European
Commission

Support study for the preparation of energy efficiency benchmarks in the context of the Revised ETS State Aid Guidelines

Final Report

Prepared by

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European Commission
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Luxembourg: Publications Office of the European Union, 2021

Catalogue number: KD-01-21-322-EN-N
ISBN: 978-92-76-42249-5
DOI: 10.2763/284129

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Acronyms

BAT	Best available technology
BREF	EU Best Available Techniques reference documents
CEPI	Confederation of European Paper Industries
DON	Direct outotec nickel process
ECI	European Copper Institute
ESA	European Sulphuric Acid Association
EU ETS	European Emissions Trading Scheme
Euro Chlor	Association of chloralkali plant operators
EUROFER	European Steel Association
IZA	International Zinc Association
JRC	Joint Research Centre
kt	Kilo tonnes
kWh/t	Kilo Watt hours per tonne
MWh/t	Mega Watt hours per tonne
OCC	Oxygen-depolarized cathodes
PCC	Precipitated calcium carbonate
RLE	Roast-Leach-Electrowin
t	Tonnes

Executive summary

Article 6 of the ETS Directive states that aid for indirect ETS costs may be granted based on ex-ante benchmarks of the indirect emissions of CO2 per unit of production.

The benchmark for efficient electricity use (expressed in MWh/t) reflects the fact that companies should only be compensated for electricity consumption based on the most energy efficient installation for a given product category in the EU. Therefore, the electricity consumption efficiency benchmark is the product-specific electricity consumption per tonne of output production achieved by the most electricity-efficient methods of production for the product. The following table presents recommendations for electricity consumption efficiency benchmarks and degressivity factors for subsectors and sectors eligible under the ETS Guidelines.

Table ES1.1 Recommended electricity consumption efficiency benchmarks

NACE4	Product benchmark	Benchmark value	Benchmark unit	Unit of production	Degressivity factor [%]	Product definition	Processes covered by product BM	Relevant Prodcom code	Description
17.11	Chemical wood pulp	0.904	MWh/t 90% sdt	Tonne of chemical wood pulp	Fall back value	Chemical wood pulp, dissolving grades	All process directly or indirectly linked to chemical pulp production, including drying, washing and screening, and bleaching	17.11.11.00	Chemical wood pulp, dissolving grades
17.11	Chemical wood pulp	0.329	MWh/t 90% sdt	Tonne of chemical wood pulp	Fall back value	Chemical wood pulp, soda or sulphate, other than dissolving grades		17.11.12.00	Chemical wood pulp, soda or sulphate, other than dissolving grades
17.11	Chemical wood pulp	0.443	MWh/t 90% sdt	Tonne of chemical wood pulp	Fall back value	Chemical wood pulp, sulphite, other than dissolving grades		17.11.13.00	Chemical wood pulp, sulphite, other than dissolving grades
17.11	Semi-chemical wood pulp	0.443	MWh/t 90% sdt	Tonne of semi-chemical wood pulp	Fall back value	Semi-chemical wood pulp		17.11.14.00	Mechanical wood pulp; semi-chemical wood pulp; pulps of fibrous cellulosic material other than wood
17.11	Mechanical pulp	Fall back approach			Fall back value	Mechanical pulp	All processes direclty or indrectly linked to mechanical pulp production, including wood treatment, refining, washing, bleaching, heat recovery		

NACE4	Product benchmark	Benchmark value	Benchmark unit	Unit of production	Degressivity factor [%]	Product definition	Processes covered by product BM	Relevant Prodcom code	Description
17.11	Recovered paper	0.260	MWh/t 90% sdt	Tonne of recovered paper	Fall back value	Recovered paper	All process direclty or indirectly linked to recovered paper production, including thickening and dispersing, and bleaching		
17.11	Deinked recovered paper	0.390	MWh/t 90% sdt	Tonne of deinked recovered paper	Fall back value	Deinked recovered paper			
17.12	Newsprint	0.801	MWh/t product	Tonne of newsprint	Fall back value	Newsprint	All processes directly or indirectly linked to production of paper, including refining, pressing and thermal drying	17.12.11.00	Newsprint
17.12	Uncoated fine paper	0.645	MWh/t product	Tonne of uncoated fine paper	Fall back value	Uncoated fine paper		17.12.12.00 17.12.13.00 17.12.14.10 17.12.14.35 17.12.14.39 17.12.14.50 17.12.14.70	Uncoated fine paper
17.12	Coated fine paper	0.538	MWh/t product	Tonne of coated fine paper	Fall back value	Coated fine paper		17.12.73.35 17.12.73.37 17.12.73.60 17.12.73.75 17.12.73.79 17.12.76.00	Coated fine paper
17.12	Tissue	0.925	MWh/t product	Tonne of tissue paper	Fall back value	Tissue		17.12.20.30 17.12.20.55 17.12.20.57 17.12.20.90 17.22.11.20* 17.22.11.40*	Tissue

NACE4	Product benchmark	Benchmark value	Benchmark unit	Unit of production	Degressivity factor [%]	Product definition	Processes covered by product BM	Relevant Prodcom code	Description
								17.22.11.60* 17.22.11.80* 17.22.12.20* 17.22.12.30* 17.22.12.50* 17.22.12.90*	
17.12	Testliner and fluting	0.260	MWh/t product	Tonne of paper	Fall back value	Testliner and fluting		17.12.33.00 17.12.34.00 17.12.35.20 17.12.35.40	Testliner and fluting
17.12	Uncoated carton board	0.268	MWh/t product	Tonne of carton board	Fall back value	Uncoated carton board		17.12.31.00 17.12.32.00 17.12.42.60 17.12.42.80 17.12.51.10 17.12.59.10	Uncoated carton board
17.12	Coated carton board	0.403	MWh/t product	Tonne of carton board	Fall back value	Coated carton board		17.12.75.00 17.12.77.55 17.12.77.59 17.12.78.20 17.12.78.50 17.12.79.53 17.12.79.55	Coated carton board
20.13	Sulphuric acid	0.056	MWh/t product	Tonne of Sulphuric acid	Fall back value	Sulphuric acid; oleum	All processes directly or indirectly linked to the production of sulphuric acid	20.13.24.34	Sulphuric acid; oleum

NACE4	Product benchmark	Benchmark value	Benchmark unit	Unit of production	Degressivity factor [%]	Product definition	Processes covered by product BM	Relevant Prodcom code	Description
20.13	Chlorine	1.846	MWh/t product	Tonne of chlorine	-2.50	Chlorine	All processes directly or indirectly linked to the electrolysis unit, including auxiliaries	20.13.21.11	Chlorine
20.13	Silicon	11.87	MWh/t product	Tonne of silicon	Fall back value	Silicon. Other than containing by weight not less than 99,99 % of silicon	All processes directly or indirectly linked to the production of silicon	20.13.21.70	Silicon. Other than containing by weight not less than 99,99 % of silicon
20.13	Silicon	60	MWh/t product	Tonne of silicon	Fall back value	Silicon. Containing by weight not less than 99,99 % of silicon	All processes directly or indirectly linked to the furnace, including auxiliaries	20.13.21.60	Silicon. Containing by weight not less than 99,99 % of silicon
20.13	Silicon carbide	6.2	MWh/t product	Tonne of silicon carbide	Fall back value	Silicon. Carbides of silicon, whether or not chemically defined	All processes directly or indirectly linked to the production of silicon carbide	20.13.64.10	Silicon. Carbides of silicon, whether or not chemically defined
24.10	Basic oxygen steel	0.03385	MWh/t product	Tonne of crude (cast) steel	-0.60	Crude steel: non-alloy steel produced by other processes than in electric furnaces	Secondary metallurgy, refratories preheating, auxiliaries and	24.10.T1.22	Crude steel: non-alloy steel produced by other processes than in electric furnaces

NACE4	Product benchmark	Benchmark value	Benchmark unit	Unit of production	Degressivity factor [%]	Product definition	Processes covered by product BM	Relevant Prodcom code	Description
24.10						Crude steel: alloy steel other than stainless steel produced by other processes than in electric furnaces	casting installations up to cut-off of crude steel products	24.10.T1.32	Crude steel: alloy steel other than stainless steel produced by other processes than in electric furnaces
24.10						Crude steel: stainless and heat resisting steel produced by other processes than in electric furnaces		24.12.T1.42	Crude steel: stainless and heat resisting steel produced by other processes than in electric furnaces
24.10	Ferro-manganese	2.2	MWh/t product	Ferro-manganese containing by weight > 2% carbon	-2.03	Ferro-manganese, containing by weight > 2% carbon, with a granulometry <= 5 mm and a manganese content by weight > 65%		24.10.12.10	Ferro-manganese, containing by weight > 2% carbon, with a granulometry <= 5 mm and a manganese content by weight > 65%
24.10				Ferro-manganese containing by weight > 2% carbon		Other ferro-manganese, containing by weight > 2% carbon (excl. ferro-manganese with a granulometry of <= 5 mm and		24.10.12.20	Other ferro-manganese, containing by weight > 2% carbon (excl. ferro-manganese with a granulometry of <= 5 mm and

NACE4	Product benchmark	Benchmark value	Benchmark unit	Unit of production	Degressivity factor [%]	Product definition	Processes covered by product BM	Relevant Prodcom code	Description
						containing by weight > 65% manganese)			containing by weight > 65% manganese)
24.10	Ferro-manganese	1.4	MWh/t product	Ferro-manganese containing by weight <= 2% carbon	Fall back value	Other ferro-manganese containing by weight less or equal than 2 % of carbon		24.10.12.25	Other ferro-manganese containing by weight less or equal than 2 % of carbon
24.10	Ferro-silicon	8.54	MWh/t product	Ferro-silicon, containing by weight > 55% of silicon	Fall back value	Ferro-silicon, containing by weight > 55% of silicon		24.10.12.35	Ferro-silicon, containing by weight > 55% of silicon
24.10	Ferro-silicon	Fall back approach			Fall back value			24.10.12.36	Ferro-silicon, containing by weight <= 55% silicon and >= 4% but <= 10% of magnesium
24.10	Ferro-nickel	9.28	MWh/t product	Ferro-nickel	Fall back value	Ferro-nickel		24.10.12.40	Ferro-nickel
24.10	Ferro-silico-manganese	3.419	MWh/t product	Ferro-silico-manganese	-1.12	Ferro-silico-manganese		24.10.12.45	Ferro-silico-manganese
24.42		13.90			-0.25		Unwrought non-alloy aluminium	24.42.11.30	Unwrought non-alloy aluminium

NACE4	Product benchmark	Benchmark value	Benchmark unit	Unit of production	Degressivity factor [%]	Product definition	Processes covered by product BM	Relevant Prodcom code	Description
	Primary aluminium		MWh/t product	Unwrought non-alloy aluminium		Unwrought non-alloy aluminium from electrolysis	from electrolysis including production control units, auxiliary processes and cast house. Also include anode plant (pre-bake). In case anodes are provided from a stan-alone plant in EU, this plant should not be compensated. For anode produced outside EU, a correction may be applied		(excluding powders and flakes)
								24.42.11.53	Unwrought aluminium alloys in primary form (excluding aluminium powders and flakes)
								24.42.11.54	Unwrought aluminium alloys (excluding aluminium powders and flakes)
24.42	Alumina (refining)	0.20	MWh/t product	alumina	-1.11		All processes directly or indirectly linked to the production of alumina	24.42.12.00	Aluminium oxide (excluding artificial corundum)
24.43	Zinc electrolysis	3.994	MWh/t product	zinc	-0.01	Primary zinc	All processes directly or indirectly to the zinc electrolysis unit including auxiliaries	24.43.12.30	Unwrought non-alloy zinc (excluding zinc dust, powders and flakes)

NACE4	Product benchmark	Benchmark value	Benchmark unit	Unit of production	Degressivity factor [%]	Product definition	Processes covered by product BM	Relevant Prodcom code	Description
								24.43.12.50	Unwrought zinc alloys (excluding zinc dust, powders and flakes)
24.44	Unwrought refined copper	0.31	MWh/t product	Copper cathodes	Fall back value	Copper cathodes	All processes directly or indirectly linked to the electrolytic refining process, including on-site anode casting where appropriate	24.44.13.30	Unwrought unalloyed refined copper (excluding rolled, extruded or forged sintered products)

1 Introduction and Methodology

1.1 Background

Article 6 of the ETS Directive states that the Commission should adopt State aid guidelines for assessing indirect emission costs compensations' scheme put in place by Member States. Indirect ETS costs stem from the fact that the electricity producers pass the carbon price on to consumers via higher electricity prices.

On 21st September 2020, the Commission adopted the new "Guidelines on certain State aid measures in the context of the system for greenhouse gas emission allowance trading post 2021"[1] (hereinafter referred to as "ETS Guidelines"), which have entered into force on 1st January 2021. In the ETS Guidelines, the Commission identified 10 sectors and 20 subsectors at significant risk of carbon leakage as a result of increased CO2 costs in electricity prices (Table 1.1).

These sectors and subsectors will be eligible to receive compensation for their indirect ETS costs, while the compensation needs to be limited to the minimum necessary to avoid competition distortion.

1.1.1 Electricity consumption efficiency benchmarks in the compensation formula

Article 6 of the ETS Directive states that the aid for indirect ETS costs may be granted based on ex-ante benchmarks of the indirect emissions of CO2 per unit of production.

The benchmark for efficient electricity use (expressed in MWh/t), reflects the fact that companies should only be compensated for electricity consumption based on the most energy efficient installation for a given product category in the EU. Therefore, the electricity consumption efficiency benchmark is the product-specific electricity consumption per tonne of output production achieved by the most electricity-efficient methods of production for the product.

1.1.2 Objective

The objective of this work is to analyse quantitative data regarding the best available technologies implemented in the production process of the subsectors and sectors eligible under the ETS Guidelines, and 1) update existing benchmarks for products eligible under the previous Guidelines, and 2) develop new benchmarks for products not previously listed in the ETS Guidelines.

Furthermore, the ETS Guidelines introduce an automatic degressivity mechanism of the efficiency benchmarks based on Article 10a(2) of the ETS Directive. As such, for products previously eligible, the objective of this work is to develop future annual efficiency benchmark reductions. For products without any existing benchmark under the previous ETS Guidelines, the objective is to develop a fall back average degressivity factor.

[1] Communication from the Commission, Guidelines on certain State aid measures in the context of the system for greenhouse gas emission allowance trading post-2021 (European Commission 2020.

Table 1.1 List of eligible sectors and subsectors according to the revised ETS State aid Guidelines

Eligible sectors (NACE-4 code)	Description
14.11	Manufacture of leather clothes
24.42	Aluminium production
20.13	Manufacture of other inorganic s basic chemicals
24.43	Lead, zinc, and tin production
17.11	Manufacture of pulp
17.12	Manufacture of paper and paperboad
24.10	Manufacture of basic iron and steel and ferro-alloys
19.20	Manufacture of refined petroleum products
24.44	Copper production
24.45	Other non-ferrous metal production
20.16	Manufacture of plastics in primary forms
Eligible subsectors (Prodcom codes)	Description
All 15 subsectors within the casting of iron sectors (24.51)	
20.16.40.15	Polyethylene glycols and other polymer alcohols, in primary forms
24.14.12.10	Glass fibre mats
24.14.12.30	Glass fibre voiles
20.11.11.50	Hydrogen
20.11.12.90	Inorganic oxygen compounds of non-metals

1.2 Methodology

1.2.1 Define the most relevant subsectors

In order to identify the most relevant subsectors in terms of electricity consumption, the first step was to identify the production volume of the individual subsectors using official Prodcom data. Production volume reported in the official data was incomplete for a large part of the subsectors (especially for almost all subsectors of the paper sector) and that the sold production volume had significantly fewer missing data. Consequently, “sold production volume” was used for calculation purposes in the subsequent steps.

Desk research was conducted to determine the specific electricity consumption per produced unit of the respective product, so that the total electricity consumption of the respective subsector could be calculated by multiplying the specific electricity consumption and the production volume. Using the total electricity consumption, the relevant subsectors for each of the nine NACE-4 sectors were ranked.[2] From this, a selection of 36 subsectors was made.

1.2.2 Define or update electricity consumption efficiency benchmarks and applicable annual degressivity factors for products

Relevant technical literature was collected and analysed on electricity consumption benchmarks, expressed in terms of MWh/tonne of output for the 50 products selected (36 subsectors identified in the previous task, and 14 subsectors with existing benchmarks). Electricity consumption efficiency benchmark is defined[3] as the product-specific electricity consumption per tonne of output achieved by the most electricity-efficient method of production for the product considered, taking into consideration the production processes in all countries currently covered by the EU ETS (European Commission 2012b). The approach is therefore based on a Best Available Technology Approach, taking the single most efficient installation as reference.

The following information on processes and their benchmarks was collected:

- The common name of the product
- The NACE code of the eligible sector
- The PRODCOM codes and the relevant description is given for the products under consideration. It must, however, be emphasised that the Prodcom codes may not be a unique descriptor of the product. That is, one Prodcom code may cover more than one product.
- The unit of production, the product definition and the description of the processes covered describe the product to which the benchmark is related to, as well as the process delimitation. The process delimitation will mainly be is based on annotations from sector organisations or BREF documents.

[2] The "Manufacture of leather clothes" sector was not considered relevant, as only one sub-sector would be covered under this sector, which is also not particularly large with an average volume of less than 10 million articles.

[3] Communication from the Commission — Guidelines on certain State aid measures in the context of the greenhouse gas emission allowance trading scheme post-2012 (European Commission 2012b), p. 4–22

- The range of benchmarks reported in literature (minimum, maximum, and average), their source, and relevance to operations in the European Union and associated countries.
- The output of this task was a list of preliminary energy efficiency benchmarks for the relevant subsectors.

1.2.3 Degressivity factor

For the 14 products with electricity benchmarks calculated in 2012, the annual degressivity factor was calculated, i.e. the annual reduction when compared to the newly calculated benchmarks. Based on the data collected, an appropriate average degressivity was determined to be applied to all other subsectors.

1.2.4 Fall back efficiency percentage

When no electricity benchmark can be established for a product, a fall back factor replaces the electricity benchmark. The fall back factor represents a certain percentage of the baseline electricity consumption. Under the previous Guidelines, this percentage was at 80%.

This fall back factor should ensure that processes receiving compensation without an explicit electricity benchmark should be treated, on average, similar to the sectors which have a benchmark. The fall back factor was calculated from the average, over all benchmarked products, of the ratio of the benchmark to average electricity consumption. The calculation considers the 50 benchmarked products (i.e., 36 new subsectors and the 14 subsectors where a previous benchmark existed).

Stakeholder engagement to present and inform the preliminary values for electricity consumption efficiency benchmarks, degressivity factor, and fall back efficiency percentage

Webinars were conducted with industry stakeholders to present preliminary values for the electricity benchmarks, degressivity factor and fall back efficiency percentage. For sectors where no benchmark was recommended, such as non-ferrous metal (outside aluminium; copper; lead, zinc and tin) and the manufacture of leather clothes, no webinars were conducted.

- 17 May 2021: Pulp (17.11), Paper and Paperboard (17.12)
- 19 May 2021: Refined Petroleum Products (19.20), and Inorganic Basic Chemicals (20.13)
- 21 May 2021: Basic iron and steel and ferro-alloys (24.10), Aluminium (24.42), Lead, zinc and tin production (24.43), and Copper (24.44)

In each webinar, the calculation methodology and the associated results were presented. Feedback, including inputs, insights, and commentary, provided by industry stakeholders was reviewed, and synthesised into a coherent and robust set of actions for each subsector, e.g., confirmation of approach and preliminary values (no further action), new insights (revise assumptions and values), or new data available (follow-up with stakeholders). The following sections present the final energy efficiency benchmarks, degressivity factors, and fall-back efficiency percentages for each of the relevant subsectors.

2 Proposed benchmarks

2.1 Manufacture of pulp (17.11)

Due to the importance of the sector in the European Union, the following sections detail the electricity efficiency benchmarks developed for the pulp sector.

2.1.1 Selection of relevant subsectors for additional benchmarks

Four Prodcom codes are listed under the pulp 17.11 NACE Code. Benchmarks were developed for all four subsectors to ensure fairness across sectors (i.e., omission of a subsector for which the fallback benchmark is then applied), and consistency with the paper sector, for which benchmarks were developed for all subsectors.

