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Final report

Identification, analysis and presentation of the products in the industrial sectors covered by the EU ETS, their economic importance and their significance for CO₂ emissions

by:

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Abstract: Identification, analysis and presentation of the products in the industrial sectors covered by the EU ETS 1, their economic importance and their significance for CO₂ emissions

This study aims to establish a solid information and data basis on CO₂ emissions and the economic significance of various products that can be attributed to the industrial activities covered by the European Emissions Trading System (EU ETS 1). First, the process steps within the scope of the EU ETS 1 are analysed based on available data sources. The focus of the analysis is on those basic materials and sectors of the industry that are very important for the EU ETS, i.e. steel, cement, aluminium, refineries and basic chemicals. This report defines the underlying concept along their value chain and establishes the material flows of selected basic materials, intermediate and final products within the scope of the EU ETS 1, the associated energy consumption and resulting emissions, as well as economic indicators for the EU27+UK and for Germany. In a second step, the further process steps along the value chain up to two selected end products are analysed: a) a passenger vehicle and b) plastic packaging. Building on the data from the previous analysis covering the EU ETS 1 scope, these two case studies were developed to determine and quantify the CO₂ emissions on the end product level and the respective CO₂ cost shares caused by these emissions through the EU ETS 1 along the value chain. The developed data basis and analyses enable the development of further (dynamic) material flow models, e.g. regarding the exposure of industrial processes and products to CO₂ prices and further decarbonization options. Such analyses are particularly important in view of the gradual reduction of free allocation in the EU ETS 1 by 2034 and the parallel introduction of an EU carbon border adjustment mechanism (CBAM), which was launched in 2023. Furthermore, synergies between industrial decarbonization and circular economy address challenges regarding sustainability and supply risks of future-relevant technologies. Consequently, material production and use as well as their connection to the energy system and greenhouse gas (GHG) emissions must be taken into account when integrating this new perspective into policymaking and the analysis of ambitious GHG emission mitigation pathways.

Abstract: Identifizierung, Analyse und Darstellung der Produkte in den vom EU-ETS 1 erfassten Industriesektoren, ihrer wirtschaftlichen Bedeutung und ihrer Bedeutung für die CO₂-Emissionen

Die vorliegende Studie zielt darauf ab, eine solide Informations- und Datengrundlage zu den CO₂-Emissionen und der wirtschaftlichen Bedeutung exemplarischer Produkte zu schaffen, die den unter das EU-Emissionshandelssystem (EU-ETS 1) fallenden industriellen Tätigkeiten zugeordnet werden können. Zunächst werden dabei die Prozessschritte, die in den Anwendungsbereich des EU-ETS 1 fallen, anhand der verfügbaren Datenquellen analysiert. Der Schwerpunkt der Analyse liegt auf Grundstoffen und Industriesektoren, die für den EU-ETS 1 von hoher Bedeutung sind, d.h. Stahl, Zement, Aluminium, Raffinerien und chemische Grundstoffe. Dieser Bericht definiert das zugrundeliegende Konzept entlang ihrer Wertschöpfungskette und quantifiziert die Materialflüsse ausgewählter Grundstoffe und (Zwischen-)Produkte im Rahmen des EU-ETS 1, die damit verbundenen Energieverbräuche und die daraus resultierenden Emissionen sowie wirtschaftliche Indikatoren für die EU27+UK und für Deutschland. In einem zweiten Schritt werden die weiteren Prozessschritte entlang der Wertschöpfungskette bis hin zu zwei ausgewählten Endprodukten betrachtet: a) einem Personenkraftwagen und b) Kunststoffverpackungen. Aufbauend auf den Daten der vorangegangenen Analyse für den Anwendungsbereich des EU ETS 1 wurden die Fallstudien entwickelt, um die CO₂-Emissionen und die durch diese Emissionen verursachten Kostenanteile durch den EU-ETS 1 entlang der Wertschöpfungskette auf Ebene der Endprodukte zu bestimmen und zu quantifizieren. Die entwickelte Datenbasis und die Analysen ermöglichen die Entwicklung weiterer (dynamischer) Stoffstrommodelle zur Analyse der Exposition relevanter industrieller Prozesse und Produkte gegenüber CO₂-Preisen und weiteren Dekarbonisierungsoptionen. Entsprechende Analysen sind insbesondere mit Blick auf die

schrittweise Rückführung der kostenlosen Zuteilung im EU-ETS 1 bis 2034 und die im Jahr 2023 gestartete parallele Einführung eines EU CO₂-Grenzausgleichssystems (CBAM) von hoher Bedeutung. Außerdem adressieren die Synergien zwischen Industriedekarbonisierung und Kreislaufwirtschaft Herausforderungen bezüglich der Nachhaltigkeit und Versorgungssicherheit zukunftsrelevanter Technologien. Folglich müssen die Materialproduktion und -verwendung sowie ihre Verbindung zum Energiesystem und zu den Treibhausgas (THG)-Emissionen berücksichtigt werden, wenn diese neue Perspektive in die Politikgestaltung und die Analyse ehrgeiziger THG-Emissionsminderungspfade integriert wird.

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List of abbreviations

Abbreviation	Description
ABS	Acrylnitril-Butadien-Styrol-Copolymer
AP	Arbeitspaket
BEV	Battery electric vehicle
BF	Blast furnace
BOF	Basic oxygen furnace
C.II/ C.III	Complexity I/ complexity III
C ₂ F ₆	Hexafluoroethane
CaCO ₃	Calcium carbonate
CAEF	The European Foundry Association
CAPEX	Capital expenditures
CDU	Crude distillation units
CEM (I, II, III, V)	Cement types based on DIN EN 197-1
CF ₄	Carbon tetrafluoride
CH ₄	Methane
CHP	Combined heat and power
CO ₂	Carbon dioxide
CO ₂ eq	Carbon dioxide emission equivalent
COP	Conference of the Parties
CRF	Cold rolled flat
CSV	Comma-separated values
Cum.	Cumulated
CWT	Complexity weighted tonne
BEV	Battery electric vehicle
EAF	Electric arc furnace
EEA	European Environment Agency
EFTA	European Free Trade Association
el index	Electricity price index
EU	European Union
EU Alumin.	European Aluminium
EU ETS	EU Emissions Trading Scheme
EU27+UK	Member states of the European Union (2015)
EUA	European Union Allowance
EUSTAT	European Statistics
EUTL	EU Transaction Log
FCCU	Fluid catalytic cracking unit
FED	Final energy demand
F-gases	Fluorinated greenhouse gases
FTIP	Federal Transport Infrastructure Plan
GDA	Gestamverband der Aluminiumindustrie

Abbreviation	Description
GGBS	Ground-granulated blast furnace slag
GHG	Greenhouse gas
GJ	Gigajoule
H ₂	Hydrogen
HCU	Hydrocracker
HDPE	High density polyethylene
HE	High efficiency
HGV	Heavy goods vehicle
HRC	Hot rolled coil
HRWS	Hot rolled wide strip
HS	Harmonised system
HVC	High value chemicals
ICAO	International Civil Aviation Organization
ICEV	Internal combustion engine vehicle
IMO	International Maritime Organization
ISIC	International standard industrial classification
Kg	Kilograms
Kt	Kilotons
kWh	Kilowatt hours
LCA	Life cycle analysis
LDPE	Low density polyethylene
LE	Low efficiency
LHV	Lower heating value
LLDPW	Linear low density polyethylene
LPG	Liquefied petroleum gas
MFA	Material flow analysis
MFCA	Material Flow Cost Accounting
MJ	Megajoule
Mm	Millimetres
Mt	Megatonnes
MWh	Megawatt hours
N ₂ O	Nitrous oxide
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
NDC	Nationally Determined Contributions (in Paris-Agreement)
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational expenditures
PA	Polyamid
PC	Polycarbonate
PDF	Portable document format

Abbreviation	Description
PE	Polyethylene
PJ	Petajoule (energy measuring unit)
PP	Polypropylene
PPI	Producer price index
PtG	Power-to-Gas (any power-based gaseous fuels)
PtL	Power-to-Liquid (any power-based liquid fuels)
PU	Polyurethane
PVC	Polyvinylchloride
RCA	Revealed Comparative Advantage
RDE	Real Driving Emissions
RES	Renewable energy sources
REV	Revision
SEC	Specific Energy Consumption
SGHG	Specific greenhouse gas emissions
SITC	Standard international trade classification
T	Tonnes
THG	Treibhausgasemissionen
TJ	Terrajoule
TWh	Terawatt hours (measuring units for energy)
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VCI	Verband der Chemischen Industrie
VDeH	Verein Deutscher Eisenhüttenleute
VDU	Vacuum distillation unit
VDZ	Verein Deutscher Zementwerke e.V.
VET	Verified emissions tables
WBMS	World Bureau of Metal Statistics
WSA	World Steel Association
WV Stahl	Wirtschaftsvereinigung Stahl

Summary

Since the start of the European Emissions Trading System (EU ETS 1) in 2005 addressing energy, industry and subsequently aviation and more recently maritime, the covered sectors have reduced CO₂ emissions EU-wide by about 48% by 2023. At the same time, the EEA report on "Trends and projections in the EU ETS 2022", for example, shows that industrial emissions fell less, i.e. by only 28% since 2005. Additionally, industrial emissions have been rather constant since the beginning of the 3rd trading period that started in 2013. Only in 2023 a significant drop was observable due to decreased industrial production in the light of the war in the Ukraine. In view of the necessary annual reduction requirements in the emissions trading sector by 2030, the question of the reduction potential of the industrial sectors is of growing importance.

Furthermore, driven by political concerns over sustainability and the reduction of supply risks for future-relevant technologies, synergies exist between circular economy, industrial decarbonization and policy agendas. Consequently, material production and uses as well as their connection to the energy system and emissions have to be taken into account when integrating this new perspective into policymaking, and the analysis of ambitious GHG emission mitigation pathways as part of the European Green Deal.

In this context, the prevention of carbon leakage (CL) also plays a central role. This is intended to be ensured on EU-level by the European Carbon Border Adjustment Mechanism (CBAM), which will gradually replace the free allocation as a CL instrument within the framework of the EU ETS 1 by 2034. From 2026, the CBAM is intended to impose the same effective CO₂ price on a selection of imported goods as applies to products manufactured in the European single market.

With a view to the further development of the CBAM, the question arises how high the cost effect of carbon pricing via the EU ETS 1 is on a) basic materials produced within the scope of the EU ETS 1 and b) further processed products that consists the basic materials as production inputs (e.g., vehicle production). This information is relevant, inter alia, for the question of potential further ("downstream") sectors to be included in the CBAM, or for the impact that the CBAM has on exports to third countries in replacing free allocation. The CBAM currently mainly covers basic materials such as steel, aluminium, cement, fertilisers, and hydrogen.¹ Discussions on potential sectors for an additional inclusion cover, among others, basic chemicals, not least (poly-)olefins as precursors for plastic products.

Knowledge on the material flows of products in the industrial sectors covered by the EU ETS 1, their respective energy consumption, relevance for overall CO₂ emissions as well as key economic figures to put these into perspective, are all important building blocks. In this respect, a comprehensive and consistent data basis must first be established including product-related emission balances, which are not yet available. **The aim of this study is to establish such a solid information and data basis on energy demand, CO₂ emissions and the economic significance of various products that can be attributed to the industrial activities covered by the EU ETS 1.** In this project, the focus has therefore been on the **derivation, and exemplary application, of methods to compile statistical data from different sources in a consistent way** and to establish a data basis with which data on material flows, energy consumption and emissions can be combined to **derive key figures such as specific energy demand and CO₂ emission for both direct and indirect** (i.e., related to electricity use) **emissions.** This is complemented by key economic figures on main cost components and on external trade, which help in assessing the significance of the CO₂ cost impact implied by the before-mentioned specific CO₂

¹ Hydrogen is covered irrespectively of its use as either a basic material (for further industrial processes) or as a fuel. In addition to basic materials, the CBAM also covers imports of electricity into the EU.

emissions for the selected products. The intention is that the methods applied can be used also by a reader of this report at a later date, using more recent figures from the sources presented.

For this goal, data extraction was based on a common reference year that was available for all selected key figures. At the time of the data mining for this project in 2019 and 2020, this was the year 2015. **For this year all relevant data could be obtained from different sources in a complete and methodically consistent way.** In general, it can be stated that the energy demand as well as the direct CO₂ emissions per unit of basic material product has been largely unchanged since 2015. An exception is the electricity mix and the associated “indirect emissions” from the use of electricity in the production of the basic materials. Here, it can be stated that the average emissions related to the electricity mix decreased compared to 2015. For example, an emission factor of 0.587 kg CO₂/kWh was taken into account for Germany in 2015, which decreased to 0.410 kg CO₂/kWh in 2021 (Koffi et al., 2017; Icha & Lauf, 2023). In order to understand the contribution of the decreasing indirect to the overall CO₂ emissions, they are presented separately if the available data sources allow it. Another factor that has changed substantially since 2015 are the prices of ETS allowances, that are multiplied by the specific CO₂ emissions to derive the cost effects of the EU ETS 1. In the relevant chapter of this report, we accordingly **also apply more recent (from 2021 and 2022, respectively) market prices for ETS allowances and key energy carrier prices.** During 2023 and the first half of 2024, ETS allowance prices have been in a comparable range to those in 2021 and 2022.

In this report, we first analyse the process steps that are covered by the scope of the EU ETS 1 (chapter 2). The focus of the analysis is on basic materials and sectors of the industry that are very important for the EU ETS 1, i.e. steel, cement, aluminium, refineries and basic chemicals. First, this report defines the underlying concept along their value chain. Second, the material flows of selected final products, the associated energy consumption and resulting emissions are developed for the EU27+UK and Germany (DEU), respectively. Moreover, economic indicators from statistics and literature are summarized, i.e. trade, costs and prices. The results (energy consumption, GHG emissions and costs) are used for the subsequent analysis. **In chapter 3, we address further process steps through the value chain up to the level of two selected end products: (1) a passenger car (combustion engine and battery electric, respectively) and (2) two plastic packaging products.** Building on the data compiled in chapter 2, the case studies were developed to determine and quantify the CO₂ emissions and the cost shares caused by these emissions through the EU ETS 1 along the value chain.

Chapter 2: Key figures for selected industrial sectors and products covered by the EU ETS 1

The main findings from chapter 2 concerning the selected industrial sectors and products covered by the EU ETS 1 are described in the following.

For the **iron and steel industry**, a simplified material and energy flow model is developed. This includes a detailed discussion of potential conventions for the allocation of by-product (“waste”) gases. **The four selected final analysed steel products – hot rolled coil sheet and strip, wire rod, hot rolled bars and concrete reinforcing bars – have high economic impact and represent the two main production routes in the steel industry (primary and secondary). Products of the blast furnace route (e.g. hot rolled coil, sheet and strip) show higher cumulated CO₂-emissions** (Table 1) than the products from the electric arc furnace (EAF) route (e.g., concrete reinforcing bars, hot-rolled bars and wire rod). Compared to iron production and steelmaking, further processing steps (e.g., rolling) are less relevant in terms of energy and emissions.

Table 1 Key figures for steel (see Tables 18, 19, 21 and 22 in this report)

Product	Specific cumulated energy demand [GJ/t]		Specific cumulated CO ₂ emissions [t CO ₂ eq/t]		Specific indirect CO ₂ emissions [t CO ₂ eq/t]	
	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU
Concrete reinforcing bars	3.94	3.15	0.38	0.44	0.03	0.05
Hot rolled bars	3.94	3.15	0.38	0.44	0.03	0.05
Wire rod	4.17	3.37	0.42	0.49	0.06	0.09
Hot rolled coil, sheet and strip	19.23	19.52	2.23	2.32	0.07	0.10

Source: own calculation based on the data sources stated in chapter 2 (reference year 2015).

