

Managing Product Carbon Footprints in Semi-Finished Copper and Copper Alloy Manufacturing

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Reliable product carbon footprint (PCF) data is essential for transparent greenhouse gas accounting in the manufacturing industry utilizing copper-based products, yet published values vary widely due to differences in data quality and calculation methodologies. This paper introduces a hybrid approach for calculating product carbon footprints of semi-finished products made from copper and copper alloys, combining bottom-up and top-down data allocation. The method aligns with the Greenhouse Gas Protocol and ISO 14040/14044/14067 standards, ensuring relevance, completeness, and accuracy while leveraging existing enterprise resource planning (ERP) datasets for automated calculations, scalability and global deployability. Key influencing factors

such as alloy composition, recycled content, and processing depth are analyzed, alongside energy efficiency considerations in melting, casting, and forming processes. Results demonstrate that PCFs can be significantly reduced through increased recycled content and energy efficiency measures. The proposed methodology enhances transparency and comparability of product carbon footprint data, supporting decarbonization efforts across the copper value chain.

Keywords:

Product carbon footprint (PCF) – Decarbonization – Semi-finished copper-based products – Greenhouse Gas Protocol – Automated hybrid calculation methodology

Management von produktbezogenen Carbon Footprints bei der Herstellung von Halbfabrikaten aus Kupfer und Kupferlegierungen

Zuverlässige Daten von produktbezogenen Carbon Footprints sind essenziell für eine transparente Treibhausgasbilanzierung in Wirtschaftszweigen, die kupferbasierte Produkte herstellen oder verwenden. Allerdings variieren veröffentlichte Werte aufgrund von Unterschieden in Datenqualität und Berechnungsmethoden erheblich. Dieser Beitrag stellt einen hybriden Ansatz zur Berechnung von produktbezogenen Carbon Footprints für Halbfabrikate aus Kupfer und Kupferlegierungen vor, der Bottom-up- und Top-down-Datenallokation kombiniert. Die Methode orientiert sich am Greenhouse Gas Protocol sowie an den Normen ISO 14040/14044/14067 und gewährleistet Relevanz, Vollständigkeit und Genauigkeit. Vorhandene ERP-Datensätze (Enterprise Resource Planning) werden für eine automatisierte Berechnung herangezogen. Sie gewährleisten die Skalierbarkeit und globale Übertragbarkeit. Zen-

trale Einflussfaktoren wie Legierungszusammensetzung, Rezyklatanteil und Verarbeitungstiefe werden analysiert, ebenso wie Aspekte der Energieeffizienz in Schmelz-, Gieß- und Umformprozessen. Die Ergebnisse zeigen, dass sich produktbezogene Carbon Footprints durch einen höheren Rezyklatanteil und Maßnahmen zur Steigerung der Energieeffizienz erheblich reduzieren lassen. Die vorgeschlagene Methodik verbessert die Transparenz und Vergleichbarkeit von produktbezogenen Carbon-Footprint-Daten und unterstützt damit Dekarbonisierungsmaßnahmen entlang der gesamten Kupfer-Wertschöpfungskette.

Schlüsselwörter:

Produktbezogener Carbon Footprint (PCF) – Dekarbonisierung – Kupferbasierte Halbfabrikate – Greenhouse Gas Protocol – Automatisierte hybride Berechnungsmethode

Gestion de l'empreinte carbone des produits dans la fabrication de produit semi-fini en cuivre et en alliages de cuivre Gestión de la huella de carbono de los productos en la fabricación de semiacabados de cobre y aleaciones de cobre

1 Introduction

Upstream greenhouse gas (GHG) emissions in Scope 3 account for the largest share of total GHG emissions in many manufacturing companies. For example, in Germany's metalworking industry, around 70 % of GHG emissions are attributable to Scope 3, while in the downstream ve-

hicle and mechanical engineering sectors, this proportion approaches 90 % [1]. In metal processing companies, Scope 3 is frequently driven by purchased goods and feedstocks required for production [2, 3]. It is therefore important for companies to calculate the GHG emissions resulting from the procurement of raw materials completely and accurately. This requires suitable data from the upstream value chain,

which can be used to assess the raw materials in terms of their GHG emissions. Semi-finished product manufacturers in particular are required to provide such data because semis are used in many different end products and value chains.

Primary, supplier-specific product carbon footprints [4] or alternatively secondary not plant-specific emission factors (EF) [5] are used to calculate the mass of carbon dioxide equivalents CO_2e from the tonnage of purchased goods and feedstocks. The product carbon footprint (PCF), which is the focus of this publication, is the result of a product-related life cycle assessment with defined system boundaries in accordance with DIN EN ISO 14067. In the metal industry, PCFs usually cover the GHG emissions of the upstream production (cradle-to-gate) and have the manufactured

mass as declared unit. An EF is often a generic average value that can be drawn from publicly accessible databases [6, 7]. In case of purchased goods, the physical unit of both PCF and EF is tons of carbon dioxide equivalents per ton of fabricated metal product, $\text{tCO}_2\text{e/t}$. When evaluating purchased raw materials for the company's own production in terms of GHG emissions in Scope 3, PCFs should be preferred instead of EFs [8].

Since primary PCF data from suppliers is often unavailable, companies have to fall back on secondary EFs or PCFs from databases or publications. Table 1 provides examples of secondary data for metals used in the manufacturing of copper-alloy products. The range of values is significant in certain cases.

Table 1:
PCF and EF values for pure metals and copper alloys from secondary sources (p.r.: primary refined, s.r.: secondary refined, n.s.: not specified)

Metal	Metallurgical production	PCF or EF [$\text{tCO}_2\text{e/t}$]			Source
		Average	(from) Min	(to) Max	
Copper (Cu)	p.r.	2.6	1	9	[9]
	p.r.	5.5	1.1	64.9	[10]
	p.r.	3.965	n.s.	n.s.	[11]
	p.r.	6.86	n.s.	n.s.	[7]
	s.r.	1.73	n.s.	n.s.	[7]
Zinc (Zn)	p.r.	4.1	2.7	6.1	[10]
	n.s.	2.69	n.s.	n.s.	[7]
Nickel (Ni)	p.r.	13	7	27	[10]
	p.r.	17.53	n.s.	n.s.	[7]
	s.r.	1.08	n.s.	n.s.	[7]
Tin (Sn)	p.r.	17	n.s.	n.s.	[10]
	n.s.	10.38	n.s.	n.s.	[7]
Aluminium (Al)	p.r.	16	2	41	[10]
	p.r.	9.89	n.s.	n.s.	[7]
	s.r.	0.53	n.s.	n.s.	[7]
Brass (CuZn)	n.s.	5.69	n.s.	n.s.	[7]
Bronze (CuSn, CuAl, CuSnPb)	n.s.	7.25	n.s.	n.s.	[7]

Table 2:
Factors influencing PCF or EF values of copper from metallurgical production

Metallurgical production of copper	Variables	Range of PCF or EF [$\text{tCO}_2\text{e/t}$]		Source
		(from) Min	(to) Max	
Primary production: mining & crushing ores → concentration (beneficiation) → smelting → refining	Ore type resp. process route (pyrometallurgical vs. hydrometallurgical production)	3.3	6.2	[12]
	Energy carriers: fossil fuels vs. combination of renewable energy sources	0.6	3.2	[10]
	Geographical region of pyrometallurgical production (Chile vs. South Africa)	1.4	8.5	[13]
	Different production plants in Chile using hydrometallurgy	1	3.9	[13]
	Time of data collection or LCA calculation (2.5 years difference)	6.66	6.86	[7, 14]
	LCA software and convenient database	3.51	4.75	[15]
Secondary production: collecting scrap → sorting → smelting → refining	Scrap quality (depending on complexity or Cu content of secondary material to be recycled)	0.2	1.9	[9]
	Scrap quality (high grade vs. low grade)	0.4	1.8	[13]
	Dismantling technology (mechanical vs. manual) of waste electrical and electronic equipment WEEE in Europe	1	1.2	[13]
	Geographical region of mechanical WEEE dismantling (Europe or India)	1	1.2	[13]