2.1.2 Revised and new benchmarks

- **Prodcom codes:**
  - 17.11.11.00
  - 17.11.12.00
  - 17.11.13.00
  - 17.11.14.00
- **Production volume**: See Table 2.1 (Note: production volumes reported by the Confederation of European Paper Industries (Cepi) and Prodcom differ)
- **Current benchmark**: None
- **Main production countries in the EU:** There were 171 pulp mills listed in the EU ETS in 2020. According to Cepi statistics, Sweden and Finland each account for almost one third of the production volume, followed by Portugal and Germany with about 7% and 6% of the production volume, respectively. Table 2.1 shows the average sold production volume of the relevant subsectors in pulp production from the years 2017-2019 in t 90% sdt in the EU27 according to Prodcom data. The subsector “Chemical wood pulp, soda or sulphate, other than dissolving grades” is by far the most important subsector with a sold production volume of more than 15 million tons 90% sdt. A precise analysis of the Prodcom data in terms of production volume in the individual Member States was not possible, since most Member State data is marked confidential.

Table 2.1 Production volume and electricity consumption of all Prodcom codes of the pulp sector in the EU27

Prodcom Code	Prodcom Definition	Unit[4]	Volume 2017-2019
17.11.11.00	Chemical wood pulp, dissolving grades	t 90% sdt	1,975,170
17.11.12.00	Chemical wood pulp, soda or sulphate, other than dissolving grades	t 90% sdt	15,640,971
17.11.13.00	Chemical wood pulp, sulphite, other than dissolving grades	t 90% sdt	442,223

[4] t 90% sdt: A unit of mass equal to one thousand kilograms of a named substance that is 90% dry.

Prodcom Code	Prodcom Definition	Unit[4]	Volume 2017-2019
17.11.14.00	Mechanical wood pulp; semi-chemical wood pulp; pulps of fibrous cellulosic material other than wood	t 90% sdt	1,649,890

Source: Own estimation based on Eurostat, Prodcom data

- **Data availability:** Data on specific electricity consumption in the pulp sector is usually not available by Prodcom logic, but by process. It is important to note that the values shown in the following section are rough estimates. Electricity consumption can vary greatly between installations due to the characteristics of the equipment. Roughly, pulp production can be divided into three main processes: chemical pulp process, mechanical pulp process and recovered paper process. These can in turn be subdivided into different processes, but there is a big difference between these three main processes in terms of specific electricity consumption. The mechanical pulp process has a significantly higher electricity consumption than the chemical pulp process or the recovered paper process.

2.1.2.2 Chemical pulp

- **PRODCOM codes:**
  - 17.11.11.00
  - 17.11.12.00
  - 17.11.13.00
  - 17.11.14.00
- **Process and electricity consumption:** The chemical pulp process includes three of the four subsectors (17.11.11.00, 17.11.12.00, 17.11.13.00) and can roughly be divided into sulphate pulp (17.11.12.00) and sulphite pulp (17.11.13.00). Prodcom code 17.11.11.00 is dissolving pulp, which can be produced by either the sulphate or sulphite process. The difference between dissolving pulp and pulp is the higher purity (cellulose content). This is necessary for use, e.g., in chemical processes.

  The main process for pulp production is the sulphate process. It has by far the largest production volume and new modern plants are almost exclusively sulphate process plants. The importance of sulphite pulp is declining as the advantages of this process become less and less important, while the disadvantages remain. On the one hand, bleaching is less complex and the odor is significantly lower than in the sulfate process. But on the other hand, the sulphite process damages the fibers more severely, which affects the strength properties of the paper. Furthermore, the sulphite process can only be used for hardwoods. In the meantime, odor formation no longer plays a special role in the sulphate process. All this contributes to the fact that almost no new sulphite process plants are built. Since the sulphate process is the main process and differences to the sulphite process in terms of specific electricity consumption are not expected to be particularly large, a benchmark for the sulphate process was developed. For the dissolving grades a benchmark was developed based on RISI data. Fleiter et al. (2013) identify 11 process steps in which electricity is consumed (see Table 2.2). In total, they estimate the electricity consumption in the production of one t 90% sdt of sulphate pulp at 639 kWh. Drying, washing and screening, and bleaching are the most electricity-intensive steps.

This value is lower than the 2015 BREF documents (Suhr et al. 2015), which give a range of 700 to 800 kWh/t 90% sdt. (Moya and Pavel 2018) draw on data from the RISI database and give a range of 443 to 1398 with a mean value of about 888 kWh/ t 90% sdt. As with the emission benchmarks, this report also distinguishes between short and long fibre kraft pulp, although the differences between these two categories in terms of the average and maximum values are rather small. The lowest value for long fibre kraft pulp is 443 kWh/t 90% sdt, whereas the minimum for short fibre kraft pulp is 575 kWh/t 90% sdt. Other sources, such as Climate Strategies or Navigant (Roth et al. 2016; Healy and Schumacher 2012; Godin 2019), on the sulfate pulp process suggest similar ranges of electricity consumption.

- **Stakeholder feedback:** Stakeholder feedback was provided by Cepi. Cepi proposed not to apply just one benchmark for the chemical pulping processes. Cepi provided data from the RISI database that suggests that a benchmark value of 0.904 MWh/t 90% sdt seems appropriate for 17.11.11. Furthermore, Cepi recommended special pulp under 17.11.11. should not be covered by the benchmark, but the fallback approach be applied instead. The fallback approach would be used in this case because no plant-specific information could be provided due to the small number of plants in Europe. Cepi argued that due to the high cellulose content, the production has about 3-4 times higher electricity consumption than the other products under this Prodcom code.

  For code 17.11.12, Cepi recommended that kraft pulp gets its own benchmark value. For this purpose, Cepi provided data from the RISI database showing the specific electricity consumption for kraft pulp. The most efficient plant in the kraft pulp process shows 0.329 MWh/t 90% std. However, Cepi recommended setting the value to the second most efficient plant, which has a value of 0.547 MWh/t 90% std. Cepi argued that the investment made by this efficient plant was one of the largest ever made in the forest industry in Finland and included the complete redesign of the mill. Such a large investment would be beyond what most plant operators can handle, and best available technology means that it is also economically available to plant operators, Cepi continues.
- **Benchmark:** Based on the principle that the benchmark should be based on the most efficient plant, we recommend a benchmark value of <u>0.443 MWh/t 90% sdt</u> pulp production by chemical process for the sectors 17.11.13 and to the *"semi-chemical wood pulp"* in sector 17.11.14. We follow Cepi's recommendation to set a separate benchmark for 17.11.12 and recommend a value based on the most efficient plant at 0.329 MWh/t 90% sdt. Cepi's recommendation to go for the second lowest value contradicts the rule of using the most efficient plant as a basis for the benchmark. Since this efficiency level could also be achieved by other plants, there is insufficient reason to set the benchmark based on the second most efficient plant.

  For sector 17.11.11, based on the data provided by Cepi, a benchmark value of <u>0.904 MWh/t 90% sdt is recommended</u>. For specialty pulps, we recommend using the fallback approach, if possible. If there are monitoring difficulties so that the specialty pulps cannot be identified, we recommend applying the benchmark value of 0.904 MWh/t 90% sdt to the whole Prodcom code 17.11.11.

  <u>17.11.11:</u> 0.904 MWh/t 90% sdt (fallback approach for specialty pulps)
  <u>17.11.12:</u> 0.329 MWh/t 90% sdt
  <u>17.11.13:</u> 0.443 MWh/t 90% sdt
  <u>17.11.14:</u> 0.443 MWh/t 90% sdt (only for semi-chemical wood pulp)
- **Average consumption:** Average specific electricity consumption for the proposed benchmarks.

  <u>17.11.11:</u> 1.15 MWh/t 90% sdt
  <u>17.11.12:</u> 0.708 MWh/t 90% sdt

17.11.13: 0.888 MWh/t 90% sdt
17.11.14: 0.888 MWh/t 90% sdt (only for semi-chemical wood pulp)

Table 2.2 Electricity consumption in the process steps in the sulphate pulp process

Process step	% kWh/t 90% sdt
Wood treatment	7%
Cooking	10%
Washing and Screening	14%
Delignification	7%
Bleaching	13%
Drying	16%
Thickening by evaporation	4%
Boiler	9%
Lime kiln	3%
Other	17%
Total	**100%**

Source: Own calculation based on Fleiter et al. (2013)

2.1.2.3 Mechanical pulp process

- **PRODCOM codes:**
  - 17.11.14.00 where applicable
- **Process and electricity consumption:** The mechanical pulp process includes only parts of the subsector 17.11.14.00 (see proposed benchmark for recovered paper below). Mechanical pulp production is divided into various processes such as the groundwood process, the pressure groundwood process, the refiner mechanical pulp process, the thermo-mechanical pulp process and the chemo-thermo-mechanical pulp process. All these processes have different electricity requirements. The variants produce products with different properties and can only be substituted to a very limited extent. The wide spread in energy intensity is not primarily due to different efficiency levels. Rather, several factors overlap, such as the degree of grinding or the use of different types of wood. Mechanical pulp is produced from wood by mechanical pulping processes. The wood is crushed by mechanical shear forces. A large part of the energy introduced into the wood is dissipated as heat in the process. In the wood pulping process, about 95% of the mechanical energy introduced is converted into heat. The heat generated is so enormous that the wood must be moistened to prevent it from burning during the grinding process. Thus, a lot of electricity, but no external heat, is required. Unlike other pulping processes, much of the lignin remains in the pulp and yields are much higher, typically 900 kg of wood pulp per ton of wood or more. The high lignin content causes the paper to yellow more quickly than chemical

pulp-based paper. Also, the tear strength is lower because the wood fibers are damaged during mechanical pulping. Furthermore, the capacity-specific investments are significantly lower than in pulp production and production almost always takes place at the paper production site (Fleiter et al. 2013).
The lowest electricity demand is found in the groundwood process, which requires about 2000 kWh/t 90% sdt (Fleiter et al. 2013). Table 2.3 shows the electricity consumption over the process steps of the mechanical pulping process. It can be seen directly that the grinding explains the high electricity consumption compared to the chemical pulp process. Overall, a specific electricity demand of about 2,000 kWh/t 90% sdt of wood pulp is assumed. Different values from the BREF document (Suhr et al. 2015) show similar levels, with some of the BREF data showing lower values around 1,300 kWh/t 90% sdt. In contrast, other sources such as from (Healy and Schumacher 2012) tend to show higher values of around 2,200 kWh/t.
Since, in practice, recovered paper is often added to mechanical pulp, which can significantly reduce the specific electricity consumption and thus the comparability of the different products produced, it is difficult to define a single benchmark value. For example, the BREF document (Suhr et al. 2015) in Table 5.17 gives a wide range of specific electricity consumption, which is also highly dependent on the share of mechanical pulp.

- **Stakeholder feedback:** Cepi did not submit any specific adjustment recommendations for this benchmark.
- **Benchmark:** Due to the wide range of specific electricity consumption given in the literature, which is also due to the share of mechanical pulp in the final product, and due to the lack of information from stakeholders, we recommend using the fallback approach for the mechanical pulping process.
- **Average consumption:** The average specific electricity consumption is 2.295 MWh/t 90% sdt.

Table 2.3 Electricity consumption in the process steps in the mechanical wood pulp process

Process step	% kWh/t 90% sdt
Wood treatment	3%
Refining	90%
Washing	3%
Bleaching	5%
Heat recovery	0%
Total	**100%**

Source: Own calculation based on Fleiter et al. (2013)

2.1.2.4 Recovered Paper

- **Prodcom codes:**
  - 17.11.14.00 where applicable
- **Process and electricity consumption:** Recovered Paper, like the mechanical pulp process, falls under code 17.11.14.00. In addition to the benchmark shown above for the mechanical pulp process, the following benchmark addresses *"pulps*

of fibrous cellulosic material other than wood" and is based on the electricity demand of the recovered paper process. The reason for two benchmarks is that the Prodcom code is a mixture of different products and the mechanical pulp process has significantly higher electricity requirements than other processes. Recovered paper is mainly used in the newsprint and packaging sectors, but also in the hygiene sector. Depending on the intended use of the recovered paper stock, the required properties and thus the preparation process differ. This is particularly true with regard to the optical properties. Here, a large part of the printing inks is removed (so-called deinking). If high demands are placed on the recovered paper stock, the preparation can become relatively complex. The most important and frequently used process steps are shown in Table 2.4. It shows the electricity consumption across the process steps. It can be seen that de-inking in particular is more electricity-intensive. In sum, however, only little electricity is consumed in the entire process. Data from (Moya and Pavel 2018) from the RISI database also show a value of 260 kWh/t 90% sdt for the most efficient plant, an average value of 800 kWh/t 90% sdt and a maximum of 3,126 kWh/t 90% sdt. Other sources such as (Healy and Schumacher 2012) or (Godin 2019) also show values around 300 kWh/t 90% sdt and lower.

- **Stakeholder feedback:** Cepi provided two comments for this benchmark. First, Cepi recommended a second benchmark for recovered paper, which should be applied to deinked recovered paper, as the deinking process has a high electricity consumption and paper recycling should not be penalized. Cepi provided data on this but only showed one value of 390 kWh/t 90% sdt. Furthermore, the thermal energy consumption for de-inked recovered paper is about 3 times higher than for non-de-inked, whereas the electricity consumption is only about twice as high. Within the emissions benchmarks, no distinction was made between the two types of recovered paper. Cepi did not provide an explanation why this is more important for the electricity efficiency benchmarks than for the emissions benchmarks. Secondly, Cepi recommended that all other pulps classified as *"pulps of fibrous cellulosic material other than wood"* should be assigned to the respective benchmark under which the substituted product is classified. In most cases they would replace high-value products such as short and long fibre kraft.
- **Benchmark:** Based on the principle that the benchmark should be based on the most efficient plant, we recommend a benchmark value of <u>0.260 MWh/t 90% sdt recovered paper and 0.390 MWh/t 90% sdt for deinked recovered paper.</u> For all pulps falling under *"pulps of fibrous cellulosic material other than wood"* that are not recovered paper, the benchmark of the substituted product should be applied. For example for pulps which are substituting sulphate pulps the benchmark of 17.11.12 should be used. If such a fine-grained distinction creates difficulties in monitoring, we recommend to set one benchmark for recovered paper and for *"pulps of fibrous cellulosic material other than wood"* at <u>0.260 MWh/t 90% sdt</u>.
- **Average consumption:** The average specific electricity consumption is <u>0.800 MWh/t 90% sdt.</u>

Table 2.4 Electricity consumption in the process steps in the recovered paper process

Process step	**% kWh/t 90% sdt**
Substance dissolving	15%
Screening and cleaning	19%

De-inking	31%
Thickening and dispersing	15%
Bleaching	12%
Other	8%
Total	**100%**

Source: Own calculation based on Fleiter et al. (2013)

2.1.3 General issues in setting benchmarks for the pulp industry

In pulp production, the range of specific electricity consumption is very high. According to the literature (e.g. Fleiter et al. (2013)), these differences are often due to specific requirements and not necessarily to the efficiency of a plant. This means that by setting restrictive benchmarks, some plants would receive significantly lower compensation payments than in the case of the fallback approach and at the same time would not be able to improve their situation with investments in efficiency measures. However, it can be seen that in the case of thermal energy use, the spread is even larger. That is, in the case of the calculation of free allocations of allowances for the EU ETS this problem seems to exist as well. The extent to which restrictive electricity efficiency benchmarks therefore may have a negative impact on the European pulp industry could not be clarified within the scope of this project. Furthermore, there might be problems when monitoring production volumes since the recommended benchmarks require higher levels of detail than the Prodcom codes. Therefore, the fallback approach may also be used to calculate the compensation payments instead of the benchmarks proposed above.

2.2 Manufacture of paper and paperboard (17.12)

No electricity efficiency benchmarks exist in the paper sector to date. Due to the importance of the sector in the European Union, the following sections present the proposed electricity efficiency benchmarks for the paper sector.

2.2.1 Selection of relevant subsectors for additional benchmarks

53 Prodcom codes are listed under the paper 17.12 NACE Code. It was decided to develop benchmarks that will cover most of the subsectors. The main reason for this is that the existing data on specific electricity consumption in production processes is not detailed enough to distinguish between the 53 different products. In addition, the existing data sets show a wide range of specific electricity consumption for the individual end products. For example, electricity consumption in different plants sometimes varies widely even when manufacturing the same product, and in certain processes less efficient plants consume up to 8 times more electricity than efficient plants. An attempt is therefore made to develop benchmarks for the most important paper categories. For the paper industry, this has the advantage that (almost) all the production volume within NACE code 17.12 will be assigned with benchmarks specifically for the paper industry and there is no need to rely on a fallback benchmark.

2.2.2 Revised and new benchmarks

- **Prodcom codes:**
  - All codes under 17.12
- **Production volume**: See Table 2.5 (Note: Production volumes reported by Cepi and Prodcom differ)
- **Current benchmark:** None
- **Main production countries in the EU:** In 2020, 549 paper mills were listed in the EU ETS. This number is significantly lower than Cepi's key statistics, which show just under 1,300 paper mills. Based on key statistics, the largest producers in Europe are Germany with just under a quarter of total production, followed by Finland, Sweden and Italy with about 10%. Table 2.5 shows the average sold production volume of the most relevant subsectors in paper production for the years 2017-2019 in t in the EU27 according to Prodcom data. The subsector "Recycled fluting and other fluting" is the most important subsector with a sold production volume of more than 9 million tons. A precise analysis of the Prodcom data in terms of production volume in the individual Member States is not possible, as for most Member States the data are marked confidential.

Table 2.5 Production volume of the most relevant Prodcom codes of the paper sector in the EU27

Prodcom Code	Prodcom Definition	Unit	Volume 2017-2019
17.12.34.00	Recycled fluting and other fluting	t	9,325,317
17.12.73.36	Coated bases for paper and paperboard of a kind used for: photo-, heat- and electro-sensitive paper and having 10 % or less of mechanical and chemi-mechanical fibres, and paper and paperboard of a kind used for writing, printing or other graphic purposes, which weighs less than or equal to 150 g/m²	t	6,754,173
17.12.35.20	Uncoated testliner (recycled liner board), weight ≤ 150 g/m², in rolls or sheets	t	6,493,248
17.12.11.00	Newsprint in rolls or sheets	t	5,684,909
17.12.14.39	Graphic paper, paperboard : mechanical fibres ≤ 10 %, weight ≥ 40 g/m² but ≤ 150 g/m², sheets	t	4,923,658
17.12.14.70	Graphic paper, paperboard : mechanical fibres > 10 %	t	4,071,926
17.12.14.35	Graphic paper, paperboard : mechanical fibres ≤ 10 %, weight ≥ 40 g/m² but ≤ 150 g/m², in rolls	t	3,520,989
17.12.31.00	Uncoated, unbleached kraftliner in rolls or sheets (excluding for writing, printing or other	t	3,432,868

Prodcom Code	Prodcom Definition	Unit	Volume 2017-2019
	graphic purposes, punch card stock and punch card tape paper)		
17.12.73.60	Lightweight coated paper for writing, printing, graphic purposes, m.f. > 10 %	t	3,430,164
17.12.73.75	Other coated mechanical graphic paper for writing, printing, graphic purposes, m.f. > 10 %, rolls	t	2,924,229
17.12.42.80	Other uncoated paper and paperboard, in rolls or sheets, weight ≥ 225 g/m² (excluding products of HS 4802, fluting paper, testliner, sulphite wrapping paper, filter or felt paper and paperboard)	t	2,748,964
17.12.79.55	Multi-ply paper and paperboard, coated, with one bleached outer layer	t	2,681,270
17.12.35.40	Uncoated testliner (recycled liner board), weight > 150 g/m², in rolls or sheets	t	2,304,975
17.12.78.50	Multi-ply paper and paperboard, coated, others	t	2,057,587
17.12.33.00	Semi-chemical fluting	t	2,025,442

Source: Own estimation based on Eurostat, Prodcom data

- **Data availability:** Data on specific electricity consumption in the paper sector is usually not available by Prodcom logic, but mostly at a broader product level. It is important to note that the values shown in the following section are rough estimates. Electricity consumption can vary greatly between installations due to the characteristics of the equipment. Other factors such as the type of paper produced or whether it is an integrated plant (pulp and paper production at one site) also play a role.
  In the literature on paper production, there is hardly any detailed data from which the specific electricity consumption for the 53 Prodcom codes can be identified. Instead, the literature usually only distinguishes between 3 or 5 paper types and identifies the specific energy and electricity consumption for these. Common categories are newsprint, graphic papers, tissue papers, packaging papers or special papers. Given the available data, a different approach for the paper sector was used. That is, selecting a few subsectors for which a benchmark is then developed was not robust due to the low level of detail in the available data, as the benchmark developed for this one subsector could just as easily be given to other very similar subsectors. Therefore, the highest possible level of detail in the available data to cover the largest possible number of subsectors was used. The data always shows the electricity consumption of the process and not the electricity that the plants draw from the grid. This is important to mention because many plants operate their own small power plants and thus produce a significant part of the electricity used themselves.