For the **cement industry**, a similar model is developed. The analysis presents the material flows, final energy demand and CO₂-emissions differentiated by cement type. **We find a high influence of clinker production in general and clinker share in cement in particular on specific emission factors** (see Table 2). Moreover, the indicative assignment of the cement types to the concrete delivery types, i.e. transport concrete (ready-mix) or precast, is highly relevant for the differentiation of end products. **The clinker share in the final products strongly impacts the embedded CO₂-emissions in mass-equivalent concrete end uses** (see Table 2). Thus, within the scope of the EU ETS 1 emissions pre-cast concrete shows a higher CO₂-intensity on a by-mass basis than transport concrete, and thus the associated CO₂ cost component is also more relevant for this concrete type. However, we stress that this analysis is focused on the EU ETS 1 scope, and is not intended to provide insights on the relative sustainability of both concrete types even in terms of overall CO₂ emissions. Thus, a further analysis should also investigate the actual application of concrete products in construction (performance-based) and the end-of-life phase. This would complete the insights gained from the production phase, which this report is restricted to due to its focus on the EU ETS 1.

Table 2 Key figures for cement (see Tables 34, 35, 36 and 37 in this report)

Product	Production [Mt]		Specific cumulated fuel demand [GJ/t]		Specific cumulated electricity demand [kWh/t]		Specific cumulated CO ₂ emissions [t CO ₂ eq/t]		Specific indirect CO ₂ emissions [t CO ₂ eq/t]	
	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU
Clinker	125.0*	23.4*	3.73	3.75	47	47	0.94	0.83	0.02	0.03
Cement	157.0*	31.2*	2.59	2.76	116	112	0.77	0.66	0.03	0.04
Transport concrete	646.9	110.6	0.30	0.30	15	14	0.12	0.12	0.002	0.003
Precast concrete	243.1	43.0	0.59	0.60	20	19	0.18	0.16	0.003	0.004

*from statistics, not calculated

Source: own calculation based on the data sources stated in chapter 2 (reference year 2015). For cement, the figures shown indicate the averages across all cement types (weighted by their respective production volume shares).

Aluminium is a metal with a very complex material flow model structure, starting from local production of primary and secondary routes. Especially the secondary production route plays a key role in Europe. Thus, a material flow model is developed that aggregates available scrap in two streams: First, transport (including the automobile industry), construction and renovations, second, packaging, renewable energy technologies and machine production. The resulting dataset excludes the mining of bauxite and the production of alumina. **The demand for aluminium semi-finished products and finished products is very diverse as observed in the resulting material flows. This also reduces the overall volatility of demand for these markets. The role of secondary aluminium flows (i.e. input material availability of the secondary route) is very important for the future development of the energy efficiency and emission intensity of the aluminium industry** (see also Table 3). Thus, improving recycling practices and analysing alloying elements is crucial. In contrast to the other materials assessed above, the indirect emissions arising from the use of electricity play a major role for the primary production of aluminium. Consequently, decreasing average emissions of the electricity mix affect the results for the specific cumulated CO₂ emissions presented below.

Table 3 Key figures for aluminium (see Tables 48, 49, 50 and 51 in this report)

Product	Specific cumulated fuel demand [GJ/t]		Specific cumulated electricity demand [MWh/t]		Specific cumulated CO ₂ emissions [t CO ₂ eq/t]		Specific indirect CO ₂ emissions [t CO ₂ eq/t]	
	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU
Primary	2.4	2.4	14.79	14.79	7.53	10.43	5.78	8.69
Secondary	1.6	1.6	0.095	0.095	0.13	0.15	0.04	0.04
Castings	7	7	1.3	1.3	2.41	3.27	0.51	0.76
Flat rolled	0.95	0.95	0.31	0.31	1.69	1.66	0.12	0.18
Extrusions	4.1	4.1	0.091	0.091	2.04	1.71	0.04	0.05

Source: own calculation based on the data sources stated in chapter 2 (reference year 2015).

Refineries are highly complex production systems with a broad variety of products based on crude oil as raw material input. Thus, the “complexity weighted tonne” (CWT) approach is applied, which establishes refinery-specific GHG emissions and is already widely applied, e.g., for purposes of setting the product benchmark and thereby determine free allocation of emission allowances in the EU-ETS. Additionally, a series of interviews with refinery representatives was conducted due to the complexity of the analysis. **The analysis highlights the challenges and limitations of attempting to determine generalised material flow-based key figures for GHG emissions and energy consumption for refinery products. However, the analysis showed that the production structure for naphtha has significant influence on the related CO₂ emissions** (see Table 4, which shows results for four refinery types differentiated by complexity).

Table 4 Key figures for naphtha differentiated by refinery type (see Tables 55, 56, 58 and 59 in this report)

Refinery type	Specific cumulated energy demand [GJ/t]		Specific cumulated CO ₂ emissions [t CO ₂ eq/t]	
	EU27+UK	DEU	EU27+UK	DEU
Complexity I	no data available			
Complexity II	4.65	4.78	0.282	0.294
Complexity III	15.4	14.7	0.977	0.931
Complexity IV	no data available			

Source: own calculation based on the data sources stated in chapter 2 (reference year 2015).

Naphtha can be further processed to the downstream “polyolefin” products **polyethylene (PE) and polypropylene (PP)**. These products are relevant basic chemicals, which are analysed in two separate material flow models. **These analyses underpin that especially the steam cracking of naphtha to produce ethylene and propylene is relevant in the context of CO₂ emissions, whereas the processing into polyethylene and polypropylene, and the plastic products based on them are far less relevant** (see Table 5). Moreover, indirect emissions from the use of electricity are only relevant for the downstream products PE and PP. **In contrast to the other products investigated in this study, polyolefins consist of fossil carbon (non-energy use). This is released as CO₂ at the end of the life cycle, even though it may take a long time.** A second important difference to the other materials considered is the fact that plastics do not “mineralize” in the environment and thereby exerts a threat to fauna and flora.

Table 5 Key figures for the basic chemicals PE and PP (see Tables 65, 66, 67 and 68 in this report)

Product	Specific cumulated fuel demand [GJ/t]		Specific cumulated electricity demand [GJ/t]		Specific cumulated CO ₂ emissions [t CO ₂ eq/t]		Specific indirect CO ₂ emissions [t CO ₂ eq/t]	
	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU
Ethylene	16.5	16.5	n/a	n/a	0.76	0.76	n/a	n/a
Propylene	16.5	16.5	n/a	n/a	0.76	0.76	n/a	n/a
PE	-0.2	-0.2	2.7	2.7	0.35	0.35	0.36	0.36
PP	1.2	1.2	2	2	0.35	0.35	0.27	0.27

Source: own calculation based on the data sources stated in chapter 2 (reference year 2015).

Chapter 3: Case studies for estimating the CO₂ cost shares at the stages of further processing

The case studies for estimating the CO₂ cost share at the stages of further processing from chapter 3 are described below.

Building on the data compiled in chapter 2, two case studies were developed to determine and quantify the CO₂ emissions and the cost shares caused by these emissions through the EU ETS 1

along the value chain of end products. This analysis covers the cumulated energy and CO₂ emissions for the end products as well as labour and material costs for the products in chapter 2.

The first case study analyses two types of passenger cars: a combustion engine and a battery electric vehicle, respectively. The second case study addresses a selection of plastic products, namely, a plastic bag and a plastic bowl. Throughout the calculations it becomes clear which production processes and materials have the largest share in energy consumption and CO₂ emissions. However, due to the different procedure for determining the mass balances on which the calculation is based, the results of passenger cars and plastic products are not directly comparable.

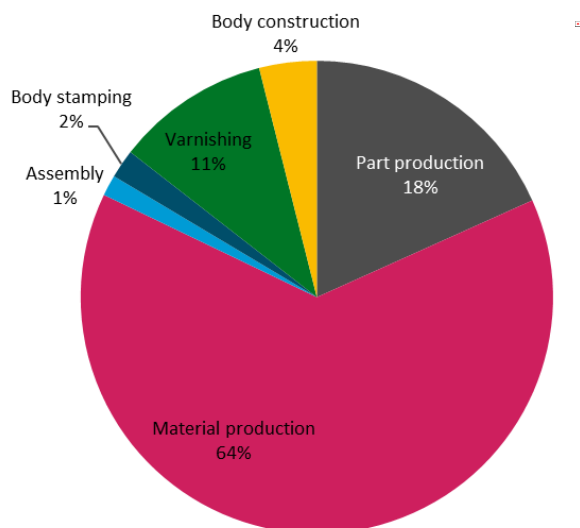
Assessment of the CO₂ cost shares along the value chain for the production of passenger cars

Material balance, energy demand and GHG emissions

For the compilation of the material balance of the passenger car and the energy balance for the production process, a bottom-up approach is used. Thus, the materials used in a passenger car are identified based on the parts of a generic medium car. Steel is by far the most widely used material in the vehicle, followed by aluminium. Steel, aluminium, iron (here as differentiated from steel), and plastics, which are among the materials considered in chapter 2, sum up to 88 % of the total material balance. The energy balance and resulting GHG emissions are calculated based on the materials used as well as on the production and manufacturing processes applied to those materials. The total energy demand consists of the energy used in vehicle assembly as well as material (e.g. hot rolled coils, as quantified in chapter 2 of this report) and part (e.g. air-bag and brakes) production (see Figure 76 in this report). Note that the energy use and GHG emissions from the resource mining and extraction activities are excluded from our analysis as it focuses on products in the scope of the EU ETS 1 and selected end products. Different data sources are used, i.e. plant data, literature and databases. The chemical, steel, and aluminium products from chapter 2 of this project are allocated to the parts of the vehicle and are to be complemented by a production process. The GHG emissions are then calculated based on the energy demand and respective emission factors.

The total energy demand, for material and part production and vehicle assembly for a combustion engine vehicle amounts to 32,533 MJ and for the battery electric vehicle to 35,530 MJ (see Figure 1 for distribution). The share of “Material production” (i.e. energy consumption to produce materials within the scope of the EU ETS 1 as established in chapter 2 of this report) dominates the overall energy consumption, followed by “Part production” and the three activities related to the car body (construction, stamping and varnishing), respectively. Regarding the battery electric vehicle, it is assumed that most parts are constructed of the same materials and by the same processes (with equal energy consumption) as the conventional internal combustion engine vehicle. Only the drive train (including the electric engine and the battery) are considered different.

Figure 1 Share of energy demand in vehicle production by productive phase for combustion engine vehicle (left) and battery electric vehicle (right) (see Figures 87 and 96 in this report)

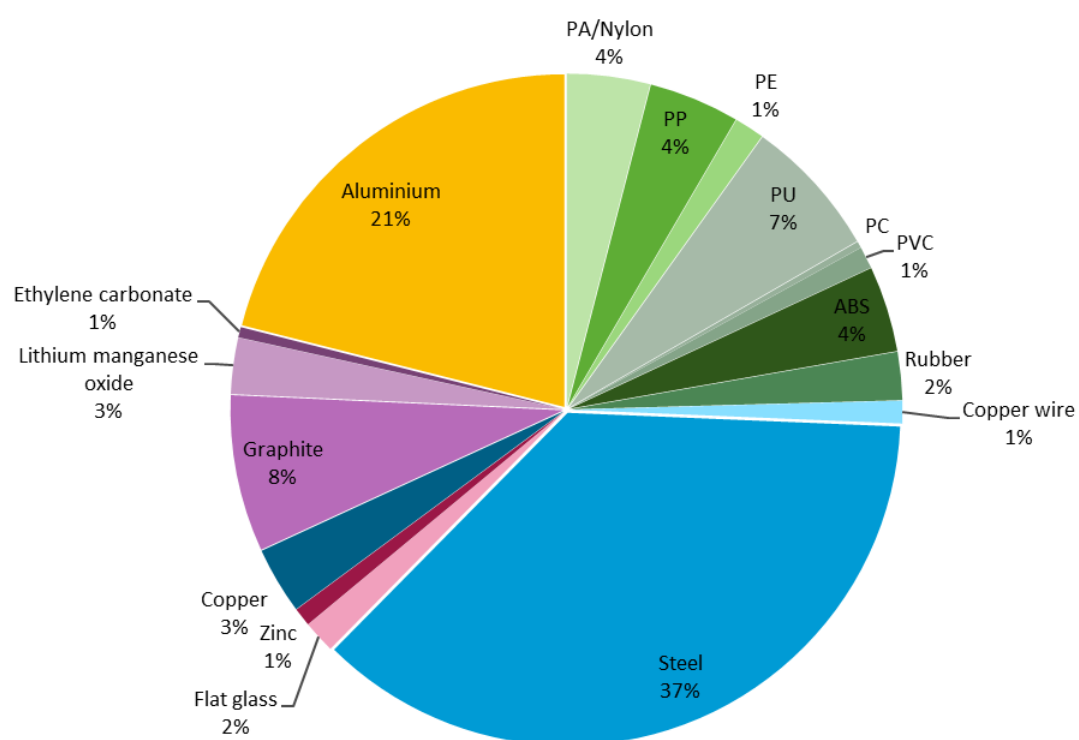


Source: own calculation based on the data sources stated in chapter 2 (reference year 2015), Argonne National Library (2020), Sato & Nakata (2020), Van der Welden et al. (2012).

In total, 3,505 kg CO₂eq are emitted for the production of a passenger car with a combustion engine and 3,700 kg CO₂eq for the electric passenger car (see Figure 2 for distribution). For the combustion engine vehicle, the coils used in the stamping of the body already have the highest embedded emissions of 932 kg CO₂eq. In general, GHG emissions associated with the materials production make up for the dominant share in the overall cumulated emissions for both car types, followed by the steps of processing the car body and the part production (see Tables 89 and 93 as well as Figures 88 and 97 and the associated report text below).

As the drive train of the electric vehicle is slightly heavier than that of the combustion engine vehicle (battery weight: 232 kg according to Notter et al. (2010)), relatively more energy is used in the production process. In comparison to the combustion engine vehicle less steel is used in the electric vehicle. In addition, the production of the battery is adding another 444 kg CO₂eq to the total GHG emissions of the electric vehicle.

Figure 2 Share of GHG emissions by material for combustion engine vehicle (top) and battery electric vehicle (bottom) (see Figures 89 and 98 in this report)



Source: own calculation based on the data sources stated in chapter 2 (reference year 2015), Argonne National Library (2020), Sato & Nakata (2020), Van der Welden et al. (2012).

