

7 Non-ferrous metals, a bellwether industry: challenges for non-ferrous metals production on the pathway to EU climate neutrality

7.1 Introduction: the pitfalls of a frontrunner industry

The non-ferrous metals industry can be seen as a frontrunner or bellwether industry within the overall industrial and materials transition to a climate neutral society.

First of all, non-ferrous metals production is already highly electro-intensive. It is expected that other major materials industries such as steel and chemicals will become highly electrified on the path to climate neutrality (e.g. through the electrification of heat, more use of electrochemistry and higher use of hydrogen).[239]

Secondly, non-ferrous metals are a frontrunner when it comes to circularity with very high recovery rates and a large part of the industry has established business models around the recovery of metals. Other materials and energy intensive sectors, in particular petrochemicals, cement and concrete, will have to embrace much higher levels of (high quality) circular use of materials (e.g. chemical recycling of polymers) to be able to reach deep GHG mitigation.

Thirdly, it is beyond doubt that non-ferrous metals are and will be critical for the value chains that will shape Europe's transition to a climate neutral economy. Batteries, wind- and solar energy, new transport systems, further digitisation and the electrification of other sectors and industries in general will hugely depend on the availability of all types of non-ferrous metals.

The non-ferrous metals industry has embraced industrial and sectoral symbiosis by striking better synergies between metals producers or across the value chain (to enhance recovery of metals), by delivering important by-products to other industries and by starting to integrate energy systems with other sectors (such as the buildings sector) where possible.

The industry has also been at the forefront of globalisation. Amongst the basic materials produced, it is the only industry that sees consolidated global price setting for most of its products, with the LME being a crucial pricing instrument.

Being at the forefront of a major transition also implies that the sector is amongst the first to feel possible negative side-effect, in particular, the collision between being price-takers in a global market on the one hand and on the other hand local or regional factors that have an important impact on production costs. Foremost, for an electro-intensive industry, there are the local and regional electricity price developments including cost increases due to regulatory or other interventions. Moving forward, with the transition to a climate neutral electricity system, it is possible that the exposure of non-ferrous metals producers will further increase. Furthermore, higher electricity prices might stall investments in electrification in other major materials industries and hence the over-all transition to a climate neutral economy.

Secondly, while metals are trade globally or at globally consolidated prices, this does not mean all metals are produced equally. There is strong evidence for major state-aid interventions (e.g. bailing out production over-capacity) and support (e.g. subsidies) in metals production outside of the EU, in particular in China. While this does not necessarily imply higher imports into Europe, it will depress global metals prices and the possibility for European metals producers to compete on a level playing field

7.2 Electro-intensive processes: local power pricing versus global metal markets

This section discusses the electro-intensity of EU non-ferrous metals production and its impact on production costs in comparison to other energy intensive industries as well as metals production in major producers outside of the EU. This is followed by relation between the economic sensitivity of metals production to rising electricity prices (e.g. due to regulatory costs) and the impact on economic performance and competitiveness.

Electro-intensity of metals vis-à-vis other energy intensive materials

Amongst the non-ferrous metals, aluminium is the largest consumer of electricity (63 TWh in EU28 + EFTA and 31.5 TWh in EU28) followed by Zinc (9 TWh in EU28 + Norway), Copper (4 TWh in EU28) and Nickel (0.6 TWh EU28 + Norway).[240]

At the level of electricity consumption per tonne of metal, (primary) aluminium is the most electro-intense (15.4 MWh/t) followed by silicon (12.4 MWh/t), ferro-silicon (8.9 MWh/t), nickel (5.3 MWh/t), zinc (3.9 MWh/t) and copper (1.5 MWh/t). Compared to other energy intensive industries' production processes, non-ferrous metals production electro-intensity is clearly higher, with the exception of chlorine production.

239 Wyns, Khandekar & Robson, 2018

240 Source: European Aluminium, International Zinc Association Europe and the Nickel Institute. Aluminium EU electricity use data estimated using EU production figures. Copper: assuming 1.5 MWh/t electricity use and 2.73 Mt copper production in 2015.

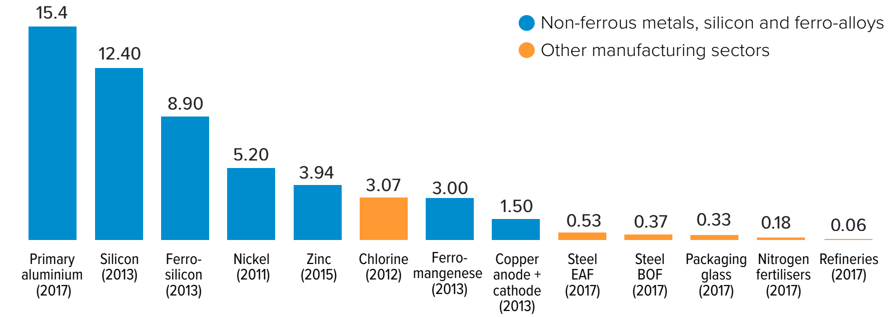


Figure 36: Average electricity use per tonne metal (MWh/t)[241]

When it comes to electricity costs as a percentage of total production costs, again, non-ferrous metals show a high share. For zinc these costs are 38.5%, for primary aluminium 38.3%, for silicon 35% and for copper 21% and nickel 19%. This is significantly higher than most other energy intensive materials with the exception of chlorine production.

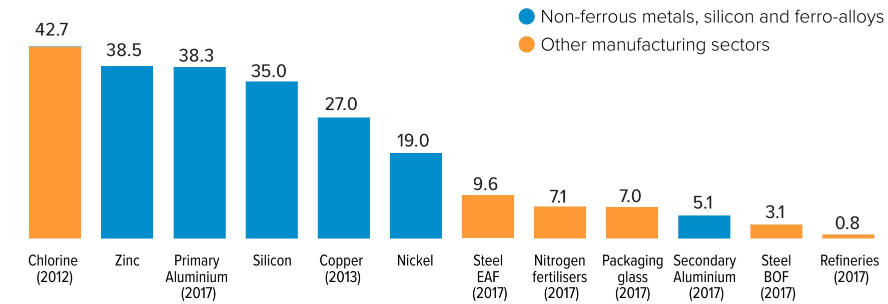


Figure 37: Electricity costs as % of total production costs[242]

EU base metals production costs and productivity compared to other large producers around the world

As shown in chapter 4, metals prices are set globally via metals exchanges. Therefore, comparing the production costs and productivity of metals production in the EU is relevant, in particular given the high share of electricity cost in total production costs.