Alloy group	Examples of alloys	Typical applications for strip material
Copper	Cu-OF, Cu-ETP, Cu-DHP	Electrical and electronic components, busbars, coaxial cables, transformer coils, heat spreaders, plate heat exchangers, roofing
Low alloyed copper	CuSn0.15, CuCrSiTi, CuFe2P, CuNi3Si1Mg	Electrical connectors, electronic components, leadframes
Brass	CuZn5, CuZn15, CuZn37, CuZn42, CuZn23Al3Co, CuZn39Pb2	Valves, jewelry, buttons, hinges, springs, electrical connectors, precision mechanical components, rolled bushings architectural items, roofing, brass instruments
Bronze	CuSn4, CuSn8	Signal connectors, springs, rolled bushings
Nickel silver	CuNi18Zn20, CuNi12Zn24	EMI/RFI shieldings, electrical connectors in low-power circuits, relay springs, tableware, cutlery
Copper-nickel	CuNi9Sn2	Electrical connectors, springs

Table 3:
Copper alloys and some of their typical applications (alloy designations according to [21])

Table 2 identifies reasons for the variation between maximum and minimum copper feedstock values. Evidently, the PCF values of primary copper extracted from ores are higher than those of secondary copper recovered from recycled scrap. In addition, the quality of the raw materials, the energy carriers used for production, the manufacturing technology, and accordingly geographical conditions influence the PCF. Furthermore, the selection of data and software utilized to conduct the life cycle assessment may significantly influence the results. It should be emphasized that a PCF always refers to a dataset covering a defined historical period and is therefore subject to change. Since PCFs reflect the decarbonization progress of an industry or company, they are expected to decrease over time. Given the wide range of published values, it is understandable that identifying the appropriate PCF is challenging.

Due to the importance of Scope 3, suppliers of semi-finished products are required to provide their customers with reliable and comparable PCFs. However, it is increasingly evident that customers also seek clarity on the calculation methodology and on potential levers for reducing provided PCFs. Moreover, the expectations for PCF calculation are continuously increasing [16]: for comparable supplier PCFs, internationally harmonized standards for the collection, calculation, and exchange of GHG emissions data as well as for data quality assessment and allocation rules should be used. Moreover, it is desirable to obtain detailed primary data determined using a bottom-up approach instead of average values from publicly available sources or commercial databases [17].

However, this desired approach is not yet in practice. The reason for this is the considerable coordination effort required across companies and industries, as well as the costs that companies would have to incur for additional measurement equipment and data analysis. As an interim solution, hybrid PCF calculation approaches can provide a practical solution [18]. This involves the use of both top-down data, which is determined at the plant level and allocated to the respective product, and product-specific bottom-up data from the production equipment.

This paper presents a hybrid method for calculating the PCF of semi-finished products manufactured from copper alloys. Examples of copper strip materials and their applications are shown in Table 3. The hybrid method is based on the Greenhouse Gas Protocol and the standards

ISO 14040/14044/14067 [4, 19, 20]. When designing the approach, attention was paid to relevance, completeness, consistency, transparency, and accuracy, i.e., all GHG-relevant activities that can be attributed to the product are recorded completely and as accurately as possible and are then applied in a traceable and reproducible manner. The hybrid method is based on already existing datasets in the company's ERP system and is implemented using commercial spreadsheet programs. In accordance with current customer requirements, PCFs are given as annual averages.

The method which will be described below was developed for semi-finished products of copper alloys. Although this work focuses on rolled products manufactured at the Wieland-Werke AG production plant in Voehringen (Germany) between October 2023 and September 2024, the method and the key results of the PCF calculation are transferable to other products and manufacturing processes.

2 System boundaries and process description

As a fabricator in the semi-finished copper industry, a cradle-to-gate system boundary is chosen which includes all attributable Scope 1, Scope 2, and Scope 3 upstream emission categories [8]. As the final function of the semi-finished products is unknown, the reference flow 1 t of shipped product serves also as the functional unit.

The cradle-to-gate system boundary includes casting, forming and surface finishing of semi-finished copper and copper alloy products. Figure 1 shows the system boundaries, important production steps, and relevant metal flows for strip material. A sub-process or entire process is inefficient if the ratio of the input (IP) of metals to the output (OP) of manufactured products is significantly greater than one.

Figure 2 depicts the most important steps of strip production, which includes strand casting, hot rolling, cold rolling, annealing, pickling, coiling, slitting, as well as surface finishing. Within the defined system boundaries, process emissions do not occur. Process emissions are greenhouse gases generated from the manufacturing or processing of materials [8]. They are, for example, known from blast furnace processes in steel production or from the fused-salt electrolysis of aluminium oxide.

Fig. 1:
System boundary in the cradle-to-gate approach with focus on metal flow in rolling processes:
IP = Input, OP = Output, 3rd letter P = purchased, 3rd letter S = sold

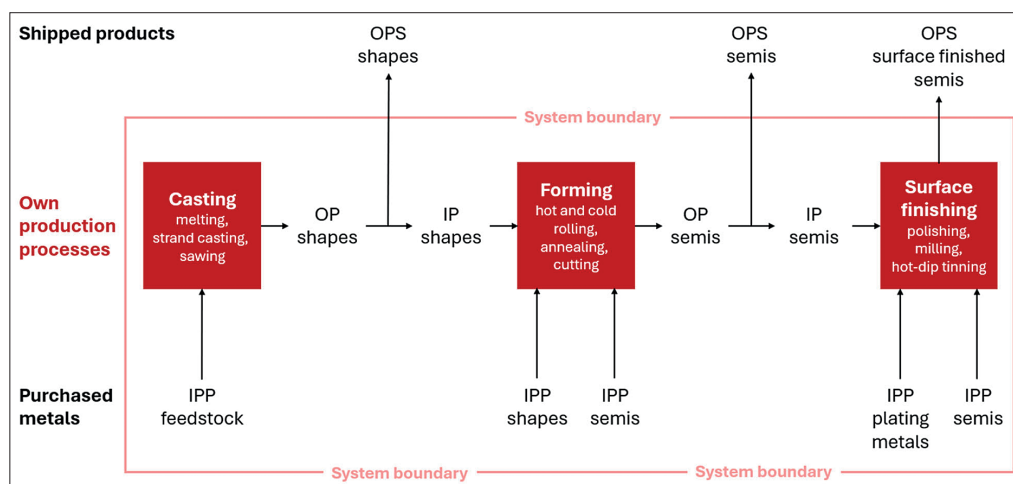
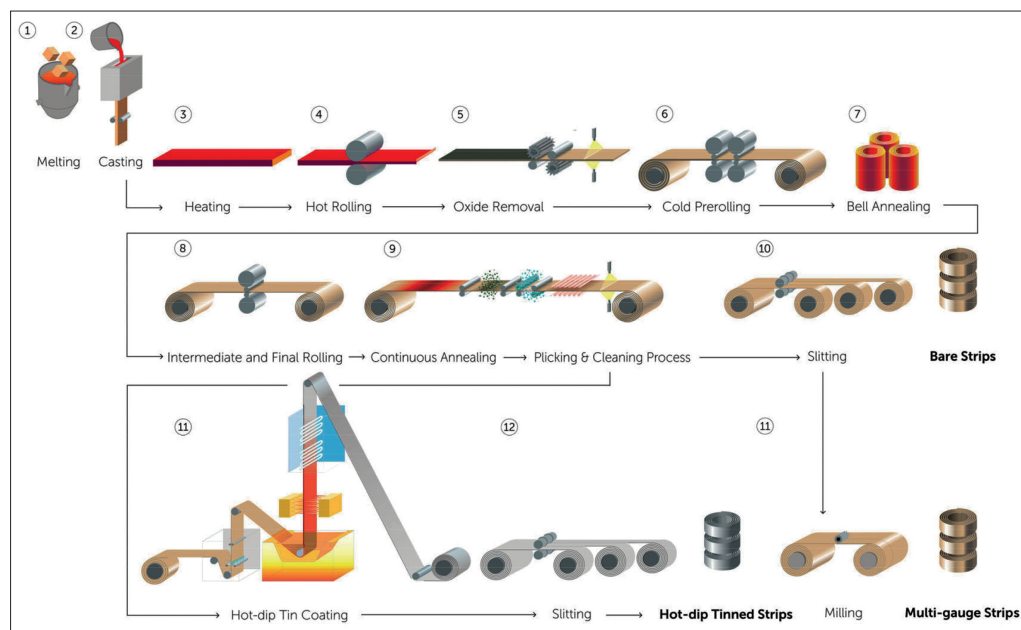


Fig. 2:
Illustrative production processes for rolled products at Wieland Group: Casting = 1, 2; Forming = 3-10 (in the forming process, there may be multiple roll-anneal cycles); Surface finishing = 11, 12



3 Preconditions for calculating carbon footprints of semi-finished products made from copper and copper alloys

The following section illustrates the approach of Wieland Group to different important aspects of carbon footprint calculations which are mentioned in different standards, however, leave room for interpretation in their application. This includes the topics of significance analysis, as well as EF assessment.