- **Production process:** After the pulp material has been produced in the pulp sector, the actual paper production begins. Three basic production stages can be distinguished: preparation of the stock, the paper machine, and paper coating (Fleiter et al. 2013). Since both production on the paper machine and the finished product place exact requirements on the properties of the stock mixture used, the aim and purpose of stock preparation is to provide a constant stock flow. In order to guarantee the pulp the properties required for the respective paper grade, it is often reground in a refiner at the paper mill. Depending on the fiber material and paper grade, this production step can be very energy-intensive. The paper machine is then used in the following. It transforms the fiber suspension into a paper roll in the following steps: paper headbox, sieve section, press section, dryer section and reel.
  Roughly speaking, the fiber suspension is placed on the sieve with a dry content of about 1%, where it is already brought to a dry content of about 15-25%. This is followed by drying using presses. In this step, modern plants achieve a dry content of about 55%. The remaining water is then evaporated from the paper with thermal drying. Table 2.6 is based on (Fleiter et al. 2013) and roughly shows the electricity consumption per process step, although the numbers are heavily dependent on the paper type. Detailed data per paper type and process step were not available.

Table 2.6 Rough estimation of electricity consumption in the paper production process steps

Process step	% kWh/t
Dissolving, pulper	2%
Refiner	25%
Preparation	6%
Headbox	8%
Sieve section/sheet forming	6%
Pressing	19%
Thermal drying	17%
Coating and finishing	8%
Other	11%
Total	**100%**

Source: Own calculation based on Fleiter et al. (2013)

- **Selection of subsectors and forming paper categories:** As mentioned above, the specific electricity consumption in paper production can vary greatly per paper type and, at the same time, the available data do not allow for a great degree of detail, an approach is presented below to assign the Prodcom codes to the available data of the specific electricity consumption.
  One data source that is useful in this context is the data from the RISI database (Moya and Pavel 2018), which has already been processed by the Joint Research

Centre (JRC) for the logic of the emission benchmarks for the EU ETS. The database contains statistical data from European paper mills. In addition to the specific thermal energy consumption, these also show the specific electrical energy consumption according to the paper categories of the emission benchmarks. Seven emissions benchmarks exist for the paper sector (see the list below). The logic of assigning the Prodcom codes to the emission benchmark categories can be found in the guidance document (European Commission 2020) and in Table 2.7.

- Newsprint
- Uncoated fine paper
- Coated fine paper
- Tissue
- Testliner and fluting
- Uncoated carton board
- Coated carton board

Table 2.7 Assignment of Prodcom codes to the logic of the emission benchmarks according to the guidance document.

Newsprint	Uncoated fine paper	Coated fine paper	Tissue	Testliner and fluting	Uncoated carton board	Coated carton board
17.12.11.00	17.12.12.00	17.12.73.35	17.12.20.30	17.12.33.00	17.12.31.00	17.12.75.00
	17.12.13.00	17.12.73.37	17.12.20.55	17.12.34.00	17.12.32.00	17.12.77.55
	17.12.14.10	17.12.73.60	17.12.20.57	17.12.35.20	17.12.42.60	17.12.77.59
	17.12.14.35	17.12.73.75	17.12.20.90	17.12.35.40	17.12.42.80	17.12.78.20
	17.12.14.39	17.12.73.79	17.22.11.20*		17.12.51.10	17.12.78.50
	17.12.14.50	17.12.76.00	17.22.11.40*		17.12.59.10	17.12.79.53
	17.12.14.70		17.22.11.60*			17.12.79.55
			17.22.11.80*			
			17.22.12.20*			
			17.22.12.30*			
			17.22.12.50*			
			17.22.12.90*			

Source: Own presentation based on (European Commission 2019)
** Excluded from electricity efficiency benchmark because sector 17.22 is not eligible for electricity efficiency benchmarks.*

■ The official assignment shows two problems in the context of electricity benchmarks.

1. Under the tissue paper benchmark are also subsectors for which State Aid payments are not provided (NACE 17.22).
2. 20 subsectors of the 53 subsectors are not assigned to any emissions benchmark.

- The first problem does not seem to be an issue, as the electricity benchmark simply will not cover these subsectors from NACE 17.22.

  For the 20 subsectors that are not assigned an emissions benchmark, the fallback efficiency percentage should be applied. Table 2.8 provides an overview of these 20 subsectors.

Table 2.8 Subsectors not covered under the developed benchmarks

Prodcom Code	**Prodcom Definition**
17.12.41.20	Uncoated, unbleached sack kraft paper (excluding for writing, printing or other graphic purposes, punch card stock and punch card tape paper)
17.12.41.40	Uncoated sack kraft paper (excluding unbleached, for writing, printing or other graphic purposes, punch card stock and punch card tape paper)
17.12.41.60	Uncoated kraft paper and paperboard weighing ≤ 150 g/m² (excluding kraftliner, sack kraft paper, for writing, printing and other graphic purposes, etc.)
17.12.41.80	Creped or crinkled sack kraft paper; in rolls or sheets
17.12.42.20	Sulphite wrapping paper in rolls or sheets
17.12.42.40	Other uncoated paper and paperboard, in rolls or sheets, weight ≤ 150 g/m² (excluding products of HS 4802, fluting paper, testliner, sulphite wrapping paper, filter or felt paper and paperboard)
17.12.43.30	Uncoated filter paper and paperboard in rolls or sheets
17.12.43.60	Uncoated felt paper and paperboard in rolls or sheets
17.12.44.00	Cigarette paper (excluding in the form of booklets or tubes), in rolls > 5 cm wide
17.12.60.00	Vegetable parchment, greaseproof papers, tracing papers and glassine and other glazed transparent or translucent papers
17.12.71.00	Composite paper and paperboard in rolls or sheets (including strawpaper and paperboard) (excluding surface coated or impregnated)
17.12.72.00	Paper and paperboard, creped, crinkled, embossed or perforated
17.12.73.36	Coated bases for paper and paperboard of a kind used for: photo-, heat- and electro-sensitive paper and having 10 % or less of mechanical and chemi-mechanical fibres, and paper and paperboard of a kind used for writing, printing or other graphic purposes, which weighs less than or equal to 150 g/m²
17.12.74.00	Kraft paper (other than that of a kind used for writing, printing or other graphic purposes), coated with kaolin or with other inorganic substances

Prodcom Code	Prodcom Definition
17.12.77.10	Tarred, bituminised or asphalted paper and paperboard in rolls or sheets
17.12.77.33	Self-adhesive paper and paperboard in rolls or sheets
17.12.77.35	Gummed paper and paperboard in rolls or sheets (excluding self-adhesives)
17.12.77.70	Paper and paperboard in rolls or sheets, coated, impregnated or covered with wax, paraffin wax, stearin, oil or glycerol
17.12.77.80	Other paper, paperboard, coated..., n.e.c.
17.12.79.70	Paper/paperboard in rolls or sheets, coated on one/both sides with kaolin or other inorganic substances excluding of a kind used for any graphic purposes, multi-ply paper/paperboard

- **Stakeholder feedback:** Cepi proposed for the coated and uncoated fine paper categories to set the benchmark values at 0.538 and 0.646 MWh/t, respectively. The underlying data had been provided and seemed plausible. However, it was not clear why the RISI data from JRC and Cepi differ from each other, although it might be due to different base years. Furthermore, Cepi suggested a separate benchmark for specialty papers of this category.
For the tissue paper category, an adjustment of the proposed benchmark to 0.925 MWh/t was proposed. The requested data were provided. Also for this case, the reasons for the deviation of the data could not be identified. However, Cepi's assumption that the JRC data in this case was mistakenly calculated on capacity and not on actual production was negated by JRC. Furthermore, Cepi suggested that Through Air Dried (TAD) tissue should not be covered by the benchmark and in this case the logic of the emission benchmarks should be followed.

  Cepi provided data for the Coated carton board category. This showed the lowest specific electricity consumption at 0.403 MWh/t (proposed benchmark by Cepi 0.431 MWh/t). Cepi argued that the lowest value is a clear outlier and therefore the benchmark should be based on the second most efficient plant (0.554 MWh/t). Cepi assumed that this most efficient plant is incorrectly assigned to Coated carton board, as this plant is listed under specialty paper and board in Cepi's statistics, not under carton board.

  In addition, Cepi suggested a category for kraft paper, which should also include specialty papers. For this purpose, data was provided - the most efficient plant had a specific consumption of 0.578 MWh/t. Cepi suggested to use the value of the second most efficient plant which was 0.618 MWh/t. Cepi's rationale is that the most efficient plant is an outlier.
- **Benchmarks:** As in pulp production, the range of specific electricity consumption between plants is also very large in paper production. According to the literature (e.g. Fleiter et al. (2013)), these differences are often due to specific requirements and not necessarily to the efficiency of a plant. This means that by setting restrictive benchmarks, some plants would receive significantly lower compensation payments than in the case of the fallback approach and at the same time would not be able to improve their situation with investments in efficiency measures. However, it can be seen that in the case of thermal energy use, the spread is even larger. That is, in the case of the calculation of free allocations of allowances for the EU ETS this problem seems to exist as well.

The extent to which restrictive electricity efficiency benchmarks therefore have a negative impact on the European paper industry could not be clarified within the scope of this project. Therefore, the fallback approach is also an option to be used to calculate the compensation payments instead of the benchmarks proposed below.

The RISI data from Moya und Pavel (2018) and the RISI data provided by Cepi are considered suitable sources as benchmark values for several reasons. The data is based on statistical data from European mills, it shows a range and thereby the minimum, the maximum and the average value, and it applies paper categories that are already used for emission benchmarks.

We recommend that the benchmark categories as well as the assignment of the products to the categories should strictly follow the rules on emission benchmarks (only exception should be tissue paper, which falls under NACE 17.22, as this NACE code is not State Aid eligible.). This provides clarity and avoids confusion with regard to the recording and monitoring of production volumes for emissions in the EU ETS as well as for compensation payments. For kraft and specialty papers that are assigned a heat benchmark in the logic of the emission benchmarks, we do not follow Cepi's recommendation to develop a benchmark for kraft paper. As described above, we recommend to strictly follow the rules of the emission benchmarks. Since no emissions benchmark exists for kraft paper, no electricity efficiency benchmark will be developed for this category either. Thus, the fallback approach should be applied for all paper categories that use the heat benchmark under the emissions benchmarks.

Based on the logic that the most efficient plant defines the benchmark value, the minimum value from the RISI data is always proposed as the benchmark value for the paper categories. It is not recommended to follow Cepi's recommendation to use the second best plant in some paper categories, because it was not clear why other plants could not achieve this value as well. In cases where the Cepi data differs from the JRC data, we recommend using the Cepi data as this is likely to be more up-to-date than the JRC data. Table 2.9 gives an overview of the values. For all paper grades that are not covered by an emission benchmark, the fallback approach is applied.

Table 2.9 Proposed benchmark by paper category

Category	**Proposed Benchmark value MWh/t**	**Average specific electricity consumption**	**Max. specific electricity consumption**
Newsprint	0.801	1.231	2.457
Uncoated fine paper	0.645	1.484	3.445
Coated fine paper	0.538	1.238	2.329
Tissue	0.925	1.215	3.347
Testliner and fluting	0.260	0.497	0.960
Uncoated carton board	0.268	0.447	1.425
Coated carton board	0.403	1.193	1.640

Source: Numbers are minimum and average values from RISI and JRC

2.3 Manufacture of refined petroleum products (19.20)

A petroleum refinery utilises a set of process units that convert relatively low-value liquid hydrocarbons (e.g., crude oil) into more valuable products such as gasoline, diesel, and jet fuel by modifying the hydrogen-to-carbon ratio of the various feeds in process units. The distillation process separates the crude into groups of molecules with a particular boiling temperature range. Each group is sent to different process units, where catalytic and thermal processes modify the carbon/hydrogen bonds and ratios of hydrocarbons while eliminating undesired components such as sulfur and nitrogen. Each refining unit has a different energy requirement depending on feedstock and end-product requirements and specifications. Part of the energy demand is met by combustion of intermediate refining products (e.g., fuel gas and catalytic coke), while the remaining energy requirement is satisfied with electricity, steam, and natural gas.

Electricity can be purchased from the grid or generated on-site from turbines (e.g., combined heat and power) using high pressure steam or fuel gas. Electric motors are used throughout the refinery and represent over 80% of all electricity use in the refinery. The major applications are pumps (60% of all motor use), air compressors (15% of all motor use), fans (9%), and other applications (16%). (US EPA 2005)

In 2017, Europe had 87 active refineries, with a total capacity of 13.6 million barrels of crude per day (Concawe 2019). Refineries operate primarily to produce transportation fuels (gasoline, jet fuel, diesel, etc.) but they also produce other, less commercially important by-products, such as liquefied petroleum gas (LPG) (i.e., 19.20.31: Propane and butane, liquefied) and fuel oil. Consequently, their process efficiencies are tuned to their primary value products, or in the case of LPG (a lighter product) its production in refineries stays fairly constant only depending on the type of crude being processed and the refinery configuration.

Seventeen Prodcom codes are listed under the Manufacture of Refined Petroleum Products, 19.20 NACE Code.

The sector is characterized by fuel-and-electricity exchangeability, and so has benchmarks for free allocation of emission allowances. These are detailed in Commission Implementing Regulation (EU) 2021/447. Furthermore, the Commission has calculated the associated annual degressivity rate for refined petroleum products.

Based on this, the development of another product electricity efficiency benchmarks for refined petroleum products is not required, and we recommend to use the existing benchmark developed in the Commission Implementing Regulation (EU) 2021/447.

2.4 Inorganic basic chemicals (20.13)

Different from some other sectors in this report, the basic inorganic chemicals sector is very heterogeneous and very different reaction routes, reactors, methods and processes are used to produce the chemicals. Some of the chemicals are manufactured in co-production processes that often produce one main product and one or more by-products. For the development of an electricity benchmark, it is therefore crucial to define beforehand how co-production will be handled. As such, electricity consumption in production is always and completely attributed to the main product. Thus, by definition, no electricity is consumed in the production of by-products. By-products are therefore not benchmarkable under this assumption.

2.4.1 Selection of relevant subsectors for additional benchmarks

For the basic inorganic chemicals sector, the production volume of the largest subsectors in the EU27 is shown in Table 2.10.

Table 2.10 Production volume (average of sold volume 2017-2019) of the most relevant Prodcom codes of the inorganic basic chemicals sector in the EU27

Prodcom Code	Prodcom Definition	Unit	Volume 2017-2019
20.13.24.34	Sulphuric acid; oleum	t H_2SO_4	11,235,259
20.13.25.27	Sodium hydroxide in aqueous solution (soda lye or liquid soda)	t NaOH	7,078,039
20.13.43.10	Disodium carbonate	t Na_2CO_3	6,743,888
20.13.41.65	Sulphates (excluding those of aluminium, barium, magnesium, nickel, cobalt, titanium)	t	6,141,659
20.13.43.40	Calcium carbonate (precipitated)	t	6,072,119
20.13.21.11	Chlorine	t	3,999,667
20.13.24.13	Hydrogen chloride (hydrochloric acid)	t HCl	3,405,866
20.13.31.39	Other chlorides n.e.s.	t	2,789,354
20.13.52.50	Distilled and conductivity water and water of similar purity	t	2,778,434
20.13.43.20	Sodium hydrogencarbonate (sodium bicarbonate)	t	1,817,838
20.13.66.00	Sulphur (excluding crude, sublimed, precipitated and colloidal)	t	1,655,227
20.13.21.30	Carbon (carbon blacks and other forms of carbon, n.e.c.)	t	1,621,706
20.13.62.40	Silicates; commercial alkali metal silicates	t SiO_2	1,446,912
20.13.21.20	Sulphur, sublimed or precipitated; colloidal sulphur	t	1,405,003

Source: Eurostat, Prodcom data

Of the 14 subsectors listed here, Chlorine (20.13.21.11) has an existing electricity benchmark and Carbon black (20.13.21.30) has a fuel switch benchmark. Which is why they are not considered when selecting new sectors for an electricity benchmark.

Other subsectors can also be excluded from the list because they are by-products from the production of other chemicals. For example, sulphates (20.13.41.65) such as Glauber's salt (Na_2SO_4) are produced as a by-product in the extraction of sodium chloride, soda ash, viscose fibers or chlorides (20.13.31.39) such as Calcium chloride ($CaCl_2$) are produced as a by-product in the Solvay process for soda ash production. Furthermore, sodium hydroxide (20.13.25.27) is produced in the chlorine production process, but in this case, the chlorine is considered the main product. Sulfur products (20.13.66.00, 20.13.21.20) are often waste products from desulfurization. Hydrogen chloride is often a by-product of chlorination see (Austin and Glowacki 2000): "By far the largest amounts of hydrogen chloride and hydrochloric acid are produced as byproducts of chlorination". As defined above waste and by-products should not have an electricity efficiency benchmark because the main product is usually produced regardless of the sales value of the by-product or waste product. Silicates (20.13.62.40) and distilled and conductive water production (20.13.52.50) can also be considered unsuitable for an electricity efficiency benchmark due to low electricity intensity in the production process. Therefore, from the 14 largest subsectors, only sulfuric acid (20.13.24.34), disodium carbonate (20.13.43.10), calcium carbonate (20.13.43.40) and sodium bicarbonate (20.13.43.20) are suitable for a new electricity efficiency benchmark.

In addition to a high production level, the specific electricity consumption per manufactured unit of the respective product is also important for the total electricity consumption of a subsector. The subsectors "Compounds, inorganic or organic, of rare-earth metals or of mixtures of these metals; cerium compounds" (20.13.65.10, 17-30 MWh/t) and "Phosphorus" (20.13.21.81, 12.5 MWh/t product) are particularly relevant here, although neither subsector has a large production volume (4,500 t and 905 t, respectively) and are therefore excluded from the exercise. Furthermore, the silicone compounds also have a high electricity consumption in production, whereby for the subsectors "Silicone. Containing by weight not less than 99.99 % of silicon" (20.13.21.60, 60 MWh/t product), "Silicone. Other than containing by weight not less than 99.99% of silicon" (20.13.21.70, 11.87 MWh/t product) and "Carbides of silicon, whether or not chemically defined" (20.13.64.10, 6, 200 MWh/t product) benchmarks already exist[5] and are therefore excluded from the selection process for the development of new benchmarks.

An initial estimate of the total electricity consumption of the subsectors in the inorganic basic chemicals sector shows that, in addition to the subsectors already excluded above for the selection of new benchmarks, five other subsectors are relevant with each having an electricity consumption of significantly more than 100,000-megawatt hours per year. Table 2.11 provides an overview of the subsectors suitable for benchmark development, as well as the production volume and electricity consumption of these sectors. Since the data for the sector "Chlorates and perchlorates; bromates and perbromates; iodates and periodates" turned out to be very thin and hardly available, we also excluded this sector. While data for chlorates were at least partially available, no reliable data could be found for perchlorates, promates/perbromates and iodates/periodates. We have therefore selected the following three sectors:

- 20.13.43.40 Calcium carbonate (precipitated)
- 20.13.24.34 Sulphuric acid; oleum
- 20.13.43.10 Disodium carbonate

[5] Source: Communication from the Commission amending the Communication from the Commission Guidelines on certain State aid measures in the context of the greenhouse gas emission allowance trading scheme post-2012.

Table 2.11 Suitable subsectors identified for the selection of new electricity benchmarks are marked in dark green, subsectors with existing benchmarks are included for completeness, marked in light green, possible fallback candidates are marked white, products that are a by-product of chlorine production are grayed out.

Prodcom Code	**Prodcom Definition**	**Unit**	**Volume 2017-2019**	**Specific electricity consumption MWh/t**[6]	**Overall electricity consumption in MWh**
20.13.25.27	Sodium hydroxide in aqueous solution (soda lye or liquid soda)	t NaOH	7,078,039	2.4610	17,419,054
20.13.21.11	Chlorine	t	3,999,667	2.4610	9,843,179
20.13.21.60	Silicon. Containing by weight not less than 99,99 % of silicon	t	161,922	60.0000	9,715,341
20.13.32.50	Chlorates and perchlorates; bromates and perbromates; iodates and periodates	t	673,015	5.0000	3,365,077
20.13.43.40	Calcium carbonate (precipitated)	t	6,072,119	0.4160	2,526,002
20.13.25.30	Potassium hydroxide (caustic potash)	t KOH	599,969	2.4610	1,476,523
20.13.24.13	Hydrogen chloride (hydrochloric acid)	t HCl	3,405,866	0.4160	1,416,840
20.13.64.10	Carbides of silicon, whether or not chemically defined	t	144,413	6.2000	895,362
20.13.24.34	Sulphuric acid; oleum	t H_2SO_4	11,235,259	0.0556	624,680
20.13.25.25	Sodium hydroxide (caustic soda), solid	t NaOH	239,449	2.4610	589,283
20.13.21.70	Silicon. Other than containing by weight not less than 99,99 % of silicon	t	31,419	11.8700	372,941

[6] Note: This was a first estimation to make the selection of the subsectors.