For primary aluminium, the EU's production costs are higher, with exception of China. This does not however take into account state support given to aluminium production in China (see Chapter 7.3.) which enables Chinese firms to sell their metal at much lower prices than EU smelters, despite higher 'nominal' production costs. The extremely low aluminium production costs in Kazakhstan are explained by a combination of favourable factors such as low electricity prices, low cost of raw material (alumina comes from its own alumina refinery) and low labour costs. The low electricity prices in Iceland and Russia are due to the hydroelectric origin of the power consumed and explain much of their cost advantage compared to the production costs in the EU, in which the energy costs account for around 40 % of total production costs. In Norway, which also has a large share of hydropower production, electricity prices are higher due to linkage with the EU (Nordic and continental electricity) market, including the indirect CO_2 costs which are passed through via marginal (fossil fuel-based) power production plants.[243]

Production costs of zinc and copper show that the EU can still offer competitively priced metals even if electricity and labour costs are often higher compared to other countries. In the case of copper smelters, the EU has similar production costs to South American countries, which are the leaders in producing copper. China is still benefiting from low labour costs.[244]

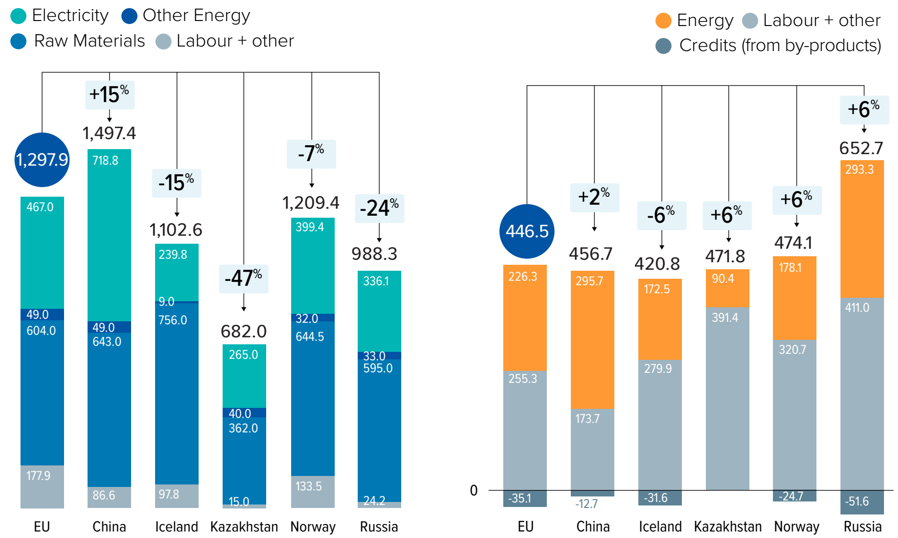


Figure 38: (left) Production costs EUR/t cast aluminium (2013) (right) Production costs EUR/t zinc slab (2013) (Source:JRC, 2016)

241 Sources: Aluminium, steel, packaging glass, nitrogen fertilisers and refineries (CEPS, ECOFYS, 2018); chlorine (CEPS, 2014); Silicon, Ferro-silicon and ferro-manganese (Euroalliages); Zinc (International Zinc Association – Europe); Nickel (Nickel Institute); Copper figure as sum of anode and cathode production (JRC, 2016).

242 Sources: Aluminium, steel, packaging glass, nitrogen fertilisers and refineries (CEPS & ECOFYS, 2018); chlorine (CEPS, 2014); Silicon, (Euroalliages); Zinc, assuming 40% energy costs and electricity representing 96% of total energy use (International Zinc Association – Europe); Nickel, 19% energy costs in total production and assuming electricity costs are almost total energy costs (Ecorys, 2011); Copper figure as sum of anode and cathode production deduced from data in JRC, 2016. For copper it is important to note that the JRC, 2016 figures are not representative of the complexity and diversity of EU copper productions. They exclude the secondary production disregarding the variability in energy and cost in the copper industry. The copper sector is heterogeneous. The energy/electricity consumption varies significantly depending on the scale of operation, complexity of raw materials, production routes/technologies and process configuration.

243 JRC, 2016

244 Ibidem

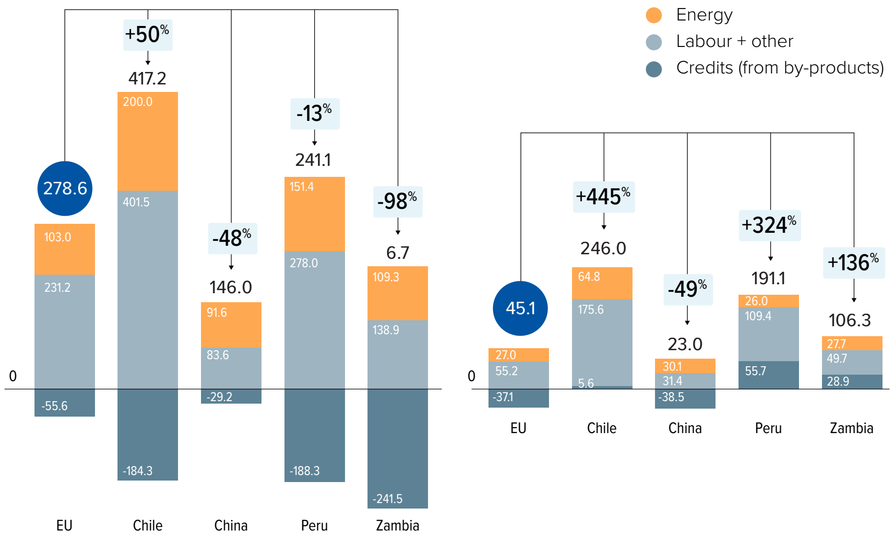


Figure 39: (left) Production costs EUR/t copper anode (2013) (right) Production costs EUR/t copper cathode (2013) (Source:JRC, 2016)

The EU's competitive pricing can be explained by the high productivity of metals production in the EU, in particular the high level of energy efficiency visible as the MWh/t metal required.

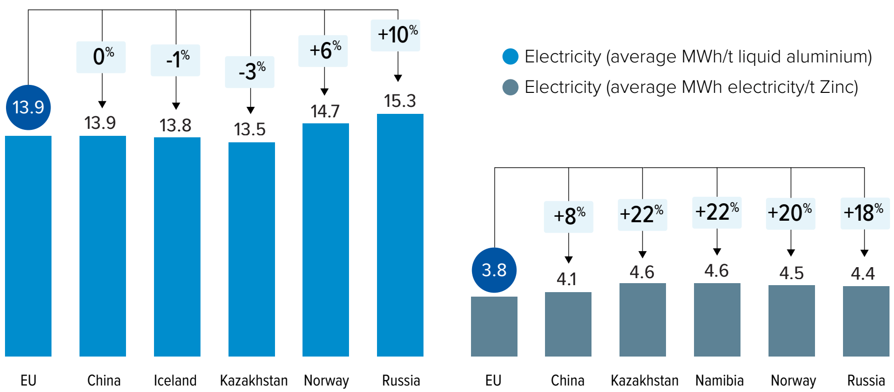


Figure 40: (left) electricity use per tonne liquid aluminium (MWh/t) (2013) (right) electricity use per tonne zinc (MWh/t) (2013) (Source:JRC, 2016)

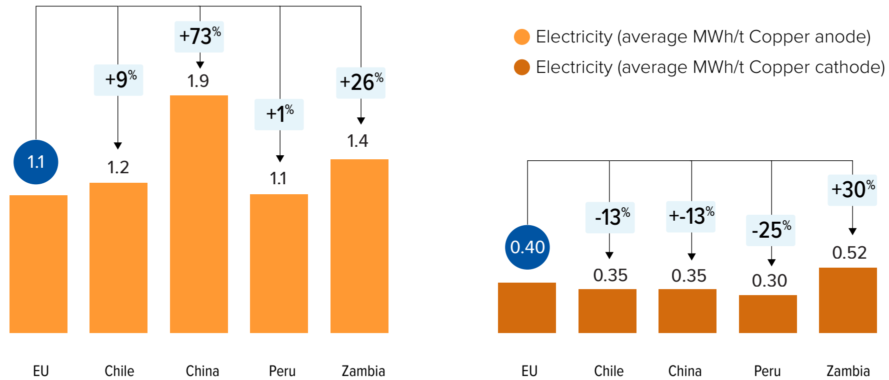


Figure 41: (left) Electricity use per tonne copper anode (MWh/t) (2013) (right) electricity use per tonne copper cathode (MWh/t)(2013) (Source:JRC, 2016)[245]

The productivity of the EU copper industry is one of the highest in the world. In the case of copper refineries, the EU has one of the lowest production costs. The higher recycling rate could be an advantage for the EU, as copper anodes can be produced by either the primary or the secondary route and be processed in the same copper refineries. In copper cathode production, the higher electricity consumption per tonne cathode compared to international competitors is due to higher electro-intensity in the EU, but over-all energy use per tonne of cathode produced is lower compared to the other countries. EU zinc smelters have some of the lowest total average production costs among the countries compared and one of the highest productivities.[246]

While the high productivity does mostly off-set the higher electricity and labour costs in the EU, this does not imply that future (large) increases in electricity costs in the EU will not impact the competitiveness of EU metals production. Further productivity gains become more difficult while other countries will also seek to improve the efficiency of metals production, while in many cases facing lower electricity costs.