3.1 Significance analysis

The significance analysis is based on requirements of the Science Based Targets initiative to cover at least 95 % of company-wide Scope 1 and 2 GHG emissions [22]. The electricity and natural gas consumption of each plant is utilized as indicators for their emission intensity. It is justified to focus on electricity and natural gas consumption, as these are by far the most important energy carriers: within the Wieland Group, they account for more than 95 % of total energy consumption. Moreover, electricity and natural gas consumption data are consistently available regardless of plant size which

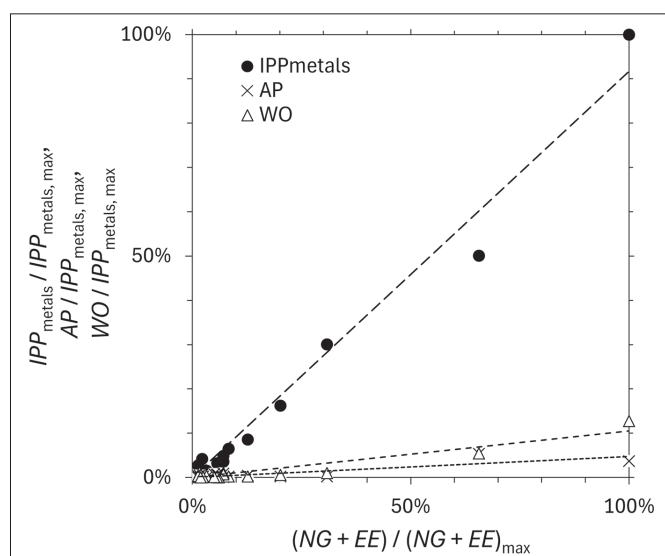


Fig. 3: Correlation of normalized natural gas and electricity consumption of 20 production plants with the Scope 3 emission categories: total purchased metal input for processing $IPP_{metals} = \sum IPP_{feedstock} + \sum IPP_{shapes} + \sum IPP_{semis}$, purchased auxiliary materials AP, and waste generated in operation WO. The reference value is the highest energy consumption $(EE + NG)_{max}$ or metal input $IPP_{metals, max}$ of all plants.

facilitates a cost-efficient approach. The significance analysis reveals that approx. 20 % of Wieland's production plants account for more than 95 % of total energy consumption.

Figure 3 demonstrates the correlation between energy consumption as sum of natural gas and electricity and the activity data of the Scope 3 emission categories: purchased metals, auxiliary materials, and waste. It is possible to infer other important activity data from energy consumption. When specific data points for a plant are missing, the identified correlations enable interpolation or extrapolation based on the plant's electricity and natural gas consumption. However, this approach should only be applied when the missing data point accounts for less than 3 % of the total GHG emissions inventory.

3.2 Emission factor assessment

To assess the data quality of PCFs or EFs, the Greenhouse Gas Protocol recommends the application of five data quality indicators: technological representativeness, temporal representativeness, geographical representativeness, completeness, and reliability [17].

When using EFs, one should place a high importance on primary, verified data to increase the primary data share, such as market-based EF for electricity, and consequently the reliability of the data. If secondary data is inevitable, the following hierarchy is applied which ensures a pragmatic approach:

1. free of cost data from government agencies, ministries, or industry associations,
2. if 1. is not available, peer reviewed publications,
3. if 1. and 2. are not available, own calculations or estimates based on engineering or natural science principles.

The hierarchy levels 1 and 2 provide a high degree of reliability. In addition, governmental data ensures temporal representativeness, as it is typically updated every few years. Data from industry associations is particularly technologically representative. If there are multiple EFs for a specific activity at a given hierarchical level and a selection must be made, the most conservative value is preferred.

Within Wieland's metals activity data, scrap plays a significant role. There are three major sources of scrap:

- fabricator's scrap from own production,
- customer's scrap from processing semis,
- scrap purchased from outside the company, e.g., from traders or recycling plants.

In general, Wieland Group follows the cut-off approach regarding recycling [23,24]. It allocates all emissions to the final product without any credit for the potential recycling of the product in the next life cycle. Scrap has no burden from its previous life cycle when used as input material. Consequently, the fabricator scrap from own production and customer's semis processing scrap is evaluated with 0 tCO₂e/t. Emissions from transportation within the own sites and from the customer to the sites are included in upstream transportation. However, the availability of EFs covering outbound logistics, disassembly, shredding, sorting, and compacting of copper scrap is limited. For purchased scrap

EF = 0.07 tCO₂e/t is used. This EF is based on data from a recycling plant of the Wieland Group. It considers internal electricity consumption for shredding and sorting insulated copper wire and pressing copper granules into pucks. Additionally, the Germany location-based electricity EF is applied, and an average inbound transportation of 500 km assumed. It should be emphasized that the values above can only be used for so-called direct melt scrap which can be remelted directly without further metallurgical refining.

4 Product carbon footprint

This chapter introduces the methodology used for the calculation of PCFs at Wieland Group and includes an initial top-down approximation, as well as a detailed hybrid calculation approach. It first explains general methodological considerations and allocation principles before presenting the mathematical framework for bottom-up and top-down emission allocation.

4.1 First PCF approximation

A first approximation for a PCF calculation can be implemented by calculating a top-down average PCF, which divides the total attributable emissions of a plant by the total shipments. Figure 4 shows this top-down average PCF values of different plants of the Wieland Group containing a casting shop.

The differences between the top-down average PCF values can be explained by the

- product portfolio, e.g. different semi-finished products, alloys, or gauges,
- location, e.g. differences in sourcing possibilities and grid electricity EFs,
- casting technology, e.g., continuous or discontinuous casting of slabs, billets, wire, tubes, or strips,
- share of cast shapes that are purchased externally (see Figure 1: IPP shapes).

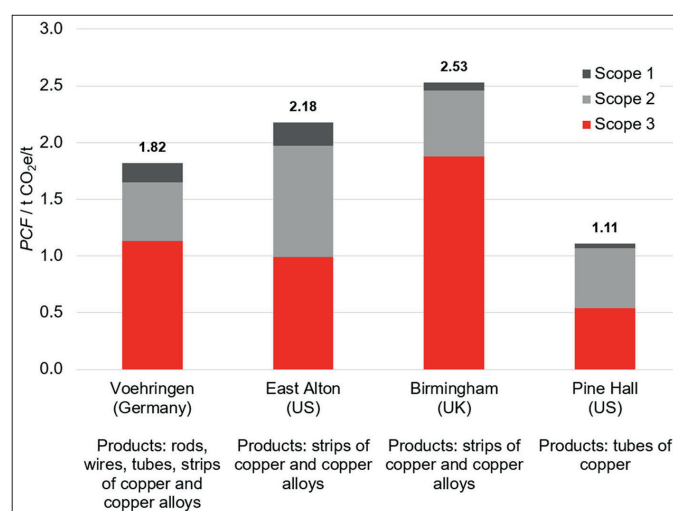


Fig. 4: Top-down average PCF values of different production plants of Wieland Group calculated for the period October 2023 to September 2024; Breakdown of the PCF according to [8]: Scope 1 = direct GHG emissions, Scope 2 = electricity indirect GHG emissions, Scope 3 = other indirect GHG emissions

If a company or plant only manufactures a limited number of products, the top-down calculation can already be a sufficient level of detail. However, if a large variety of different products is manufactured, as it is the case for most Wieland production plants, a bottom-up approach is necessary.