Assessment of CO₂ cost shares of the overall production costs

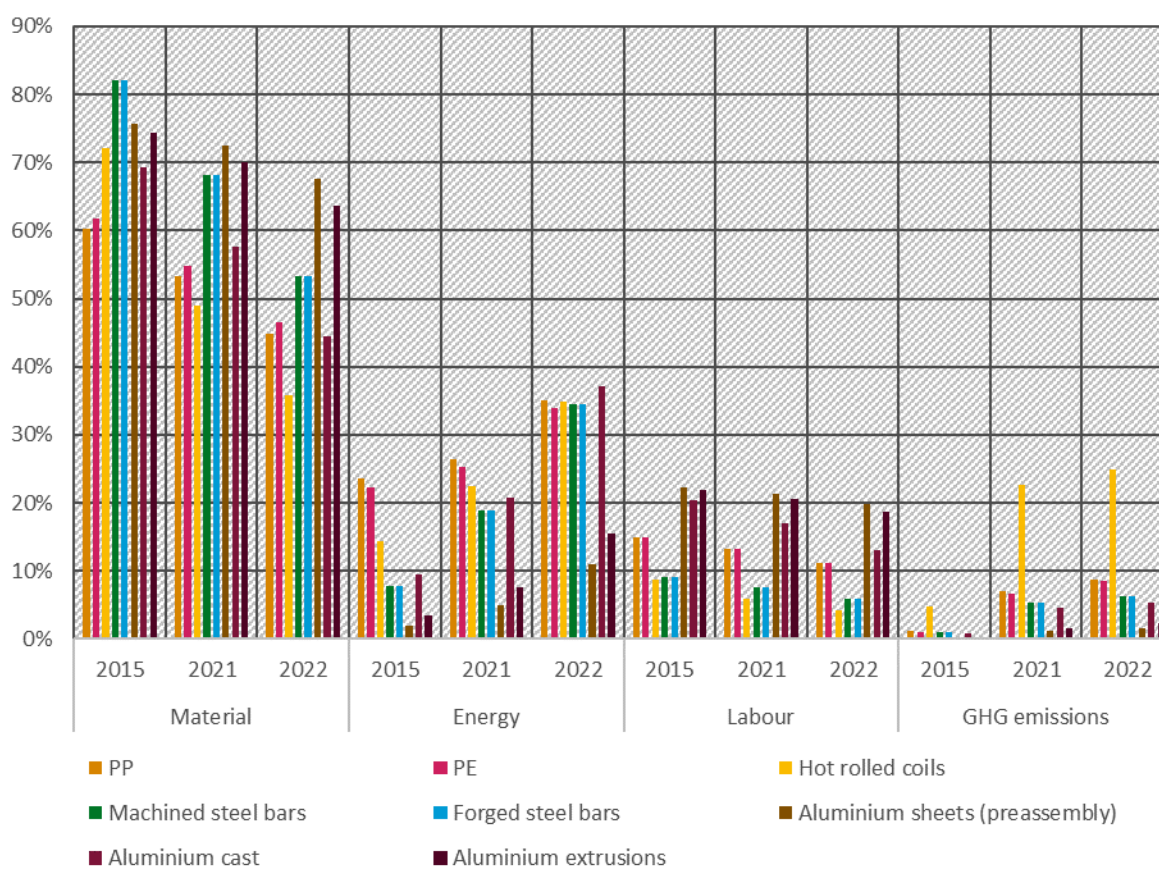
For the calculation of the CO₂ cost shares, the cost for energy and GHG emissions are calculated for all materials used in the vehicles for material and part production as well as for the production and assembly of the vehicle. For the (semi-)products addressed in chapter 2 that are used as inputs to the vehicle production, also the costs of labour and raw materials are considered. For other inputs to the vehicle production such as glass, the cost of labour and raw materials has not been compiled in chapter 2 and is therefore not considered here. We consider allowance costs on a “face value” basis. This means that we abstract from free allocations or compensation payments for indirect emissions that might be (at least partially) passed on by the ETS firms to their clients. Hence, the CO₂ costs stated here are “calculatory”, and not necessarily also “monetary” costs of the products analysed in chapter 2. An analysis setting additional assumptions on pass-through rates is beyond the scope of this study.

Looking at the cumulative energy balance of all materials used (including but not limited to the products from chapter 2), **it becomes clear that even with different price levels, the energy costs are significantly higher than the costs for GHG emissions.** With the annual average EUA² price in the year 2015 of 7.7 €, costs for GHG emissions amount to 24 € and have an average share of 11 % of the aggregated costs for energy and GHG emissions (hence, energy costs largely dominate in direct comparison). In 2021 (EUA price of 53.2 €), GHG costs on average account for 26 % (164 €). In 2022 (EUA 80 €/t CO₂eq), the costs for GHG emissions have a lower average share of 19 % of the combined costs for energy and GHG emissions due to the even higher increase in energy costs, even though the total amount of GHG costs is increasing to 246 €. **Regarding the relative distribution of GHG costs along the value chain, the most relevant costs are those associated with the materials production (e.g., hot-rolled coils).** Nevertheless, the shares depend on the level of costs for energy and EUA.

As the (semi-)products from chapter 2 (included in the “Materials production” in Figure 1) **represent large shares in the cumulated energy consumption and GHG emissions in the car production, we present their cost composition here separately.** As mentioned in the summary of chapter 2, labour costs and (raw) material input costs (e.g. for iron ore) have been researched additionally to the energy and CO₂ costs for these materials, so we present here the share of GHG costs and energy costs not only versus each other (as above), but in relation to the total production costs. Moreover, the baseline for calculating the GHG costs are the GHG emissions determined in chapter 2. **In 2015, due to the then low ETS allowance prices of 7.7 €/t CO₂eq, the GHG emissions have the lowest share of the considered costs for the production of materials.** Absolute costs for GHG emissions from the products in chapter 2 amount to 11.3 €, leading to an average share of 1.7 % of the total relevant costs (energy, GHG emissions, labour and material). In 2021 and 2022, the shares of energy and GHG costs are significantly higher: In 2021 (EUA 53.2 €/t CO₂eq), the CO₂ cost share is on average 8.6 % (78.3 €). In 2022 (EUA 80 €/t CO₂eq), the costs for GHG emissions amount to 117.6 €, with an average share of 10 % of total costs for energy, GHG emissions, labour and material.

² EUA price = EU allowance price (denominated in € per ton of CO₂-equivalent).

Figure 3: Cost shares for the products from chapter 2 (see Figure 92 in this report)



Source: own calculation based on the data sources stated in chapter 3. Material includes the (raw) material input costs for the products from chapter 2.

Assessment of the CO₂ cost shares in the production of plastic products

Material balance, energy demand and GHG emissions

For the purpose of this case study, a production of 1,000 plastic bags and 1,000 plastic bowls is assumed. The methodology of the assessment of the CO₂ cost share follows the one for passenger cars detailed above. First, the production processes of both products are evaluated. After that, the mass and material balances are developed to serve as a basis for the calculation of the total energy demand and GHG emissions. Finally, the CO₂ cost shares are calculated.

The chosen plastic bag is made of low-density polyethylene (LDPE) and the plastic bowl is made of polypropylene (PP). PE and PP are produced mainly from naphtha in a steam cracker, and then polymerised. Thus, the data for PE and PP from chapter 2 are used as a proxy. The energy balance for the production of 1,000 plastic bags and 1,000 plastic bowls is shown in Table 6. Comparing the specific energy demand for both products, the production of plastic bags requires 20.7 MJ per kg and the production of plastic bowls requires 24.4 MJ per kg. In contrast to the passenger car, GHG emissions resulting from the production of plastic bags come exclusively from the energy required for production, i.e. no emissions are allocated to the base material naphtha. For the production of 1,000 plastic bags and bowls, 45 kg CO₂eq and 1,027 kg of CO₂eq is emitted, respectively. Most greenhouse gas emissions result from the use of naphtha as energy carrier in the production of ethylene and propylene.

Table 6 Energy balance for the production of 1,000 plastic bags and 1,000 plastic bowls (see Tables 98 and 99 in this report)

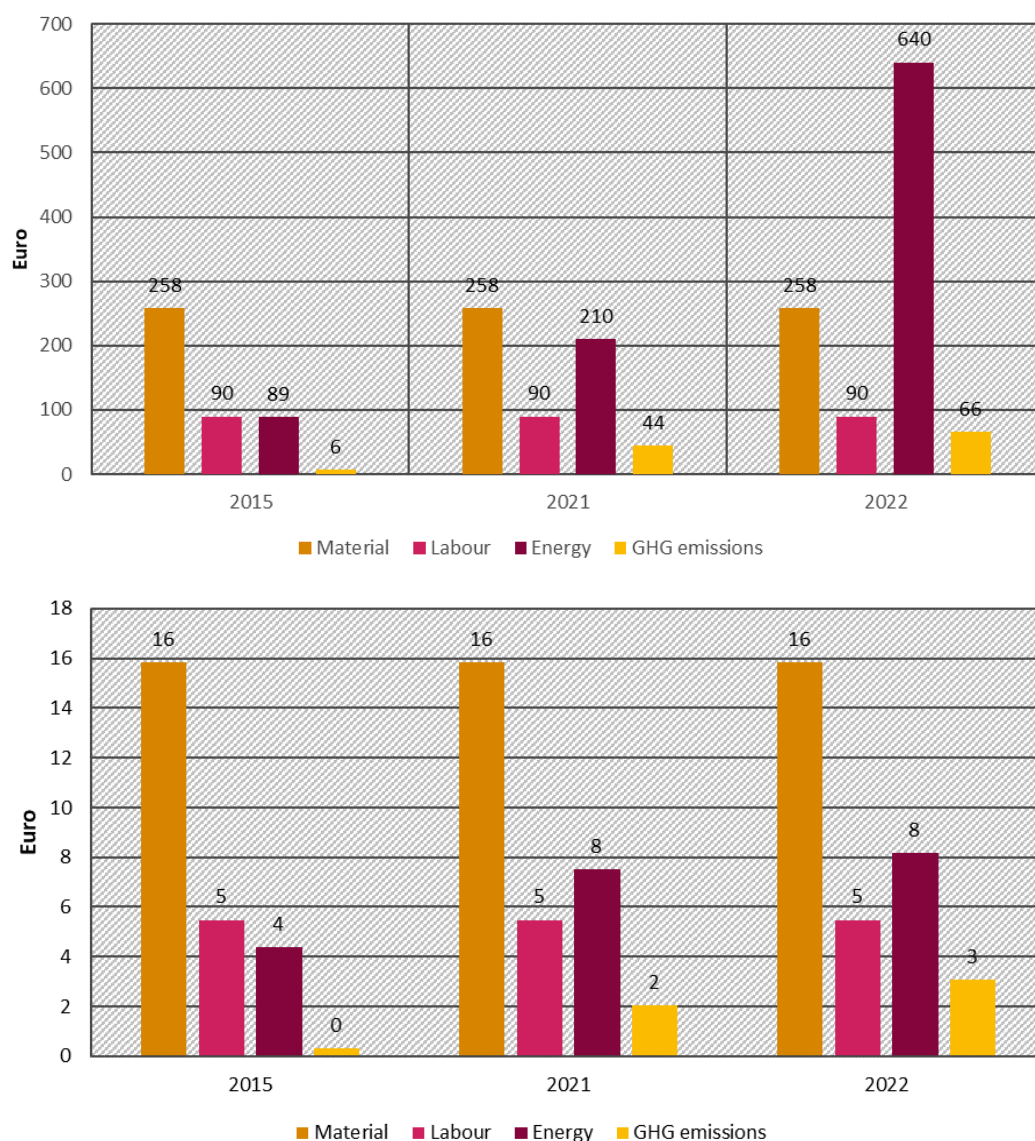
	Naphtha [MJ]		Electricity [MJ]		Natural gas [MJ]	
	Plastic bags	Plastic bowls	Plastic bags	Plastic bowls	Plastic bags	Plastic bowls
Steam cracker	396	6.930				
Polymerisation			64.8	840		504
Extruder			23.95	998	36.48	340
Injection moulding				1.361		

Source: own calculation based on the data sources stated in chapter 3.

Assessment of CO₂ cost shares of the overall production costs

The following Figure 4 shows the cost composition for both analysed products. In 2015, the aggregate costs for energy, GHG emissions, material and labour for the production of 1,000 plastic bowls amount to 444 €. In 2021, the costs increased to 602 €, in 2022 to 1,055 €. In 2015, material has with 58 % the highest share of the considered cost, followed by costs for energy and labour with a share of 20 % each. The costs for GHG emissions amount to only 1 %. **With rising costs for energy and emission allowances, the share of material and labour decreases for plastic bowls, whereas the shares of energy and GHG emissions increases.** In 2021 (EUA price of 53.2 €), the costs for GHG emission have a share of 7 %. In 2022 (EUA price of 80 €), the costs for GHG emissions amount to 6 % of the costs for energy, GHG emissions, material and labour. The costs for energy, GHG emissions, material and labour for the production of 1,000 plastic bags amount to 26 € in 2015. The relative distribution of the costs is similar to the plastic bowl. **With the increase in energy prices, the importance of material costs decreases. Nevertheless, the material costs remain the main cost driver of plastic bags.** In 2015 (EUA price of 7.7 €), costs for GHG amount to 1 % of the considered. In 2021 (EUA price 53.2 €), the costs for GHG emissions have a share of 7 %. In 2022 (EUA price 80 €), the costs for GHG emissions amount to 9 % of the costs.

Figure 4 Cost structure of the production of 1,000 plastic bowls out of propylene (top) and of 1,000 plastic bags out of ethylene (bottom) (see Figures 102 and 103 in this report)



Source: own calculation based on the data sources stated in chapter 3. Material includes the (raw) material input costs for the products from chapter 2.

The developed data basis and analyses enable the future development of (dynamic) material flow models for relevant industrial processes and products, e.g. regarding the exposure of producers of materials, parts, and final products to CO₂ prices and further decarbonization options. Henceforth, this is the baseline for ambitious GHG mitigation pathways by integrating material production and their connection to the energy system and emissions. This gains momentum in the European political debate driven by concerns over sustainability and supply risks for future technologies. It becomes clear that synergies exist between the decarbonization, the circular economy and industrial agendas. In addition, and as mentioned above, the data sets established in this project can be used – possibly together with data from other sources – for estimating typical cost impacts related to the CBAM introduction, which will affect the cost composition and prices of both basic materials and of further processed products, such as vehicles.

Zusammenfassung

Seit dem Start des Europäischen Emissionshandelssystems (EU-ETS 1) für die Sektoren Energie und Industrie sowie den Luft- und Seeverkehr im Jahr 2005 haben die erfassten Sektoren ihre CO₂-Emissionen bis 2023 EU-weit um etwa 48 % reduziert. Gleichzeitig zeigt beispielsweise der EEA-Bericht "Trends and projections in the EU ETS 2022", dass die Industrieemissionen weniger stark zurückgegangen sind, nämlich nur um 28 % seit 2005. Außerdem sind die Industrieemissionen seit Beginn der dritten Handelsperiode, die 2013 begann, relativ konstant geblieben. Lediglich im Jahr 2023 war in diesem Sektor ein signifikanter Rückgang zu beobachten, der auf eine geringere Industrieproduktion aufgrund des Angriffskrieges Russlands auf die Ukraine zurückzuführen war. Angesichts der notwendigen jährlichen Reduktionsvorgaben im Anwendungsbereich des EU-ETS 1 bis 2030 gewinnt die Frage nach dem Reduktionspotenzial der Industriesektoren an Bedeutung.

Auch in diesem Kontext erfährt die Kreislaufwirtschaft zunehmend politische Anerkennung, da sie Herausforderungen hinsichtlich der Nachhaltigkeit und Versorgungssicherheit zukunftsrelevanter Technologien adressieren kann. So bestehen Synergien zwischen industriepolitischen Zielsetzungen, der Industriedekarbonisierung und der Kreislaufwirtschaft. Folglich müssen die Materialproduktion und -verwendung sowie ihre Verbindung zum Energiesystem und zu den Emissionen berücksichtigt werden, wenn diese neue Perspektive in die politische Entscheidungsfindung und die Analyse ehrgeiziger THG-Emissionsminderungspfade als Teil des europäischen Green Deals integriert wird.

In diesem Zusammenhang spielt auch die Vermeidung von Carbon Leakage (CL) eine zentrale Rolle. Dies soll auf EU-Ebene durch den European Carbon Border Adjustment Mechanism (CBAM) gewährleistet werden, der bis 2034 schrittweise die kostenlose Zuteilung als CL-Instrument im Rahmen des EU-ETS 1 ablösen wird. Ab 2026 soll der CBAM eine Auswahl von Importgütern mit dem gleichen effektiven CO₂-Preis belegen, wie er für im europäischen Binnenmarkt hergestellte Produkte gilt. **Mit Blick auf die weitere Entwicklung des CBAM stellt sich die Frage, wie hoch der Kosteneffekt der CO₂-Bepreisung über den EU-ETS 1 auf a) Grundstoffe, die im Rahmen des EU-ETS 1 hergestellt werden, und b) weiterverarbeitete Produkte, die aus den Grundstoffen als Produktionsmittel bestehen (z.B. Fahrzeugbau), ist. Diese Informationen sind unter anderem für die Frage relevant, welche weiteren ("nachgelagerten") Sektoren in den CBAM aufgenommen werden sollen, oder für die Auswirkungen des CBAM auf Exporte in Drittländer, welche die kostenlose Zuteilung ersetzen.** Der CBAM deckt derzeit hauptsächlich Grundstoffe wie Stahl, Aluminium, Zement, Düngemittel und Wasserstoff ab. Die Diskussionen über mögliche Sektoren für eine zusätzliche Aufnahme umfassen unter anderem chemische Grundstoffe, nicht zuletzt (Poly-)Olefine als Vorprodukt für Kunststoffprodukte.