Last but not least, the CO_2 intensity of EU metals production is low, mainly due to the efficiency of production and the low CO_2 intensity of power production. In China, the largest metals producer in the world, the CO_2 intensity is notably higher with CO_2 emissions per tonne aluminium 186% higher than the intensity in the EU (20 t CO_2/t Al versus 7t in the EU), for nickel this is 678% higher (70 t CO_2/t Ni versus 9t) and for silicon (11.6 t CO_2/t Si versus 3.4t) and zinc (6.1 t CO_2/t Zn versus 2.5t) respectively 241% and 150% higher.

245 It is important to note that these figures are not representative of the complexity and diversity of EU copper productions. They exclude the secondary production disregarding the variability in energy and cost in the copper industry. The copper sector is heterogeneous. The energy/electricity consumption varies significantly depending on the scale of operation, complexity of raw materials, production routes/technologies and process configuration.

246 JRC, 2016

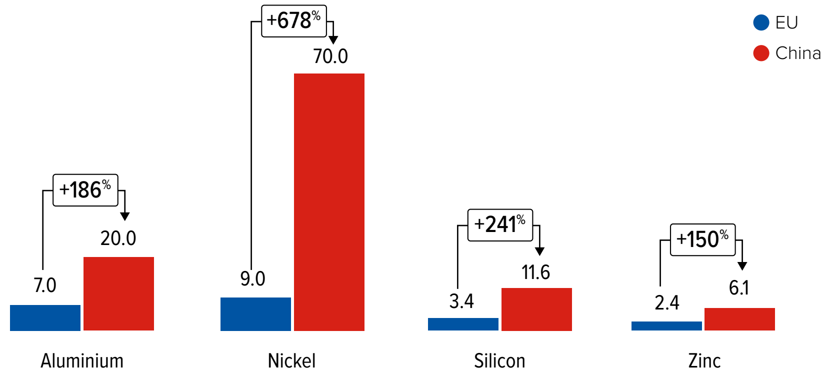


Figure 42: CO_2 intensity of metals production - EU vs. China (t CO_2/t metal)[247]

High economic sensitivity to electricity prices

Not only does the electricity cost impact the competitiveness with metals produced outside of the EU, the profitability of highly electro-intensive metals production is very sensitive to electricity prices. For instance, electricity costs for primary aluminium plants observed between 2008 and 2017 were much higher than profitability indicators such as EBITDA and EBIT.[248]

Recent research on German metals production showed the high importance of regulatory relief in electricity pricing for metals. Without regulatory relief[249] schemes, the electricity price for aluminium electrolysis would be more than three times higher. The cost of having to pay all regulatory price components would completely consume the gross value added of the aluminium electrolysis and even turn negative (i.e. a loss of EUR 75 million). The GVA of a large aluminium rolling mill would drop by approximately 32% (EUR 58 million). For a large copper rolling mill, the elimination of regulatory relief schemes would result in a reduction of the GVA by approximately 18% (EUR 35 million). The economic sensitivity to higher electricity prices is high for metals producers. An increase of EUR 10 /MWh would correspond to a reduction in gross value added of 2.3% for the metals industry, while the impact for the entire manufacturing industry would be five times less (-0.5%).[250]

Given that electricity costs already constitute a major factor in the production costs for EU metals producers, such price increases can seriously impact the competitiveness with major producers outside Europe (see above), especially given that metals prices are set globally (see chapter 4).

247 European Aluminium Association, 2018c, The Nickel Institute. Nickel class I produced in the EU compared to Chinese Nickel Pig Iron production. Actual nickel CO_2 intensity in Europe is 2t/t nickel class I but mining and smelting happens outside the EU. Silicon, 2016 AlloyConsult study on CO_2 emissions in silicon and manganese ferroalloys. Zinc, Congcong Qi, et al., 2017 and the Zinc institute.

248 CEPS & ECOFYS, 2018

249 It should also be noted that such regulatory relief is often justified economically. For example, numerous Member States implement network charge reductions for large, baseload consumers due to the stabilising effects that these consumers have on the network, reducing network costs. In such cases, regulatory relief is actually necessary in order to ensure that such charges are cost-reflective.

250 EWI, 2019

In addition to the economic impact of regulatory costs themselves, another important factor is long term certainty with regard to regulatory relief (e.g. EU ETS indirect cost compensation). Currently, the decision on indirect cost compensation is taken at Member State level and can change from year to year (e.g. linked to the availability of budgets). This creates a highly uncertain investment climate e.g. for measures related to energy savings or investments in new production technologies.

Finally, while higher electricity prices do have an important impact on competitiveness of metals production, they do not necessarily lead to faster GHG mitigation in metals production and will have a limited impact on energy efficiency improvements. Modelling by the JRC[251] showed that a scenario with higher CO_2 price, but electricity prices not being affected by the CO_2 price (e.g. through indirect cost compensation) brings the fastest and deepest GHG mitigation in aluminium production in the period 2020-2050. On the other hand, over the same period, the efficiency improvements in aluminium production will not change significantly over different scenarios, including the ones that have high electricity prices. This can be explained by, on the one hand, new mitigation technologies that reduce direct emissions (e.g. CCS or inert anodes) being deployed sooner and, on the other hand, the limitation to reduce energy use given that most major possibilities for energy improvements are already exhausted. Hence, there is little or no climate benefit to be derived from high electricity prices for primary aluminium production.

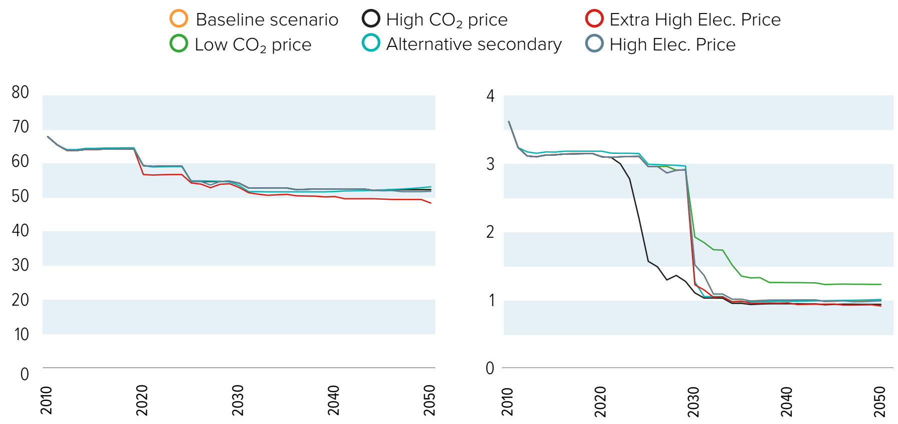


Figure 43: 2050 scenario's for aluminium production. (left) direct CO_2 emissions t CO_2/t cast aluminium, (right) energy use GJ/t primary aluminium (Source: JRC, 2015[252])