4.2 General considerations regarding carbon footprint calculations

Wieland's approach to PCF calculations is based on three preconditions:

- Alignment with the CCF: consistent approach between CCF and PCF calculation to avoid additional efforts and increase efficiency.
- Scalability to the portfolio: data-driven, automatable approach that can be applied to the entire product portfolio.
- Global deployability: possibility for roll-out to multiple business units and plants.

The hybrid PCF calculation methodology, combining bottom-up and top-down data allocation, is based on these preconditions. The CCF is dominated by three major emission categories: metals, electricity consumption, and natural gas consumption, which account for 88 % of the total CCF on average over the last four years. For PCF calculation a detailed bottom-up emission allocation is conducted for these emission categories. It is based on working plans and bills of material, which are already existent in the ERP system and used for cost calculation purposes. For all other emission categories, a top-down approach is applied which ensures the allocation of the emissions across the product portfolio, while increasing efficiency of the calculation.

4.3 Equations for the hybrid PCF calculation

This section introduces a universal PCF equation, details the bottom-up allocation of emissions from metals and energy consumption, and specifies a top-down approach for all remaining activities to ensure comprehensive emission coverage.

4.3.1 Universal PCF equation

$$PCF = \frac{1}{OP} \cdot \sum_{i=1}^M A_i \cdot EF_i \quad (1)$$

Equation (1) describes the PCF of a product that leaves a system, e.g. a workshop, plant, or company, in which GHG have been generated by a number of M different activities A_i to manufacture this product. Activity A_i refers to the resource consumption directly attributable to a product and its associated production process. The ratio OP/A_i of the system's output to an activity required to achieve that output serves as a measure of efficiency. The emission of CO_2e , obtained by multiplying all activities by their respective EF_i , is related to the process output OP . This aligns with the cut-off approach. As mentioned in chapter 3.2, EF_i should be replaced by supplier specific PCF_i , if this data is available.

4.3.2 Bottom-up analysis

Emissions from metals

Based on the main production processes (see Figure 1) the calculation of emissions caused by purchased metals PCFM is conducted for each shipped output OPS. This leads to the partial product carbon footprints $PCFM_{shapes}$, $PCFM_{semis}$, and $PCFM_{platedSemis}$.

$PCFM_{shapes}$ consists of a number of N different foundry feedstock metals ($IPP_{feedstock}$), such as pure metals, master alloys, or scrap, which are melted and cast to produce the output OP_{shapes} in the own foundry.

$$PCFM_{shapes} = \frac{1}{OP_{shapes}} \cdot \left(\sum_{i=1}^N IPP_{feedstock,i} \cdot EF_{metal,i} \right) \quad (2)$$

$PCFM_{shapes}$ applies to both, slabs that undergo further processing within the facility, and to those that exit the system boundary, i.e. the "gate", when shipped to the customer.

$PCFM_{semis}$ incorporates O different self-cast and P different purchased shapes, as well as a number of Q different purchased semi-finished products in a simple intermediate form, which are processed into higher-value semis in own workshops through hot working, cold working, and annealing.

$$PCFM_{semis} = \frac{1}{OP_{semis}} \cdot \left(\sum_{i=1}^O IPP_{shapes,i} \cdot PCFME_{shapes,i} + \sum_{i=1}^P IPP_{shapes,i} \cdot EF_{shapes,i} + \sum_{i=1}^Q IPP_{semis,i} \cdot EF_{semis,i} \right) \quad (3)$$

where $IP_{shapes} = OP_{shapes} - OPS_{shapes}$. $PCFM_{semis}$ applies both to semis that are shipped and to those that undergo plating within own workshops.

$PCFM_{surface\ finished\ semis}$ defines the portion of the product carbon footprint that results from surface finishing of bare strips, such as hot-dip tinning. It consists of R different internally formed as well as S different purchased semis and U different purchased metals for plating.

$$PCFM_{surface\ finished\ semis} = \frac{1}{OP_{surface\ finished\ semis}} \cdot \left(\sum_{i=1}^R IP_{semis,i} \cdot PCFM_{semis,i} + \sum_{i=1}^S IPP_{semis,i} \cdot EF_{semis,i} + \sum_{i=1}^U IPP_{plating\ metals,i} \cdot EF_{plating\ metals,i} \right) \quad (4)$$

At the Voehringen plant, hot-dip tinning of rolled strips is the only plating process that is carried out in-house.

Emissions from energy consumption of the production equipment

A number of V machines are involved to manufacture a particular product. For simplicity, it is assumed that these machines only operate with electric energy EE and/or natural gas NG .

$$PCFE = \frac{1}{OP_{product}} \sum_{i=1}^V EE_{product,i} \cdot EF_{EE,i} + NG_{product,i} \cdot EF_{NG,i} \quad (5)$$

There are two approaches to determine the energy content of natural gas NG_i (unit: MWh) and the electricity EE_i

(unit: MWh) which is needed to run the machine i . These approaches are explained using the example of electricity:

- Allocation by mass: the energy consumption of machine i is weighted with the material input for the product in relation to the total material input into the machine.

$$EE_{\text{product},i} = EE_i \cdot \frac{IP_{\text{product},i}}{\sum_{\text{all products}} IP_i} \quad (6)$$

- Allocation by time: the energy consumption of machine i is weighted with the time needed for the processing of the product in relation to the total operating hours of the machine.

$$EE_{\text{product},i} = EE_i \cdot \frac{t_{\text{product},i}}{\sum_{\text{all products}} t_i} \quad (7)$$

The decision to use one approach or the other depends mainly on the availability and accessibility of the required data. At Wieland Group, allocation by mass is used for the casting process steps, whereas allocation by time is used for forming and surface finishing processing.

4.3.3 Top-down analysis

For the remaining activities (RA), which are attributable to the product, a top-down approach is applied. Those activities are:

- other fossil fuels than natural gas used for processing the product, e.g., diesel fuel for company-owned forklifts,
- electricity and natural gas consumption which cannot be attributed directly to single products such as the energy consumption of the central dust extraction system in the foundry,
- other purchased goods besides metal, which are attributable to the product, i.e., auxiliaries or packaging materials,
- fuel- and energy-related activities,
- upstream transportation and distribution,
- waste generated in production.

The contribution of these W activities A_{RA} to the PCF is determined by dividing the total emissions of those activities by the total output of the system, e.g. a workshop, plant, or company. Consequently, the PCFRA is identical for all products.

$$PCFRA = \frac{1}{\sum_{\text{all products}} OP} \cdot \sum_{i=1}^W A_{RA,i} \cdot EF_{RA,i} \quad (8)$$

4.4 Application of the hybrid PCF calculation

The total PCF of a product y is calculated by summing the individual values for metal and energy consumption, and all remaining activities.

$$PCF_y = PCFM_y + PCFE_y + PCFRA_y \quad (9)$$

Customers in the downstream value chain are interested in the total cradle-to-gate PCF_y. Semi-finished product manufacturers also thoroughly analyze individual summands to identify effective measures for reducing the PCF.