Wichtige Entscheidungsbausteine sind in diesem Kontext Kenntnisse über die Stoffströme der Produkte in den vom EU-ETS 1 erfassten Industriesektoren, deren jeweiliger Energieverbrauch, die Relevanz von Produkten für die gesamten CO₂-Emissionen einer Branche sowie wirtschaftliche Kennzahlen, um diese einzuordnen. Dazu muss zunächst eine umfassende und konsistente Datenbasis geschaffen werden, die auch produktbezogene Emissionsbilanzen einschließt, die bisher nicht verfügbar sind. **Ziel dieser Studie ist es, eine solche solide Informations- und Datenbasis für den Energiebedarf, die CO₂-Emissionen und die wirtschaftliche Bedeutung verschiedener Produkte zu schaffen, die den unter den EU-ETS 1 fallenden industriellen Aktivitäten zugerechnet werden können.** In diesem Projekt lag der Schwerpunkt daher auf der **Ableitung und beispielhaften Anwendung von Methoden, um statistische Daten aus unterschiedlichen Quellen konsistent zusammenzuführen** und eine Datenbasis zu schaffen,

mit der Daten zu Stoffströmen, Energieverbrauch und Emissionen kombiniert werden können, **um Kennzahlen wie den spezifischen Energiebedarf und die spezifischen CO₂-Emissionen sowohl für direkte als auch für indirekte (d. h. stromverbrauchsbedingte) Emissionen abzuleiten.** Ergänzt wird dies durch wirtschaftliche Kennzahlen zu den wichtigsten Kostenkomponenten und zum Außenhandel, die helfen, die Bedeutung der CO₂-Kostenauswirkungen zu beurteilen, die sich aus den vorgenannten spezifischen CO₂-Emissionen für die ausgewählten Produkte ergeben. Es ist beabsichtigt, dass die angewandten Methoden auch von Lesenden dieses Berichts zu einem späteren Zeitpunkt unter Verwendung neuerer Zahlen aus den vorgestellten Quellen verwendet werden können.

Zu diesem Zweck wurde bei der Datensammlung ein Referenzjahr zugrunde gelegt, das für alle ausgewählten Kennzahlen verfügbar war. Zum Zeitpunkt der Datensammlung für dieses Projekt in den Jahren 2019 und 2020 war dies das **Jahr 2015. Für dieses Jahr konnten alle relevanten Daten aus verschiedenen Quellen vollständig und methodisch konsistent beschafft werden.** Bei der Interpretation der Daten lässt sich generell feststellen, dass sowohl der Energiebedarf als auch die direkten CO₂-Emissionen pro Einheit des Grundstoffprodukts seit 2015 weitgehend unverändert geblieben sind. Eine Ausnahme bildet der Strommix und die damit verbundenen "indirekten Emissionen" aus dem Einsatz von Strom bei der Herstellung der Grundstoffe. Hier lässt sich feststellen, dass die durchschnittlichen Emissionen im Zusammenhang mit dem Strommix im Vergleich zu 2015 gesunken sind. So wurde beispielsweise für Deutschland im Jahr 2015 ein Emissionsfaktor von 0,587 kg CO₂/kWh berücksichtigt, während dieser 2021 bei 0,410 kg CO₂/kWh lag (Koffi et al., 2017; Icha & Lauf, 2023). Um den Anteil der sinkenden indirekten Emissionen an den gesamten CO₂-Emissionen zu beurteilen, werden diese separat dargestellt, sofern die verfügbaren Datenquellen dies zulassen. Ein weiterer Faktor, der sich seit 2015 erheblich verändert hat, sind die Preise für ETS-Zertifikate, die mit den spezifischen CO₂-Emissionen multipliziert werden, um die Kostenauswirkungen des EU-ETS 1 zu ermitteln. Im entsprechenden Kapitel dieses Berichts verwenden wir daher auch neuere (ab 2021 bzw. 2022) Marktpreise für ETS-Zertifikate und die wichtigsten Energieträgerpreise. Im Jahr 2023 und in der ersten Hälfte des Jahres 2024 lagen die Preise für ETS-Zertifikate in einer vergleichbaren Größenordnung wie in den Jahren 2021 und 2022.

In diesem Bericht analysieren wir zunächst die Prozessschritte im Rahmen des EU-ETS 1 (Kapitel 2). Der Schwerpunkt der Analyse liegt auf Grundstoffen und Industriezweigen, die für den EU-ETS 1 sehr wichtig sind, d.h. Stahl, Zement, Aluminium, Raffinerien und Basischemikalien. Zunächst definiert dieser Bericht das zugrundeliegende Konzept entlang dieser Wertschöpfungsketten. Darüber hinaus werden die Stoffströme ausgewählter Endprodukte, der damit verbundene Energieverbrauch und die daraus resultierenden Emissionen für die EU27 und das Vereinigte Königreich (UK), bzw. für Deutschland (DEU) entwickelt. Außerdem werden wirtschaftliche Indikatoren aus öffentlicher Statistik und Literatur zusammengefasst, d.h. Handel, Kosten und Preise. Die Ergebnisse (Energieverbrauch, Treibhausgasemissionen und Kosten) werden für die anschließende Analyse verwendet. **In Kapitel 3 werden weitere Prozessschritte entlang der Wertschöpfungskette bis hin zu zwei ausgewählten Endprodukten behandelt: (1) ein Pkw (Verbrennungsmotor bzw. batterieelektrisch) und (2) zwei Kunststoffverpackungsprodukte.** Aufbauend auf den in Kapitel 2 zusammengestellten Daten wurden die Fallstudien entwickelt, um die CO₂-Emissionen und die durch diese Emissionen verursachten Kostenanteile durch den EU-ETS 1 entlang der Wertschöpfungskette zu ermitteln und zu quantifizieren.

Kapitel 2: Indikatoren für ausgewählte Industriesektoren und Produkte, die unter den EU-ETS 1 fallen

Die wichtigsten Ergebnisse aus Kapitel 2 zu den ausgewählten Industriesektoren und Produkten, die vom EU-ETS 1 abgedeckt werden, werden im Folgenden beschrieben.

Für die **Eisen- und Stahlindustrie** wird ein vereinfachtes Stoff- und Energieflussmodell entwickelt. Dazu gehört auch eine ausführliche Erörterung möglicher Konventionen für die Zurechnung von Kuppelgasen ("waste gases"). **Die vier ausgewählten und analysierten Stahlerzeugnisse - warmgewalzte Bleche, Walzdraht, warmgewalzter Stabstahl und Betonstahl - haben große wirtschaftliche Bedeutung und repräsentieren die beiden Hauptproduktionswege in der Stahlindustrie (primär und sekundär). Die Produkte der Hochofenroute (z. B. warmgewalzte Bleche) weisen höhere kumulierte CO₂-Emissionen auf (Table 7). Im Vergleich zur Erzeugung des Roheisens und Rohstahls sind die weiteren Verarbeitungsschritte (z. B. Walzen) weniger relevant in Bezug auf Energie und Emissionen.**

Table 7 Indikatoren für Stahl (siehe Tables 18, 19, 21 und 22 im vorliegenden Bericht)

Produkt	Spezifischer kumulierter Energiebedarf [GJ/t]		Spezifische kumulierte CO ₂ -Emissionen [t CO ₂ äq/t]		Spezifische indirekte CO ₂ -Emissionen [t CO ₂ äq/t]	
	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU
Betonstahl	3,94	3,15	0,38	0,44	0,03	0,05
Stabstahl	3,94	3,15	0,38	0,44	0,03	0,05
Walzdraht	4,17	3,37	0,42	0,49	0,06	0,09
Blech	19,23	19,52	2,23	2,32	0,07	0,10

Quelle: eigene Berechnung basierend auf den in Kapitel 2 genannten Datenquellen (Referenzjahr 2015).

Für die **Zementindustrie** wird ein ähnliches Modell entwickelt. In der Analyse werden die Stoffströme, der Endenergiebedarf und die CO₂-Emissionen differenziert nach Zementsorten dargestellt. **Es zeigt sich ein hoher Einfluss der Klinkerproduktion im Allgemeinen und des Klinkeranteils im Zement im Besonderen auf die spezifischen Emissionsfaktoren** (siehe Table 8). Darüber hinaus ist die indikative Zuordnung der Zementsorten zu den Betonlieferanten, d.h. Transportbeton oder Fertigteile, für die Differenzierung der Endprodukte von großer Bedeutung. **Der Klinkeranteil in den Endprodukten wirkt sich stark auf die enthaltenen („grauen“) CO₂-Emissionen in masseäquivalenten Betonendenwendungen aus** (siehe Table 8). So weist Fertigteilbeton im Rahmen des EU-ETS 1 eine höhere CO₂-Intensität auf Massenbasis auf als Transportbeton, und daher ist die damit verbundene CO₂-Kostenkomponente für diese Betonart auch relevanter. Wir betonen jedoch, dass sich diese Analyse auf den Geltungsbereich des EU-ETS 1 konzentriert und nicht dazu gedacht ist, Erkenntnisse über die relative Nachhaltigkeit der beiden Betonarten auch im Hinblick auf die gesamten CO₂-Emissionen zu liefern. Daher sollten weitere Analysen auch die tatsächliche Anwendung von Betonprodukten im Bauwesen (performance-basiert) und die End-of-Life-Phase untersuchen. Dies würde die Erkenntnisse aus der Produktionsphase vervollständigen, auf die sich dieser Bericht aufgrund der Fokussierung auf den EU-ETS 1 beschränkt.

Table 8 Indikatoren für Zement (siehe Tables 34, 35, 36 und 37 im vorliegenden Bericht)

Produkt	Produktion [Mt]		Spezifischer kumulierter Brennstoffbedarf [GJ/t]		Spezifischer kumulierter Strombedarf [kWh/t]		Spezifische kumulierte CO ₂ -Emissionen [t CO ₂ äq/t]		Spezifische indirekte CO ₂ -Emissionen [t CO ₂ äq/t]	
	EU27+ UK	DEU	EU27+ UK	DEU	EU27+ UK	DEU	EU27+ UK	DEU	EU27+ UK	DEU
Klinker	125,0*	23,4*	3,73	3,75	47	47	0,94	0,83	0,02	0,03
Zement	157,0*	31,2*	2,59	2,76	116	112	0,77	0,66	0,03	0,04
Transportbeton	646,9	110,6	0,30	0,30	15	14	0,12	0,12	0,002	0,003
Fertigteilbeton	243,1	43,0	0,59	0,60	20	19	0,18	0,16	0,003	0,004

*aus Statistik, nicht berechnet

Quelle: eigene Berechnung basierend auf den in Kapitel 2 genannten Datenquellen (Referenzjahr 2015). Für Zement geben die Zahlen Durchschnittswerte für alle Zementsorten an (gewichtet nach ihrem jeweiligen Anteil am Produktionsvolumen).

Aluminium ist ein Metall mit einer sehr komplexen Materialflussmodellstruktur ausgehend von der lokalen Produktion von Primär- und Sekundärrohstoffen. Insbesondere die sekundäre Produktionsroute spielt in Europa eine Schlüsselrolle. Daher wird ein Materialflussmodell entwickelt, welches den verfügbaren Schrott in zwei Strömen zusammenfasst: Erstens, Transport (einschließlich Automobilindustrie), Bau und Renovierung, zweitens, Verpackungen, erneuerbare Energietechnologien und Maschinenproduktion. Der resultierende Datensatz schließt den Abbau von Bauxit und die Herstellung von Aluminiumoxid aus. **Die Nachfrage nach Aluminium-Halbzeugen und -Fertigprodukten ist sehr unterschiedlich, wie die resultierenden Materialflüsse zeigen. Dies verringert auch die Gesamtvolatilität der Nachfrage auf diesen Märkten. Die Rolle der Sekundäraluminiumströme (d.h. die Verfügbarkeit von Material auf dem Sekundärweg) ist für die künftige Entwicklung der Energieeffizienz und Emissionsintensität der Aluminiumindustrie sehr wichtig** (siehe auch Table 9). Daher ist die Verbesserung der Recyclingpraktiken und die Analyse der Legierungselemente von entscheidender Bedeutung. Im Gegensatz zu den anderen oben genannten Grundstoffen spielen die indirekten Emissionen aus dem Stromverbrauch bei der Primärproduktion von Aluminium eine große Rolle. Folglich wirken sich sinkende durchschnittliche Emissionen des Strommixes auf die unten dargestellten Ergebnisse für die spezifischen kumulierten CO₂-Emissionen aus.

Table 9 Indikatoren für Aluminium (siehe Tables 48, 49, 50 und 51 im vorliegenden Bericht)

Produkt	Spezifischer kumulierter Brennstoffbedarf [GJ/t]		Spezifischer kumulierter Strombedarf [MWh/t]		Spezifische kumulierte CO ₂ -Emissionen [t CO ₂ äq/t]		Spezifische indirekte CO ₂ -Emissionen [t CO ₂ äq/t]	
	EU27+ UK	DEU	EU27+ UK	DEU	EU27+ UK	DEU	EU27+ UK	DEU
Primär	2,4	2,4	14,79	14,79	7,53	10,43	5,78	8,69
Sekundär	1,6	1,6	0,095	0,095	0,13	0,15	0,04	0,04
Gussteile	7	7	1,3	1,3	2,41	3,27	0,51	0,76

Produkt	Spezifischer kumulierter Brennstoffbedarf [GJ/t]		Spezifischer kumulierter Strombedarf [MWh/t]		Spezifische kumulierte CO ₂ -Emissionen [t CO ₂ äq/t]		Spezifische indirekte CO ₂ -Emissionen [t CO ₂ äq/t]	
	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU
Flachprodukte	0,95	0,95	0,31	0,31	1,69	1,66	0,12	0,18
Strangpressprodukte	4,1	4,1	0,091	0,091	2,04	1,71	0,04	0,05

Quelle: eigene Berechnung basierend auf den in Kapitel 2 genannten Datenquellen (Referenzjahr 2015).

Raffinerien sind hochkomplexe Produktionssysteme mit einer Vielzahl von Produkten, die auf Rohöl als Ausgangsmaterial basieren. Daher wird der Ansatz der "komplexitätsgewichteten Tonne" ("complexity weighted tonne", CWT) angewandt, der raffineriespezifische THG-Emissionen ermittelt und bereits in anderen Kontexten angewandt wird, z. B. zur Festlegung der Produktbenchmark und damit zur Bestimmung der kostenlosen Zuteilung von Emissionszertifikaten im EU-ETS. Zusätzlich wurde aufgrund der Komplexität der Analyse eine Reihe von Interviews mit Raffinerievertretenden durchgeführt. **Die Analyse verdeutlicht die Herausforderungen und Grenzen des Versuchs, verallgemeinerte stoffstrombasierte Kennzahlen für THG-Emissionen und Energieverbrauch für Raffinerieprodukte zu ermitteln. Die Analyse zeigte jedoch, dass die Produktionsstruktur für Naphtha einen erheblichen Einfluss auf die damit verbundenen CO₂-Emissionen hat** (siehe Table 10, welche die Ergebnisse für vier nach Komplexität unterschiedene Raffinerietypen zeigt).

Table 10 Indikatoren für Naphtha je Raffinerietyp (siehe Tables 55, 56, 58 und 59 im vorliegenden Bericht)

Raffinerietyp	Spezifischer kumulierter Energiebedarf [GJ/t]		Spezifische kumulierte CO ₂ -Emissionen [t CO ₂ äq/t]	
	EU27+UK	DEU	EU27+UK	DEU
Complexity I	Keine Daten verfügbar			
Complexity II	4,65	4,78	0,282	0,294
Complexity III	15,4	14,7	0,977	0,931
Complexity IV	Keine Daten verfügbar			

Quelle: eigene Berechnung basierend auf den in Kapitel 2 genannten Datenquellen (Referenzjahr 2015).