251 JRC, 2015

252 Ibidem

7.3 Trade related issues

Trade is a key factor in determining the competitiveness of Europe's non-ferrous metals industry. The EU metals industry faces a plethora of trade-related challenges. Growing protectionism in third countries is a major concern – in addition to subsidies, there exist import and export taxes and duties. Discriminatory public procurement policies in some major countries mean that EU companies lack a fair chance. Moreover, cheaper energy and lower environmental and social standards in third countries impact the overall price and demand in the global market.[253] While the non-ferrous metals industry in the EU has to achieve ever higher energy efficiency standards and commitments, those in third countries can prioritise production over energy efficiency and environmental and labour standards. The globalised nature of the world economy means that what happens in China and India (their economic cycles) impacts the cost of resources in Europe.[254]

The EU is a mature economy with a low growth rate. Compared to the developing world, the EU's low rate of urbanisation and industrialisation translate into a lower rate of demand for basic materials of which non-ferrous metals. On the other hand, the transition to a low-carbon economy is slowly but steadily generating a demand for non-ferrous metals which are essential to their manufacture. The EU has a high import dependency on raw materials – 100% in the case of a number of precious, speciality and rare earth metals as illustrated in Chapter 3.2.2. This means that the EU is not only a price taker as concerns raw materials but must also compete for limited global supplies.

Geopolitical vulnerabilities in supplying countries (in particular those which dominate the supply of a certain resource) can moreover be a major hindrance to imports (for instance conflict minerals or mining practises which employ child labour) given social pressures within the EU[255]. Supply security is also exacerbated by the illegal trade in scrap, collection, disassembly and reprocessing of scrap.[256] As mentioned in Section 3.4, illegal trade in scrap includes 17,000 containers of illegally exported e-waste annually from Europe or between 3-4 million end-of-life vehicles or a third of all vehicles unaccounted for each year resulting in nearly 0.5 Mt roughly of EU aluminium scrap leaving the EU. This scrap not only represents a loss of metals stock but also mostly ends up in countries which do not have the facilities or may not have the legal obligations to appropriately recycle. Several countries on the other hand have put in place export restrictions on scrap metal. One example is that of Russia – one of the largest import partners of the EU - which has in place as much as 50% export taxes for aluminium and copper scrap and has since 2000 virtually not exported any copper scrap.[257]

253 JRC, 2017b
254 Ibidem
255 Ibidem
256 Ecorys, 2011
257 Ibidem

China plays a prominent role when it comes to trade related issues. As mentioned in Chapter 3, China is the largest producer and consumer of a number of non-ferrous metals, in particular rare earth metals. China therefore not only impacts global non-ferrous metals supply but also influences global prices. China's non-ferrous sector is characterised by a large number of state-owned enterprises and national champions which receive significant government subsidies (direct and indirect).[258] Aluminium Corp of China for example has received more than EUR 60 million every single year between 2012 and 2014 allowing for a reduction of its total energy costs by nearly 3%.[259] According to the OECD,[260] 85% of all support identified in the global aluminium sector was received by just five firms, all of which were Chinese. This breaches the WTO's principles of free & fair trade. These subsidies have fuelled the massive boom in China's global market share, violating the WTO's principles of free & fair trade and threatening the viability of the European aluminium sector due to in particular over-production and subsequent dumping. As a result, China's excess aluminium capacity is 5 times that of EU aluminium annual production.[261] Likewise, in the case of silicon, the over-capacity is even more acute with Chinese capacity around 7 million tons against world consumption of silicon around 2.9 million tons (for 2019).[262] China also has huge and chronic overcapacity in ferroalloy production, with a capacity utilisation often below 50%.[263]

Other direct interventions (income subsidies) come in early in the value chain in the form of pricing of capital, labour, land, raw-materials and basic inputs to the production process which impact global price signals. There exist other generous financial and nonmonetary support and other non-operating income subsidies such as plant relocations, green development, technology innovation, industry revitalization, trademark and patent development, research & development, and so on.

The OECD calculated that for aluminium production alone Chinese government support to this sector amounted to USD 63 Bn over the period 2013-2017. [see figure 44]

Moreover, the Chinese government also utilizes instruments such as import and export duties, quotas, licenses, explicit restrictions and promotional subsidies, taxes and tax rebates control cross-border flows. Nonetheless, import of raw materials (ores, scrap, etc.) and advanced machinery required for industry operations as well as the export of processed metal products are promoted by the Chinese government. Subsidies upstream confer significant support to downstream activities while distorting global value chains. In particular, access to cheap inputs has enabled Chinese producers to expand production and compete in global markets at lower cost which mean that excess capacity leads to depressed global prices which threatens the viability of producers worldwide.[264]

258 Taube, 2017, pp. 145-151.
259 Ibidem
260 OECD, 2019
261 Source?
262 Euroalliages internal data
263 AlloysConsult, 2017
264 OECD, 2019

Finally, there exist other non-tariff issues such as technical barriers to trade (TBT), customs procedures, restrictions on primary and secondary raw material exports in third countries, state support and competition policy, and intellectual property rights (IPR).[265]

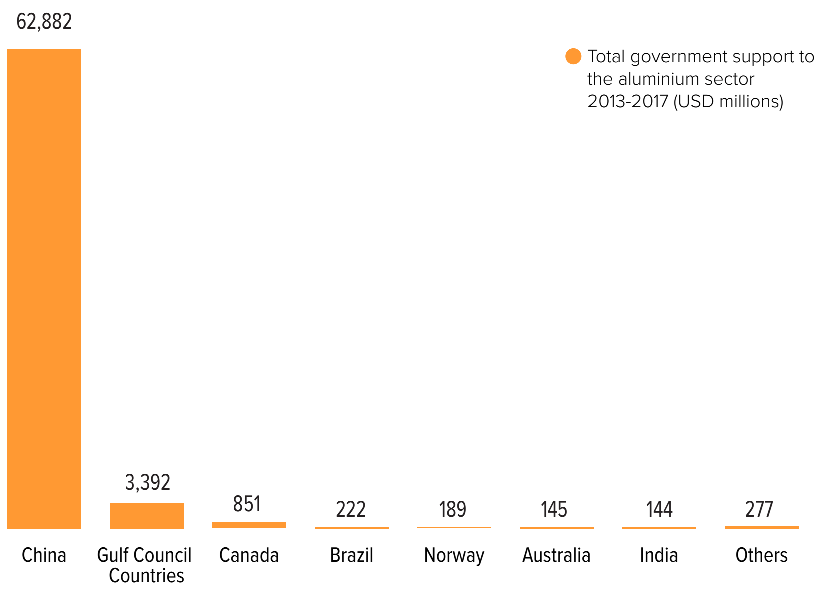


Figure 44: Government support to aluminium production (million USD, period 2013-2017) (Source: OECD 2019)

7.4 Other regulatory challenges

While this report focusses on the metals industry's contribution to a climate neutral economy and the challenges of electro-intensive processes in a global context, there is a broader regulatory environment to consider briefly. The latter can impact the metals industry and in particular pose challenges towards higher levels of circularity or reductions of energy use and GHG emissions.

The non-ferrous metals industry is subject to numerous environmental regulations on issues such as pollution control (e.g. industrial emissions directive (IED)), waste (including treatment and recycling), the protection from harmful substances for the environment and human health (REACH).