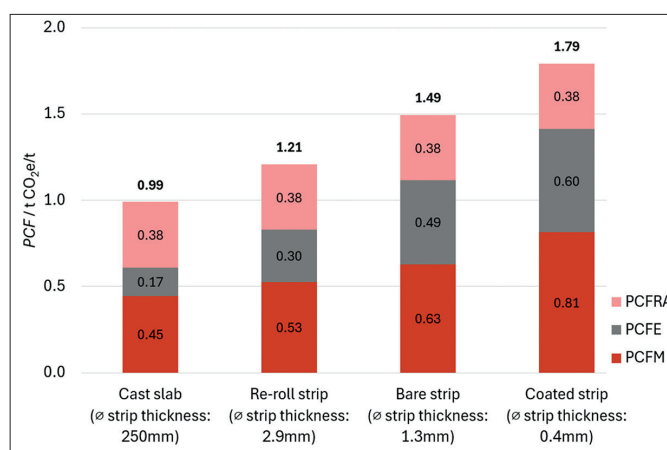


Fig. 5: PCF development of CuZn37 depending on processing depth in the rolling mill

The application of the equation (2) to (9) results in PCFs depending, among others, on the processing depth of the product. Figure 5 provides an example based on CuZn37. The displayed values show a volume-weighted average PCF of all single product PCFs within the defined product category (cast slab, re-roll strip, bare strip, coated strip) produced in one year.

The PCFRA is identical for all products due to the top-down allocation (see chapter 4.3.3). PCFE increases with processing depth as the energy consumption of additional processing steps accumulates. PCFM increases as the input-output-ratio IP/OP increases and additional metals for hot-dip tinning are included.

The resulting emissions can also be allocated to the different emission scopes according to the Greenhouse Gas Protocol. PCFM is allocated to Scope 3. PCFE covers natural gas and electricity emissions which are allocated to Scope 1 or Scope 2 respectively. PCFRA covers a range of different emissions (see chapter 4.3.3) which, depending on the emission category, is allocated to either Scope 1, Scope 2, or Scope 3 accordingly.

Theoretically, the sum of all PCFs within a system equals the CCF, minus emissions not attributable to product processing, such as employee commuting or building heating. However, due to the usage of experience-based ERP plan data in the PCF calculation, minor differences remain in comparison to the CCF data, which is calculated using actual consumption volumes. At Wieland Group the typical difference between all PCFs and the CCF amounts to $\pm 10\%$. The difference between the sum of all PCFs and the CCF can be used to double-check PCF calculation results. If the difference is greater than $\pm 10\%$, data sources, calculation files, conversion factors, etc. must be verified.

5 Discussion

Hybrid PCFs are valuable for understanding and comparing emissions across different products and alloys. They enable the identification of key factors that influence the magnitude of emissions. The following subchapters elaborate on several parameters affecting metal-related emissions, energy consumption associated with melting and

casting processes, as well as energy required for forming and manufacturing operations.

5.1 Influencing parameters on PCFM

PCFM depends on the chemical composition of the alloy (including impurity levels), as well as the recycled content (RC) of purchased metals $IPP_{\text{feedstock}}$, IPP_{shapes} , IPP_{semis} , $IPP_{\text{plating metals}}$. RC refers to the portion of recycled material used in a product. Its calculation is based on international standards [25, 26].

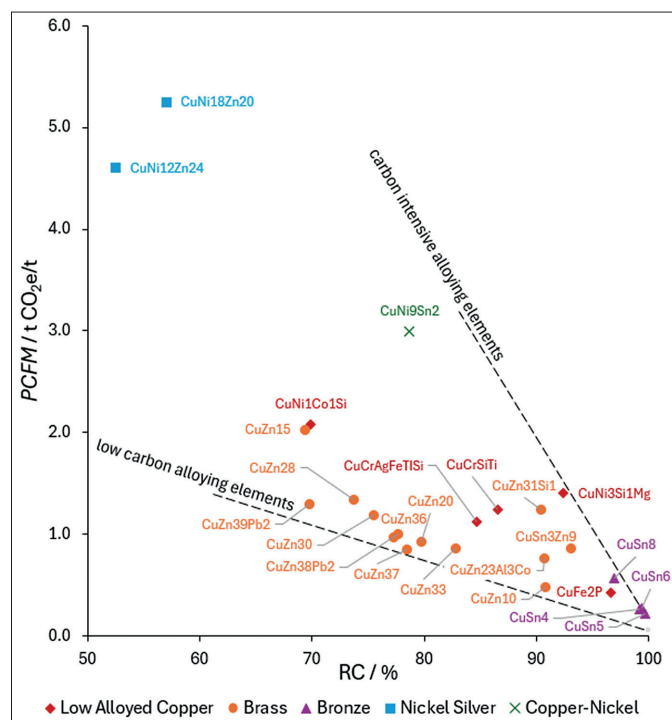


Fig. 6: Correlation between PCFM and recycled content RC of purchased input material for bare strips

As shown in Figure 6, the PCFM decreases with increasing recycled content to the value 0.07 tCO₂e/t (see chapter 3.2) of direct melt scrap or of purchased metals made from 100 % scrap. Alloys containing carbon intensive alloying elements with large EFs, such as tin and nickel are more sensitive to changes in the RC than brass with its low carbon alloying element zinc, for example (see Table 1).

In some cases, the RC cannot be freely selected. For example, to meet the regulatory product requirements of the CPSIA [27] or the optional Oeko-Tex standard [28] re-

garding a maximum permissible lead content of 0.01 % and 0.009 % respectively, large quantities of pure high-grade metals must be used. This usually implies a lower share of scrap feedstock which increases PCFM. For CuZn42 brass which has a lead content of maximum 0.2 % [21] a reduction to 0.01 % lead can be achieved by reducing the RC by a factor of approximately two. However, this increases the PCFM by a factor of four.

5.2 Influencing parameters on PCFE of melting and casting

The PCFE in the foundry results from the consumption of electricity required for inductive melting of the foundry feedstock $IPP_{\text{feedstock}}$, strand casting of rolling slabs, and sawing of the slab ends. The consumption of fossil fuels is negligible.

The production plant in Voehringen has several semi-continuous slab casting lines, each of which is supplied with melt by several induction melting furnaces. Each strand casting machine forms a subsystem with its associated melting furnaces, which is technically optimized for a limited group of alloys. The PCFE of a slab made of a specific alloy cast in one of these subsystems is calculated using equations (5) and (6).

Table 4 shows the PCFEs of selected alloys as well as system characteristics and material parameters relevant for casting. The data presented can be used to explain the range of PCFEs caused by melting and casting in qualitative terms.

In principle, the PCFE decreases with increasing energy efficiency $OP/(EE_i + NG_i)$, see equation (5). Brass has relatively low PCFEs as it can be cast in three strands with a large slab cross-section which implies a high output OP.

Next to equipment technology, energy efficiency is also determined by the castability of the material. Good castability means high output of shapes and low volumes of generated scrap, slag, or dross. Castability is influenced by several material properties, such as melt viscosity, solidification behavior, tendency to react with oxygen or refractory materials, hot cracking tendency, etc. [29]. Among other factors, the alloy's high thermal conductivity λ has a favorable effect, as it enables large slab cross-sections and high casting speeds [30, 31]. This results in a high casting output per unit time at constant energy input. The differences in λ

Table 4: PCFE, manufacturing parameters of the Voehringen foundry, and material properties of selected copper materials (it is assumed that the thermal conductivity normalized to copper is independent of temperature)

Alloy	PCFE [tCO ₂ e/t] of melting and casting	Cross-section area of the slabs relative to the largest cross-section area produced	Number of strands of the casting machine	Thermal conductivity λ in relation to λ of copper	Liquidus temperature TL [°C]	Estimated ideal PCFE [tCO ₂ e/t] for melting
CuZn15	0.16	1.0	3	0.41	1025	0.08
CuZn37	0.17	1.0	3	0.31	920	0.07
CuZn39Pb2	0.17	1.0	3	0.28	895	0.07
CuSn0.15	0.21	1.0	2	0.90	1083	0.08
CuSn6	0.21	0.8	3	0.19	1040	0.08
CuCrSiTi	0.28	1.0	2	0.84	1066	0.08
CuNi9Sn2	0.31	1.0	2	0.14	1130	0.09

explain why, with the same machine technology, the PCFE values of the brasses CuZn15 or CuZn37 are lower than that of CuSn6.