20.13.43.10	Disodium carbonate	t Na_2CO_3	6,743,888	0.0450	303,475

Source: Own calculation based on Prodcom data and several sources[7]

2.4.2 Revised and new benchmarks

2.4.2.1 Calcium carbonate (precipitated)

- **Prodcom code:** 20.13.43.40
- **Production volume:** 6,072 kt average values for 2017-2019
- **Current benchmark:** None
- **Main production countries in the EU:** Main production countries based on Prodcom data are Italy and Finland (some Member State data are marked as confidential)
- **Process and electricity consumption:** Synthetic calcium carbonate (CaCO3) is referred to as PCC (precipitated calcium carbonate). PCC can be produced in various ways. Well-known processes include precipitation with carbon dioxide, the soda-lime process and the Solvay process, in which PCC is a by-product of ammonia production. Precipitation with carbon dioxide is the most commonly used process, especially in the on-site plants of the paper industry. Clean limestone or quicklime is first slaked to calcium hydroxide and then fed as a thin suspension to the reactor. There, carbon dioxide is fed in until the calcium hydroxide is completely converted to calcium carbonate.
  Hydration of quick lime: CaO + H2O → Ca(OH)2
  Precipitation: Ca(OH)2 + CO2 → CaCO3 + H2O

  The chemical reaction is usually followed by the separation of impurities and dewatering, grinding and drying, which are all electricity-consuming steps. The available data on electricity consumption in calcium carbonate production is thin. This is partly due to the fact that plants often manufacture several different products and the electricity consumption for the individual process steps is difficult to collect. BREF documents (European Commission 2007) indicate energy consumption of 0-7.5 GJ per ton of PCC and electricity consumption of 60-500 kWh per ton of PCC. This is a considerable range, but may be due to the different manufacturing processes, and to different product qualities in terms of grind and the associated different drying requirements. Data from the Ecoinvent database (Wernet et al. 2016) for a plant at the Gendorf Chemical Park indicate a specific electricity consumption of 416 kWh per ton of PCC. This is a considerable range, but may be due to the different manufacturing processes, and different product qualities in terms of grind and the associated different drying requirements.
- **Stakeholder feedback:** We did not receive stakeholder feedback specifically related to calcium carbonate.
- **Benchmark:** The value from the BREF document of 0.060 MWh/t PCC is quite old (from 2007) and bears the risk that it is no longer up-to-date. Furthermore, a wide range is given in the BREF document and a possible substitutability of electricity and fossil fuels could not be excluded. Due to these uncertainties and the missing stakeholder feedback, we recommend to continue using the fallback approach to calculate the State Aid compensation.

[7] 20.13.32.50: Viswanathan and Tilak 1984; Wernet et al. 2016;
20.13.43.10 Lee and Wen 2017.

- **Average consumption:** The average specific electricity consumption is 0.28 MWh/t.

2.4.2.2 Sulphuric acid; oleum

- **PRODCOM code:** 20.13.24.34
- **Production volume:** 11,235 kt average values for 2017-2019
- **Current benchmark:** None
- **Main production countries in the EU:** Main production countries based on Prodcom data are Germany, Spain, Poland and Bulgaria (some Member State data are marked as confidential)
- **Process and electricity consumption:** Sulfuric acid (H_2SO_4) is mainly produced by two different processes. One is the contact process, which can be considered the main process, or the wet sulfuric acid process. In the contact process, the starting point is sulphur, which is burned to form sulphur dioxide. Sulphur trioxide is then produced from sulphur dioxide with the aid of a catalyst (vanadium pentoxide) and the addition of oxygen. This takes place under a temperature of 420 to 620 degrees Celsius, as the catalyst is only effective within this temperature range. After formation of the sulphur trioxide, this is converted to sulfuric acid. Since the direct reaction of sulphur trioxide with water is too slow, the gas is passed into concentrated sulfuric acid. In this process, disulfuric acid $H_2S_2O_7$ (Oleum) is quickly formed. When this is diluted with water, it decomposes to two molecules of sulfuric acid. This process does not produce pure sulfuric acid, but concentrated acid with 98 % acid content. To produce pure sulfuric acid, the amount of sulphur trioxide that corresponds to the amount of substance of the excess water of the concentrated acid must be injected into the concentrated acid. In addition to the thermal energy, which is brought into the process with the chemically bonded energy of the feedstock during sulfuric acid production, compression energy in the form of electrical energy for the fan is required for gas transport. This electrical energy required for the blower, which accounts for a large proportion of the electrical energy demand of a sulfuric acid plant, is in the range of 0.035-0.050 MWh/t H_2SO_4 depending on the crude gas content and increases with decreasing SO_2 content in the crude gas (Wiesenberger and Kircher 2001). Data from the Ecoinvent database (Wernet et al. 2016) show an electricity demand of around 0.055 MWh per ton of sulfuric acid, although this represents more an average value and not the most efficient plant.
- **Stakeholder feedback:** Stakeholder feedback was provided by the European Sulphuric Acid Association (ESA). ESA underlined that the benchmark value based on the literature was only based on the air blowers and recommended a benchmark value that includes the auxiliary services. The data provided include the specific electricity consumption of 10 plants in Europe. The electricity consumption was divided into air blowers and auxiliary services. In addition, the production process was shown. The plants can be classified into three different types of processes: sulphur burning, smelter gas and recycling. In total, data from 2017 to 2020 were provided, but for two plants the data was not complete. For auxiliary services, only the electricity consumption directly attributable to sulfuric acid production was taken into account. The lowest specific electricity consumption shown in the data was 0.056 MWh/t of sulfuric acid. This value was reached by one plant in 2017 and by another plant in 2020. Considering air blowers and auxiliary services separately and taking the minimum from each, a minimum of 0.0411 MWh/t sulfuric acid was reached in 2020 but from two different plants. However, since these two plants use different production processes (sulfur burning, smelter gas) and these can lead to different specific electricity requirements for auxiliary and air blowers, a benchmark based on a combination

of the electricity consumption of different plants did not seem to make sense. The data provided cannot be verified, but seems plausible, as the specific electricity consumptions of the air blowers for some plants are well below the lower values found in the rather old literature.
However, ESA argued that the three main processes of sulfuric acid production are not comparable and interchangeable because they have different sulphur dioxide production processes dictated by the sulphur source. Therefore, a single benchmark value would lead to major disadvantages for certain producers, as they would not be able to bring their production to the same energy efficiency level through investments. In addition, ESA noted that determining a single value requires a clear calculation method and clear definition of system boundaries. ESA also highlighted that sulfuric acid could be considered a by-product in some cases and processes (e.g. in metallurgical production), which should not be, as a consequence, placed under the same category for the benchmark. Finally, ESA noted that the regeneration of sulfuric acid requires a higher purification effort than other processes and therefore often has a higher electricity consumption. These plants would have a disadvantage with a benchmark based on the sulphur burning process.

- **Benchmark:** We recommend to set the benchmark at 0.056 MWh/t sulfuric acid based on data provided by stakeholders. This value was based on two sulphur burning plants and includes auxiliary and air blower. ESA argued that a single benchmark value seems inappropriate for very different processes, but it is against the benchmarking principles to set different benchmarks on different processes producing the same product[8]. The issue of sulfuric acid being considered a by-product for certain manufacturing processes depends on whether or not the electricity consumed is clearly attributable to sulfuric acid production. In cases where the consumed electricity cannot be clearly attributed to sulfuric acid production, it could indeed be defined as a by-product. However, this problem is independent of whether one or more benchmarks or the fallback approach are used. In all of these cases, there would be no State aid payments for a by-product. Furthermore, the incentivization of recycling is not seen as a mandatory incentive target of the electricity efficiency benchmarks. This problem can be addressed in other areas.
- **Average consumption:** The average specific electricity consumption based on stakeholder data is 0.0798 MWh/t.

2.4.2.3 Disodium carbonate

- **Prodcom code:** 20.13.43.10
- **Production volume:** 6,744 kt average values for 2017-2019
- **Current benchmark:** none
- **Emissions benchmark:** 0.843 allowances per ton of soda ash
- **Main production countries in the EU:** Main producing Member States are not identifiable based on Prodcom data, as almost all of them are marked as confidential.
- **Process and electricity consumption:** The most important sodium carbonate (Na_2CO_3) production process is the Solvay process. The Solvay process consists of the following process steps: brine purification, lime burning, lime milk preparation, sodium bicarbonate production by introduction of carbonic acid and ammonia and its precipitation, thermal decomposition of sodium bicarbonate by calcination and ammonia recovery from the ammonium chloride with lime milk and its return to the process. In formulas, it can be expressed as follows.

[8] https://ec.europa.eu/clima/sites/default/files/ets/allowances/docs/benchm_co2emiss_en.pdf; Principle 2.

2 NaCl + 2 CO2 + 2 NH3 + 2 H2O → 2 NaHCO3 + 2 NH4Cl
2 NaHCO3 → Na2CO3 + H2O + CO2

Electricity is mainly required to operate the gas compressors during the process. Several sources can be found for the electricity consumption during the production process. The BREF document (European Commission 2007) assumes 50 - 130 kWh/t. These values can also be found in (Fleiter et al. 2013). Data from the Ecoinvent database (Wernet et al. 2016) shows a value of 42 kWh/t.

- **Stakeholder feedback:** Independent consultant Vianney Schyns on behalf of the Conseil Européen des Fédérations de l'Industrie Chimique (Cefic) prepared the stakeholder feedback. The feedback received showed an exchangeability of electricity and fuel in some cases. The main example concerned compressors used to send the atmospheric pressure CO_2 of the limekilns in the process. These compressors can be powered by fuel to produce steam or can be powered by electricity. The feedback included data on 11 installations including the specific direct emissions as well as the specific electricity consumption of the installations based on the weighted average from 2016-2017. Indeed, a negative correlation between direct emissions and electricity consumption can be seen, which supports the statement on the exchangeability of fossil fuels and electricity. Based on the electricity emission factor, an exchangeability approach is then undertaken. The data seem plausible, as especially the data on direct emissions would lead to a benchmark value similar to the official EU ETS benchmark value.
- **Benchmark:** However, disodium carbonate is not on the official European list of products with exchangeability of fossil and electrical energy. The approach followed in the feedback can therefore not be applied for the running trading period. In order to comply with the benchmarking rules, the benchmark for disodium carbonate would therefore have to be set on the basis of the plant with the lowest specific electricity consumption. However, this plant has about 27% higher direct emissions than the most efficient plant in terms of direct emissions. Under the plausible assumption of energy exchangeability for the compressors, setting a benchmark on the plant with the lowest electricity consumption does not seem reasonable. Such an approach would counteract the desired electrification and create incentives to continue using the gas-powered compressors. Therefore, we recommend to not apply an electricity efficiency benchmark for disodium carbonate for this trading period, but continue to use the fallback approach to calculate state aid payments.
- **Average consumption:** The average specific electricity consumption based on Stakeholder feedback is 0.136 MWh/t.

2.4.2.4 Chlorine

- **PRODCOM code:** 20.13.21.11
- **Production volume:** 4,000 kt average values for 2017-2019
- **Current benchmark:** 2.461 MWh/t
- **Main production countries in the EU:** Main producing Member States are Germany and France.
- **Process and electricity consumption:** There are three production technologies to produce chlorine (Cl2) by electrolysis of a salt solution (NaCl or KCl): the amalgam process, the diaphragm process and the membrane process (Ecofys 2009). All the processes produce the same product. The membrane technology, which has the lowest specific electricity consumption, produces more than 80% of Europe's chlorine, according to the Chlor-alkali Industry Review (Eurochlor 2020).

The present benchmark listed above is also based on this process. However, since around 2013 a technology developed by the materials manufacturer covestro and the plant manufacturer Thyssenkrupp has been marketable. It reduces electricity requirements by up to 25% (thyssenkrupp 2020) and up to 30% (Covestro). Such a reduction would result in setting the benchmark level at respectively 1.846 MWh/t or 1.723 MWh/t. This so-called oxygen-depolarized cathodes (ODCs) method is based on the membrane process of chlor-alkali electrolysis. The innovation of this process is that the hydrogen-generating electrode normally used is replaced by an oxygen-consuming cathode. The supply of oxygen to the cathode then prevents the formation of hydrogen, so that only chlorine and caustic soda are produced. This process requires a voltage of only two volts instead of three (Covestro). However, this process has not yet gained widespread adoption in Europe.

- **Stakeholder feedback:** Stakeholder feedback was submitted by Eurochlor. Eurochlor argued against a benchmark on the new ODC process and proposed to base the new benchmark on the average of the 10% best plants. This would lead to a benchmark value of 2.39 MWh/t chlorine (best plant would be on the ODC process). Several reasons were given. (i) the market share of the ODC process is very low at 0.2%, (ii) there is currently only one plant manufacturer and thus a monopoly situation, and (iii) the overall energy balance of the ODC process is significantly worse compared with the membrane process. The first two arguments should not influence the benchmark setting. However, the overall energy balance could be considered. Eurochlor argued that in the ODC process additional oxygen is needed, which causes on average another 0.248 MWh/t chlorine in electricity consumption. Furthermore, the ODC process does not produce hydrogen, which is a by-product of the membrane process. According to Eurochlor, if the amount of hydrogen produced as a by-product per ton of chlorine (28.2 kg) in the membrane process would be produced via water electrolysis, a further 1.55 MWh/t electricity would be consumed. In this case, the oxygen required in the ODC process would be a by-product of water electrolysis and would therefore not have to be produced separately. If the two options for producing the two products are compared, we find that the membrane process requires 2.39 MWh of electricity for one ton of chlorine and 28.2 kg of hydrogen, whereas the alternative production (ODC and water electrolysis) would require 3.396 MWh (1.846 + 1.55) for one ton of chlorine and 28.2 kg of hydrogen. In such a calculation, the membrane process would be the significantly more energy-efficient process. According to feedback from Eurochlor, about 40% of the hydrogen typically produced was used to produce steam and 60% was used as chemical feedstock. It was not clear where and how the 10-15%[9] of unused emitted hydrogen is accounted for in these proportions.
- **Benchmark:** We recommend a benchmark value of 1.846 MWh/t chlorine since the rules of the electricity efficiency benchmarks specify the setting of the benchmark value based on the most efficient process and any by-products of production should not be included. Possible deviations from this rule were not the subject of this project.
- **Average consumption:** The average specific electricity consumption is 2.461 MWh/t.

2.4.2.5 Silicon. Other than containing by weight not less than 99,99 % of silicon

- **Prodcom code:** 20.13.21.70
- **Production volume:** 31 kt average values for 2017-2019

[9] https://www.eurochlor.org/news/hydrogen-from-chlor-alkali-production-as-green-as-green-can-be/

- **Current benchmark:** 11.87 MWh/t
- **Main production countries in the EU:** Production volumes at the Member State level are not published in Prodcom due to the low number of plants.
- **Process and electricity consumption:** Silicon (90-99.99%) is mainly used in metal, non-metal and chemical industry. Silicon metal (purity 90-99.99%) is commonly produced in low-shaft three phase submerged electric arc furnaces. The electric furnace can be of the open or semi-closed type. The BREF document for the Non-Ferrous Metals Industries (Cusano et al. 2017) notes in Table 8.7 that the specific electricity consumption is between 10.8 – 12.0 MWh/t silicon metal, which refers to a commonly used open or semi-closed submerged electric arc furnace without energy recovery. The BREF document also states that the ideal energy consumption for the production of silicon metal is 10.1 MWh/t, which probably only includes the furnace and not auxiliary systems like fans or environmental protection and process steps like refining and crushing. More recent studies and publications are rather rare and are in the same range as the older figures (Chen et al. 2018; Li and Wehrspohn 2019).
- **Stakeholder feedback:** Feedback was provided by Euroalliages and by Wacker (European manufacturer), with only Wacker providing more details on specific electricity consumption. Wacker wrote that a lot of research was done before building a new plant in 2019 to reduce electricity consumption. According to Wacker, the new plant was running at full capacity since 2020 and the specific electricity consumption was slightly higher than the existing benchmark value of 11.87 MWh/t silicon. However, Wacker did not provide any certified data on this. In addition, Wacker provided average specific electricity consumption across all plants in the world. These values are around 0.11 MWh/t lower than the existing benchmark value. Based on their research and due to the increasing competitive pressure from China, Wacker recommended to keep the existing benchmark.
- **Benchmark:** Stakeholders did not provide data on European sites. Therefore, there are two options to set the new benchmark. (i) the existing benchmark could be kept, which has the advantage that this value is based on real data from Euroalliages. However, these are quite old. (ii) the new benchmark could be set based on the BREF document, which would mean a reduction to 10.8 MWh/t. However, this value is older than the existing benchmark. <u>Based on the available information, we recommended to keep the existing benchmark of 11.87 MWh/t.</u>
- **Average consumption:** Based on the available data, no average value could be calculated.

2.4.2.6 Silicon. Containing by weight not less than 99,99 % of silicon

- **Prodcom code:** 20.13.21.60
- **Production volume:** 162 kt average values for 2017-2019
- **Current benchmark:** 60 MWh/t
- **Main production countries in the EU:** Production volumes at the Member State level are not published in Prodcom due to the small volume and number of plants.
- **Process and electricity consumption:** Part of the production of silicon metal (grade 90-99.99%) goes to the production of polysilicon (crushed hyperpure silicon with a purity > 99.9999999 %). It is therefore a pre-product for this second type of material with distinct characteristics and applications Polysilicon is used as a raw material by the solar photovoltaic and electronics industry. Due to low production capacities, there is limited available data. Hamilton and Rami (2010) give the specific electricity consumption as 60-70 MWh/t, from which the old benchmark value was probably derived. More recent public figures are scarce. Mitin and Kokh (2018) speak of electricity saving opportunities that can reduce specific electricity consumption to below 70MWh/t.

- **Stakeholder feedback:** Wacker the only European manufacturer provided feedback. Wacker did not present its own figures on production or electricity consumption, but a specific electricity consumption of 60 MWh/t of super-pure silicon can be derived from the table shown on electricity consumption and capacity in the EU. This assumes that the plant is running at full capacity. However, the values appear to be rough estimates rather than robust data. In addition to this information, information about the Chinese market was provided by Wacker. For example, a graph from China Photovoltaic Industry Association showed that specific electricity consumption should decrease by 1 MWh/t per year from 70 MWh/t in 2019 to 65 MWh/t in 2025. In addition, data on specific electricity consumption of the brand new and probably most efficient Tongwei plant shows specific consumption of 55 MWh/t. Other plants in China show consumption between 62-73 MWh/t. However, Wacker put the Chinese specific consumption into perspective, noting that hyperpure silicone for semiconductors has a significantly higher electricity consumption than hyperpure silicone for solar. According to Wacker, the Chinese plants produce mainly for the solar industry, whereas Wacker in Europe produces larger shares for the semiconductors industry and thus has a higher specific electricity consumption than the Chinese plants. However, exact figures are not shown. Wacker therefore recommends to keep the current benchmark value.
- **Benchmark:** Based on information provided by Wacker, the benchmark could be reduced to 55 MWh/t or kept at 60 MWh/t. However, the reduction of the value would be based exclusively on data from Chinese plants and therefore does not seem reasonable. Data from the only European plant is unfortunately not available. Therefore, we recommend to keep the benchmark value at 60 MWh/t.
- **Average consumption:** The average specific electricity consumption is 60 MWh/t.