265 Ecorys, 2011

When it comes to reducing emissions to air (e.g. sulphur dioxide) and water, these mitigation techniques can lead to higher energy use and hence CO_2 emissions.

The REACH authorization and restriction processes impact on the non-ferrous metals industry mainly pertains to administrative burdens, additional costs (for extra administration for authorisation applications, ...), investments in the development of substitutes or alternative production processes, and constraints on production and supply of certain non-ferrous metals compounds such as Lead. In particular (valuable and critical) metals recyclers can be affected by this given their dependence on the production and use of carrier metals, several of which are substances of concern (like lead). Additionally, the substitution of certain metals may result in metals losing their recovery potential or require much higher energy demand to maintain their recovery or recycling potential. Furthermore, restrictions on the use of certain substances are not implemented and controlled consistently across all Member States, including at EU borders, with a risk to disrupt the level playing field between EU and non-EU competitors by imported articles. Product imports could contaminate EU waste streams and disadvantage European metals recyclers.

EU regulations related to end-of -life articles and waste (e.g. waste framework directive, WEE directive and the restriction on hazardous substances (RoHS) directive) do impact the non-ferrous metals industry. The impact of these legislations is felt across the whole non-ferrous metals industry in terms of additional costs[266], constrained recycling[267] and reduced efficiency.

In some cases, there can be real conflicts between REACH, waste policies and circular economy objectives. Metals recyclers are burdened by the lack of harmonised conditions for substances or objects to be recognised as by-products, not waste, or even valuable material streams. Member States declare by-product status in different ways, creating uncertainty. For example, certain metals slags fulfil the requirements of by-products (or even products). They are therefore registered as substances under REACH, meaning they should be excluded from Waste legislation. This is however not recognised by all authorities, forcing recyclers to comply with both waste and product legislation requirements.

266 Due to stringent technical provisions and costs (e.g. for the land-filling of hazardous wastes), and in terms of packaging and labelling of scrap material,

267 Non-ferrous industry is obligated to comply with stricter limit values amidst the concern that recycling of metals may fall under the co-incineration definition of the Directive

Industrial policy for non-ferrous metals towards a climate neutral economy: the canary that survives the coalmine

8 Industrial policy for non-ferrous metals towards a climate neutral economy: the canary that survives the coalmine

8.1 Introduction (summary of contributions and challenges)

Europe's non-ferrous metals industry finds itself at the forefront of the transition to a circular and climate neutral European economy. Major new and growing value chains that will power a climate neutral economy critically depend on the availability of non-ferrous metals and their value chains. Non-ferrous metals have already fully embraced the circular economy and strive to increase shares of recycled metals in European production. Major steps have been taken to reduce direct and indirect GHG emissions with current direct and indirect GHG emissions currently over 60% lower compared to 1990. The industry is further innovating to reduce energy use, GHG emissions, improve recovery of metals and increase symbiosis between metals producers and other sectors in the economy. It is hence possible for non-ferrous metals production as a whole to achieve further large emission reductions by 2050.

However, such evolution will depend on factors that are not in the hands of metals producers themselves. First of all, the overwhelming share of future GHG mitigation will depend on the decarbonisation of the EU's power sector. This does not only mean eliminating the GHG emissions in the power sector but doing this in a way that electricity for electro-intensive non-ferrous metals producers remains competitively priced and reliable. To further advance with new technologies that lower energy consumption and GHG emissions innovation support will be required, in particular for high risk and capital-intensive pilot and demonstration plants. Benefitting from new green value chains (e.g. batteries, electric vehicles) and enhanced circularity will require more horizontal industrial strategies that cover the entire value chains, including the end-of-life of products. Such industrial strategy must also include a more assertive approach towards international trade distortion as well as ensuring that the rest of the world follows Europe's higher environmental standards.

8.2 Non-ferrous metals powering and powered by a carbon free electricity system

As mentioned before (Chapter 5), a decarbonized electricity system in the EU will bring about the most important GHG emission reductions related to metals production. Furthermore, electrification and the climate friendly energy transition will create increased demand for metals (Chapter 3). Hence, the transition to a climate neutral economy will be powered by metals. The transition which on its turn will enable metals production to achieve very deep emission reductions.

At the same time, the electro-intensity of metals production also comes with a competitiveness vulnerability to higher electricity prices (chapter 7). It will therefore be essential to ensure that non-ferrous metals industries have access to competitively priced, stable and carbon-neutral electricity to power the road to a climate neutral economy.

Electro-intensive industries source power for their consumption based on various strategies, normally a portfolio of day-ahead, 1 to 5 years forward hedging on the exchanges and bilateral longer-term contracts of 5 to 30 years (more commonly referred to as power-purchase-agreements). The chosen portfolio – i.e. the power price risk management strategy – will depend, among others, on global competitive position, willingness to take pricing position in a long-term contract, appetite for fluctuating wholesale prices, expectation of power prices development and other factors.

A smart design of EU renewables and industrial policies could create a virtuous cycle where long-term contracts with utility scale renewables reduce the cost of investments and hence promote further investments in renewables. Non-ferrous metals producers can also help facilitate the challenges that come with more variable sources of electricity through:

- Higher engagement in climate friendly power-purchase-agreements (PPA's)
- Ancillary services (e.g. demand response) to an electricity system that will need integration of more variable power generation.

Climate friendly (e.g. carbon free energy) PPA's can be mutually beneficial for both industrial energy consumers and electricity producers. The consumer will get a long-term contract which can offer price stability, the producer will receive a guaranteed revenue stream which will reduce the risks associated with large investments in e.g. renewable production and hence reduce the cost of capital. Expected further declining costs in renewable electricity will make climate friendly PPA's an interesting long-term contracting option for industrial consumers.

Non-ferrous metals producers are baseload consumers, with predictable updates in electricity. While wind energy has a more variable production profile, non-ferrous metals producers are able to engage in this type of contract. In 2018 Norsk Hydro secured 1.65 TWh baseload supply for a period of 19 years from wind energy. Alcoa, also in Norway, has obtained a 0.8 TWh baseload supply from wind energy.[268] In Belgium, Nyrstar secured a 25-year PPA contract for solar energy (85 GWh/pa). Globally, the largest industrial renewable energy PPA is one pinned down by the Russian aluminium producer RUSAL (28 TWh, hydro).[269]

Regardless of decreasing levelized cost of energy for solar and wind power, renewable energy (RE) PPAs can still be quite expensive. In fact, when negotiating the selling price, generators look at the wholesale market price rather than at generation costs as the electricity market represents the main alternative opportunity to selling electricity via a PPA. This also means that the 'strike price' in RE PPAs includes EU ETS indirect costs as long as such costs are embedded in the wholesale electricity price.[270] Furthermore, energy suppliers will need to firm-up the variable renewable energy generation (with other power production) to match the flat load from the electro-intensive consumer. This additional cost can be included in the PPA or alternatively, the electro-intensive consumer matches possible power shortfalls with other purchasing contracts. This explains the success of RE PPA's in Norway, where variable wind can be easily matched with hydropower (which can act as a virtual battery).[271]

As mentioned in Chapter 5, electro-intensive metals production (e.g. aluminium and zinc) are already providing ancillary services to the power system (e.g. load shedding, temporary interruptability) and will be able to extend these instruments in the future. This will be important given that fossil fuel baseload power production will gradually be replaced by renewable electricity, hence requiring storage and large-scale demand response to balance supply and demand. To have metals producers actively invest and engage, it is important to facilitate market access and compensation for providing these services. Furthermore, while demand response services might increase the efficiency of the energy system, it might lead to less efficient (e.g. temporarily interrupted) production of metals at site level. Finally, more variable demand from electro-intensive consumers might lead to higher grid fees by transmission system operators, who expect flat loads. It is hence important to strive for regulatory alignment.