If the liquidus temperature T_L of the alloy is high, more energy is required to heat cold foundry feedstock to the melting temperature and to apply the melting enthalpy, which is approximately proportional to the absolute melting temperature. The minimum energy required for melting can be estimated using the approximation equation $EE_{\min} \approx 1.4 \cdot c_p \cdot T_L$ [32], where the specific heat c_p is approximately $400 \text{ J/(kg} \cdot \text{K)} = 0.11 \text{ kWh/(t} \cdot \text{K)}$ for many copper materials. The ideal PCFE values calculated using this estimation and the EF for electricity lie at an average of $0.08 \text{ tCO}_2\text{e/t}$. The actual PCFE values are approximately two to three times larger. PCFE for melting and casting cannot be explained solely by the alloy's liquidus temperature, as manufacturing factors also play a role which reduce the efficiency of the process significantly. For example, it is known that energy consumption increases when the packing density of solid feedstock metals and the fill level of the induction furnace decreases [33]. In addition, the melting capacity, i.e., the amount of melt produced per unit of time, and thus also the energy efficiency of a crucible induction furnace is impaired by oxygen-affine alloying elements such as Al, Ti, Si, and Cr. If the power induced electrically into the feedstock metal is increased to accelerate melting, the bulging of the melt surface and the melt circulation in the furnace is also increased. This promotes oxygen ab-

sorption and encourages the slagging of easily oxidizable elements, which significantly reduces the output of the melting furnace. To prevent this, the melting capacity of the CuCrSiTi alloy is deliberately limited. This is why the PCFE of CuCrSiTi is 25 % greater than that of CuSn0.15, even though T_L and λ of the two alloys differ only slightly.

5.3 Influencing parameters on PCFE of forming and manufacturing

The further processing of the cast slabs into bare strips involves hot rolling, repeated cold rolling, heat treatments, cleaning, and pickling of the strip surfaces, as well as cutting processes such as milling the hot-rolled plates, trimming the strips after cold rolling, and slitting or cross-cutting the finished strips (see Figure 2). This multi-stage process is performed to achieve tight dimensional tolerances, high surface quality, and adjust the temper of the strip.

More than half of the PCFE for this production stage is attributed to the power consumption of stationary electric drives. The rest is dominated by natural gas consumption of the annealing furnaces. The consumption of other fossil fuels, such as diesel fuel for forklift transport, is negligible and included in the PCFRA.

Figure 7 indicates that the PCFE for the forming and annealing process increases as strip thickness d decreases: for low-alloyed copper and alpha brass, the regression equation $PCFE \approx 0.19 \text{ tCO}_2\text{e/t} \cdot (d [\text{mm}])^{0.78}$ applies (dashed line in Figure 7).

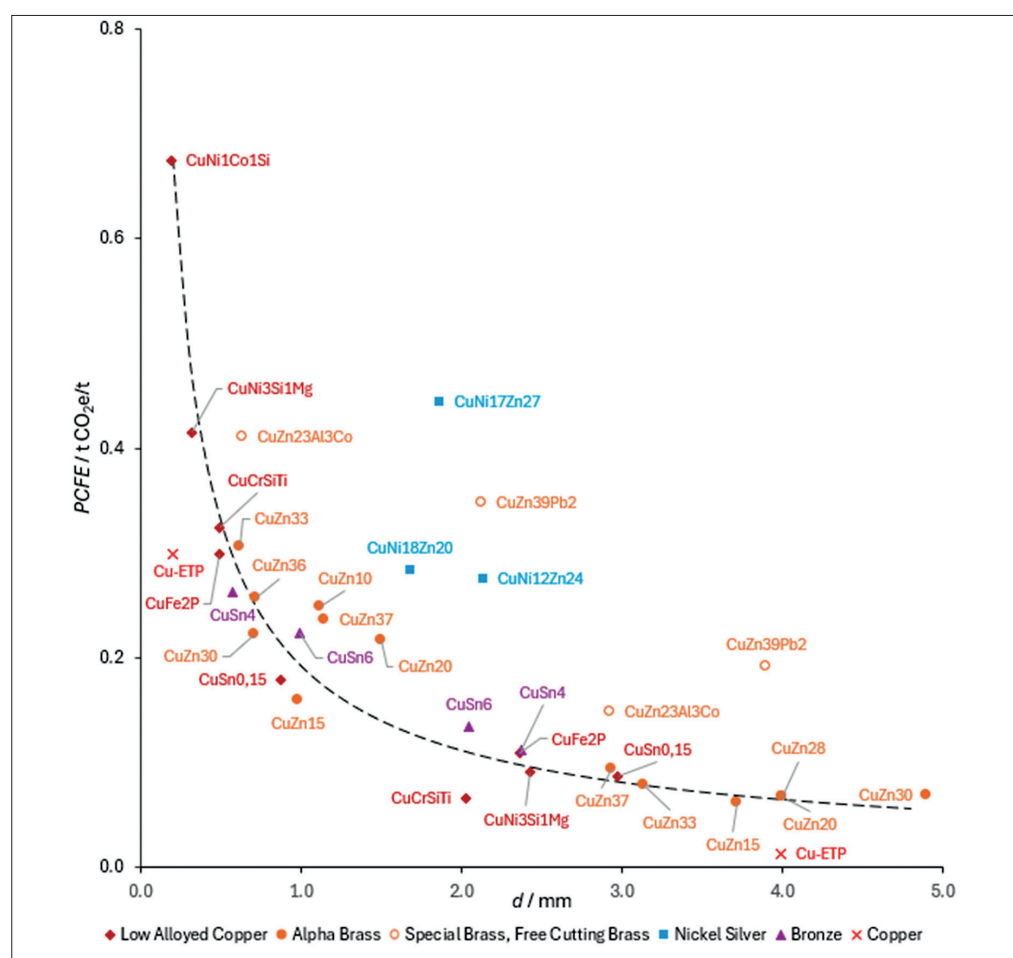


Fig. 7: PCFE values of bare strips grouped by alloy as a function of their strip thickness d . The dashed line represents a non-linear fit of strip thickness to PCFE values for low-alloyed copper and alpha brass, i.e. binary copper zinc alloys with Zn-contents up to 37 %.

Basically, the curve can be explained by the fact that in plastic deformation processes, the flow strength of the metal increases, while its formability decreases. The total deformation is limited to ensure that maximum permissible rolling torques are not exceeded and the strips remain undamaged. As a first approximation, it can be assumed that this forming limit expressed by the strain $\varepsilon_{\max} = \Delta d_{\max}/d_0$ is a constant for each alloy, i.e., the maximum thickness reduction $\Delta d_{\max}$ is proportional to the initial strip thickness d_0 . Before $\varepsilon_{\max}$ is reached, the material must be soft annealed to restore its formability and reduce its flow strength. If d_0 is small, many of these cold roll-anneal cycles are required to achieve a larger absolute thickness reduction Δd . This means that the required energy consumption and the PCFE are larger for smaller than for thicker gauges to reach a certain Δd .

In addition, as the number of roll-anneal-cycles increases, production-related metal losses from trimming the strip edges and material removal through brushing and pickling also increase. As a result, the input-output-ratio IP/OP for thin strips is higher than for thick strips. This increases the PCFE additionally.

To discuss purely material differences, the strip thickness must be the same. In Figure 7 there are four materials, CuCrSiTi, CuSn6, CuNi12Zn24, and CuZn39Pb2, at $d \approx 2.1$ mm with PCFE values between 0.07 and 0.35 tCO₂e/t. The differences of the PCFE values can be explained by the work hardening and annealing behavior of the alloys.