2.4.2.7 Silicon. Carbides of silicon, whether or not chemically defined

- **PRODCOM code:** 20.13.64.10
- **Production volume:** 144 kt average values for 2017-2019
- **Current benchmark:** 6.2 MWh/t
- **Main production countries in the EU:** Production volumes at the Member State level are not published in Prodcom due to the small volume and number of plants.
- **Process and electricity consumption:** Silicon carbide is commercially produced by a high temperature electrochemical reaction of high grade silica sand (quartz) and carbon (usually low or medium sulphur petroleum coke), selected for their purity and their particle size. The process carried out in electric resistor furnaces operated batch wise is highly energy intensive. Silicon carbide can be further processed into very hard ceramics, but is also used in the electrical engineering sector. The BREF document (European Commission 2007) gives a range of 5.2 to 6.2 MWH/t for the most efficient European plant, where the value 5.2 corresponds to a net value that includes the electrification of waste gases. However, this electricity generation from waste gases in turn generates CO_2 costs and should therefore be outside the system boundary for the calculation of the electricity benchmarks. Therefore, no distinction is made between electricity from the grid and self-generated electricity. Therefore, the old benchmark is based on the value of 6.2 MWh per ton of silicon carbide. The Ecoinvent database (Wernet et al. 2016) shows a specific electricity consumption of 8.6 MWh/t in a time span of 2000-2020 based on different plants in Europe.
- **Stakeholder feedback:** Stakeholder feedback was submitted by independent consultant Vianney Schyns on behalf of Cefic. The feedback document lists two papers from 2001 and 2002 that show ranges of specific electricity consumption

of 6-12 and 6.2-9.0 MWh/t SiC, respectively. Other data from associations and producers from 1993 to 1999 show specific electricity consumption between 7 and 10 MWh/t SiC, with most plants showing consumption between 7 and 8 MWh/t SiC. Schyns contacted several plant operators in Europe and asked for data, but only received data from what was believed to be the most efficient plant. The plant shows an electricity consumption from the grid of 5.9-6.5 MWh/t SiC depending on the year, and a total electricity consumption of 6.8-7.5 MWh/t SiC. Schyns argued that the existing benchmark value of 6.2 MWh/t is incorrect and too low because it only includes electricity from the grid. A more correct value would therefore be the total consumption shown in the data (6.84 MWh/t (value from 2003) SiC for the previous period and 6.91 MWh/t SiC for the coming period (value from 2020).). Schyns therefore recommended setting the benchmark at the value of 6.91 MWh/t SiC. However, the BREF document from which the existing benchmark value was taken indicates a total specific consumption of 6.2-7.2 MWh/t or a specific consumption reduced by self-generated electricity of 5.2-6.2 MWh/t. See text from the BREF document below.
Installations using the freiland furnace technique need less energy. The furnaces are larger and better insulated. The specific energy consumption in the Dutch plants amounts to 6.2-7.2 MWh per tonne 100 % SiC. Design of the freiland furnaces further enables the recovery of energy from the process gas after its desulphurisation. The SiC plant in the Netherlands is, however, the only installation in the world, which has an energy recovery plant. In this installation, energy consumption amounts to 5.2-6.2 MWh per tonne 100 % SiC. (European Commission 2007, page 465)
Schyns assumes that there was a data transmission error when the BREF document was created.

- **Benchmark:** The stakeholder data seems plausible, but cannot be directly verified. In addition, data was only provided for one plant in Europe. Even if Schyns claims that this is the most efficient plant in Europe, the supplied data basis does not seem sufficient enough to increase the benchmark value based on it. Given the fact that the data provided was not sufficient to serve as a basis for the benchmark, we recommend to keep the existing benchmark value of 6.2 MWh/t SiC.
- **Average consumption:** The average specific electricity consumption is 7.4 MWh/t.

2.5 Manufacture of basic iron and steel and ferro-alloys (24.10)

2.5.1 Selection of relevant subsectors

This sector covers numerous products with different production volumes. For most of the subsectors under this sector, we propose not to develop electricity benchmarks. For many products, the energy required for forming the final product will come from the heat still contained in the product due to initial production (e.g., 'hot-rolled') and not from electricity. In our selection of possible candidates for electricity benchmarks, we therefore exclude all those subsectors that include these secondary products. In addition, some primary products of this sector are accounted for under the ETS with a fuel switch benchmark (under EAF carbon steel, EAF high alloy steel, iron casting) and are also not considered here despite high electricity consumption. These have also been recently updated for the fourth trading period[10] (European Commission 2021).

Seven subsectors of this sector have an electricity benchmark. These include the benchmarks for 'steel produced in other processes than electric furnaces', which is associated with the Prodcom codes 24.10.T1.22, 32 and 42 in the current nomenclature, though no production volume is reported. Three more existing electricity benchmarks are from the ferro-alloy subsectors. In the current nomenclature, the benchmark for 'ferro-manganese in accordance with BREF' for high carbon ferro-manganese can be associated with two Prodcom codes (24.10.12.10 and 24.10.12.20). In total, seven subsectors can be considered to have an existing electricity benchmark, covered by four benchmarking values.

Ferro-alloys are commonly associated with high specific electricity consumption, as electric arc furnaces are used. For this reason, we propose to develop additional benchmarks for those with the highest overall electricity consumption, which are also those with the highest production volume. Due to its high approximate specific electricity consumption, the next subsector in terms of total electricity consumption is 24.10.12.39 (Other ferro-silicon), which in turn has a low production volume. For completeness, all ferro-alloy subsectors are given in Table 2.12. By following this approach, almost all bulk ferro-alloys are associated with a benchmark, while special ferro-alloys will be associated with the fallback percentage.

Table 2.12 presents the subset of subsectors which we consider possible candidates to determine electricity benchmarks. The table lists production volumes of 2019 only, as the Prodcom classification of some of the respective subsectors was split prior to 2019. Those subsectors with existing electricity benchmarks are highlighted in light green, those proposed for new benchmarks in dark green.

Table 2.12 Production volume (values of 2019) of ferro-alloys in the EU27 which report production in 2019. Those subsectors with existing electricity benchmarks are marked in light green, subsectors considered for new benchmarks are marked in dark green. In addition, those subsectors with existing electricity benchmarks for crude steel are also listed.

Prodcom Code	Prodcom Definition	Unit	Volume 2019
24.10.12.60	Ferro-chromium	t	600,000
24.10.12.45	Ferro-silico-manganese	t	200,000
24.10.12.35	Ferro-silicon, containing by weight > 55% of silicon	t	191,426
24.10.12.25	Other ferro-manganese containing by weight less or equal than 2 % of carbon	t	129,761
24.10.12.36	Ferro-silicon, containing by weight <= 55% silicon and >= 4% but <= 10% of magnesium	t	108,961
24.10.12.20	Other ferro-manganese, containing by weight > 2% carbon (excl. ferro-manganese with a granulometry of <= 5 mm and containing by weight > 65% manganese)	t	60,000

[10] The benchmark for EAF carbon steel has been changed from 0.283 allowances/t to 0,215 allowances/t. The benchmark for EAF high alloy steel was changed from 0.352 allowances/t to 0.268 allowances/t.

Prodcom Code	Prodcom Definition	Unit	Volume 2019
24.10.12.40	Ferro-nickel	t	50,000
24.10.12.55	Ferro-titanium and ferro-silico-titanium	t	35,700
24.10.12.10	Ferro-manganese, containing by weight > 2% carbon, with a granulometry <= 5 mm and a manganese content by weight > 65%	t	30,000
24.10.12.65	Ferro-vanadium	t	20,649
24.10.12.55	Ferro-titanium and ferro-silico-titanium	t	35,700
24.10.12.75	Ferro-molybdenum	t	9,172
24.10.12.39	Other ferro-silicon, containing by weight <= 55% silicon (excl. that containing by weight >= 4% but <= 10% of magnesium)	t	6,300
24.10.12.85	Ferro-silico-magnesium	t	3,951
24.10.12.80	Ferro-phosphorus	t	2,165
24.10.12.50	Ferro-tungsten and ferro-silico-tungsten	t	1,400
24.10.12.70	Ferro-niobium	t	1,400
24.10.12.95	Other ferro alloys nowhere else specified or included	t	120,000
24.10.T1.22	Crude steel: non-alloy steel produced by other processes than in electric furnaces		-
24.10.T1.32	Crude steel: alloy steel other than stainless steel produced by other processes than in electric furnaces		-
24.10.T1.42	Crude steel: stainless and heat resisting steel produced by other processes than in electric furnaces		-

Source: Eurostat, Prodcom data, no data reported for 24.10.T

2.5.2 Revised and new benchmarks: crude steel subsectors

- **Prodcom codes:**
  - 24.10.T1.22: Crude steel: non-alloy steel produced by other processes than in electric furnaces
  - 24.10.T1.32: Crude steel: alloy steel other than stainless steel produced by other processes than in electric furnaces
  - 24.12.T1.42: Crude steel: stainless and heat resisting steel produced by other processes than in electric furnaces
- **Production volume:** no data reported in Prodcom database. Feedback from Eurofer (see below) points at a total EU production of 98.2Mt production in 2019.
- **Current benchmark:** 0.036 MWh/t
- **Main production countries in the EU:** no data reported
- **Process and electricity consumption:** This benchmark covers auxiliary systems of the steelmaking process. The existing benchmark defines these to be

secondary metallurgy, refractories preheating, auxiliaries (in particular dedusting) and casting installations up to cut-off of crude steel products. The diversity in this list of processes summed under the benchmarked value explains why the previous and the proposed benchmarks cover different Prodcom codes. As these systems are not the main drivers of total energy demand in the steel making process, it explains why there is close to no public information on the energy or electricity consumption in these processes. The relevant BREF document (Roudier et al. 2013) dates from 2013, which does not make it a valuable source for updated best efficiency numbers.

- **Stakeholder feedback:** When asked to provide anonymised, plant specific data, Eurofer provided data for fourteen plants (data from 2019), the lowest reaching an electricity consumption of 33.85kWh/t, or 6.0% below the current benchmark. When asked to define the scope of the electricity consumption behind these values, Eurofer made reference to the existing benchmark definition. However, this data was collected from members of the association for this task explicitly, with the remaining 9 production sites not responding to the survey by Eurofer. No validation of this data could be provided.

  The average electricity consumption from the data provided by Eurofer was at 50.94kWh/t, with 5 plants above 50kWh/t, reaching a maximum of 84.94kWh/t. Eurofer reported that the data from the fourteen sites accounted for 56Mt (corresponding to 57%) of the BOF steel making in Europe, but was not in a position to provide plant specific production data for the fourteen sites due to confidentiality agreements.
- **Benchmark:** In view of the lack of any other information, we recommend using the data provided by Eurofer. As such, we recommend a benchmark of 33.85kWh/t or 0.03385MWh/t.
- **Average consumption:** Following from the data provided by Eurofer, we use an average consumption of 0.05094MWh/t.

2.5.3 Revised and new benchmarks: Ferro-manganese

Ferro-manganese alloys are classified according to their carbon content into high-carbon (HC), medium-carbon (MC) and low-carbon (LC) ferro-manganese (FeMn), with maximum of 7.5%, 2.5% and 0.75% carbon content respectively. Depending on the carbon content required in the product, the production route varies. All production routes use electric arc furnaces, but the reducing agent varies (Cusano et al. 2017).

HC FeMn uses the carbothermic route, using coke or a different carbon source as the reducing agent. MC FeMn is either produced from decarburized HC FeMn, by an oxygen blown converter, or through the silicothermic process, where silicon serves as the reducing agent. In Europe, it is commonly produced by decarburization of HC FeMn. LC FeMn is exclusively produced by way of the silico-thermic process (Cusano et al. 2017).

The benchmarks were developed according to Prodcom classification, which recognises three types of FeMn, two of which can be classified as HC or MC FeMn, the third being LC FeMn (see the following subsections for the exact definitions). Only the HC/MD FeMn currently are associated with a benchmark. Following from the above statements, this study considers the carbothermic process for HC and MC FeMn and the silicothermic for LC FeMn.

It is important to recognise that the production of industrial gases – in this case the oxygen required for decarburization – is not to be included in the benchmark, as the production of industrial gases is not eligible for compensation by way of the current legislation.

The H2020 PREMA project[11] is investigating ways to reduce the energy consumption specifically of FeMn production.

2.5.3.1 Ferro-manganese, containing by weight > 2% carbon, with a granulometry <= 5 mm and a manganese content by weight > 65%

- **Prodcom code:** 24.10.12.10
- **Production volume:** 30,000 t in 2019
- **Current benchmark:** 2.76 MWh/t
- **Main production countries in the EU:** France, Sweden
- **Process and electricity consumption:** HC FeMn and MC FeMn both fall under this Prodcom code. As explained above, the carbothermic process route is used in Europe for both products, with MC FeMn being produced from HC FeMn through decarburization. The oxygen production is not covered by this benchmark. Cusano et al. (2017) (the relevant BREF document) give a range of 2.2 MWh/t to 3.2 MWh/t for the electric arc furnace. This is in line with the Ecoinvent database (Wernet et al. 2016), which gives a total of 2.57 MWh/t of high carbon (and high manganese) FeMn, both with reference to global and European data from 2003-2013. (Larssen et al. 2019) study a system for HC FeMn production and report 2.456 MWh/t, also citing (Olsen et al. 2007) to report as little as 2.152 MWh/t of product, but specify no further details.
  Cusano et al. (2017) report an additional use of 2.6 - 3.7 MWh/t for the decarburization process, which is not considered as part of the benchmark because this includes the supply of oxygen to the process. Cusano et al. (2017) give a range of 2.2 MWh/t to 3.2 MWh/t for the electric arc furnace. This is in line with the Ecoinvent database (Wernet et al. 2016), which gives a total of 2.57 MWh/t of high carbon (and high manganese) FeMn, both with reference to global and European data from 2003-2013. (Larssen et al. 2019) study a system for HC FeMn production and report 2.456 MWh/t, also citing (Olsen et al. 2007) to report as little as 2.152 MWh/t of product, but specify no further details.
- **Stakeholder feedback:** No feedback was provided by stakeholders (Euroalliages in particular) on this benchmark.
- **Benchmark:** We recommend a benchmark at the lowest end of the range given by Cusano et al. (2017), 2.2 MWh/t ferro-manganese.
- **Average consumption:** The average specific electricity consumption is 2.7 MWh/t.

2.5.3.2 Other ferro-manganese, containing by weight > 2% carbon (excl. ferro-manganese with a granulometry of <= 5 mm and containing by weight > 65% manganese)

- **Prodcom code:** 24.10.12.20
- **Production volume:** 60,000 t in 2019
- **Current benchmark:** 2.76 MWh/t
- **Main production countries in the EU:** France, Slovakia
- **Process and electricity consumption:** This Prodcom code covers the same basic production process as 24.10.12.10 (see above).
- **Stakeholder feedback:** No feedback was provided by stakeholders (Euroalliages in particular) on this benchmark.
- **Benchmark:** We recommend to apply the same benchmark as for 24.10.12.10, 2.2 MWh/t ferro.manganese.

[11] https://www.spire2030.eu/prema

- **Average consumption:** The average specific electricity consumption is 2.7 MWh/t.

2.5.3.3 Other ferro-manganese containing by weight less or equal than 2 % of carbon

- **Prodcom code:** 24.10.12.25
- **Production volume:** 129,761 t in 2019
- **Current benchmark:** None
- **Main production countries in the EU:** France, Spain
- **Process and electricity consumption:** This Prodcom code refers to the LC FeMn product, which is produced by way of the silicothermic process. Cusano et al. (2017) give a range of 1.4 MWh/t to 2 MWh/t of product. (Randhawa and Minj 2020) report a similar range for industrial scale production, and show in a modelling study that a strong reduction of electricity consumption is possible through an improved mixture of raw materials.
- **Stakeholder feedback:** No feedback was provided by stakeholders (Euroalliages in particular) on this benchmark.
- **Benchmark:** We recommend adopting the lower end of the range given in Cusano et al. (2017) as the benchmark, 1.4 MWh/t ferro-manganese.
- **Average consumption:** The average specific electricity consumption is 1.7 MWh/t.

2.5.4 Revised and new benchmarks: Ferro-silicon

Technically, ferro-silicon (FeSi) is referred to as such up to a percentage of 96% of silicon, above which it would be termed as silicon metal (Cusano et al. 2017), which is covered under chemicals. FeSi is produced in electric arc furnaces. Cusano et al. (2017) make no difference to the amount magnesium or silicon in the alloy, as is done under Prodcom, but discusses that the electricity demand is in part determined by the amount of silicon. (Tangstad 2013) shows that the electricity varies between 2.1 MWh/t for FeSi with 20% silicon mass fraction and 8.8 MWh/t for more than 75% silicon (Cusano et al. 2017).

Euroalliages confirmed the linear relationship between silicon content and electricity consumption. On production volume, Euroalliages stated that the production volumes reported by Prodcom are not representative of real values. The most commonly produced grade is 75% mass fraction FeSi, as in the definition of the benchmark. Other production grades present only minor shares of the total produced volume, reaching at most 10% of the production volume in only a limited amount of production sites.

2.5.4.1 Ferro-silicon, containing by weight > 55% of silicon

- **Prodcom code:** 24.10.12.35
- **Production volume:** 191,426 t in 2019
- **Current benchmark:** 8.54 MWh/t
- **Main production countries in the EU:** France, Germany, Poland, Slovakia, Slovenia, Sweden
- **Process and electricity** consumption: Cusano et al. (2017) report 9 MWh/t as average specific electricity consumption for FeSi, specifying 75% silicon mass fraction. Ecoinvent database (Wernet et al. 2016) gives a value of 8.56 MWh/t for China and global average values for the years 2008 to 2012, just above the current benchmark, for ferro-silicon.

- **Stakeholder feedback:** No feedback was provided by stakeholders on the proposed benchmark value itself, but Euroalliages stated that the incompressible electricity consumption due to thermodynamical limits is at 8.1 MWh/t.
- **Benchmark:** Therefore, we recommend to maintain the existing benchmark value of 8.54 MWh/t.
- **Average consumption:** The average specific electricity consumption is 9 MWh/t.

2.5.4.2 Ferro-silicon, containing by weight <= 55% silicon and >= 4% but <= 10% of magnesium

- **Prodcom code:** 24.10.12.36
- **Production volume:** 108,961 t in 2019
- **Current benchmark:** none
- **Main production countries in the EU:** France, Germany, Spain
- **Process and electricity consumption:** This Prodcom code covers the same basic production process as 24.10.12.35 (see above), but refers to a lower silicon content. As noted by (Tangstad 2013), the electricity consumption varies strongly with the silicon content. Tangstad gives 2.1 MWh/t for 20% silicon content, 2.7 MWh/t for 25% silicon, 4.8 MWh/t for 45% silicon content, which corresponds to a linear relationship between silicon content and electricity consumption. The average between the consumption at 20% silicon content and 55% is at 4.1 MWh/t.
- **Stakeholder feedback:** No feedback was provided by stakeholders on the proposed benchmarking value itself, but Euroalliages pointed out that this product category is of limited importance and confirmed that there is a strong dependency of the electricity consumption on the silicon fraction, also referring to the literature cited above.
- **Benchmark:** We recommend to not use benchmark for this sector but rather apply the fallback percentage. This seems reasonable due to the two points raised by Euroalliages.
- **Average consumption:** The average specific electricity consumption is not determined.

2.5.5 Revised and new benchmarks: Other ferro-alloys

2.5.5.1 Ferro-nickel

- **Prodcom code:** 24.10.12.40
- **Production volume:** 50,000 t in 2019
- **Current benchmark:** none
- **Main production countries in the EU:** France, Greece, Spain
- **Process and electricity consumption:** Ferro-nickel (FeNi) is also produced in electric arc furnaces. Cusano et al. (2017) give an electricity demand of 10 MWh/t for 20% nickel in the product, making this the most electricity intensive of the bulk ferro-alloys considered here. A similarly high specific consumption is given by (Mistry et al. 2016), who perform an life cycle impact assessment of nickel products, referring to 29% nickel FeNi. Their report mentions a level of 11.53 MWh/t, specifying that this is largely determined by the ore used in the process. Ecoinvent database (Wernet et al. 2016) give a global average of 9.28 MWh/t for the period 1994-2003.
- **Stakeholder feedback:** No feedback was provided by stakeholders on this product.
- **Benchmark:** We recommend a benchmark of 9.28 MWh/t ferro-nickel, based on the value given by Ecoinvent database (Wernet et al. 2016). (Wernet et al. 2016).

- **Average consumption:** The average specific electricity consumption is 10 MWh/t.

2.5.5.2 Ferro-silico-manganese

European Commission (2012a)specifies a benchmark for 'silico-manganese excluding FeSiMn', but there is no Prodcom code for silico-manganese. As the two terms are often used interchangeably, we associate the production of silico-manganese and the respective benchmark with this prodcom code.

This has been confirmed by stakeholders. Euroalliages has pointed out that there are two families of manganese alloys, ferro-manganese and silico-manganese, the latter being referred to as either FeSiMn or simply SiMn.