Building a supportive regulatory framework might also entail changes to current policies which might stand in the way of higher electrification or harm electro-intensive production. This includes indirect costs under the EU ETS which can deter investments in (new) processes that require high amounts of electricity (due to (i) the lack of certainty with regard to whether compensation mechanisms will actually be applied from year to year, and (ii) the declining maximum aid intensity foreseen in the current guidelines) and other regulatory costs related to electricity consumption by non-ferrous metals producers across the EU.

268 See for example Financial Times, 2018
269 Irena, 2018
270 European Commission, 2019b
271 Ibidem

It is therefore important for EU and national policy makers to develop an integrated energy and industry strategy for the development of a full range of low-carbon and carbon-neutral energy carriers and related energy infrastructure and energy storage in Europe. This should include a market-based and market responsive framework that delivers cost efficient low CO_2 electricity. Furthermore, a positive regulatory framework for PPAs and long-term power contracts would be essential for electro-intensive industries. Finally, it is essential to adequately value the non-ferrous metals industry's current and future role in balancing the profile of electricity markets.

More specifically, the following actions can be considered[272]:

- Member States could provide long-term guidance when it comes to regulated components of electricity prices.
- The EU should draft multiannual guidelines enabling compensation for indirect EU ETS costs and for renewable energy support scheme. This long-term EU guidance could be accompanied by a stable budgetary and regulatory framework at the national level securing compensation for energy-intensive players
- In particular companies that purchase electricity via RE PPAs should be entitled to full compensation for indirect EU ETS costs
- Cross-border PPAs should be encouraged by (i) further developing interconnector capacities between Member States and maximizing their use, and (ii) ensuring that suitable, cost-competitive products are offered for the long-term allocation of interconnector capacities (i.e. for a period of multiple years, which is necessary in order to provide certainty to consumers with regard to their ability to actually import the energy).
- Innovative PPAs that can better match the needs of electro-intensive producers should be supported or at least not be prevented. For instance, multi-buyer PPAs (where more companies together take on a joint contract) and multi-technology PPAs (which mix different (renewable) technologies). Both can in theory partially address issues such as high balancing costs e.g. by mixing complementary load profiles or renewable technologies.
- Continue the revision of the existing renewable energy support schemes and the introduction of market-based auction mechanisms for (mature and utility scale) technologies

Finally, it is beyond doubt that the transition to a decarbonized power system will require large upfront capital investments for e.g. generation and long-distance transmission. Given the nature of such transformative processes, it should be further considered to maximise

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the use of EU financing and investment instruments (e.g. (strategic) projects of common European interest) with the goal to reduce the cost of capital and hence costs that will be passed through to consumers.

8.3 Supporting climate friendly innovation and investments

As shown in Chapter 5, the non-ferrous metals industry has the potential to further and sometimes even radically innovate its production processes. Many of the technologies mentioned have not yet reached pilot or large-scale demonstration stage and will hence require high risk and capital-intensive investments.

The non-ferrous metals industry, in all its diversity, should pro-actively engage itself fully in important EU initiatives supporting breakthrough innovations related to industrial processes and resource efficiency. Important examples are SPIRE 2050 (sustainable process industry, resource efficiency) and Horizon Europe for lower TRL innovation and the EU ETS innovation fund for the financing of industrial pilot and demonstration projects. The industry will have to both engage in projects that can serve multiple metals production routes and in cooperation with other industries (e.g. on CC(U)S and Hydrogen) through industrial partnerships.

The EU's R&D framework is starting to address the important innovation challenges that exist for energy intensive industries. While Horizon Europe, the Innovation Fund, Invest EU and the Connecting Europe Facility are seen as part of a broader innovation architecture linking basic R&D to piloting, demonstration and later commercialisation; the governance or oversight required to ensure this linkage with the goal to create solid innovation chains is still not optimal. Robust and regular monitoring of progress of the state of innovation will be important together with the flexibility to reorient financing in case certain areas do not progress sufficiently. For companies engaging in industrial process innovation it will be important to see a smooth and reliable innovation support process from basic R&D to commercialisation over different innovation support instruments.

The development of new technologies in itself does not secure their deployment (in the EU). Some low-CO_2 solutions e.g. basic materials produced with breakthrough technologies will be more expensive compared to production with incumbent technologies. This price difference can become smaller over time as more experience is gained of new production technologies and these become incrementally more cost-efficient. For this learning curve to materialise however, sufficient demand for low-CO_2 products must exist in the first place. It is therefore important to create domestic lead markets.

Reforms in the standard setting procedures, reforms in the formulation of standards, and the promotion of voluntary standards/labelling/certifications, can help bring products using innovative processes, high shares of circular materials use and/or having low emissions over the full lifecycle[273] to the market. Procurement practices are still underutilized as a strategic tool to drive a low-CO_2 transition, for example in large infrastructure and buildings projects which are major end use sectors of some of the base metals. European policy makers could improve public procurement practices across the EU by making better use of the existing Public Procurement Package, by improving coordination at the EU level and by linking public procurement to low-CO_2 standards. Some metals companies are already working on and using voluntary standards (e.g. usage of post-consumer scrap or footprint direct and indirect CO_2 emissions).[274] [275] This can help bring about EU standards for metals use in products or through public procurement. Because of the EU's large internal consumer market such standard might become internationally tradeable (e.g. LME EU green aluminium premium) and can hence allow producers to ask price premium and pass through some of the additional costs associated with low CO_2 production.

The full transition to a climate neutral industry will require a significant increase in investments compared to today. Companies will only make these investments if the conditions are right. This includes having mature technologies at hand, a growing market for low-CO_2 solutions and infrastructure in place, together with access to reliable, green and competitively priced energy. These enabling conditions will be necessary but might not be sufficient. A radical transformation of industry over a relatively short time period (compared to 30-year investment cycles) will likely require additional support to facilitate and accelerate the necessary investments on an EU-wide scale. Fiscal instruments can assist in guiding investments towards low-CO_2 solutions but also bigger (new) EU financing instruments such as investment platforms or even an industrial sovereign wealth fund can be considered. In many cases the transition of industrial processes will occur at the same site, therefore brownfield conversion will become an important feature of Europe's industrial transition.

273 Including the impact of mining and transport of raw materials
274 Hobson, 2017
275 One of the largest building projects in Norway, the Økern Portal, is using Norsk Hydro's Circal 75R aluminium as facade material in its new, innovative office building. Circal 75R aluminium is a newly developed alloy with a minimum content of 75% post-consumer recycled aluminium. It has a carbon footprint of below 2.3 kg CO_2 per kg aluminium. The production process is fully traceable, and the product is certified by an independent third party (DNV GL). The building and construction industry represent up to 40% of total CO_2 emissions and EU targets require all new buildings to be nearly zero-energy from 2021. The Økern Portal project is a successful example of how the aluminium industry can provide low-carbon solutions to meet customers' increasing demand for green materials, which are needed to meet their own sustainability targets. The recycled aluminium façade of 14,600 m2 will not only help to reduce the total carbon footprint of the building, but can also be fully dismantled and reused, making it a truly low-carbon and circular project. Sustainability is a key element in the project, which is also incentivized by the BREEAM Excellent certification, a voluntary certification setting high sustainability requirements to all materials used in the project. This contributes to bring innovative products to the market. The Owned by Oslo Pensjonsforsikring, the Økern Portal is scheduled for completion in 2021.