Figure 8 shows that the flow strength σ_F , which is defined as the average of the yield strength $R_{p0.2}$ and tensile strength R_m [32], depends on the alloy and increases with increasing engineering strain $\varepsilon = \Delta d/d_0$. The greater the flow strength of the material the larger the rolling force, the rolling torque, and the electric energy consumption EE of the drives in the

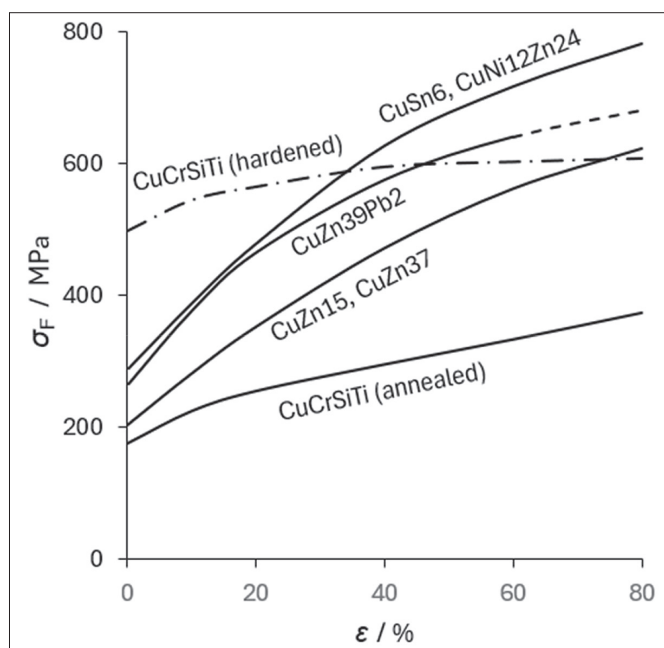


Fig. 8: Indicative values for the average flow strength $\sigma_F = 0.5 \cdot (R_{p0.2} + R_m)$ of various copper alloys as a function of the relative thickness reduction $\varepsilon = \Delta d/d_0$ through cold rolling

cold rolling mill. Under ideal lossless conditions, i.e., for an efficiency of 100 %, the following approximation [32] can be used to estimate the specific energy consumption of the rolling process $EE/OP \approx [\sigma_F(0\%) + \sigma_F(\varepsilon)] \cdot \varepsilon / (2 \cdot \rho)$ with density ρ .

Figure 9 shows heat treatment parameters of exemplary selected alloys [34]. High output in a short time and with low energy consumption can be achieved with materials which have a high thermal diffusivity and can also be annealed at low temperatures, such as copper or CuSn0.15. A high thermal diffusivity ensures rapid temperature equalization

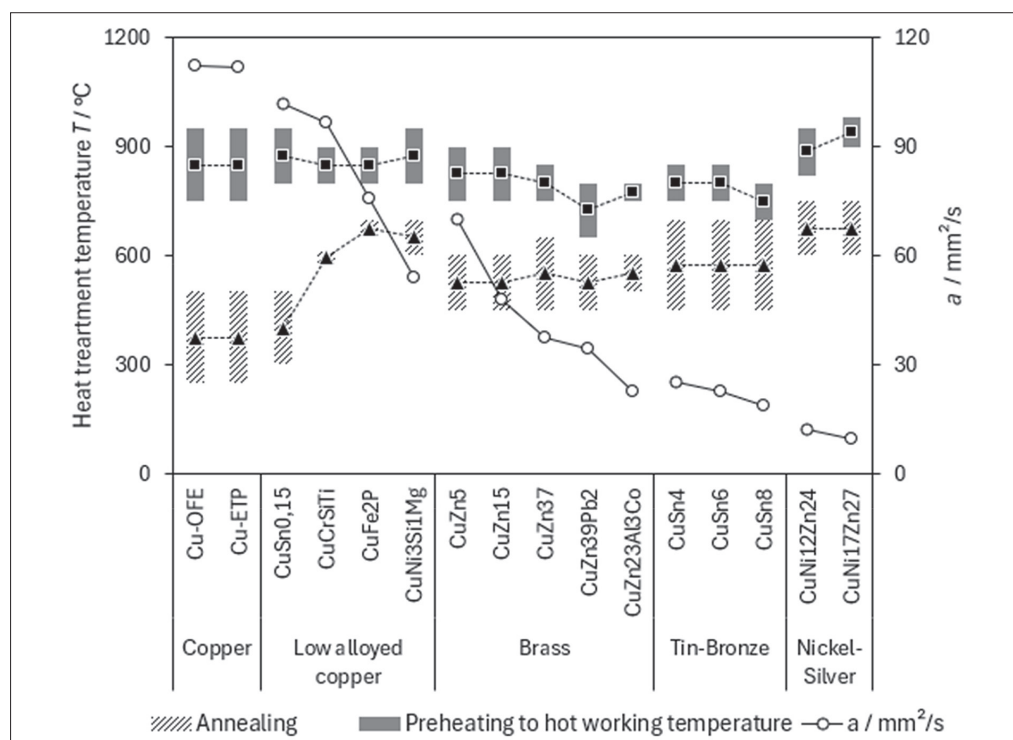


Fig. 9: Recommended heat treatment temperatures for soft annealing and preheating before hot working, as well as the thermal diffusivity at room temperature of various copper alloys

Alloy	Ideal specific energy for cold rolling up to 80 % strain EE/OP [kWh/t]	Ideal specific energy for heating to hot working temperature Q [kWh/t]	Ideal specific energy for heating to annealing temperature Q [kWh/t]	Carbon footprint of bare strips with d = 2.1 mm PCFE [tCO ₂ e/t]
CuCrSiTi (annealed)	7	88	61	0.07
CuZn15	11	84	53	0.11*
CuZn37	11	82	55	0.11*
CuSn6	14	81	58	0.13
CuNi12Zn24	14	91	69	0.28
CuZn39Pb2	(12)	73	52	0.35

Table 5:
Ideal specific energy consumption (i.e. machine efficiency 100 %) for preheating slabs before hot rolling, for soft annealing, and for cold rolling up to the strain $\varepsilon = 80$ % as well as the PCFE of 2.1 mm thick strips. (* calculated using the non-linear regression in Figure 7)

in the material and allows to shorten the holding times in bell annealers or to increase the strip speed in continuous furnaces. A low heat treatment temperature T leads to low net energy, defined as $Q \text{ [kWh/t]} = c_p \cdot \Delta T = 0.11 \text{ kWh/(t} \cdot \text{K)} \cdot (T - 293 \text{ K})$.

Table 5 contains data on the influence of the alloys considered on the ideal lossless energy consumption per ton for heat treatment and cold rolling. The values were calculated using the relationships shown in Figure 8 and Figure 9. In general, a single cold roll-anneal cycle requires significantly more energy for heat treatment than for cold working. This relationship can also be found in hot rolling processes.

Due to their high flow strength, the alloys CuSn6, CuNi12Zn24, and CuZn39Pb2 need more energy EE than CuZn15 and CuZn37 for a cold rolling deformation of $\varepsilon = 80$ %. Annealed CuCrSiTi behaves like copper, i.e., the flow strength and the energy consumption for forming are low. Also, annealed CuCrSiTi achieves the final strip gauge with fewer rolling passes because greater thickness reductions are possible per pass. This shortens the throughput time during rolling and improves energy efficiency. Good formability is the main reason for the low PCFE of annealed CuCrSiTi compared to alpha brass. The strength of CuCrSiTi can be significantly increased by precipitation hardening, which is realized by additional, multi-stage heat treatment. This leads to a higher PCFE, however.

During cold rolling, relative thickness reductions of 75 to 90 % can be achieved with most copper alloys before their forming limits are reached [35]. An exception to this is free cutting brass CuZn39Pb2 with $\varepsilon_{\max} \approx 60$ % [34]. This is due to the alloying element lead, which facilitates machining but also severely affects cold formability. Free cutting brass must be annealed more often than lead-free alloys, which explains the comparatively high PCFE of the 2 mm thick strips made of CuZn29Pb2.

The nickel silver CuNi12Zn24 has a high flow strength, must be heat treated at high temperatures, and has low thermal diffusivity. The combination of these properties explains why the PCFE of this alloy is higher than that of brass.

As in the casting shop, the PCFE also depends on the energy efficiency of the production equipment used. This is highly dependent on idle times [35]. If many cold roll-anneal cycles are required to achieve the final gauge, as is the case for free cutting brass, it enlarges the cumulative non-productive time, decreases the throughput rate, and increases the ener-

gy consumption. Small production batches, which require frequent equipment changeovers, have a similar effect.