The production of silico-manganese (SiMn) uses the same production route as HC FeMn (see above), often using the same production plant at a different time (Cusano et al. 2017).

- **Prodcom code:** 24.10.12.45
- **Production volume:** 200,000 t in 2019
- **Current benchmark:** 3.85 MWh/t
- **Main production countries in the EU:** Czechia, France, Slovakia, Spain
- **Process and electricity consumption:** SiMn is produced in electric arc furnaces, using manganese ore and quartz as raw material. The manganese ore may be replaced by slag from FeMn production. Cusano et al. (2017) report a range of 3.8 - 6 MWh/t of product (both standard and low carbon), the lower end just below the current benchmark. This is higher than the values reported by (Larssen et al. 2019), who give a range of 3.5 - 4.5 MWh/t for standard SiMn.[12] The specific system studied by (Larssen et al. 2019) shows a consumption of 3.419 MWh/t.
- **Stakeholder feedback:** No feedback on the proposed benchmark value has been provided by stakeholders.
- **Benchmark:** We recommend setting the benchmark at the lowest value reported by (Larssen et al. 2019), 3.419 MWh/t ferro-silico-manganese. In addition, we recommend dropping the specification the revised annex in European Commission (2012a) stating that this benchmark should be valid for 'silico-manganese excluding FeSiMn'.
- **Average consumption:** The average specific electricity consumption is 4.71 MWh/t.

2.5.5.3 Ferro-chromium

- **Prodcom code:** 24.10.12.60
- **Production volume:** 600,000 t in 2019
- **Current benchmark:** none
- **Main production countries in the EU:** Finland, Germany, Sweden
- **Process and electricity consumption:** Similar to ferro-manganese, Cusano et al. (2017) describe different grades of ferro-chromium (FeCr), depending on their carbon content also differentiated to high, medium and low carbon (HC, MC and LC) content. The production pathways are also analogous to those of ferro-manganese. In contrast to ferro-manganese, Prodcom represents only one product category. Cusano et al. (2017) go on to specify electricity consumption for HC FeCr between 3.1 - 4.5 MWh/t, depending on the preheating and prereduction as well as the furnace type. LC FeCr is reported with a consumption of 3.4 MWh/t.

[12] A similar range (3.8-4.8 MWh/t) is given by https://www.mccreathlabs.com/applications-industries/foundry/silico-manganese/.

In general, the chromium content of the alloy in part determines the energy required. These numbers are within the range of other literature, Ecoinvent database (Wernet et al. 2016) giving 3.33 MWh/t for the years 1998 to 2003 on a global level. Biermann et al. (2012) study the production in a modelling activity and give a range of 2 - 4 MWh/t, also stating this depends on pre-heating and pre-reduction levels but giving no further details.

- **Stakeholder feedback:** Euroalliages confirmed that ferro-chromium is produced at three production sites in Europe only, with the production in Germany being a specialty site. The production site in Sweden produces FeCr of 65% chromium content, while the production site in Finland produces 55% FeCr. Euroalliages further pointed out that the electricity consumption depends highly on the chromium content to be achieved in the final production, with the relationship between electricity consumption and chromium content being exponential.
- **Benchmark:** We recommend not developing any specific benchmark for ferro-chromium for the reasons provided above, and propose a fallback approach instead. Different benchmarks would be required in view of the strong dependency on chromium content. However, this would mean developing one benchmark per production site, which does not fit with the purpose of setting benchmarks.
- **Average consumption:** The average specific electricity consumption is not determined as it is not meaningful for the reasons given above.

2.6 Aluminium production (24.42)

2.6.1 Selection of relevant subsectors

The top ten subsectors in terms of production for this sector are given in Table 2.13. Out of these, unwrought aluminium alloys in primary form (24.42.11.53), aluminium oxide (24.42.12.00) and unwrought non-alloy aluminium (24.42.11.30) already have an electricity benchmark. As an additional subsector (to be covered by the unwrought aluminium benchmark, see below), we propose to include unwrought aluminium alloy (24.42.11.54) as this has replaced 24.42.11.53 in Prodcom nomenclature. The benchmarked products then cover all primary products and are responsible for the largest part of electricity consumption in this sector.

Table 2.13 Production volume (average 2017-2019) of the most relevant Prodcom codes of the aluminium sector in the EU27.

PRODCOM Code	PRODCOM Definition	Unit	Volume 2017-2019
24.42.11.54	Unwrought aluminium alloys (excluding aluminium powders and flakes)	t	6,056,972
24.42.12.00	Aluminium oxide (excluding artificial corundum)	t	5,523,262
24.42.24.50	Aluminium alloy plates, sheets and strips > 0,2 mm thick	t	4,301,486
24.42.22.50	Aluminium alloy bars, rods, profiles and hollow profiles (excluding rods and profiles prepared for use in structures)	t	2,772,096
24.42.24.30	Aluminium plates, sheets and strips > 0,2 mm thick	t	1,300,211

24.42.25.00	Aluminium foil of a thickness (excluding any backing) ≤ 0,2 mm	t	1,057,858
24.42.11.30	Unwrought non-alloy aluminium (excluding powders and flakes)	t	477,562
24.42.22.30	Aluminium bars, rods and profiles (excluding rods and profiles prepared for use in structures)	t	379,758
24.42.26.50	Aluminium alloy tubes and pipes (excluding hollow profiles, tubes or pipe fittings, flexible tubing, tubes and pipes prepared for use in structures, machinery or vehicle parts, or the like)	t	155,319
24.42.23.30	Non-alloy aluminium wire (excluding insulated electric wire and cable, twine and cordage reinforced with aluminium wire, stranded wire and cables)	t	133,542
24.42.11.53	Unwrought aluminium alloys in primary form (excluding aluminium powders and flakes)	t	(Prodcom reports 0)

2.6.2 Revised and new benchmarks

2.6.2.1 Unwrought non-alloy aluminium (excluding powders and flakes)

- **Prodcom code:** 24.42.11.30
- **Production volume:** 6,056 kt, average for 2017-2019
- **Current benchmark**: 14.256 MWh/t
- **Main production countries in the EU:** Top five countries in their order of production: Germany, Italy, Spain, France, Austria
- **Process and electricity consumption:** Energy consumption in primary aluminium production is estimated at 212 GJ/t primarily used in the form of electricity during the electrolysis (approximately 82%, Fleiter et al. 2013). This takes place in Hall-Heroult cells containing a cryolitic bath of alumina (aluminium oxide). During the electrolysis, the anode reacts with the oxygen, CO_2 is formed and the anode is used up in the process. Inert anodes are a topic of ongoing research (Fleiter et al. 2013). There are two alternative anode technologies, the Soderberg technology which uses a paste, and the pre-bake (I.e. solid) anode technology, for which the anodes are produced in a separate process, but also used up in the aluminium production. The existing benchmark is defined to include the anode production. A correction term may be considered for the application of the anode in case it is imported from outside Europe. Generally, the pre-bake technology is more common today (Fleiter et al. 2013). The theoretical lower limit for aluminium production through electrolysis is at 6.4 MWh/t (Tabereaux and Peterson 2014). BREF report (Cusano et al. 2017) gives a current range of 13.6 - 15.7 MWh/t for the electrolysis using pre-bake anodes and 15.1 - 17.5 MWh/t for the electrolysis in Soderberg cells. However, the electricity consumption to produce the pre-bake anodes is not taken into account here. In its latest environmental report, the industry association European Aluminium mentioned a value of 14.79 MWh/t for a mix 95% pre-bake and 5% Soderberg electrolysis. This is slightly higher than the value reported by the International Aluminium Institute (IAI), for which the report from European Aluminium mentions 14.21 MWh/t

(European Aluminium 2018). (Tabereaux and Peterson 2014) reports that industry has pushed the electricity consumption to 13.2 MWh/t, but again considering only the electrolysis.

For anode or paste production, (European Aluminium 2018) gives a value of 89 kWh/t of material. Approximately 500 kg of anode material are used per tonne of aluminium, resulting in an electricity use of 0.178 MWh/t of aluminium. The same report gives a value of 0.095 MWh/t of aluminium in the cast house, which is also accounted for in the benchmark.

- **Stakeholder feedback:** The industry association European Aluminium provided feedback on the numbers mentioned above. The electricity consumption in the cast house is reported per tonne of final product, while the consumption reported in the BREF document is mentioned per tonne of liquid aluminium. The benchmark is defined per tonne of liquid material. As reported by European Aluminium, approximately 30% of mass (scrap, alloying elements) is added in the cast house, which makes it necessary to rescale the specific electricity consumption in the cast house to the tonne of liquid aluminium, i.e. to 0.1235 MWh/t of liquid aluminium (specific consumption in the cast house only). The total specific consumption is the sum of the consumption in anode production, in the electrolysis and in the cast house.
- **Benchmark:** We recommend a benchmark of 13.90 MWh/t aluminium. This is the sum of the lowest value of the range given in Cusano et al. (2017) report for electrolysis (13.60 MWh/t) and the values given by the European Aluminium for anode production (0.178 MWh/t) and electricity consumption in the cast house (0.1235 MWh/t), all given relative to the tonne of liquid aluminium.
- **Average consumption:** Average specific electricity consumption is at 14.95 MWh/t.

2.6.2.2 Unwrought aluminium alloys in primary form (excluding aluminium powders and flakes)

- **Prodcom code:** 24.42.11.53
- **Production volume:** no data reported since 2012
- **Current benchmark:** 14.256 MWh/t
- **Main production countries in the EU:** not available
- **Process and electricity consumption:** (as for 24.42.11.54) The alloying of aluminium happens in the cast house, where corresponding elements are added to the liquid metal. The energy and electricity demand are therefore mainly determined by the demand of non-alloy aluminium production.
- **Stakeholder feedback:** No specific feedback from stakeholders.
- **Benchmark:** We recommend using the same benchmark as for 24.42.11.30 - Unwrought non-alloy aluminium (excluding powders and flakes), 13.90 MWh/t aluminium alloy.
- **Average consumption:** Average specific electricity consumption is at 14.95 MWh/t.

2.6.2.3 Unwrought aluminium alloys (excluding aluminium powders and flakes)

- **Prodcom code:** 24.42.11.54
- **Production volume:** 478 kt, average for 2017-2019; data reported since 2013
- **Current benchmark:** none
- **Main production countries in the EU:** Top five countries in their order of production: Hungary, Italy, France, Portugal, Poland
- **Process and electricity consumption:** (as for 24.42.11.53) The alloying of aluminium happens in the cast house, where corresponding elements are added

to the liquid metal. The energy and electricity demand are therefore mainly determined by the demand of non-alloy aluminium production.

- **Stakeholder feedback:** No specific feedback from stakeholders.
- **Benchmark:** We recommend using the same benchmark as for 24.42.11.30 - Unwrought non-alloy aluminium (excluding powders and flakes), 13.90 MWh/t aluminium alloy.
- **Average consumption:** Average specific electricity consumption is at 14.95 MWh/t.

2.6.2.4 Aluminium oxide (excluding artificial corundum)

- **Prodcom code:** 24.42.12.00
- **Production volume:** 5.523 kt; average for 2017-2019; in their contribution, the industry association European Aluminium indicated a value of 5,255 kt as the average total production for 2017-2019.
- **Current benchmark:** 0.225 MWh/t
- **Main production countries in the EU:** Top five countries in their order of production: Germany, Romania, Denmark, Finland; data supressed for others; European Aluminium indicated that alumina is produced in Ireland, Spain, Greece, Germany, Romania and none in Denmark or Finland
- **Process and electricity consumption:** Aluminium oxide (also: alumina) is produced from bauxite and is the pre-product of aluminium, but also used for other purposes. In Europe, literature reports that 2.1 - 2.2 t of bauxite are used to produce one tonne of aluminium oxide (Fleiter et al. 2013; European Aluminium 2018). The process is referred to as Bayer process and entails several steps, including digestion with caustic soda and lime at temperatures between 100°C and 350°C ((European Aluminium 2018; Cusano et al. 2017)) report 100°C-320°C) and calcination of aluminium hydroxide at about 1100°C (European Aluminium 2018). To supply this thermal energy ((European Aluminium 2018) report 9.0 GJ/t of alumina; (Cusano et al. 2017) give 7.6-11.7 GJ/t, a notable fuel switch from heavy oil to natural gas has taken place over the last years, the latter now being the dominant fuel in Europe (European Aluminium 2018). The average electricity consumption has also dropped from 181 kWh/t in 2010 to 141 kWh/t in 2015 ((European Aluminium 2018); equal to 0.5 GJ/t). As the electricity required in the production process is only a small share of the overall energy demand, most literature does not explicitly account for it (Fleiter et al. 2013; EAA 2018).
- **Stakeholder feedback:** European Aluminium provided data from all five of their members producing alumina. This data is from a regular data collection exercise, the association stated that '*The data were provided by the companies, extracted from their internal data systems. These figures are externally verified on a yearly basis, in the context of the EU ETS verification process. The scope is the same as used for the 2012 guidelines, hence for determining the current benchmark of 0.225 MWh/t.*' The lowest value from this data collection (average 2017-2019) is at 0.20 MWh/t. The average specific consumption from the data collection (2017-2019, all five installations) was 0.251MWh/t.
- **Benchmark:** We recommend setting the benchmark to 0.20MWh/t.
- **Average consumption:** Average specific electricity consumption is taken at 0.251MWh/t.

2.7 Lead, zinc and tin production (24.43)

2.7.1 Selection of relevant subsectors for additional benchmarks

This sector has six listed subsectors (see Table 2.14). Of these six subsectors, unwrought non-alloy zinc (24.43.12.30) and unwrought zinc alloys (24.43.12.50).

Table 2.14 Production volume (average 2017-2019) of the most relevant PRODCOM codes of the Lead zinc and tin sector in the EU27.

PRODCOM Code	PRODCOM Definition	Unit	Volume 2019
24.43.12.30	Unwrought non-alloy zinc (excluding zinc dust, powders and flakes)	t	1,583,754
24.43.11.30	Refined unwrought lead (excluding lead powders or flakes)	t	884,753
24.43.12.30	Unwrought zinc alloys (excluding zinc dust, powders and flakes)	t	739,903
24.43.11.90	Unwrought lead (excluding lead powders or flakes, unwrought lead containing antimony, refined)	t	234,942
24.43.23.00	Zinc bars, rods, profiles, wire, plates, sheets, strip and foil	t	228,354
24.43.11.50	Unwrought lead containing antimony (excluding lead powders or flakes)	t	211,904

Lead production in the form of refined unwrought lead (24.43.11.30), unwrought lead (24.43.11.90), and unwrought lead with antimony (24.43.11.50), is produced primarily in Germany, Italy, and Belgium, although plants exist in France, Poland, Romania, Estonia, Greece, Croatia, Hungary, Slovakia, Bulgaria, and Denmark. The traditional primary lead production process route via sintering and shaft furnace has been phased out by most of the producers in the EU 27. In 2018, 79% of the lead in Europe was from secondary production (World Lead Factbook 2019) (mainly from recycled materials, e.g., car batteries), with primary production curtailed. Much less energy (less than half) is required for secondary production in comparison to the production of lead from ore (energy need for primary production: 7000 - 20000 MJ/t lead, secondary production: 5000 - 10000 MJ/t lead) (Ecofys et al. 2009). Secondary smelters either separate out the plastics and smelt the lead containing fractions in furnaces (mostly rotary furnaces) or process the batteries as a whole in shaft furnaces after removing the acid. Because most of the energy is consumed in rotary or shaft furnaces, electricity consumption is likely minimal and primarily used for ancillary activities. Consequently, benchmarks are not recommended for these subsectors. Zinc bars, rods, profiles, wire, plates, sheets, strip and foil (24.43.23.00) are considered unsuitable for an electricity efficiency benchmark due to low electricity intensity in the production process (i.e., the amount of electrical energy required for casting one tonne of zinc is 208 kWh, and for remelting the same amount of metal is 155 kWh (Tan and Khoo 2005)).

2.7.2 Revised and new benchmarks

2.7.2.1 Unwrought non-alloy zinc (excluding zinc dust, powders and flakes) and Unwrought zinc alloys (excluding zinc dust, powders and flakes)

- **Prodcom codes:** 24.43.12.30 and 24.43.12.50
- **Production volume:** 1,625,578 tonnes average for 24.43.12.30 and 701,686 tonnes average for 24.43.12.50 for the 2017-2019 period.
- **Current benchmark:** 4 MWh/t
- **Process and electricity consumption:** Zinc is recovered from zinc concentrate by a hydrometallurgical or pyrometallurgical route. In Europe, 10 plants produce zinc by the Roast-Leach-Electrowin (RLE) process (International Zinc Association (IZA), 2021). One plant has a pyrometallurgical ISF process and processes more complex mixed zinc-lead mineral concentrates and secondary materials. The primary energy source of the ISF plant is fossil fuel. According to the BREF report (Cusano et al., 2017), the electricity consumption of zinc in the RLE process is between 3850–4905 kWh/t. However, based on information provided by the International Zinc Association (IZA), the RLE process (including the auxiliary equipment) has specific electricity consumption of 4000 to 4100 kWh per ton of zinc (International Zinc Association 2012). A major part of this electricity - average of 3400 kWh/t Zn - is consumed in the electrolysis stage, with 500 to 600 kWh/ t Zn consumed by equipment such as pumps, mixers, fans, filters, conveyors, etc. International Zinc Association noted the physical laws or limitations that underpin the RLE process, which potentially limits significant energy efficiency improvements. Although, improvements in the efficiency of this auxiliary equipment could result in a 20% efficiency improvement that would result in a saving of about 100 kWh/ t Zn or 2.5% on the total consumption of a zinc plant (International Zinc Association 2012). (International Zinc Association 2012).

- **Stakeholder feedback:** The IZA provided verified data on zinc slab production, melting losses (cathode and zinc powder) and associated electricity consumption from 9 European RLE plants for the period 2017-2019. Electricity consumption included purchased, and internally generated from steam, fossil fuel, renewables, but excludes electricity sold to third parties, and consumed in non-refining and casting processes. The data indicated a range of specific electricity consumption of 3994 to 4393 kWh/t zinc. However, the lower value of 3994 kWh/t represented the annual average for one plant in 2017, with all other plant data across the three-year period above 4000 kWh/t. The most efficient plant had a three-year average of 4016 kWh/t, while the least efficient was 4312 kWh/t.
- **Benchmark:** Based on stakeholder feedback, we recommend a benchmark of 3994 kWh/t..

- **Average consumption:** The average specific electricity consumption is 4167 kWh/t. This reflects the weighted average of 2017-2019 data from the 9 European RLE plants.

2.8 Copper production (24.44)

2.8.1 Selection of relevant subsectors for additional benchmarks

The top seven subsectors by production volume in the copper sector are presented in Table 2.15.

Table 2.15 Production volume (average 2017-2019) of the most relevant PRODCOM codes for copper production.

Prodcom Code	Prodcom Definition	Unit	Volume 2017-2019
24.44.23.30	Copper wire, refined (transv. section > 6 mm), of copper alloy	t	2,102,480
24.44.13.30	Unwrought unalloyed refined copper (excluding rolled, extruded or forged sintered products)	t	1,871,203
24.44.24.00	Copper and copper alloy plates, sheets and strip of a thickness > 0,15 mm (excluding expanded copper metal, insulated electric strip)	t	854,624
24.44.22.00	Copper and copper alloy bars, rods, profiles and hollow profiles (excluding bars and rods obtained by casting or sintering, copper wire rod in coils)	t	1,054,163
24.44.12.00	Unrefined copper, copper anodes for electrolytic refining (including blister copper) (excluding electrocopper-plating, electroplating anodes)	t	517,524
24.44.13.70	Unwrought copper alloys (excluding rolled, extruded or forged sintered products); master alloys of copper (including alloys which are not usefully malleable) (excluding copper phosphide (phosphor copper) containing > 15 % by weight of phosphorous)	T	448,387
24.44.26.30	Copper tubes and pipes	t	403,595

Of the 7 subsectors listed here, copper wire (24.44.23.30), copper and copper alloy plates (24.44.24.00), copper and copper alloy bars, rods, profiles (24.44.22.00), unwrought copper alloys (24.44.13.70), and copper tubes and pipes (24.44.26.30) are associated with rolling and casting processes. These are considered unsuitable for an electricity efficiency benchmarks since the majority of production is associated with small and medium-sized enterprises, and so, electricity consumption is low relative to the high consumption associated with copper anode (24.44.12.00) and cathode (24.44.13.30) production. Furthermore, within these small plants there will be a wide variation in electricity consumption due to numerous factors including alloy(s) cast, starting form of alloy (solid or liquid), overall process flow, casting yield, scrap rate, cycle times, size of die-casting machine, related equipment (robots, trim presses), and downstream processing (machining, plating, assembly, etc.).