Brownfield conversion will be more complex and expensive compared to the development of a new process plant on a greenfield site. Regulatory flexibility and access to the EU ETS modernisation fund can assist with these reconversion processes.[276]

The low-carbon transition will require the industry to develop long-term investments scenarios. Industry will need to be able to rely on a safe and attractive financial market to get access to the necessary capital. A new taxonomy on green investments will have to consider the large investment challenges for energy intensive industries and the gradual process towards achieving deep emission reductions. Furthermore, it should recognize the role of the metals industry in enabling green investments in all other parts of the economy and the positive impact over the life cycle of metals.

8.4 Nurturing future value chains, circularity and industrial symbiosis

As mentioned in Chapter 3, the transition to a climate neutral economy will lead to an increased demand for all types of metals. The new and growing value chains essential for a climate neutral economy include renewable energy systems (e.g. solar, wind), battery storage, electricity transformation and transport, electrification of industrial and residential heating and electric transport systems (road, shipping and later even air transport). Furthermore, the climate transition will go together with high levels of digitisation (e.g. machine learning, AI, 5G mobile internet) which also depends on a variety of non-ferrous metals.

Given the crucial role of metals in this economic transformation, it is relevant to consider metals production as a strategic part of these value chains. The EU's strategic action plan on batteries can be seen as good example of how raw materials are integrated in an industrial strategy, including and in particular, the end-of-life stage. The strategic action plan includes a combination of targeted measures in e.g. raw materials (primary and secondary), research and innovation, financing and investment, standardisation and regulations, trade and skills development with the goal to make the EU a global leader in sustainable battery production and use in the context of the circular economy.

It can be considered to extend the strategic approach under the action plan for batteries to other value chains which are critical for Europe's transition to a climate neutral economy and strategic value chains for Europe's competitiveness. Given that the energy transition will be global, one can expect growing demand not only for critical raw materials and metals where Europe has a high import dependency but also for base metals where Europe's import dependency is currently lower. Maintaining a high level of domestic production of base metals will hence have to be part of an integrated industrial strategy for green value chains.

276 Wyns, et al., 2019

When it comes to metals the key elements of the EU materials strategy (2017) and the European Innovation Partnership on raw materials would clearly apply in this context. This includes the sustainable sourcing of raw materials from global markets, boosting sustainable domestic production of raw materials and primary metals and boosting resource efficiency and supply of secondary raw materials.

The energy transition including its high demand for metals will lead to a growing metals stock in the EU over the period 2020-2050. This stock will hence become a strategic reserve of base metals and critical raw materials. Therefore, investing in improved and cost-efficient recovery of metals from this stock through new technologies and a facilitating regulatory climate will be critical. This includes[277]:

- Supporting the development of climate friendly technologies and techniques that enhance the recovery of metals and alloys from secondary raw material streams. Ensuring that promising technologies are scaled up to pilot and demonstration level.
- Using public procurement and standards to encourage metals use with high levels of post-consumer scrap.
- Introducing product standards requiring easier and more efficient disassembly, traceability and recyclability of metals (e.g. for batteries, WEEE and automotive)
- Ensuring that metals products are collected and made available to high-quality recyclers through systemic changes in the value chains.
- Avoiding leakage of scrap outside of the EU, in particular when there are no or little guarantees that metals recovery and recycling will happen at high quality standards.

Next to integrating metals more into strategic value chains for climate neutr ality it will be equally important to further facilitate industrial symbiosis and sector coupling for the metals industry. This includes support for Member States developing regional metals clusters that maximise material symbiosis and metals recovery efficiency over different neighbouring sites (e.g. Flanders metals valley [see Chapter 3]). Such approach can enhance the economic robustness of the individual metals production sites. In this context further and regional valorisation of metals waste streams (e.g. slag residues for the construction industry) should also be considered.

Likewise, supporting metals producers to enhance energy efficiency in other sectors e.g. through the valorisation of low temperature waste heat in the residential sector can be beneficial for metals producers under the right circumstances. This includes providing the

277 Ibidem

infrastructure for sector coupling and de-risking the business model by ensuring long-term contracts for heat purchases by the residential sector. Similarly, as mentioned before, ensuring the electro-intensive metals producers can maximise their role in ancillary services to the power grid and power generation will facilitate the climate transition of the electricity system.

8.5 Assertive EU trade policies

Thus far, the EU has largely strived to maintain an open and fair market. In order to maintain a level playing field and reciprocal market access, there is a need to strike a balance between defensive and more assertive trade measures.

As the world's largest consumer market, the EU could first strengthen its standards and ensure that imported materials and products comply with the same standards as those extracted or produced in Europe.[278] Harmonisation of EU level of customs clearance practices in harbours as well as the validation methods within EU regulations for the classification of metals and alloys, beyond liquids and powders would prove useful. Public procurement is a potent tool which the EU could use to support the non-ferrous metals sector and increase uptake of metals produced with the least carbon footprint.[279]

To tackle growing international protectionism, the EU could better regulate single market access, including reciprocal market access e.g. through stronger public procurement rules, while utilising effective defence instruments in the case of unfair trade practises. This includes identifying and addressing distortive effects of foreign companies (including state ownership and financing) on the EU internal market, reducing/eliminating import tariffs and abolishing the lesser-duty rule in case of raw materials distortions (which is in any case a "WTO+" requirement).[280]

It is important that the EU is more forceful and diligent in using the existing trade defence instruments available. For anti-dumping cases the Commission need to have more concern on a serious and immediate threat of injury of its industry. It is often too late if injury has to be fully proven before actions are taken.

Other actions could include better coordination of national trade agencies and initiatives across Member States, the creation of a Raw Materials Strategy including export of waste and scrap; and a stronger investment policy.

278 JRC, 2017b
279 EPSC, Wyns et al., 2019
280 JRC, 2017b; whereby the rate of the duties offsetting dumping is based on the injury when it is lower than the dumping margin

International measures include promoting EU standards globally and subsequently influencing the London Metals exchanges to develop a new price index for raw materials that meet higher ethical and environmental standards. There is an urgent need for the EU to take up the issues of illegal dumping and subsidies more strongly in international platforms like the WTO and G20 commensurate to its weight as the world's largest market and trading block. In essence, the EU could advocate for strengthened rules to address market-distorting subsidies, including indirect industrial subsidies in the form of tax cuts, cross-subsidisation; cheap sovereign loans to state-owned enterprises and/or inflated procurement prices paid by local public authorities. Necessary reforms need to be pursued such as the improvement of the scope and implementation of relevant WTO rules and commitment to the Paris Agreement in the context of free trade agreements, formally recognizing China as a non-market economy, and (as concerns China) shifting the burden of proof within the WTO from importing countries to China to show that it has not provided unfair subsidies (China's own accession protocol to the WTO in 2001 accepts the provision of alternative methodologies to calculate countervailing duties).[281] Another option could be to add a special tax to offset the advantages Chinese SOEs derive from the nature of the Chinese economic system. The idea would be to set it as equal to the countervailing duty assessed on supported Chinese exports to the west.