Naphtha kann zu den nachgelagerten "polyolefin"-Produkten **Polyethylen (PE) und Polypropylen (PP)** weiterverarbeitet werden. Diese Produkte sind relevante Grundchemikalien, die in zwei separaten Stoffstrommodellen analysiert werden. **Diese Analysen untermauern, dass vor allem das Steamcracken von Naphtha für die Herstellung von Ethylen und Propylen für die CO₂-Emissionen relevant ist, während die Verarbeitung zu Polyethylen und Polypropylen sowie die darauf basierenden Kunststoffprodukte weit weniger relevant sind** (siehe Table 11). Darüber hinaus sind die indirekten Emissionen aus dem Stromverbrauch nur für die nachgelagerten Produkte PE und PP relevant. **Im Gegensatz zu den anderen in dieser Studie untersuchten Produkten bestehen Polyolefine aus fossilem Kohlenstoff (nichtenergetische Nutzung). Dieser wird am Ende des Lebenszyklus als CO₂ freigesetzt, auch wenn**

dies lange dauern kann. Ein zweiter wichtiger Unterschied zu den anderen betrachteten Materialien ist die Tatsache, dass Kunststoffe in der Umwelt nicht "mineralisieren" und damit eine Gefahr für Fauna und Flora darstellen.

Table 11 Indikatoren für die Basischemikalien PE und PP (siehe Tables 65, 66, 67 und 68 im vorliegenden Bericht)

Produkt	Spezifischer kumulierter Brennstoffbedarf [GJ/t]		Spezifischer kumulierter Strombedarf [GJ/t]		Spezifische kumulierte CO ₂ -Emissionen [t CO ₂ äq/t]		Spezifische indirekte CO ₂ -Emissionen [t CO ₂ äq/t]	
	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU	EU27+UK	DEU
Ethylen	16,5	16,5	n/a	n/a	0,76	0,76	n/a	n/a
Propylen	16,5	16,5	n/a	n/a	0,76	0,76	n/a	n/a
PE	-0,2	-0,2	2,7	2,7	0,35	0,35	0,36	0,36
PP	1,2	1,2	2	2	0,35	0,35	0,27	0,27

Quelle: eigene Berechnung basierend auf den in Kapitel 2 genannten Datenquellen (Referenzjahr 2015).

Kapitel 3: Fallstudien zur Abschätzung der CO₂-Kostenanteile auf den Stufen der Weiterverarbeitung

Die Fallstudien zur Schätzung des CO₂-Kostenanteils in den Weiterverarbeitungsstufen aus Kapitel 3 werden im Folgenden beschrieben.

Aufbauend auf den in Kapitel 2 zusammengestellten Daten wurden zwei Fallstudien entwickelt, um die CO₂-Emissionen und die durch diese Emissionen verursachten Kostenanteile durch den EU-ETS 1 **entlang der Wertschöpfungskette der Endprodukte** zu ermitteln und zu quantifizieren. Diese Analyse umfasst die kumulierten Energie- und CO₂-Emissionen für die Endprodukte sowie die Arbeits- und Materialkosten für die Produkte aus Kapitel 2.

In der ersten Fallstudie werden zwei Arten von Personenkraftwagen analysiert: ein Fahrzeug mit Verbrennungsmotor und ein Elektrofahrzeug mit Batterie. Die zweite Fallstudie befasst sich mit einer Auswahl von Kunststoffprodukten, nämlich einer Plastiktüte und einer Plastikschele. In den Berechnungen wird deutlich, welche Produktionsprozesse und Materialien den größten Anteil am Energieverbrauch und den CO₂-Emissionen haben. Aufgrund der unterschiedlichen Vorgehensweise bei der Ermittlung der Massenbilanzen, die der Berechnung zugrunde liegen, sind die Ergebnisse von Pkw und Kunststoffprodukten jedoch nicht direkt vergleichbar.

Bewertung der CO₂-Kostenanteile entlang der Wertschöpfungskette bei der Herstellung von Personenkraftwagen

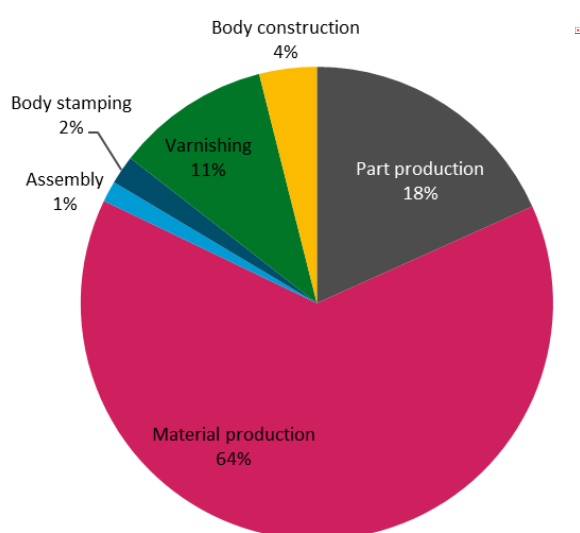
Materialbilanz, Energiebedarf und THG-Emissionen

Für die Erstellung der Materialbilanz des Personenkraftwagens und der Energiebilanz für den Produktionsprozess wird ein bottom-up-Ansatz verwendet. So werden die in einem Personenkraftwagen verwendeten Materialien anhand der Teile eines generischen Mittelklassefahrzeugs ermittelt. Stahl ist der mit Abstand am meisten verwendete Werkstoff im Fahrzeug, gefolgt von Aluminium. Stahl, Aluminium, Eisen (hier in Abgrenzung zu Stahl) und Kunststoffe, die zu den in Kapitel 2 betrachteten Materialien gehören, machen zusammen 88 % der gesamten Materialbi-

lanz aus. Die Energiebilanz und die daraus resultierenden THG-Emissionen werden auf Grundlage der verwendeten Materialien sowie der für diese Materialien angewandten Produktions- und Herstellungsprozesse berechnet. Der Gesamtenergiebedarf setzt sich aus der Energie zusammen, die bei der Fahrzeugmontage sowie bei der Herstellung von Materialien (z. B. warmgewalzte Bleche, wie in Kapitel 2 dieses Berichts quantifiziert) und Teilen (z. B. Airbag und Bremsen) verbraucht wird (siehe Figure 76 in diesem Bericht). Der Energieverbrauch und die Treibhausgasemissionen aus dem Abbau und der Gewinnung von Rohstoffen sind von der Analyse ausgeschlossen, da diese sich auf Produkte, die in den Geltungsbereich des EU-ETS 1 fallen, und ausgewählte Endprodukte konzentriert. Es werden unterschiedliche Datenquellen verwendet, d.h. Unternehmensdaten, Literatur und Datenbanken. Die Chemie-, Stahl- und Aluminiumprodukte aus Kapitel 2 dieses Projekts werden den Teilen des Fahrzeugs zugeordnet und um einen Produktionsprozess ergänzt. Die THG-Emissionen werden dann auf Basis des Energiebedarfs und der jeweiligen Emissionsfaktoren berechnet.

Der Gesamtenergiebedarf für die Material- und Teileproduktion sowie die Fahrzeugmontage beträgt für ein Fahrzeug mit Verbrennungsmotor 32.533 MJ und für das batterieelektrische Fahrzeug 35.530 MJ (siehe Figure 5). Der Anteil der Materialherstellung ("Material production", d. h. der Energieverbrauch für die Herstellung von Materialien im Rahmen des EU-ETS 1, wie in Kapitel 2 dieses Berichts dargelegt) dominiert den Gesamtenergieverbrauch, gefolgt von der Teileherstellung ("Part production") und drei Tätigkeiten im Zusammenhang mit der Fahrzeugkarosserie ("construction", "stamping" und "varnishing"). Beim batterieelektrischen Fahrzeug wird davon ausgegangen, dass die meisten Teile aus denselben Materialien und mit denselben Verfahren (bei gleichem Energieverbrauch) hergestellt werden wie beim herkömmlichen Fahrzeug mit Verbrennungsmotor. Lediglich der Antriebsstrang (einschließlich des Elektromotors und der Batterie) wird unterschiedlich betrachtet.

Figure 5 Anteil des Energiebedarfs an der Fahrzeugproduktion nach Produktionsphase für Fahrzeuge mit Verbrennungsmotor (links) und batterieelektrische Fahrzeuge (rechts) (siehe Figures 87 und 96 im vorliegenden Bericht)

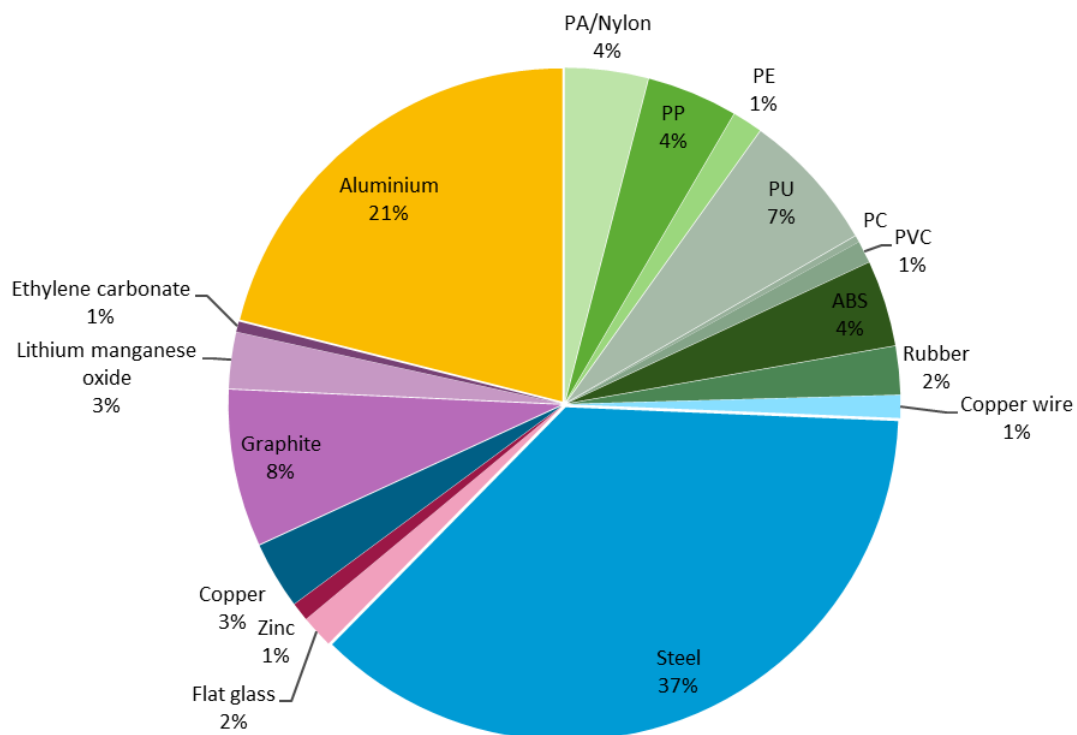


Quelle: eigene Berechnung basierend auf den in Kapitel 2 genannten Datenquellen (Referenzjahr 2015), Argonne National Library (2020), Sato & Nakata (2020), Van der Welden et al. (2012).

Insgesamt werden bei der Herstellung eines Pkw mit Verbrennungsmotor 3.505 kg CO₂ und beim Elektro-Pkw 3.700 kg CO₂ emittiert (Verteilung siehe Figure 6). Beim Fahrzeug mit Verbrennungsmotor haben Bleche, die beim Stanzen der Karosserie verwendet werden, mit 932 kg CO₂ die höchsten grauen Emissionen. Generell machen die mit der Materialherstellung verbundenen THG-Emissionen bei beiden Fahrzeugtypen den größten Anteil an den kumulierten Gesamtemissionen aus, gefolgt von den Verarbeitungsschritten der Karosserie und der Teileherstellung (siehe Tables 89 und 93 sowie Figures 88 und 97 und den zugehörigen Berichtstext unten).

Da der Antriebsstrang des Elektrofahrzeugs etwas schwerer ist als der des Fahrzeugs mit Verbrennungsmotor (Gewicht der Batterie: 232 kg), wird bei der Herstellung vergleichsweise mehr Energie verbraucht. Im Vergleich zum Fahrzeug mit Verbrennungsmotor wird im Elektrofahrzeug weniger Stahl verwendet. Darüber hinaus trägt die Herstellung der Batterie mit weiteren 444 kg CO₂ zu den gesamten Treibhausgasemissionen des Elektrofahrzeugs bei.

Figure 6 Anteil der THG-Emissionen nach Material für das Fahrzeug mit Verbrennungsmotor (oben) und das Elektrofahrzeug mit Batterie (unten) (siehe Abbildungen 89 und 98 im vorliegenden Bericht)



Quelle: eigene Berechnung basierend auf den in Kapitel 2 genannten Datenquellen (Referenzjahr 2015), Argonne National Library (2020), Sato & Nakata (2020), Van der Welden et al. (2012).

Bewertung der CO₂-Kostenanteile an den Gesamtproduktionskosten

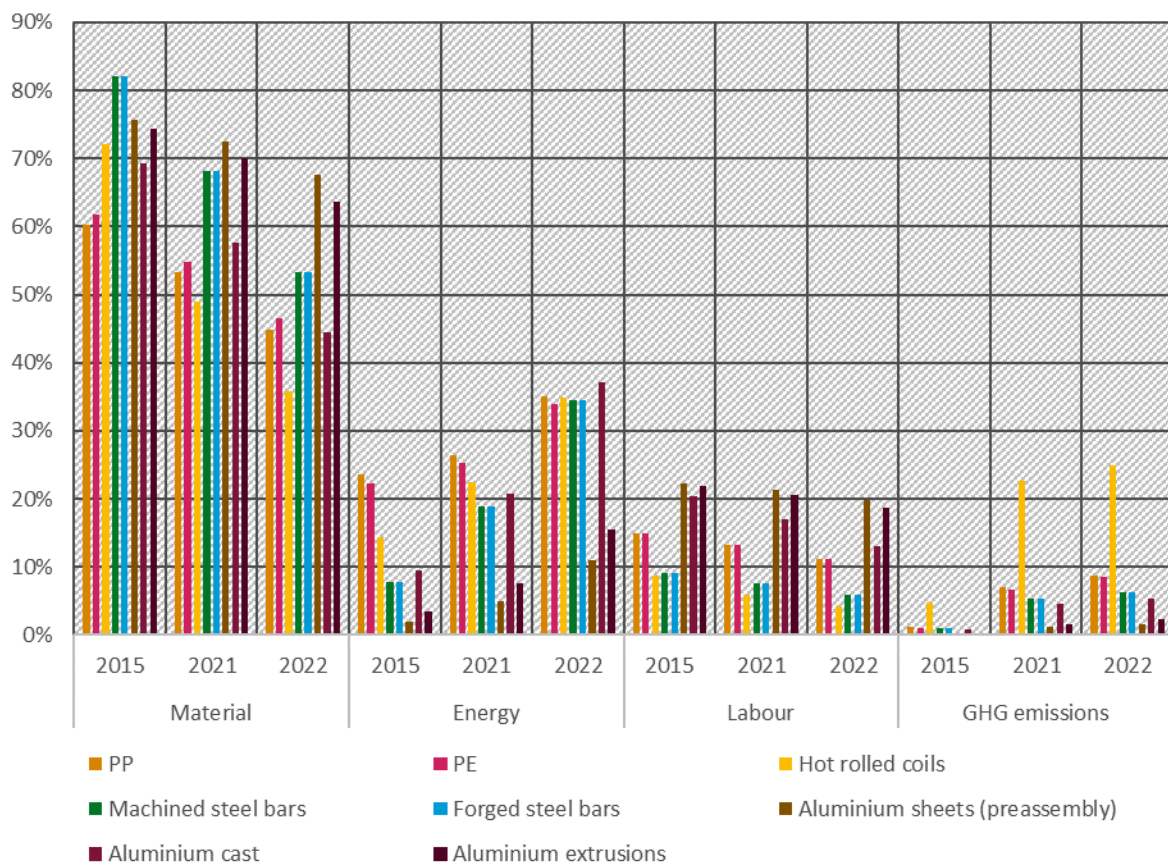
Für die Berechnung der CO₂-Kostenanteile werden die Kosten für Energie und THG-Emissionen für die in den Fahrzeugen verwendeten Materialien für die Material- und Teileherstellung sowie für die Herstellung und Montage des Fahrzeugs berechnet. Außerdem werden für die in Kapitel 2 betrachteten (Halb-)Produkte, die als Input für die Fahrzeugproduktion verwendet werden, auch die Kosten für Arbeit und Rohstoffe berücksichtigt. Für andere Inputs für die Fahrzeugproduktion, wie z. B. Glas, wurden die Kosten für Arbeit und Rohstoffe in Kapitel 2 nicht zusammengestellt und werden daher hier nicht berücksichtigt. Wir betrachten die Kosten für Zertifikate auf Basis des „Nennwerts“. Das bedeutet, dass wir von kostenlosen Zuteilungen oder Ausgleichszahlungen für indirekte Emissionen absehen, die von den ETS-Unternehmen (zumindest teilweise) an ihre Kunden weitergegeben werden könnten. Daher sind die hier angegebenen CO₂-Kosten „kalkulatorische“ und nicht unbedingt auch „monetäre“ Kosten der in Kapitel 2 analysierten Produkte. Eine Analyse, die zusätzliche Annahmen zu Preis-Durchleitungsraten enthält, würde den Rahmen dieser Studie sprengen.