6 Conclusion

Efforts along the entire value chain are necessary to reduce the GHG emissions generated by the manufacturing and utilization of a product. Effective measures to reduce the PCF of semi-finished products made of copper materials can be derived from the equations in chapters 4.3 and 4.4. These measures comprise:

1. Reduction of the quotient A_i/OP
 - a) By minimizing production scrap and quality defects, the input-output-ratio IP/OP is reduced.
 - b) Technical or organizational energy efficiency measures reduce energy consumption per output $(EE + NG)/OP$.
 - c) Efficient production planning and maintenance, as well as large production batches, reduce downtime and idle time in production. This leads to an increase in output at given energy and material consumption.
2. Reduction of EF_i (or PCF_i from suppliers)
 - a) Semi-finished product manufacturers purchase foundry feedstock, cast shapes, plating metals, or semi-finished products for further processing that have a low EF_i .
 - b) Pure metals as foundry feedstock are replaced by direct melt scrap. This measure increases the RC and has a significant impact if the semi-finished product is made up of emission-intensive alloying elements (Figure 6). However, before increasing the RC, it must be clarified whether the tolerances of the alloy composition can be maintained. In addition, copper scrap availability must be ensured.
 - c) More renewable energy sources with $EF_i = 0 \text{ tCO}_2\text{e/MWh}$ are used. If there is already a machine park that runs on electricity, switching to green electricity is technically simple. Equipment requiring fossil fuels would first have to be electrified or converted to run on green hydrogen.

The above measures 1.a), 1.b), and 1.c) reduce manufacturing costs. They have therefore always been the subject of continuous improvement measures. In contrast, the economic efficiency of low-carbon resources purchased for manufacturing, such as metals or energy, is not always ev-

ident. Modifying the machinery technically to improve its energy efficiency, to electrify it, or to convert it to hydrogen requires significant investment and time. For this reason, these measures are not implemented continuously, but at extended time intervals.

However, semi-finished products influence GHG emissions in the downstream value chain not only through their PCF. By selecting suitable materials, gauges, and tolerances of semi-finished products, GHG emissions in downstream processes and during the use phase can be indirectly reduced. The impact on the “gate-to-grave” product life cycle is illustrated below using a few specific examples of strip materials.

The strip thickness has two opposing effects on the PCF of components and parts made from strips. Thinner strip gauges result in higher PCFs (see Figure 7). However, this does not necessarily result in higher emissions in the component made from thinner strips, as less material is needed.

At comparable strip thicknesses, free cutting brass such as CuZn39Pb2 has a higher PCF than lead-free alpha brasses because of its comparatively poor cold workability. However, free cutting brass enables very effective further processing by machining methods such as drilling or milling. This results in burr-free components and low tool wear, among other things. In longitudinal turning tests, it was also found that brass with 2% Pb requires approximately 40 % less energy than machining lead-free brass [36].

Due to the intense solid solution hardening and the temperature resistance of nickel silver strips, its PCF increases rapidly during manufacture and downstream processing. Nevertheless, nickel silver can have a positive effect on the use phase of end products for which the functional unit of “produced semi-finished product tonnage” is no longer meaningful. In the case of low-current connectors, for example, the number of electrical signals transmitted without error per unit of time is of interest. During the use phase, therefore, the reliability and service life of the materials used are important. Here, nickel silver offers advantages over other materials due to its good softening and relaxation resistance as well as corrosion resistance [34, 37].

Hot-dip tinning can be used to functionalize strip surfaces specifically for connector applications. The PCF of the bare alloy strip is increased by approximately 0.2 tCO₂e/t because of the double-sided coating, about 1 to 4 µm thick. This accounts for plating metal used as well as energy consumption of the tinning line. However, the tin coating facilitates subsequent soldering processes and has a positive effect on reliability. Depending on the layer microstructure, either the electrical contact resistance can be reduced or the resistance to fretting corrosion and wear can be increased [35, 38]. Passivating tin oxide, which forms on the hot-dip tinned surface under atmospheric influence, also improves corrosion resistance [37].

In multi-gauge strips, channels are milled parallel to the rolling direction to vary the strip thickness along the strip width. The milling process increases the PCF by approximately 0.6 tCO₂e/t. However, this type of pre-material makes functional integration of electrical components easier and is used,

for example, for electronic components with thin power connections and thicker heat sinks. Otherwise, these components would have to be assembled from two stamped parts, for example. Multi-gauge strips can be produced efficiently in the rolling mill and reduce the number of manufacturing steps in the downstream value chain and thereby the GHG-emissions.

7 Summary

This study addresses the growing need for reliable and standardized PCF data in the semi-finished copper and copper alloy industry, where published values vary widely due to differences in raw material quality, energy sources, and calculation methodologies. The paper introduces a hybrid PCF calculation approach that combines bottom-up and top-down allocation of emissions, ensuring scalability and alignment with the Greenhouse Gas Protocol and ISO standards (ISO 14040/14044/14067). The methodology leverages existing ERP datasets to enable an accelerated calculation. It also focuses on major emission drivers – metals, electricity, and natural gas – while applying top-down allocation for remaining activities.

Key influencing factors on PCF include alloy composition, recycled content, gauges and processing depth as well as energy efficiency in melting, casting, and forming operations. Results demonstrate that PCFs can be significantly reduced in the cradle-to-gate system boundary through increasing recycled content, minimizing the input-output-ratio in production, and transitioning to renewable energy sources. However, it is not possible to make a general recommendation. Each manufacturer must decide for themselves which measure is most effective under the technical and economic conditions given. Nevertheless, through the selection of optimized semifinished products along the value chain, downstream emissions can be reduced.

By providing a transparent, standardized, and scalable calculation framework, this work contributes to improving comparability of PCF data within the copper industry and its associated sectors.

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Appendix

List of symbols

Symbol, Abbreviation	Unit	Meaning
a	mm ² /s	Thermal diffusivity
A	t (= 1000 kg), MWh (= 3,6 GJ), etc.	A manufacturing activity required to produce a marketable product that generates greenhouse gas emissions.
AP	t	Purchased auxiliary materials
CCF	tCO ₂ e	Corporate carbon footprint
CO ₂ e	t	Carbon dioxide equivalent
c _p	J/(g · K)	Specific heat
d	mm	Strip thickness
EE	MWh	Input resp. consumption of electrical energy
EF	tCO ₂ e/MWh tCO ₂ e/t	Proportionality factor relating an activity with carbon dioxide equivalents
ERP		Enterprise resource planning
GHG		Greenhouse gas
IP	t	(annually) input of material into the system = weight resp. tonnage of metal for a production process
IPP	t	(annually) purchased input of metal into the system = weight resp. tonnage of feedstock for a production process
NG	MWh	Input resp. consumption of energy from natural gas combustion
OP	t	(annual) output from a system
OPS	t	(annual) shipped output leaving a plant or company
PCF	tCO ₂ e/t	Product carbon footprint, i.e. emission of CO ₂ equivalents per tonnage of output PCF = CO ₂ e/OP
PCFE	tCO ₂ e/t	Part of the product carbon footprint which results solely from the consumption of energy
PCFM	tCO ₂ e/t	Part of the product carbon footprint which results solely from purchased metals
PCFRA	tCO ₂ e/t	Part of the product carbon footprint which results from top-down allocation of remaining activities
Q	MWh	Heat energy
RA	t, MWh, etc.	Remaining activities attributable to the product, which are not covered by the bottom-up approach
WO	t	Waste generated in operation
t	h (= 3600 s)	Operating hours
T	°C, K	Temperature
ε	%	Engineering strain, relative thickness reduction through rolling
ε _{max}	%	Forming limit
λ	W/(m · K)	Thermal conductivity
ρ	g/cm ³	Density, specific weight
σ _F	MPa	Average flow stress, i.e., mean of yield strength and ultimate tensile strength