Benchmarks are recommended for the two remaining subsectors: unwrought unalloyed refined copper (24.44.13.30) and unrefined copper, copper anodes (24.44.12.00) which have high specific electricity consumption and represent the primary energy intensive processes within the copper sector. There are more than a dozen major copper smelters and refineries producing these products located in the EU-27 today (Cusano et al. 2017). The largest facilities are located in Germany, Poland, Spain, Sweden, Finland, Belgium and Bulgaria:

- Atlantic Copper S.A. in Huelva, Spain (capacity of 300,000t/year, both copper anodes and cathodes); (Atlantic copper website) (Atlantic copper website)
- New Boliden AB with sites in Harjavalta and Pori, Finland and Rönnskär, Sweden (capacity of 300,000t/year, both copper anodes and cathodes)

- Aurubis AG with sites in Hamburg and Lünen, Germany; Pirdop, Bulgaria and Olen, Belgium (capacity of 500,000t/year, both copper anodes and cathodes)
- Metallo-Chimique in Beerse, Belgium with its daughter company Elmet S.L. in Berango, Spain capacity of 100,000t/year as anode and less than 50,000t/year as cathode). The company was bought by Aurbis in May 2020; (Metallo oficial website)(Metallo oficial website)
- KGHM Polska Miedź S.A. with sites in Głogów (1 and 2) and Legnica, Poland (capacity of 500,000t/year)
- Montanwerke Brixlegg, Austria with its daughter company Krompachy, Slovakia capacity of 100,000t/year)
- Umicore S.A. in Hoboken, Belgium (less than 50 000 tonnes/year)

Primary copper production sites using copper concentrates as their primary feedstock include Atlantic Copper S.A. in Huelva, KGHM, Pirdop, and Harjavalta whereas secondary copper production sites include Metallo-Chimique, Montanwerke Brixlegg, and Aurubis, Lünen, where the main feedstocks are scrap from the downstream value chain plus recycled products at their end of life. Some have the flexibility to process both primary and secondary feedstocks, like Boliden, Rönnskär and Aurubis AG, Hamburg.

2.8.2 Revised and new benchmarks

2.8.2.1 Unwrought unalloyed refined copper (excluding rolled, extruded or forged sintered products)

- **Prodcom code:** 24.44.13.30
- **Production volume:** 1 871 2030 t average for the 2017-2019 period
- **Production process and electricity consumption:** Unwrought unalloyed refined copper is produced from the electrolytic refining of copper anodes into cathodes during the pyrometallurgical process (or sometimes from electrowinning from leach or solvent extraction liquors). The electrolytic process involves placing down a sheet of copper anode (stainless steel blank or copper starting sheet) with a cathode in an electrolyte containing copper sulphate and sulphuric acid. Under the influence of the applied electrical potential, copper ions dissolve in the electrolyte and migrate from the anode to the cathode in high purity, forming cathode copper. The remaining anode is then recycled to the production process, usually the converter, to cool the reaction and recover the copper (Cusano et al. 2017). The slag treatment systems and electrorefining processes are also the same for primary and secondary copper production (Cusano et al. 2017). In some companies, a leaching and electrowinning process is installed, in order to treat copper granulate with a high amount of impurities and with a very variable copper content. (Cusano et al. 2017). To remove the impurities dissolved during electrorefining, part of the electrolyte is bled from the system for purification. Typical purification processes are copper sulphate crystallization, decopperization in electrowinning cells and nickel sulphate crystallization.(Cusano et al. 2017).

  According to (Moya and Boulamanti 2016) electricity is the main source of energy in electrolytic copper refineries. According to stakeholder feedback, most of the electricity consumption comes from direct current used for the electrolytic cells in the tank house. Additional electricity is consumed for other activities at the tank house such as automation, operation of anode preparation machine, operation of cathode stripping machine, spent electrolyte treatment. According to Cusano et al. (2017), the electricity consumed by the electrorefining step is reported to be between 300 and 400 kWh/ t Cu, "but it strongly depends on the purity of the anodes electrorefined and can be considerably higher in the case of high impurity" (Cusano et al. 2017).

The type of blank cathode used (stainless steel or copper) mainly influences the efficiency of the tank house and this can range from 92 % to 97 % in terms of current efficiency ((Cusano et al. 2017).

Differences in cell geometry, current efficiency and other characteristics of copper refineries can cause variations from a typical alternating current consumption of about 320 kWh/t cathode (Boulamanti and Moya 2016).

As shown in Table 2.16, specific electricity consumption for unwrought unalloyed refined copper is within the range of 0.3 to 0.4 MWh/t Cu_c. However, based on the most recent reference year (2013), Boulamanti and Moya (2016) indicate that the minimum specific consumption for European copper refineries is 0.31 MWh/t Cu_c, while the average is 0.40 MWh/t Cu_c.

Table 2.16 Estimated electricity requirements for the refinery production of copper

Process	Electricity usage [MWh/t]	Year of reference	Reference
Energy consumed by the electrorefining stage of copper production	0.30-0.40 MWh/t Cu_c	1998	Cusano, 2017, p.221
Copper electrorefining for whole unit	0.36-0.39 MWh/t Cu_c	2007	Cusano, 2017, p.242
Copper refining	0.40 MWh/t Cu_c	2013	Boulamanti and Moya, 2016
Electrolytic refining process, including on-site anode casting where appropriate, waste heat steam used for heating being supplied by an associated smelter, and excluding waste heat from an integrated anode casting plant	Min: 0.31 MWh/t Cu_c Average: 0.40 MWh/t Cu_c Max: 0.62 MWh/t Cu_c	2013	Moya and Boulamanti, 2016, p.149

- **Stakeholder feedback**: The European Copper Institute (ECI) advocated for an electricity consumption benchmark of 0.40 MWh/t. ECI suggested that the range of 0.30 to 0.40 MWh/t copper cathode only reflects energy consumption in the electrorefining stage and does not include other activities (such as automation, operation of anode preparation machine, operation of cathode stripping machine, spent electrolyte treatment) nor accounts for anode impurities that drive energy consumption up. However, this recommendation has not been backed with relevant data in order to maintain the data confidentiality, so this makes it difficult to verify their position.

  In comparison, various published sources listed in Table 2.16 (such as Cusano 2017) indicate that the scope of electricity consumption included in their estimates goes beyond the electrolytic cell.

- **Benchmark:** We recommend a benchmark of 0.31 MWh/t Cu_c. This represents the minimum value presented by Moya and Boulamanti, 2016, and encompasses energy consumed not only in the electrolytic refining process, but additional activities, such as on-site anode casting.
- **Average consumption:** The average specific electricity consumption is 0.40 MWh/t.

2.8.2.2 Unrefined copper, copper anodes for electrolytic refining (including blister copper) (excluding electrocopper-plating, electroplating anodes)

- **Prodcom code**: 24.44.12.00
- **Production volume:** 517,524 t average for the period 2017-2019

  Production process and electricity consumption: Unrefined copper, copper anodes for electrolytic refining are intermediate products of copper metallurgy with various degrees of copper content. They include black copper (between 60 or 85 % copper content by weight), blister copper (copper content normally about 98 % by weight) and copper anodes for electrolytic refining (copper partly refined by complete fusion and usually in the form of slabs cast) (ICSG 2015).

  Unrefined copper, copper anodes for electrolytic refining involve various steps throughout primary and secondary copper production which include:

  – **Pre-treatment and smelting**: In the case of primary copper production, following the drying phase, copper concentrates are smelted in a single furnace at high temperatures to produce a melt that can be separated into a matte (copper sulphide with some iron sulphide) and a slag rich in iron and silica. The two basic smelting processes in use include flash smelting (uses oxygen enrichment to produce an autothermal operation) and bath smelting processes (generally use a lower degree of oxygen enrichment). The type of furnace and the process steps used in secondary copper production depend on the copper content of the secondary raw material, its size and other constituents (Cusano, et al., 2017).

  – **Converting of mattes**: Converters process the matte obtained from the smelting unit by blowing through submerged tuyères[13]. The purpose of this process is to oxidise the iron sulphide and convert the copper sulphide into metallic copper. The copper matte is treated to form blister copper by a process that is performed in discrete batches using a sequence of charging, blowing, skimming, and pouring (Petkov 2007). According to Cusano et al. (2017), three types of converter processes are used during primary processes; two are matte conversion processes and one is an alloy conversion. The converting furnaces used for primary copper production are the same as those used for primary copper production. Cusano et al. (2017)

  – **Slag treatment**: Copper rich slags from smelting and /or converting are treated for copper recovery in slag treatment processes. One process is the use of an electric furnace. Alternatively, flotation processes are used after the slag has been slow-cooled, crushed and milled, and the flotation concentrate obtained is a copper-rich portion which is returned to the smelter. Cusano et al. (2017)

  – **Fire-refining**: Fire refining is a further purification step applied to the crude metal (blister copper) produced by the conversion stage. The refining step involves the addition of air and then a reducing agent (e.g. hydrocarbons) to reduce any oxide present. The fire refining process uses cylindrical rotary

[13] A pipe through which air is blown into the furnace.

furnaces (anode furnaces) using tuyères for gas addition fed with molten copper, copper scrap and anode scrap. It may also involve a reverberatory furnace with lances for air additions. The process applies a continuous melting and refining process (called Contimelt) to melt and treat blister copper, high-grade copper scrap and anode scrap to produce copper anodes. Some industry sites may rely on a combination of hearth shaft furnaces (fed with solid material for batch-wise melting) and rotary furnaces (for batch-wise reduction) which may apply for both primary (blister) and secondary (scrap) materials.

Electricity is used at all stages to produce copper anodes from copper concentrates, including, material handling and pre-treatment, smelting, converting, slag treatment and fire refining. According to Coursol et al. (2010), the main aspects considered in the smelting and converting stages requiring electricity relate to acid plant, oxygen production, matte and slag grinding, blowers, secondary gas handling, and auxiliary equipment. According to Cusano, et al (2017, p.220), energy consumption in copper production depends mainly on the concentrate (percentage of sulphur and iron), but is also influenced by the smelting unit used, the degree of oxygen enrichment and the collection and use of process heat.

Specific electricity consumption estimates presented in Table 2.17 are provided for the smelting stage as a whole (i.e., including additional equipment).

Table 2.17 Estimated electricity requirements for the smelting and production of copper

Process	**Electricity usage [MWh/t]**	**Year of reference**	**Reference**
Total energy consumed in the process of extracting copper from concentrates to produce anodes, minus the credit for power or steam generated. It includes the energy consumed in associated processes such as oxygen and acid plants, regardless of whether the smelter directly operates these processes or not.	Min: 0.58 MWh/t Cu_a Average : 1.10 MWh/t Cu_a	2013	Moya and Boulamanti, 2016, p.149;
Electricity consumption for an electric furnace at smelting stage	0.54-1.35 MWh/t Cu_a	2007	Cusano, 2017, p.242

- **Stakeholder feedback**:

  ECI suggested a benchmark for copper anode in the range 0.7 to 1.2 MWh/t Cu_a copper anode. This is based on data from copper smelters among their own membership that indicates a specific electricity consumption range of 700 to 1200 kWh/t Cu_{anode}. However, the underlying data was not provided to the study team for confidentiality reasons so the basis for these estimates, including the associated assumptions and operating conditions, could not be verified.

The ECI stressed that the benchmark should consider the important following implications on the electricity consumption for copper anodes:

– **Concentrate grades**: Ore grades are decreasing globally as the existing stock of mines age. This is resulting in lower amounts of copper and increased amounts of impurities in concentrates, leading to more energy to process low grade copper concentrates.
– **Heterogeneous production process**: There is high variability between undertakings in the copper sector in terms of product specialisation, production routes, deployed technologies, raw materials. ECI did not support a benchmark and quoted the Copper Organizational Environmental Footprint sector rules which "*found not meaningful to establish a benchmark for organisations in the copper production sector due to variability in the scale of operation and product portfolios, heterogeneous production routes and process configuration even though the representative organizations (based on a real organisation) represented all the production routes in scope*"[14].

ECI also suggested that if an accurate product benchmark cannot be determined, considering these factors, then a fallback approach should be considered.

- **Benchmark:** A number of EU smelters process secondary materials, with high impurity content, which increases their electricity consumption requirements. As such, a minimum benchmark could negatively impact these plants, as opposed to smelters that use higher purity copper concentrates as their primary feedstock. Based on this, we recommend to use a fallback value (See Section 4).

2.9 Other non-ferrous metal production (24.45)

This sector combines all "other" non-ferrous metals outside aluminium, copper, lead, nickel, and tin production, and represents 42 PRODCOM codes. The non-ferrous metals represented by this category includes the production of chrome, manganese, nickel, magnesium, titanium, cadmium, cobalt, antimony, vanadium, etc.

Currently, this sector is not represented by any electricity benchmarks.

2.9.1 Selection of relevant subsectors for additional benchmarks

Of the 42 PRODCOM codes assessed, the majority of subsectors have low production volumes (e.g., hafnium, germanium, gallium, vanadium, germanium) and/or their production processes have comparatively low electricity consumption. For example, there is currently no primary production of unwrought magnesium (24.45.30.24, 24.45.30.26) in Europe, with all production (54,000 t in 2019) reflecting secondary production, which has a low specific electricity consumption. Similarly, unwrought nickel (24.45.11.10) production (47,200 t in 2019), due to low electricity consumption, and the fact that where it is relevant, it is only applicable to a limited number of plants, is unsuitable for a benchmark.

The complex metallurgy of nickel is reflected in the wide range of extraction and refining processes in operation. Every plant presents a unique set of process features. For example, nickel ore is mined in Finland, Greece, and France (New Caledonia). The latter is laterite nickel-containing ores, the smelting of which, accounts for a large proportion of materials produced for the steel industry (i.e., ferronickel), while the electric furnace smelting of sulphidic ore (Finland) produces nickel oxide, with the subsequent refining producing nickel metal or nickel salts (i.e., nickel sulphate). Nickel

[14] https://ec.europa.eu/environment/eussd/smgp/documents/OEFSR_Copper.pdf

matte (24.45.12.10) is typically imported but is also produced at a plant in Finland using Direct Outotec Nickel flash smelting (DON process).

The mattes produced by smelting processes must be treated further to recover and refine the metal content. Nickel matte must go through a multistage refining process to remove iron and recover copper, cobalt, and precious metals, which depending on the EU facility could be utilise carbonyl, electrolytic, electrowinning/hydrogen reduction processes. Cusano et al. (2017) report that the energy consumed in the various refining stages is between 4.7–5.6 MWh per tonne of nickel. However, the majority of energy consumption in these processes is fossil fuel based, with electricity relevant to only specific plants. For example, the Eramet process uses electrolysis to remove remaining minor impurities and ensure nickel purity >99.99%.

- **Benchmark:** No benchmark is recommended for the non-ferrous metal subsectors.

3 Degressivity factor

The revision of the ETS guidelines introduce an automatic degressivity factor for the electricity benchmarks. The benchmarks will automatically be reduced by this factor annually. The factor is calculated from the difference between the existing benchmark and the newly developed benchmarks proposed under this study. For those sectors without an existing benchmark, a fallback degressivity is calculated. This is based on the annual degressivity observed in those sectors with a previous benchmark.

3.1 Degressivity factor on subsector level

The previous benchmarks were developed for the third trading period and valid for the years 2013 to 2020. The underlying studies were performed in the years 2011 to 2012, likely building on data from the preceding years. As for the current study in the year 2021, the data will have varied in terms of time between publication and use in the study. We therefore assume that 10 years have passed between the data underlying the previous benchmarks and those developed under this study. If a subsector was associated with a benchmark previously and is now again associated with a benchmark (*BM*), the annual degressivity is calculated from the following equation.

*Degressivity = (new BM – existing BM) / existing BM / 10 * 100%*

The following table gives subsectoral degressivity factor and the relevant information on each of the subsectors that has been associated with a benchmark previously. For some sectors, an update of the benchmark was not possible due to limited data availability. These subsectors are included in the table for completeness but are not considered for the calculation of the fallback degressivity factor. The fallback degressivity should be applied to this subset of subsectors.

Table 3.1 Data on the subsectors with a previous electricity benchmark, giving the subsectoral degressivity, which is used to calculate the fallback degressivity for those subsectors without a previous electricity benchmark. If the annual degressivity cannot be calculated, the reason is indicated in place of the value.

Prodcom Code	Prodcom Definition	Existing BM [MWh/t]	New BM [MWh/t]	Annual degressivity [%]
20.13.21.70	Silicon. Other than containing by weight not less than 99,99 % of silicon	11.87	11.87	No new data
20.13.21.60	Silicon. Containing by weight not less than 99,99 % of silicon	60	60	No new data
20.13.64.10	Silicon. Carbides of silicon, whether or not chemically defined	6.2	6.2	No new data

Prodcom Code	Prodcom Definition	Existing BM [MWh/t]	New BM [MWh/t]	Annual degressivity [%]
20.13.21.11	Chlorine	2.461	1.846	-2.50[15]
24.10.12.10	Ferro-manganese, containing by weight > 2% carbon, with a granulometry <= 5 mm and a manganese content by weight > 65%	2.76	2.2	-2.03
24.10.12.20	Other ferro-manganese, containing by weight > 2% carbon (excl. ferro-manganese with a granulometry of <= 5 mm and containing by weight > 65% manganese)	2.76	2.2	-2.03
24.10.12.35	Ferro-silicon, containing by weight > 55% of silicon	8.54	8.54	No new data
24.10.12.45	Ferro-silico-manganese	3.85	3.419	-1.12
24.10.T1.22	Crude steel: non-alloy steel produced by other processes than in electric furnaces	0.036	0.03385	-0.6
24.10.T1.32	Crude steel: alloy steel other than stainless steel produced by other processes than in electric furnaces	0.036	0.03385	-0.6
24.10.T1.42	Crude steel: stainless and heat resisting steel produced by other processes than in electric furnaces	0.036	0.03385	-0.6
24.42.11.53	Unwrought aluminium alloys in primary form (excluding aluminium powders and flakes	14.256	13.9	-0.25

[15] Alternatively, the fallback degressivity factor could be applied to Chlorine, since the value of -2.5% is the result of the introduction of a niche technology, and we do not reasonably expect such a technological change to happen again in the near future

Prodcom Code	Prodcom Definition	Existing BM [MWh/t]	New BM [MWh/t]	Annual degressivity [%]
24.42.12.00	Aluminium oxide (excluding artificial corundum)	0.225	0.2	-1.11
24.42.11.30	Unwrought non-alloy aluminium (excluding powders and flakes)	14.256	13.9	-0.25
24.43.12.30	Unwrought non-alloy zinc (excluding zinc dust, powders and flakes)	4	3.994	-0.01
24.43.12.50	Unwrought zinc alloys (excluding zinc dust, powders and flakes)	4	3.994	-0.01

Source: See previous chapters

3.2 Fallback degressivity factor

The fallback degressivity factor is determined from the subsectoral degressivity factors given in the previous section. Figure 3.1 shows data for those subsectors previously associated with a benchmark and used for the calculation of the fallback degressivity (values given in Table 3.1).

As applied for the previous ETS Guidelines, the average of degressivity factors is used to determine the fallback value. The assessment of the fallback degressivity factor does not consider those subsectors for which no new data could be found.

Some of the benchmarking values are applied to more than one sector (see Table 3.1). Each benchmarking value determines the electricity consumption of the most efficient installation for a certain process. The Prodcom classification, however, does not group by production process but by product. Two different products may use practically the same production process - particularly in terms of energy used - but still be classified differently by Prodcom. When aggregating different benchmarking values as is done here for the degressivity factor (or below for the fallback efficiency), this needs to be considered. Even if a certain benchmark is applied to several Prodcom codes, it should only be counted once to determine the average. The number of Prodcom codes associated with a benchmark has no relationship with the benchmark itself and the fallback degressivity should not consider the number of Prodcom codes associated with a benchmark. In practice, this means that the fallback degressivity is determined from the benchmarking values, counting each benchmarking value for a certain process only once, and not from the average over all Prodcom codes. This is the reason why some sectors are not shown in the figure below and not considered in the calculation of the fallback degressivity. This approach is also followed when determining the fallback efficiency.

Hence only seven distinct benchmarking values remain to determine the fallback degressivity. The figure below shows the average (-1.09%), not shown is the average weighted by production volume (-1.51%) and the average weighted by total electricity consumption (-1.30%).