Betrachtet man die kumulierte Energiebilanz aller eingesetzten Materialien (einschließlich, aber nicht beschränkt auf die Produkte aus Kapitel 2), **so wird deutlich, dass die Energiekosten auch bei unterschiedlichen Preisniveaus deutlich höher sind als die Kosten für THG-Emissionen.** Bei einem EUA³-Jahresdurchschnittspreis im Jahr 2015 von 7,7 € betragen die Kosten für THG-Emissionen 24 € und haben einen durchschnittlichen Anteil von 11 % an den aggregierten Kosten für Energie und THG-Emissionen (im direkten Vergleich dominieren also die Energiekosten deutlich). Im Jahr 2021 (EUA-Preis von 53,2 €) machen die THG-Kosten im Durchschnitt 26 % (164 €) aus. Im Jahr 2022 (EUA 80 €/t CO₂eq) haben die Kosten für THG-Emissionen aufgrund des noch stärkeren Anstiegs der Energiekosten einen geringeren durchschnittlichen Anteil von 19 % an den kombinierten Kosten für Energie und THG-Emissionen, auch wenn der Gesamtbetrag der THG-Kosten auf 246 € steigt. **Was die relative Verteilung der THG-Kosten entlang der Wertschöpfungskette betrifft, so sind die relevantesten Kosten die, die mit der Materialproduktion verbunden sind (z.B. warmgewalzte Bleche).** Die Anteile hängen jedoch von der Höhe der Kosten für Energie und EUA ab.

Da die (Halb-)Produkte aus Kapitel 2 (die in der Materialherstellung in Figure 5 enthalten sind) **große Anteile am kumulierten Energieverbrauch und den THG-Emissionen in der Automobilproduktion haben, stellen wir ihre Kostenzusammensetzung hier separat dar.** Wie in der Zusammenfassung von Kapitel 2 erwähnt, wurden zusätzlich zu den Energie- und CO₂-Kosten für diese Materialien auch die Arbeitskosten und die Kosten für (Roh-)Materialien (z. B. für Eisenerz) untersucht, sodass wir hier den Anteil der THG-Kosten und der Energiekosten nicht nur im Verhältnis zueinander (wie oben), sondern im Verhältnis zu den gesamten Produktionskosten darstellen. Die Basis für die Berechnung der THG-Kosten sind außerdem die in Kapitel 2 ermittelten THG-Emissionen. **Im Jahr 2015, aufgrund des damals niedrigen ETS-Zertifikatspreis von 7,7 €/t CO₂eq hatten die THG-Emissionen den geringsten Anteil an den betrachteten Kosten für die Produktion von Rohstoffen.** Absolut belaufen sich die Kosten für THG-Emissionen aus den Produkten in Kapitel 2 auf 11,3 €, was zu einem durchschnittlichen Anteil von 1,7 % der relevanten Kosten (Energie, THG-Emissionen, Arbeit und Material) führt. In den Jahren 2021 und 2022, sind die Anteile der Energie- und CO₂-Kosten deutlich höher. Im Jahr 2021 (EUA 53,2 €/t CO₂eq) liegt der CO₂-Kostenanteil im Durchschnitt bei 8.6 % (78,3 €). Im Jahr 2022 (EUA 80 €/t CO₂eq) belaufen sich die Kosten für THG-Emissionen auf 117,6 €, mit einem durchschnittlichen Anteil von 10 % der vollständigen Kosten für Energie, THG-Emissionen, Arbeit und Material.

³ EUA Preis = EU-Zertifikatspreis ("EU allowance", ausgedrückt in € pro Tonne CO₂-Äquivalent).

Figure 7 Kostenanteile der Produkte aus Kapitel 2 (siehe Figure 92 im vorliegenden Bericht)



Quelle: eigene Berechnung basierend auf den in Kapitel 2 genannten Datenquellen (Referenzjahr 2015). "Material" umfasst die (Roh-)stoffeinsatzkosten der Produkte aus Kapitel 2.

Bewertung der CO₂-Kostenanteile bei der Herstellung von Kunststoffprodukten

Materialbilanz, Energiebedarf und THG-Emissionen

Für den Zweck dieser Fallstudie wird eine Produktion von 1.000 Plastiktüten und 1.000 Plastikschalen angenommen. Die Methodik für die Bewertung des CO₂-Kostenanteils folgt der oben für Personenkraftwagen beschriebenen. Zunächst werden die Produktionsprozesse der beiden Produkte bewertet. Danach werden die Massen- und Materialbilanzen erstellt, die als Grundlage für die Berechnung des Gesamtenergiebedarfs und der Treibhausgasemissionen dienen. Schließlich werden die CO₂-Kostenanteile berechnet.

Der gewählte Kunststoffbeutel besteht aus Polyethylen niedriger Dichte ("low-density polyethylene", LDPE) und die Kunststoffschale aus Polypropylen (PP). PE und PP werden hauptsächlich aus Naphtha in einem Steamcracker hergestellt und dann polymerisiert. Daher werden die Daten für PE und PP aus Kapitel 2 als Näherungswerte verwendet. Die Energiebilanz für die Produktion von 1.000 Plastiktüten und 1.000 Plastikschalen ist in Table 12 dargestellt. Vergleicht man den spezifischen Energiebedarf für beide Produkte, so werden für die Herstellung von Plastiktüten 20,7 MJ pro kg und für die Herstellung von Kunststoffschalen 24,4 MJ pro kg benötigt. Im Gegensatz zum Pkw stammen die THG-Emissionen bei der Herstellung von Plastiktüten ausschließlich aus der für die Produktion benötigten Energie, d.h. dem Grundstoff Naphtha werden keine Emissionen zugerechnet. Bei der Produktion von 1.000 Plastiktüten und -schalen werden 45 kg CO₂ bzw. 1.027 kg CO₂ emittiert. Die meisten Treibhausgasemissionen entstehen

durch die Verwendung von Naphtha als Energieträger bei der Herstellung von Ethylen und Propylen.

Table 12 Energiebilanz für die Produktion von 1.000 Plastiktüten und 1.000 Plastikscha-len (siehe Tables 98 und 99 im vorliegenden Bericht)

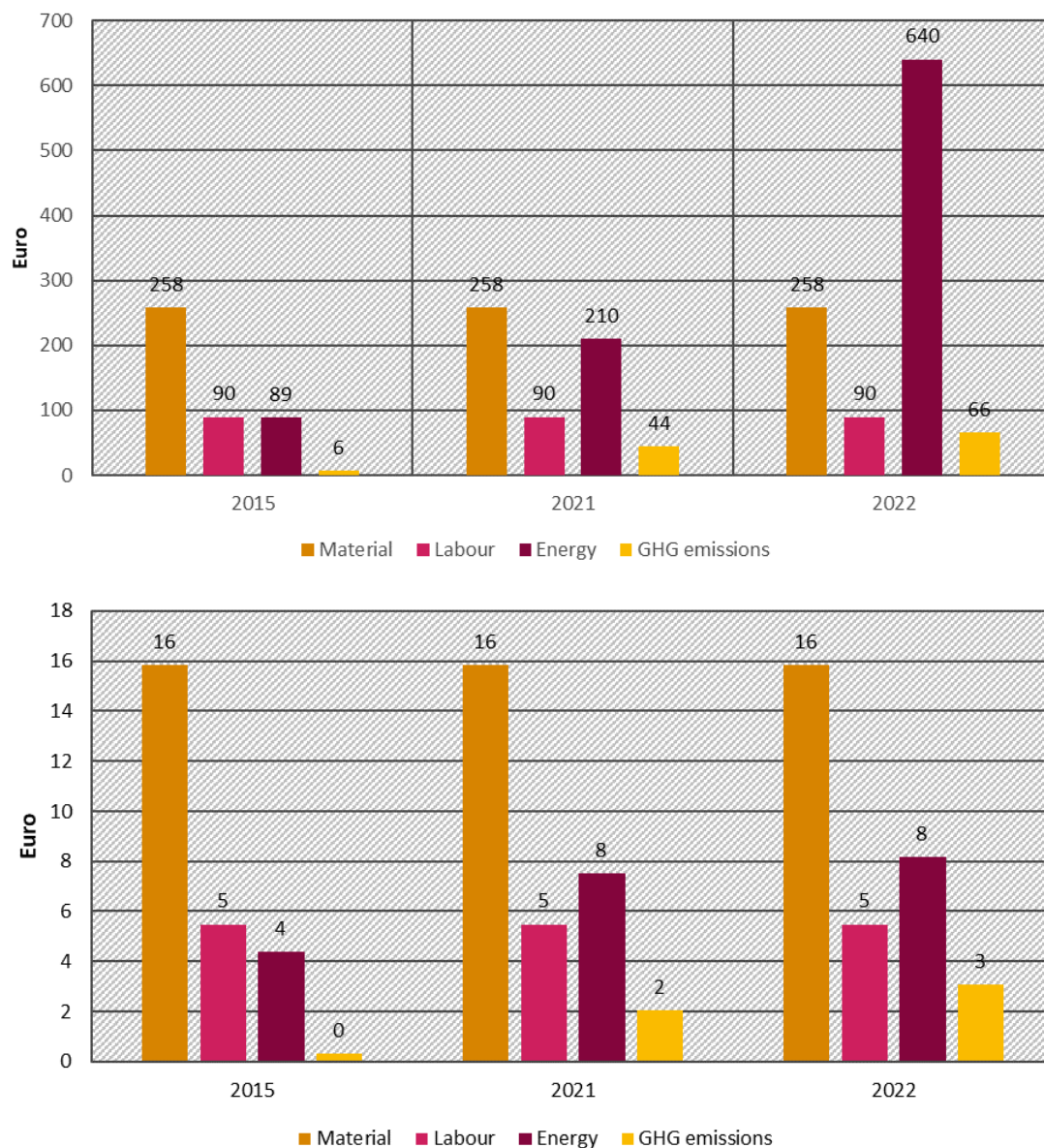
	Naphtha [MJ]		Strom [MJ]		Erdgas [MJ]	
	Plas-tiktüten	Plastikscha-len	Plas-tiktüten	Plastikscha-len	Plas-tiktüten	Plastikscha-len
Steamcracker	396	6.930				
Polymerisa-tion			64,8	840		504
Extruder			23,95	998	36,48	340
Spritzgießen				1.361		

Quelle: eigene Berechnung basierend auf den in Kapitel 3 genannten Datenquellen.

Bewertung der CO₂-Kostenanteile an den Gesamtproduktionskosten

Die folgende Figure 8 zeigt die Kostenzusammensetzung für beide untersuchten Produkte. Im Jahr 2015 belaufen sich die aggregierten Kosten für Energie, THG-Emissionen, Material und Arbeit für die Produktion von 1.000 Kunststoffschalen auf 444 €. Im Jahr 2021 steigen die Kosten auf 602 €, im Jahr 2022 auf 1.055 €. Im Jahr 2015 hat Material mit 58 % den höchsten Anteil an den betrachteten Kosten, gefolgt von den Kosten für Energie und Arbeit mit einem Anteil von jeweils 20 %. Die Kosten für THG-Emissionen machen nur 1 % aus. **Mit steigenden Kosten für Energie und Emissionszertifikate sinkt bei Kunststoffschalen der Anteil von Material und Arbeit, während der Anteil von Energie und THG-Emissionen steigt.** Im Jahr 2021 (EUA-Preis von 53,2 €) haben die Kosten für THG-Emissionen einen Anteil von 7 %. Im Jahr 2022 (EUA-Preis von 80 €) belaufen sich die Kosten für THG-Emissionen auf 6 % der Kosten für Energie, THG-Emissionen, Material und Arbeit. Die Kosten für Energie, THG-Emissionen, Material und Arbeit für die Produktion von 1.000 Kunststoffbeuteln belaufen sich im Jahr 2015 auf 26 €. Die relative Verteilung der Kosten ist ähnlich wie bei der Kunststoffschale. **Mit dem Anstieg der Energiepreise nimmt die Bedeutung der Materialkosten ab. Dennoch bleiben die Materialkosten der Hauptkostentreiber bei Plastiktüten.** Im Jahr 2015 (EUA-Preis von 7,7 €) belaufen sich die Kosten für THG auf 1 % des betrachteten Wertes. Im Jahr 2021 (EUA-Preis 53,2 €) haben die Kosten für Treibhausgasemissionen einen Anteil von 7 %. Im Jahr 2022 (EUA-Preis 80 €) belaufen sich die Kosten für THG-Emissionen auf 9 % der Kosten.

Figure 8 Kostenstruktur der Produktion von 1.000 Plastischalen aus Propylen (oben) und von 1.000 Plastiktüten aus Ethylen (unten) (siehe Figures 102 und 103 im vorliegenden Bericht)



Quelle: eigene Berechnung basierend auf den in Kapitel 3 genannten Datenquellen. "Material" umfasst die (Roh-)material-einsatzkosten der Produkte aus Kapitel 2.

Die entwickelte Datenbasis und Analysen ermöglichen die zukünftige Entwicklung von (dynamischen) Stoffstrommodellen für relevante industrielle Prozesse und Produkte, z.B. hinsichtlich der Exposition von Produzenten von Materialien, Teilen und Endprodukten gegenüber CO₂-Preisen und weiteren Dekarbonisierungsoptionen. Dies ist die Grundlage für ehrgeizige THG-Minderungspfade durch die Integration der Materialproduktion und deren Verbindung zum Energiesystem und den Emissionen. Diese Verknüpfung gewinnt in der europäischen politischen Debatte immer mehr an Bedeutung, die von Bedenken hinsichtlich Nachhaltigkeit und Versorgungsrisiken von Zukunftstechnologien bestimmt wird. Es wird deutlich, dass Synergien zwischen der Industriedekarbonisierung und der Kreislaufwirtschaft bestehen. Dar-

über hinaus können, wie bereits erwähnt, die in diesem Projekt erstellten Datensätze - möglicherweise zusammen mit Daten aus anderen Quellen - zur Abschätzung typischer Kostenauswirkungen im Zusammenhang mit der CBAM-Einführung verwendet werden, die sich auf die Kostenzusammensetzung und die Preise sowohl von Grundstoffen als auch von weiterverarbeiteten Produkten wie Fahrzeugen auswirken werden.

1 Introduction

Since the start of emissions trading in 2005, the EU ETS sector has reduced about 48% of Europe's CO₂ emissions by 2023. At the same time, the EEA report on "Trends and projections in Europe 2022", for example, shows that industrial emissions fell less by only 28% since 2005. Additionally, industrial emissions have been rather constant since the beginning of the 3rd trade period in 2013 (EEA 2022). In view of the necessary annual reduction requirements in the emissions trading sector by 2030, the question of the reduction potential of the industrial sectors is of growing importance. In addition to increasing energy efficiency, the use of renewable energy sources (RES), secondary energy sources based on renewable energies and new low CO₂ production processes, the question arises what the potential contribution of changes in product demand for CO₂-intensive goods could be.

In general, three types of greenhouse gas (GHG) emission sources can be distinguished:

- ▶ Direct energy-related emissions from on-site fossil fuel combustion.
- ▶ Direct process-related emissions from chemical reactions within the production process (process emissions).
- ▶ Indirect emissions from the consumption of electricity and district heating.