As mentioned in Chapter 3.2.1, the EU does not have free trade agreements (FTAs) with any of its top non-ferrous metals trading partners and China. FTAs could provide a reliable framework in which the EU may possibly agree on standards of production in the case of sensitive industries, strengthen chapters on social rights to a mandatory enforcement similar to the US; and address the circumvention of import duties through the intentional use of wrong trade codes. In the meantime, the EU needs to step up/create bilateral dialogues with its key trade partners for non-ferrous metals and industrial decarbonisation. Both FTAs and bilateral dialogues could help sectors promote and jointly develop technological innovations and export expertise in recovery of materials with third countries. Drawing up a trade strategy targeting emerging markets and their growing demand would also be useful. In the case of conflict minerals, more can be done to ensure coordination between EU and its member states (national trade agencies and initiatives) to ensure the control of origin at the EU's borders.[282] Politically, strengthened diplomacy both at the EU level and at the UN would also be needed to reduce political instability in emerging markets.

281 Tran Hung, 2019
282 In order to address the concerns over security of supply and other aspects regarding sourcing from the DRC, the Cobalt Institute has developed a new tool called CIRAF - Cobalt Industry Responsible Assessment Framework. The CIRAF tool provides a good practice-based framework that allows the Cobalt producers to identify and respond to core risks relating to Human Rights, and for Community Engagement, and in due course, also the risks to the Environment and Occupational Health & Safety (OHS). The new CIRAF has been rolled out for use by the cobalt-producing companies and is being extended to downstream users in the cobalt value chain, as well as other stakeholders in the metals industry Source: Cobalt Institute, 2019a

8.6 Strategic regulatory alignment

It is important to ensure consistency and integration among the broader enabling and regulatory framework affecting the non-ferrous metals industry. This includes the recognition of its role in creating a climate neutral economy and the opportunities within the circular economy for metals.

In particular the recognition that metals production forms an eco-system with strong technical and economic interlinkages between primary and secondary production (industrial symbiosis) and foremost the role of carrier metals to enable the production and recovery of other (sometimes rare) metals.

In the context of a circular and resource efficient economy it is essential that the regulatory environment promotes, or at least does not prevent, society as a whole and the metals industry to maximise the value of by-products and enhanced recovery of metals in waste streams.

Finally, consistency is required with regard to the application of important EU legislation such as REACH in particular for materials and especially articles entering the EU. This would prevent materials and articles meeting lower environmental and health standards of escaping REACH authorisation duties, leaking into the EU and affecting the competitiveness and quality of metals production in the EU.

In general, when considering non-ferrous metals as a strategic part of crucial value chains for the transition to a climate neutral economy there is need for enhanced fine-tuning alignment and integration of the over-all regulatory environment as to allow the metals industry to play its full role in this transition while maintaining the highest standards on environmental and climate protection.

Table 8: Industrial policy framework for the sustainable transition of the non-ferrous industry to a climate neutral Europe

1. Competitively-priced carbon-free electricity

- Develop an integrated strategy for the development of a full range of low-carbon and carbon neutral energy carriers and related energy infrastructure and energy storage in Europe
- Provide a market-based and market responsive framework that delivers cost-efficient electricity meeting industrial needs
- Guarantee stable and predictable compensation for indirect EU ETS costs & renewable energy support schemes
- Introduce a positive regulatory framework for power purchase agreements and long-term power contracts (including cross-border PPAs)
- Adequately value industry's current and future role in balancing the profile of electricity markets

2. Innovation & investments support

- Optimise the governance and coherence of Europe's innovation architecture, including robust and regular monitoring and flexibility for reorientating financing when necessary
- Use fiscal and financial instruments to assist in guiding industrial investments towards low-CO_2 solutions
- Improve public procurement practices across the EU by making better use of the existing Public Procurement Package & by linking public procurement to low-CO_2 standards.
- Support brownfield conversion through regulatory flexibility and access to the EU ETS modernisation fund
- Ensure that the new sustainable finance taxonomy considers the large investment challenges for energy-intensive industries and the role of metals in enabling downstream green investments

3. Nurturing value chains & industrial symbiosis

- Extend the strategic approach under the action plan for batteries to other value chains which are critical for Europe's transition to a climate-neutral economy
- Encourage a higher level of domestic production of all metals as part of an integrated industrial strategy for green value chains, including high sustainability standards.
- Further facilitate industrial symbiosis and sector coupling for the metals industry, including the development of regional clusters
- Take care that chemicals management measures are designed to maintain investment predict-ability into metals operations, while achieving the primary objective of safe chemicals use.
- Support metals producers to enhance energy efficiency in other sectors, e.g. through the valorisation of low temperature waste heat in the residentials sector

4. An ambitious Circular Economy framework

- Invest into Europe's capacity for state-of-the-art recovery of metals from existing and emerging stock, including through new technologies
- Avoid leakage of scrap outside of the EU when there are not sufficient guarantees that metals recovery will happen at the necessary standards
- Support development of climate friendly technologies and techniques that enhance the recovery of metals and alloys from secondary raw material streams.
- Improve product design, through requiring easier and more efficient disassembly, traceability and recyclability of metals (e.g. for electronics waste)
- Optimise the collection and sorting infrastructure for metals scrap and products, in order to improve recycling rates

5. Assertive trade & competition policies

- Encourage a more forceful and diligent EU utilisation of existing trade defence instruments, and act sooner in cases of a serious and immediate threat of injury to domestic industry
- Pursue a globally focussed competition policy, as well as addressing the distortive effects of foreign companies on the EU internal market, including state ownership and financing
- Pursue necessary reforms of the World Trade Organisation, in order to tackle the growing issues of state subsidisation and excess capacities
- Use free trade agreements and bilateral dialogues to improve cooperation with countries that are key suppliers of primary raw materials to Europe
- Strengthen EU standards, use public procurement, and harmonise customs clearance practices at harbours

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10 List of Abbreviations

AMRT	Advanced Mineral Recovery Technology
BAU	Business as Usual
CO2	Carbon dioxide
CO2eq	Carbon dioxide equivalent
COMEX	New York Mercantile Commodity Exchange
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CNMP	Carbon Neutral Metal Production
EAF	Electric Arc Furnaces
EU	European Union
EUR	Euros
EU ETS	EU Emissions Trading System
E-Waste	Electronic million tonnes
G	Gibbs constant
GHG	Greenhouse Gases
HKMEx	Hong Kong Mercantile Exchange
HPAL	High pressure acid leaching
IED	Industrial Emissions Directive
IPR	Intellectual Property Rights
ISF	Imperial Smelting Furnace
Kg	Kilogram
Kt	Kilo tonnes
LED	Light Emitting Diode
LIBS	Laser Induced Breakdown Spectroscopy
LME	London Metals Exchange
MWh	Megawatt hour
PJ	Petajoule
MOFs	Metal-organic frameworks
PFC	Perfluorocarbon
PPA	Power-Purchase-Agreements
R&D	Research and Development
RE	Renewable Energy
RFBs	Redox flow batteries
RLE	Roasting – Leaching – Electrolysis
SHFE	Shanghai Futures Exchange
SX-EW	Solvent Extraction and Electrowinning
T	Tonne
TBT	Technical Barriers to Trade
TiB2	Titanium diboride
TRBs	Thermally regenerative batteries
TRABs	Thermally regenerative ammonia-based batteries
TRL	Technology Readiness level
TWh	Terawatt hour
WEEE	Waste from Electrical And Electronic Equipment
WTO	World Trade Organisation

Annex

List of contributors

Companies

Alcoa

Aurubis

Boliden

Ecobat

Elkem

Hydro

KGHM

Mytilineos

Nyrstar

Trimet

Umicore

Vimetco

Wieland

Commodity associations

European Aluminium

European Copper Institute

EPMF

The Nickel Institute

International Lead Association

International Zinc Association The Cobalt Institute

National associations

Norsk Industri - Norway

VNMI – The Netherlands

WVMetalle – Germany

WKO – Austria

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