The degressivity observed in the subsectors is likely determined by many aspects, such as electricity consumption, production volume, the chemical minimum requirement of energy or the share of costs of electricity in the overall production costs. There is no reason to assume that the production volume or total electricity consumption determine to a large degree by themselves the degressivity. We therefore propose not to use a weighted average.

Note that the percentage rate is an annual reduction value to be applied to the original benchmark. It is not a growth rate but a linear reduction factor.

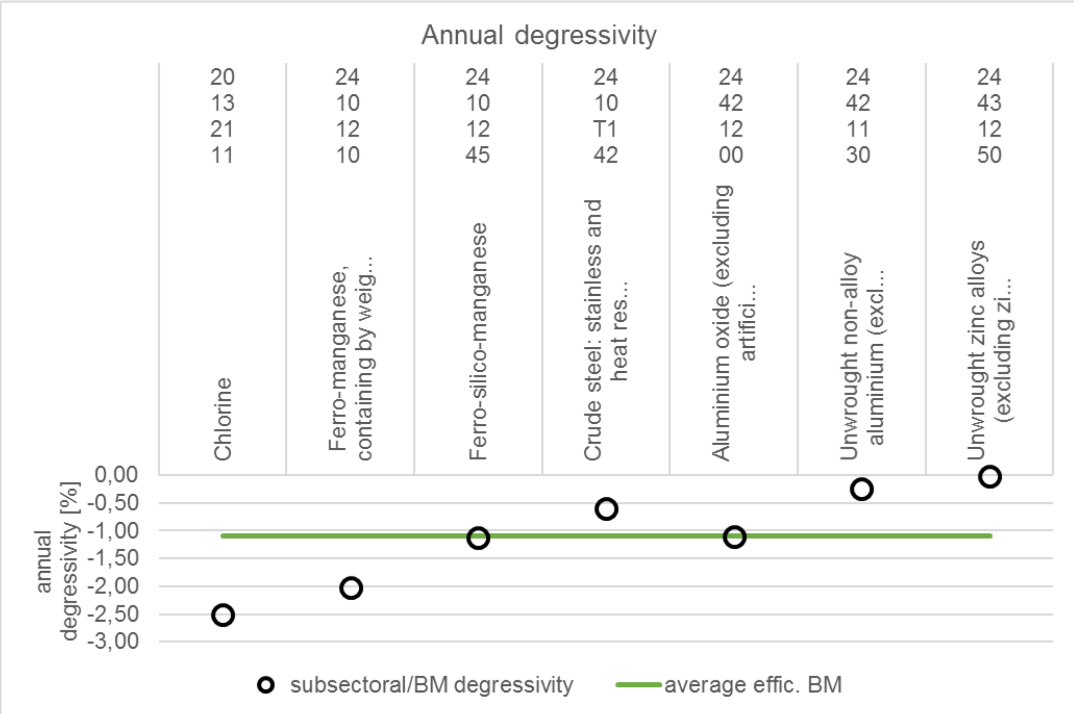

Figure 3.1 Degressivity calculated from previous benchmarks and benchmarks proposed by this study. Horizontal lines indicate average values. Note that the figure also includes data on those direct emission benchmarks that fall under fuel exchangeability and are therefore state aid eligible.

We propose that the unweighted average of the subsectoral degressivity factors is used as a fallback value. As discussed above and in line with the calculation underlying the fallback efficiency, we propose to consider only distinct benchmark values in averaging. From those subsectors previously associated with a benchmark and those with a new benchmark, we recommend a fallback degressivity of **-1.09%** per year, to be applied as annual linear reduction of the benchmark value.

4 Fallback efficiency percentage

Those subsectors not associated with a benchmark will be associated with a fallback efficiency percentage. This percentage sets the share of the electricity consumption of each installation that is compensated as if the benchmark had been set at this value. Currently, the fallback efficiency percentage is set at 80%.

To determine the efficiency percentage of the benchmarks, we apply the following formula.

*Efficiency = (new BM) / (average specific electricity consumption) * 100%*

From these values on subsector level, we determine the fallback efficiency percentage as the average of the subsectoral efficiency benchmarks. We follow the same logic as for the fallback degressivity factor: Each benchmarking value determines the electricity consumption of the most efficient installation for a certain process. The Prodcom classification, however, does not group by production process but by product. Two different products may use practically the same production process - particularly in terms of energy used - but still be classified differently by Prodcom. Thus, even if a certain benchmark is applied to several Prodcom codes, it should only be counted once to determine the average efficiency. The number of Prodcom codes associated with a benchmark has no relationship with the benchmark itself and the fallback efficiency should not consider the number of Prodcom codes associated with a benchmark. In practice, this means that the fallback efficiency is determined from the benchmarking values, counting each benchmarking value for a certain process only once, and not from the average over all Prodcom codes. The benchmarks of the pulp sector (17.11.14.00) are also considered separately.

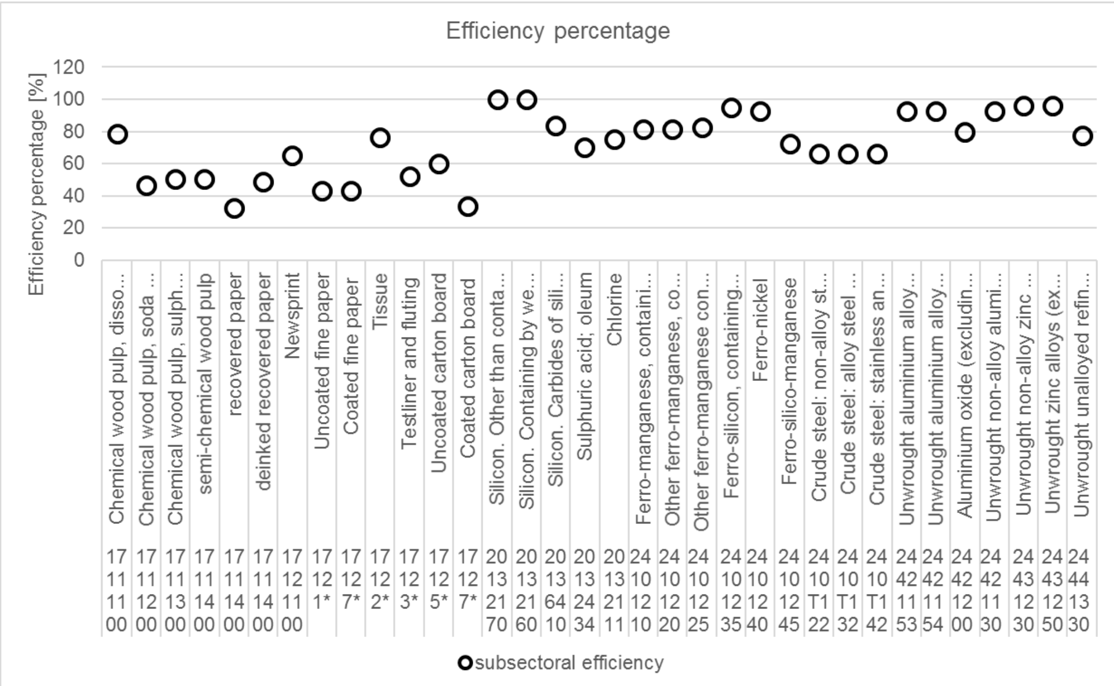

Figure 4.1 Efficiencies calculated for each subsector from benchmark.

The above figure shows data for all subsectors and benchmarks analysed in this study (17.11.14.00 has been split according to the text above). Those subsectors not associated with a benchmark are not shown (and naturally not considered in the analysis). The plain average over all subsectors (73.7%) is not an adequate measure for the reasons given above. In order to arrive at the fallback efficiency, only distinct benchmarking values relevant for different processes are considered, i.e. duplicate uses of benchmarks removed where relevant. This is true for chemical and semi-chemical wood pulp (i.e., two subsectors for one benchmark), coated and uncoated fine paper (two subsectors), high carbon ferro-manganese (two subsectors), crude steel (three subsectors), unwrought aluminum (three subsectors) and unwrought zinc (two subsectors). Following this approach, the fallback efficiency is calculated at 70.21%. In addition, we recommend excluding the silicon subsectors due to the low data availability (as is also done for the fallback degressivity), which lowers the calculated fallback efficiency to 67.28%.

Similar to the degressivity factor, weighting would imply that a dominant driver of the efficiency is known and then considered by weighting. Neither the production volume nor the total electricity consumption determines the efficiency. We therefore propose to use the unweighted average value.

Following this approach, some sectors still dominate the overall average, in particular pulp and paper, due to the large number of subsectors. We therefore recommend to first aggregate to a higher level of the Prodcom classification where appropriate, again considering similarities in the underlying process. We recommend using the averages in the pulp, paper, ferro-alloy subsectors to reduce the influence of these sectors on fallback efficiency. The aggregated efficiency values are given in the following table. If this grouping is applied, the average efficiency is determined at 74.73%.

Table 4.1 Efficiency of grouped subsectors, see text for details.

Grouped sector	Efficiency
Pulp	51.33%
Paper	53.45%
Sulphuric acid	70.18%
Chlorine	75.01%
Ferro-alloys	84.82%
Crude steel	66.45%
Aluminium	92.98%
Alumina	79.68%
Zinc	95.85%
Copper	77.50%

The chain of arguments underlying this analysis is associated with high uncertainties. The benchmarking values are associated with uncertainties due to the availability of the underlying data, the average specific electricity consumption is likely more uncertain as it builds on an even larger spread of data and draws information from more sources. The arguments for grouping are valid but the grouping is nevertheless an additional source for uncertainty. This should be considered when determining the final value for the fallback efficiency.

We propose the unweighted, grouped average of the efficiency percentages of the benchmarks be used as reference for the fallback value. The uncertainties in the underlying assessment should be considered. We propose to establish the **fallback efficiency at 74.73%**.

5 Publication bibliography

Atlantic copper website. Available online at https://www.atlantic-copper.es/en/production-process/the-metallurgical-complex.

Austin, Severin; Glowacki, Arndt (2000): Hydrochloric Acid. In : Ullmann's Encyclopedia of Industrial Chemistry. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA.

Biermann, W.; Cromarty, R.D; Dawson, N. F. (2012): Economic modelling of a ferrochrome furnace. In *The Journal of The Southern African Institute of Mining and Metallurgy*.

Boulamanti, Aikaterini; Moya, Jose Antonio (2016): Production costs of the non-ferrous metals in the EU and other countries: Copper and zinc. In *Resources Policy* 49, pp. 112–118. DOI: 10.1016/j.resourpol.2016.04.011.

Chen, Zhengjie; Ma, Wenhui; Wu, Jijun; Wei, Kuixian; Lei, Yun; Lv, Guoqiang (2018): A Study of the Performance of Submerged Arc Furnace Smelting of Industrial Silicon. In *Silicon* 10 (3), pp. 1121–1127. DOI: 10.1007/s12633-017-9584-3.

Concawe (2019): EU refinery capacity. Available online at https://www.concawe.eu/refineries-map.

Coursol; Mackey; Diaz (2010): Energy Consumption in Copper Sulphide Smelting. Available online at https://www.xps.ca/files/28/Presentations/175/Energy-Consumption-in-Cu-Smelting---June-6th-2010-by-Coursol-Mackey-Dias-.pdf.

Covestro: Chlorproduktion mit Sauerstoffverzehrkathoden. Available online at https://www.covestro.com/de/sustainability/lighthouse-projects/sauerstoffverzehrkathode.

Cusano, Gianluca; Delgado Sancho, Luis; Farrell, Frank; Rodrigo Gonzalo, Miguel; Roudier, Serge (2017): Best available techniques (BAT) reference document for the non-ferrous metals industries. Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). Luxembourg: Publications Office of the European Union (EUR, Scientific and technical research series, 28648).

Ecofys (2009): SERPEC-CC.

Ecofys; Fraunhofer ISI; Öko-Institut (2009): Methodology for the free allocation of emission allowances in the EU ETS post 2012. Sector report for the non-ferrous metals industry. Available online at https://ec.europa.eu/clima/sites/default/files/ets/allowances/docs/bm_study-non_ferrous_metals_en.pdf.

Eurochlor (2020): Chlor-alkali Industry review. Edited by Eurochlor. Available online at https://www.eurochlor.org/wp-content/uploads/2020/09/Industry-Review-2019_2020.pdf.

European Aluminium (2018): Environmental Profile Report. Life-Cycle inventory data for aluminium production and transformation processes in Europe. European Aluminium.

European Commission (Ed.) (2007): Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Solids and Others industry. Available online at https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/lvic-s_bref_0907.pdf.

European Commission (2012a): Communication from the Commission amending the Communication from the Commission Guidelines on certain State aid measures in the context of the greenhouse gas emission allowance trading scheme post-2012. 2012/C 387/06. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52012XC1215(02)&from=EN.

European Commission (2012b): Guidelines on certain State aid measures in the context of the greenhouse gas emission allowance trading scheme post-2012. SWD(2012). Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52012XC0605(01)&from=EN.

European Commission (2019): Guidance Document n°9 on the harmonised free allocation methodology for the EU-ETS post 2020; Sector-specific guidance 2019. Available online at https://ec.europa.eu/clima/sites/default/files/ets/allowances/docs/p4_gd9_sector_specific_guidance_en.pdf.

European Commission (2020): Guidelines on certain State aid measures in the context of the system for greenhouse gas emission allowance trading post-2021. (2020/C 317/04). Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020XC0925(01)&from=EN.

European Commission (2021): Determining revised benchmark values for free allocation of emission allowances for the period from 2021 to 2025 pursuant to Article 10a(2) of Directive 2003/87/EC of the European Parliament and of the Council. 2021/447. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0447&qid=1620747635846&from=en, checked on 5/11/2021.

Fleiter, Tobias; schlomann, barbara; eichhammer, wolfgang (2013): Energieverbrauch und CO2-Emissionen industrieller Prozesstechnologien. Einsparpotenziale, Hemmnisse und Instrumente. Stuttgart: Fraunhofer-Verl. (ISI-Schriftenreihe "Innovationspotenziale").

Godin, Hélène (2019): Energiewende in der Industrie Potenziale und Wechselwirkungen mit dem Energiesektor. Branchensteckbrief der Papierindustrie. Edited by Navigant Energy Germany GmbH. Available online at https://www.bmwi.de/Redaktion/DE/Downloads/E/energiewende-in-der-industrie-ap2a-branchensteckbrief-papier.pdf?__blob=publicationFile&v=4.

Hamilton, John R.; Rami, Anand C. (2010): Best in Class Polysilicon Technology. In *ECS Trans.* 27 (1), pp. 1007–1013. DOI: 10.1149/1.3360743.

Healy, Sean; Schumacher, Katja (2012): Product Classification and it's implication on Competitiveness and Carbon Leakage: Pulp, Paper and Paperboard. Edited by Climate Strategies. Available online at https://climatestrategies.org/publication/product-classification-and-its-implication-on-competitiveness-and-carbon-leakage-pulp-paper-and-paperboard/.

ICSG (2015): Statistical Yearbook. International Copper Study Group.

International Zinc Association (2012): Sectoral roadmap zinc 2050. Available online at https://eurometaux.eu/media/1907/sectoral-roadmap-zinc-2050.pdf.

Larssen, Trine Asklund; Kero, Ida; Tangstad, Merete (2019): Energy Distribution in HC FeMn and SiMn - Energy vs Exergy Analyses. In *The Southern African Journal of Mining and Metallurgy*. Available online at https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2673629.

Lee, Jason C.K.; Wen, Zongguo (2017): Rare Earths from Mines to Metals: Comparing Environmental Impacts from China's Main Production Pathways. In *Journal of Industrial Ecology* 21 (5), pp. 1277–1290. DOI: 10.1111/jiec.12491.

Li, Xiaopeng; Wehrspohn, Ralf B. (2019): Nanometallurgical Silicon for Energy Application. In *Joule* 3 (5), pp. 1172–1175. DOI: 10.1016/j.joule.2019.03.025.

Metallo oficial website. Available online at https://www.metallo.com/.

Mistry, Mark; Gediga, Johannes; Boonzaier, Shannon (2016): Life cycle assessment of nickel products. In *Int J Life Cycle Assess* 21 (11), pp. 1559–1572. DOI: 10.1007/s11367-016-1085-x.

Mitin, V. V.; Kokh, A. A. (2018): Polysilicon Market Development and Production Technologies. In *Russ Microelectron* 47 (8), pp. 553–558. DOI: 10.1134/S1063739718080085.

Moya, J. A.; Pavel, C. C. (2018): Energy efficiency and GHG emissions. Prospective scenarios for the pulp and paper industry. Luxembourg: Publications Office of the European Union (EUR, Scientific and technical research series, 29280).

Moya, Jose A.; Boulamanti, Aikaterini (2016): Production costs from energy-intensive industries in the EU and third countries. Luxembourg: Publications Office (EUR, Scientific and technical research series, 27729).

Olsen, Sverre E.; Tangstad, Merete; Lindstad, Tor (2007): Production of manganese ferroalloys. Trondheim: Tapir.

Petkov, Veselin (2007): Degradation mechanisms of copper anode furnace refractory linings. Available online at https://www.mtm.kuleuven.be/onderzoek/semper/Hitemp/publications/doctoral-theses/petkov, checked on 6/29/2021.

Randhawa, Navneet Singh; Minj, Rajesh Kanyut (2020): An Improved Process for the Production of Low-Carbon Ferromanganese in the Electric Arc Furnace. In *Trans Indian Inst Met* 73 (8), pp. 2105–2111. DOI: 10.1007/s12666-020-02010-x.

Roth, Susanna; Zetterberg, Lars; AcWorth, William; Kangas, Hannah-Liisa; Neuhoff, Karsten; Zipperer, Vera (2016): The pulp and paper overview paper. Sector analysis for the Climate Strategies Project on Inclusion of Consumption in Carbon Pricing. Edited by Climate Strategies. Available online at https://www.diw.de/documents/dokumentenarchiv/17/diw_01.c.534645.de/cs-pulp-and-paper.pdf.

Roudier, Serge; Delgado Sancho, Luis; Aguado-Monsonet, Miguel A.; Remus, Rainer (2013): Best available techniques (BAT) reference document for iron and steel production. Industrial emissions Directive 2010/75/EU : integrated pollution prevention and control. Luxembourg: Publications Office (EUR (Luxembourg. Online), 25521).

Suhr, Michael; Klein, Gabriele; Kourti, Ioanna; Rodrigo Gonzalo, Miguel; Giner Santonja, Germán; Roudier, Serge; Delgado Sancho, Luis (2015): Best Available Techniques (BAT) reference document for the production of pulp, paper and board. Luxembourg: Publications Office (EUR, Scientific and technical research series, 27235).

Tabereaux, Alton T.; Peterson, Ray D. (Eds.) (2014): Aluminum Production: Elsevier (Treatise on Process Metallurgy, 3).

Tan, Reginald; Khoo, Hsien H. (2005): Zinc Casting and Recycling (8 pp). In *Int J Life Cycle Assess* 10 (3), pp. 211–218. DOI: 10.1065/lca2004.08.172.

Tangstad, Merete (2013): Ferrosilicon and Silicon Technology. In Michael Gasik (Ed.): Handbook of Ferroalloys: Elsevier, pp. 179–220.

thyssenkrupp (2020): Chlor-Alkali Electrolysis Three Best-in-Class Technologies. Edited by thyssenkrupp. Available online at https://d2zo35mdb530wx.cloudfront.net/_binary/UCPthyssenkruppBAISUhdeChlorineEngineers/en/products/chlor-alkali-electrolysis/link-tkUCE_Chlor-Alkali_Electrolysis.pdf.

US EPA (2005): Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries. Available online at https://eta-publications.lbl.gov/sites/default/files/lbnl-56183.pdf, checked on 5/9/2021.

Viswanathan, K.; Tilak, B. V. (1984): Chemical, Electrochemical, and Technological Aspects of Sodium Chlorate Manufacture. In *J. Electrochem. Soc.* 131 (7), pp. 1551–1559. DOI: 10.1149/1.2115908.

Wernet, Gregor; Bauer, Christian; Steubing, Bernhard; Reinhard, Jürgen; Moreno-Ruiz, Emilia; Weidema, Bo (2016): The ecoinvent database version 3 (part I): overview and methodology (9).

Wiesenberger, Herbert; Kircher, Joachim (2001): Stand der Technik in der Schwefelsäureerzeugung im Hinblick auf die IPPC-Richtlinie. Edited by Federal Environmental Agency - Austria. Available online at https://www.umweltbundesamt.at/fileadmin/site/publikationen/M137.pdf.

World Lead Factbook (2019). Available online at https://www.ilzsg.org/generic/pages/file.aspx?file_id=2643.

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