With 33%, the non-metallic minerals sector is the largest source of verified industrial CO₂ emissions in 2022 (European Commission 2023). It is dominated by the production of cement clinker having a high share of process emissions. Other CO₂-intensive products in the non-metallic minerals sector are lime, calcination of dolomite and magnesite, glass, bricks and ceramics. The production of pig iron and steel in the iron and steel industry was responsible for around 21% of industrial CO₂ emissions in 2022. The main share of emissions stems from the use of coal and coke in blast furnaces (technically required in this process). In addition, basic chemical processes such as ammonia, ethylene or methanol production contribute significantly to industrial emissions and make the chemical industry the fourth largest source of verified CO₂ emissions.

In terms of end-use, most industrial greenhouse gas emissions stem from process heat: either from steam or hot water generation, or from the direct firing of various furnace types for high temperature heat. These two end uses account for 26% and 41% respectively of total direct greenhouse gas emissions⁴. The high temperatures and specific technical requirements limit the use of renewable energy sources to biomass or RES secondary energy sources (e.g. RES-H₂, RES-electricity⁵).

As the concept of circular economy gains momentum in the European political debate, driven by concerns over sustainability and the reduction of supply risks for future-relevant technologies, synergies exist between the decarbonization, the circular economy and industrial agendas. Consequently, the production and use of materials as well as their connection to the energy system and emissions have to be taken into account when integrating this new perspective into policy-making, and the analysis of ambitious GHG mitigation pathways.

In order to be able to pursue possible analyses of demand-side options to reduce CO₂-emissions a comprehensive and consistent data basis must first be established. In order to be able to estimate the impact of such options on GHG emissions reliably, corresponding product-related emission balances are necessary, which are not yet available.

⁴ Own calculation Fraunhofer ISI/FORECAST

⁵ e.g. hydrogen-based steel and chemical feedstock production.

The aim of this study is to establish such a solid information and data basis on CO₂ emissions and the economic significance of various products that can be attributed to the industrial activities/sectors covered by the ETS. Concepts are developed that enable targeted analyses with the help of the available and determined data in order to answer the relevant questions on emissions.

Furthermore, analyses are carried out for selected ETS sectors and products, and corresponding key figures are developed and integrated in the study. The focus of the analysis is on the products and sectors of the industry that are most relevant to the ETS.

2 Key figures for selected industrial sectors and products covered by the EU ETS

Since the start of emissions trading in 2005, the EU ETS sector has reduced about 26% of Europe's CO₂ emissions by 2017. At the same time, the EEA report on "Trends and projections in the EU ETS 2017", for example, shows that industrial emissions have been rather constant since the beginning of the 3rd trade period. In view of the necessary annual reduction requirements in the emissions trading sector of at least 48 Mt CO₂eq by 2030, the question of the reduction potential of the industrial sectors is of growing importance. In addition to increasing energy efficiency, the use of renewable energy sources, secondary energy sources based on renewable energies and new low CO₂ production processes, the question arises what the potential contribution of changes in product demand for CO₂-intensive goods could be.

Turning the EU economy and in particular the production and consumption of CO₂-intensive materials into a material efficient circular economy could substantially contribute to the objective of a CO₂-neutral economy as set out in the long-term vision proposed by the European Commission. As the concept of circular economy gains momentum in the political debate across all stakeholders, synergies exist between the decarbonisation and the circular economy policy agendas. Currently the effects of circular economy as well as material efficiency and substitution are only roughly considered in these studies from a modelling point of view (European Commission 2018).

Knowledge of the material flows of products in the industrial sectors covered by the EU ETS and their economic importance and importance for CO₂ emissions is therefore an important building block for further research in this area.

This chapter provides a comprehensive overview of selected important products of the steel, cement, aluminium, chemical and refinery sectors covered by EU emissions trading with their (cumulative) CO₂ emissions and key figures on their economic importance. The importance of the products has been determined by their environmental (energy, CO₂-emissions) and economic relevance. Both direct and indirect emissions (from electricity consumption) are included in the calculation of specific and cumulated emissions by product.

2.1 Concept definition

In the following, six central concepts will be used to define the flow structure for the selected energy- and CO₂-intensive industrial sectors (Table 13). The overall system boundary of the analysis is the scope of application of the Emissions Trading Directive (European Parliament, 2003). However, if necessary the analysis is extended to products not directly related to the covered ETS-activities. Reasons for such an extension can be: high economic relevance of the products, high shares of emissions in production steps outside the ETS, the need for further product-differentiation to allocate products to their end use sectors, and significant differences in specific CO₂-emissions of different product types. The general concepts of this approach are described in Table 13 and will be translated to sectoral application in the section 2.3 to 2.5. Depending on the sector investigated, the use of these concepts can vary according to the characteristics of the sector.

Table 13: General concept definition

Concept	Description
Upstream material/product	Raw materials used for the production of energy intensive bulk products. E.g. mining and quarrying activities, scrap collection activities, raw material processing.
ETS-product	Industrial activities as defined in the EU ETS (Directive 2003/87/EC) and documented by the European Environment Agency (EEA) EU ETS data viewer. Relevant activity codes within this study: 21-44 ⁶⁷ .
ETS-intermediate	Intermediate products, which are produced within the framework of ETS-activities. These products are not traded at all or only to a very limited extent. In some sectors the boundaries between ETS-product, ETS-intermediate product and ETS-final analysed product are blurring, which leads to the need for sector-specific definitions. E.g. basic chemicals.
Final analysed product	(Tradeable) Products that can be assigned to the industrial activities covered by the EU ETS. The importance of the products is generally determined by their CO ₂ emission share and/or economic importance.
Further processing	Processing stage of ETS-products or final analysed products.
End product	Market-ready products manufactured from processed ETS-products and/or final analysed products and other inputs ⁸ .

2.2 Approach

To analyse the most important energy and emission-related, mass flow-related, and economic products in the industrial sectors covered by the EU ETS - which are expected to be associated mostly with additional costs of emission trading - a variety of different factors need to be considered including both - absolute/cumulated quantities and specific quantities per product:

- Mass balances of the material flows of the products and their interrelations along the value chain,
- Associated energy consumption and resulting emission shares (incl. process emissions as well as direct- and indirect energy related emissions),
- Economic shares of products in foreign trade and value added.

In accordance with these requirements and to calculate the effect of carbon pricing on energy intensive industry products, we developed a three-step approach. First, for the selected sectors/products the material flow along the value chain is generated, covering raw material preparation, intermediate products up to the final analysed products and their end-uses. Second, the individual emissions of each production step and its products are calculated based on the generated material flow and the associated energy consumptions. This includes process- and energy-related emissions. Process-related emissions stem from chemical reactions within the production process. Energy-related emissions include direct energy-related emissions from on-site fossil fuel combustion as well as indirect emissions from the consumption of electricity.

⁶ For a detailed description of the EU Emissions Trading System data viewer and a list of EUTL activities (Geres et al., 2019).

⁷ The study uses the EU ETS benchmarks of the 3rd trading period. Since then, there has been an update of the EU ETS benchmarks, which took place after the completion of the subsequent work and consequently could not be taken into account.

⁸ Detailed analyses for selected end products will take place in chapter 3.

Third, economic indicators of the selected products are assessed. Besides costs and prices of the production, foreign trade data are determined via desk research and the evaluation of trade statistics. For assessing the trade relevance, a comparison of relative export and import structures is calculated revealing the actual 'comparative advantages' of a good in foreign trade (Revealed Comparative Advantage: RCA). The RCA indicator⁹ considers the trade balance of a good in relation to the trade balance of total manufactured goods. Positive RCA values indicate specialization advantages, negative RCA values specialization disadvantages. The gathered information is then assessed and related to the added value of the final analysed products.

Due to the varying data availability and data quality a general (rough) own estimation of the level of confidence is given where possible. This takes into account the type of the data point (simple transparent value or complex compound data) and the source (transparency, coverage, range of values in the sources).

2.3 Iron and steel

2.3.1 Production overview

Steel production can be divided into four major steps along the value chain. Basis for the production of crude steel is iron ore or scrap depending on the production route used (BF/BOF or EAF). **Mining and raw material collection** (mainly iron ore and end-of-life scrap) is not included in the ETS ('A' in Figure 9) and is not considered further in this study.

The **iron and steel making** ('B' in Figure 9) involves three key process stages: raw material preparation, iron making, and steel making. Here it is important to distinguish between the two main production routes of the steel industry: **primary steel making** in blast furnaces (BF) producing iron and subsequently in basic oxygen furnaces (BOF) converting the iron to steel; and **secondary steel making** in electric arc furnaces (EAF). Primary steel making using direct reduction plants, is at present not largely used in the EU and is therefore not considered in detail in this study.

During **raw material preparation** in primary production, metallurgical coal is converted into coke through a pyrolysis process in a coke oven plant, producing coke (solids which are raw material fed into the iron making process), coke oven gas (used as fuel after cleaning) and liquids. To enable the iron ore reduction process in the next stage, the raw materials go through sintering or pelletisation. This is the first part of production step 'B' in Figure 9¹⁰. During **iron making** raw material (coke, sinter, / pellets, lump ore) is fed into the Blast Furnace (BF) that reduces the iron oxides to hot metal. In the last stage of the primary **steel making** process, impurities are regulated within the hot metal feedstock including the reduction of carbon content, regulation of desirable elements, and burning of impurities in the BOF. These process steps ('B' in Figure 9) are subsumed under activity codes 22, 23 and 24 in the EU ETS Directive.

The **secondary steel making** process involves direct smelting of materials containing steel typically from scrap and recycled iron feedstock from waste streams (summarised as an alternative step 'B' in Figure 9), essentially omitting the energy intensive processes of coal pyrolysis, sintering and iron ore reduction. In this process, the steel scrap is melted and refined in an EAF. To

⁹ $RCA = (\text{trade value of the export of the selected steel product} / \text{trade value of the import of the selected steel product}) / (\text{trade value of all industry exports} / \text{trade value of all industry imports})$; >1 comparative advantage, <1 comparative disadvantage (Gerspacher et al. 2011, p. 25)

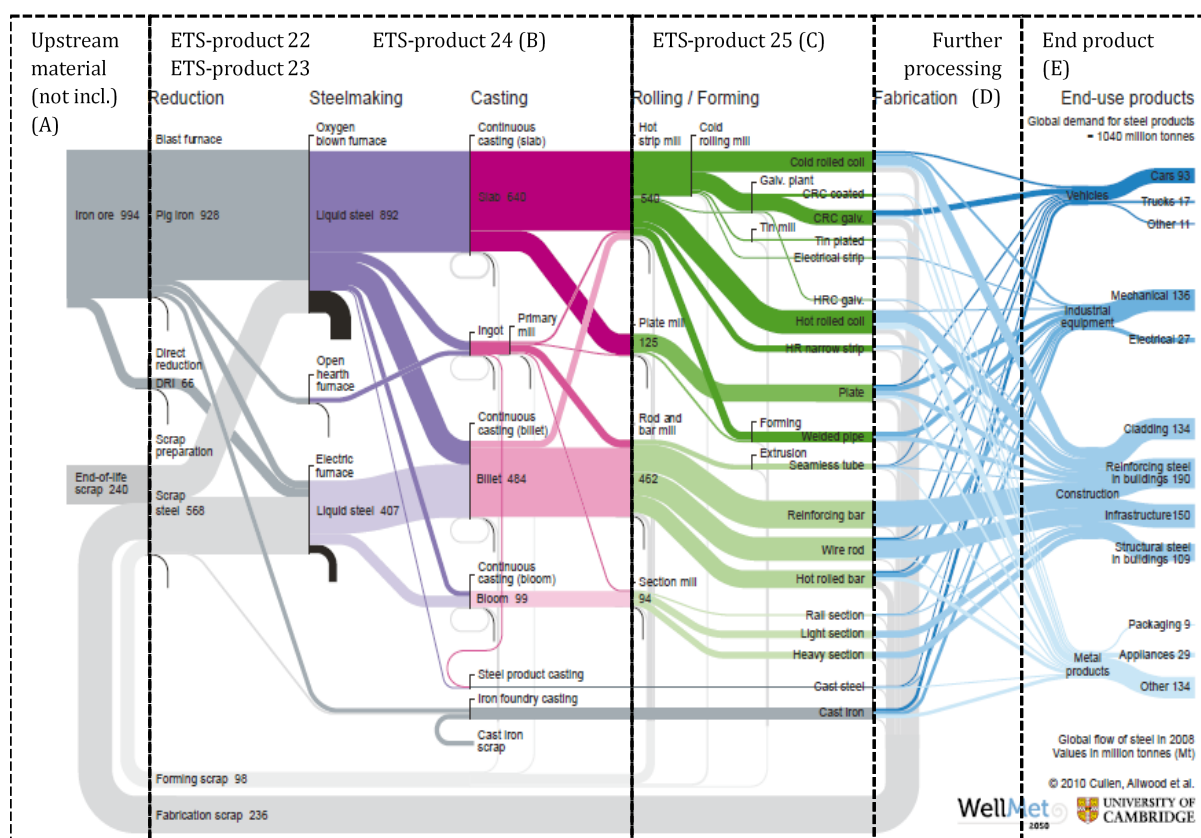
¹⁰ In Figure 9, the raw material preparation – coke production, sintering and palletisation (Activity codes no. 22 and 23 in the EU ETS Directive) – are not explicitly deployed, but we count them as part of the Step 'B' because they are an integral part of the (crude) steel making process in the BF/BOF route.

achieve higher steel purity, secondary metallurgical treatment in ladle furnaces and vacuum de-gassing plants may be applied.

In both the primary and secondary route the liquid molten steel is then cast into **crude steel forms** (slabs, blooms, billets) for further processing (also step 'B' in Figure 9) (Chan et al. 2019). These crude steel forms can be produced in continuous and ingot casters. Of this, the continuous casting has the significantly larger share.

Finished steel products are usually classified in two main categories: flat and long. Long products are mainly produced from blooms and billets and go through further finishing to form seamless pipes, bars, rolls or wires. In contrast, flat products are commonly produced from slabs. Flat products go through a finishing process to form cold rolled sheets, steel plates, welded pipes, coated sheets, etc. (section 'C' in Figure 9, ETS-activity 25¹¹) (Chan et al. 2019).

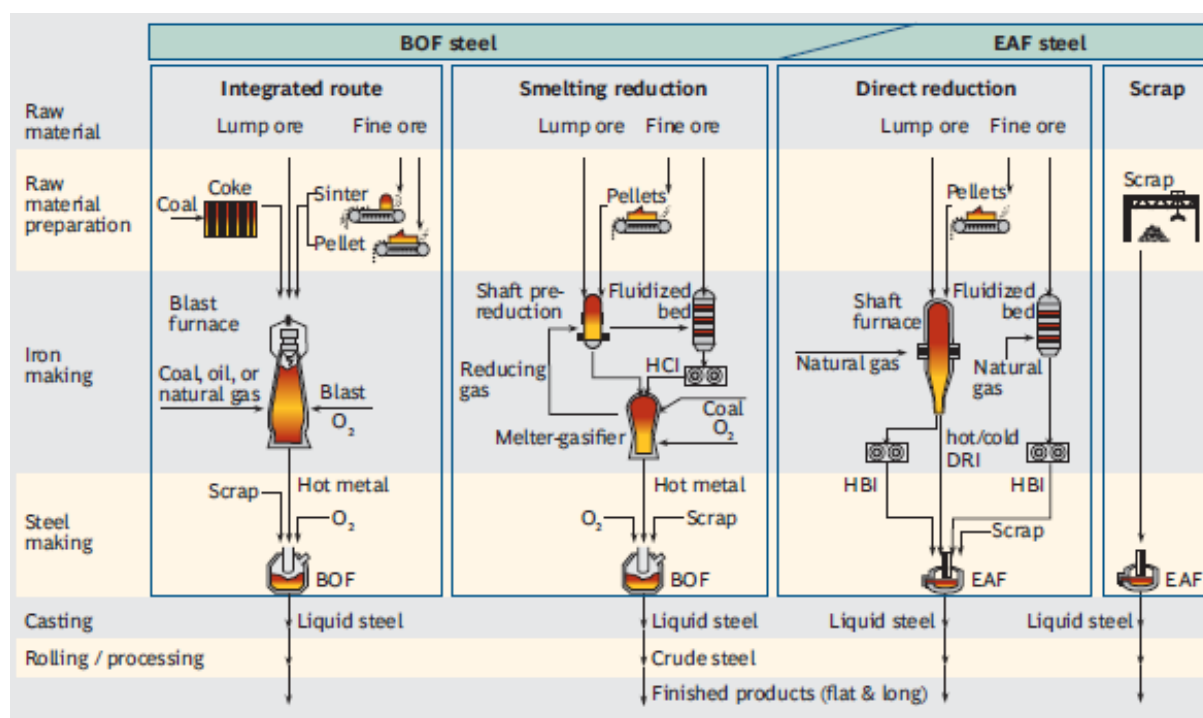
Figure 9: Exemplary material flow in steel production



Source: Allwood et al. (2011 (edited))

¹¹ Cumulated emissions for the production of the ETS-product 25 will be calculated including emissions from steps 'B' and 'C'. Additionally, the emissions from 'B' and 'C' will also be reported separately.

Figure 10: Process steps in steel production



Source: Wörtler et al. (2013)

2.3.2 Steel flow model: important concepts

Following this categorisation as shown in 2.3.1 it is suggested to further differentiate the **'long finished steel products'** and **'flat finished steel products'** of the ETS-activity 25 by **product type**.

An initial differentiation of the CO₂ content of these product groups has been made by **assigning common process steps**. In this context, the assumption had to be made, that long products can largely be assigned to the secondary (EAF) route and flat products to the primary (BF/BOF) route. Of course, this is a simplification, which is however necessary for the further analyses at system level. Similar assumptions have been made in other studies (Renda et al., 2013 and Eurofer, 2018). To validate this assumption, plant capacities listed in the VDEh Steel Plantfacts database were evaluated for the year 2015. The results show that 86% of the European continuous slab casters are supported by a BF/BOF steel plant, while 88% of the European continuous billet casters are supported by an EAF steel plant (VDEh 2015). For continuous bloom casters the picture is not quite so clear, however also 59% are supported by an EAF steel plant (VDEh 2015). This analysis supports the proposed simplification of assigning long products to the EAF route and flat products to the BF/BOF route for the purpose of this study.

For the **selection of the final analysed products** within this study, a further differentiation of these two ETS-product 25 categories by **product types** has been necessary. The products to be further analysed were selected according to their volume relevance based on data from the World Steel Association (2018). From the category of flat products, **'hot rolled coil, sheet and strip'** has been chosen, having a volume share of 54% (around 50 Mt). From the category of long products, **'wire rod'** (33%, around 20 Mt), **'hot rolled bars'** (19%, around 11 Mt), and **'concrete reinforcing bars'** (18%, around 11 Mt) have been chosen for further analysis.

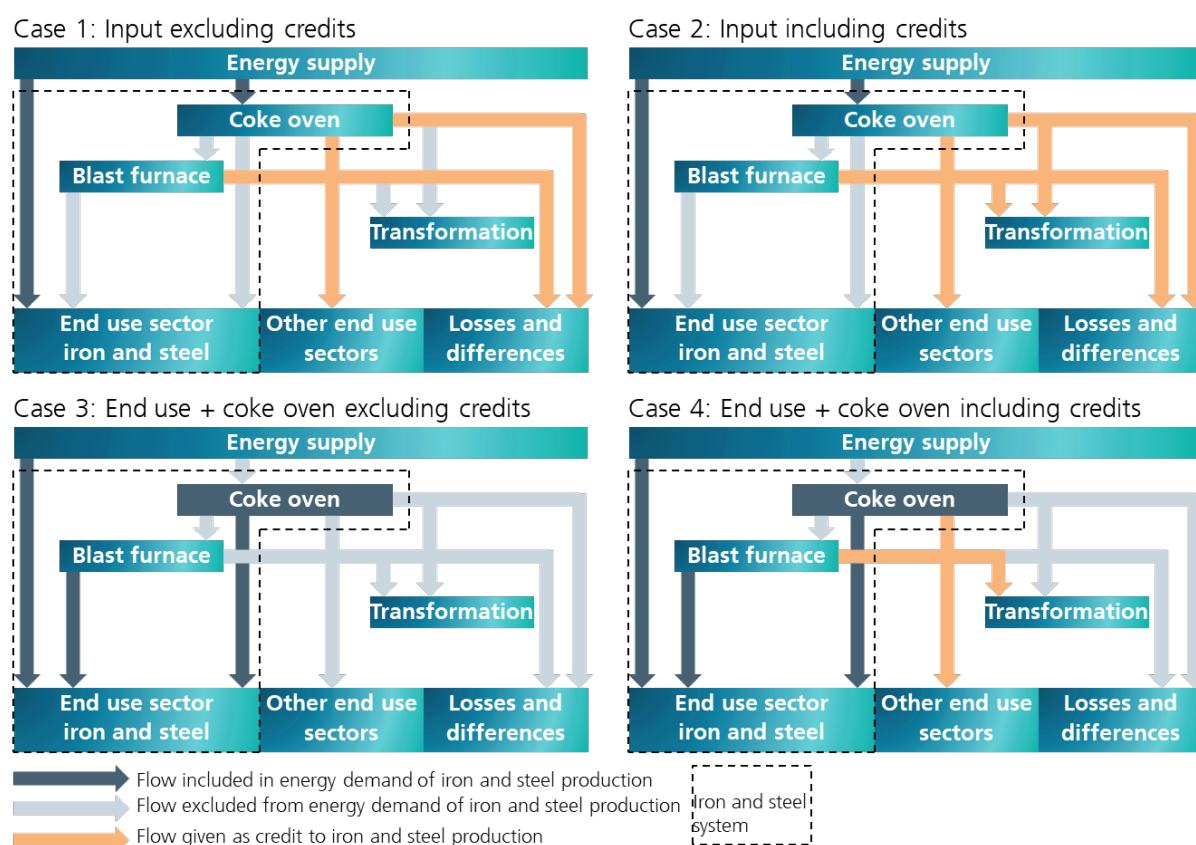
In iron and steel production, particularly in the **BF/BOF route**, **several types of gases** (coke oven gas, blast furnace gas, converter gas) are produced as **by-products**. In 2016, the by-product (also labelled 'waste') gases generated in coke ovens and blast furnaces were 230 TWh¹², 7% of the entire industry's energy demand (Eurostat 2020a). The majority of this energy demand is blast furnace gas (58%). A considerable share of these gases is used within the industry itself (2016: 117 TWh). About 92 TWh are used in thermal power plants and thus, according to the energy balance approach, outside the sector (18 TWh are lost or statistical differences). Some of these power plants are, however, 'autoproducers', generating electricity and heat for the steel industry itself. At least two theoretical cases can be distinguished: First, the power plant is located at the industrial site, receives fuel (e.g. blast furnace gas) mostly or exclusively from the industrial activity, and delivers electricity and heat mostly or exclusively back to the process. From an energy-flow point of view, these power plants are fully integrated in the industrial process and all emissions can reasonably be allocated to the products. Second case: the power plant is located near the industrial site and receives some blast furnace gas out of opportunity or convenience. It produces for the public grid. In these cases, it is plausible to allocate the emissions to the power plant. These cases are usually covered by allocating emission or energy 'credits' to the iron and steel industry to account for the delivered energy (Arens et al., 2017, Fruehan et al., 2000). There is uncertainty about how high these credits should be – given the energy flows to and from power plants.

For this study, four approaches for the allocation of 'credits' have been compared based on an analysis of the energy flows in the Eurostat energy balance (Eurostat 2020a), considering the entire system of blast furnace, coke oven, the sectoral allocation ('Iron and steel') and the flows to power plants. These options create a solution space in which the reality is included – where exactly can only be approximated in this study. The four approaches respectively describe a different system boundary and definition of allocable derived gases:

1. Input energy (to entire system) without credits for external use of derived gases,
2. Input energy (to entire system) including credits for external use of derived gases,
3. End use energy in 'Iron and steel' plus coke oven energy use without credits for external use of derived gases,
4. End-use energy in 'Iron and steel' plus coke oven energy use including credits for external use of derived gases.

¹² The types of gas are not differentiated in this approach – all by-product gases are taken as aggregate.

Figure 11: Approaches for derived gases allocation



Source: own depiction

The first option considers the energy entering the blast furnaces (incl. converter), coke ovens and end-use sector of the energy balance 'Iron and steel' (incl. all further process) and. From this, statistical differences and losses are deducted. The result includes the derived gases used in power plants and allocates them entirely to the steel production (thus the approach is 'without credits'). It thus assumes that power plants and the steel system have a net-zero exchange. This fits with a statement by Arens et al. (2017), in which a similar assumption was made with regard to the flow of coke oven gas and other by-product gases. The specific energy consumption of the iron and steel system – the indicator is calculated as energy use per tonne of crude steel (166 Mt) – in this case is 14.98 GJ/t_{Steel}, the emission intensity is 1.16 tCO_{2-eq}/t_{Steel}¹³.

The second option, additionally, reduces this energy amount by the derived gases delivered to power plants ('autoproducers' and main activity), refineries and heating plants (Germany 2015: ~26 TWh). It thus gives credits, assuming that no energy from power plants is returned to the steel sector. The resulting energy demand (and greenhouse gas emissions) is lower than in approach 1. The specific energy consumption of the iron and steel system – the indicator is calculated as energy use per tonne of crude steel – in this case is 12.81 GJ/t_{Steel}, the emission intensity is 0.84 tCO_{2-eq}/t_{Steel}.

The third option only considers energy flows directly going to the end use sector ('Iron and steel') and the consumption of coke ovens, cutting out the balance of blast furnaces (and their external flows). In terms of energy use, case 2 and 3 yield the same results. The specific energy

¹³ Note that this value is a virtual one and should not be confused with the emission intensity of primary steel. This indicator merely distributes the total emissions to a selected activity value (here: crude steel production) and serves as means to compare the approaches among themselves.

consumption of the iron and steel system – the indicator is calculated as energy use per tonne of crude steel – in this case is 12.81 GJ/t_{Steel}, the emission intensity is 1.12 tCO_{2-eq.}/t_{Steel}. In terms of emission intensity, case 2 and 3 differ. This is caused by different energy carrier shares: In case 2, the energy considered for the calculation mainly consists of coal and other solid fuels (emission factor 0.094 tCO_{2-eq.}/GJ) and natural gas (emission factor 0.056 tCO_{2-eq.}/GJ). In addition, credits are given for delivered derived gases (mainly blast furnace gas with a high emission factor of 0.26 tCO_{2-eq.}/GJ). In case 3, the energy use considered for calculation consists mainly of coke and other solid fuels (emission factor 0.108 tCO_{2-eq.}/GJ for coke) and blast furnace gas. In addition, no credits are given for the export of blast furnace gas. Due to the aggregated nature of the available data, no further insights regarding which approach is more "correct" could be gained. While the closer representation of the actual end-use in case 3 seems appealing, the detailed representation of derived gas flow in case 2 has its merits as well. Further research, e.g. on site-level might be needed to improve the understanding in this area.

The fourth option considers, in addition to the third option, credits for export of derived gases from the blast furnace to external uses (similar to option two in this regard). This, however, has to assume that the energy consumption in the blast furnace (which is a net-zero balance in the used version of the Eurostat energy balance¹⁴) is included in the sector ('Iron and steel'). Given the results of this approach with very low specific energy demand and emissions, this assumption seems to be wrong. The specific energy consumption of the iron and steel system – the indicator is calculated as energy use per tonne of crude steel – in this case is 10.86 GJ/t_{Steel}, the emission intensity is 0.65 tCO_{2-eq.}/t_{Steel}.

Comparing this to our approach described in section 2.3.3.2, no variant of consideration can be clearly determined based on the available data, as the Eurostat energy balance and production statistics report differently. However, the preceding analysis can determine the extent to which the chosen approach is appropriate in context of the present report. Our approach takes into account credits for by-product gas exports to other end users, line losses and statistical differences. Consequently, the values can be prescribed in the range of the options listed above close to case three but not conclusively assigned. This implies that this approach is not sufficient to describe any given individual steel plant and its interaction with power plants. In contrast, a system perspective is implemented to identify significant emission flows within this sector. In-depth analyses would require a more detailed data basis and investigations on plant level.

2.3.3 Key figures steel industry

2.3.3.1 Material flow

Figure 12 and Figure 13 present a simplified material flow for the EU27+UK and German steel industry, respectively. The illustration starts at the raw material preparation (coke and sinter) linked to ETS-activities 22 and 23 and follows the steelmaking/casting process via the BF/BOF and the EAF route (linked to the ETS-activity 24) to the delivery of rolled and formed steel in different products (linked to ETS activity 25). These are then distributed to four main end-uses: vehicle construction, industrial equipment, construction and tubes, and metal products.

The assessment of material flows has been carried out for the year 2015 for the EU27+UK and Germany. For the EU27+UK, a comprehensive data set from the World Steel Association (2018) has been used, which provides both the quantities of crude steel produced (by process) and the production in further processing by product type for the year 2015. For the case of Germany,

¹⁴ Please note that the methodology regarding blast furnaces has changed in the meantime in Eurostat.

statistical data provided by the WV Stahl (2016) has been used to supplement the country specific information of the World Steel Association (2018) for raw material and rolling/forming. EU level information has been adjusted accordingly (see Figure 13). For the calculation of the material input in the 'raw material preparation' phase, a publication of the World Steel Association (2019) has been used. The source provides the raw material input per process route. For the BF/BOF route these can be used for the EU (see Table 14). However, the material input for the EAF route differs compared to the world average: The utilization of scrap is higher in the EU than the global average (World Steel Association, 2018). Therefore, the iron and iron ore utilization in the EU has to be lower than the global average. However, the use of iron ore is not recorded separately for the BF/BOF and the EAF route in the available statistics. Consequently, a literature-based approach for closing the data gap has been taken. Thus, a literature value for the iron ore utilization for direct reduction was used¹⁵, as direct reduced iron is mostly used in the EAF. From this, the iron ore demand can be determined for the EAF route. The quantities of EAF-utilized direct reduced iron can be derived from the respective production and trade statistics (3.595 Mt; World Steel Association 2018). For closing the mass balance, the production losses of the EAF route are needed. These are derived from the statistically recorded data for Germany (13.5%; WV Stahl et al., 2016).

For Germany, the same approach is used (direct reduced iron utilization 1.191 Mt; WV Stahl et al. 2016). Additionally, the iron ore utilization for the BF/BOF route can be adjusted as the total iron ore utilization of the German steel industry is reported (41.4 Mt; WV Stahl, 2016). The iron ore demand for the BF/BOF route is consequently 40.2 Mt. In addition, the statistical data for Germany were adjusted to close data gaps for the rolling/forming. For this a comparison of the data provided by the WSA (2018) and by WV Stahl (2016) for individual years has been carried out, based on an assignment of equivalent products groups. Consequently, the following was identified: the sum of hot rolled products provided by the WV Stahl (2016) includes the two product groups 'hot rolled plate' and 'hot rolled coil, sheet and strip'. Processed products from these products are not included. This leads to the conclusion that the sum of hot rolled products by the WV Stahl (2016) is depicting the situation before further processing steps as e.g. cold rolling. Consequently, in this report the quantities of further processed are withdrawn from the sum of hot rolled products to prevent double counting.

From 338 Mt of raw material (79 Mt metallurgical coal, 142 Mt iron ore, 84 Mt scrap and 33 Mt limestone) for the EU27+UK around 166 Mt crude steel are produced (61% via BOF, 39% via EAF) of which ~161 Mt are continuously cast steel - only a negligible proportion are ingots (~5 Mt) and liquid steel for casting (~0.3 Mt). For primary production, a sinter and coke volume of ~93 Mt and ~39 Mt was calculated using an EU sinter factor of 0.92 t sinter/t steel and a coke factor of 0.39 t coke/t steel (see Table 14) which is in the same order of magnitude as the values provided by WV Stahl (2016) for Germany. In further processing, long (~60 Mt) or flat (~93 Mt) products are then produced, which can be further differentiated in different product types depending on their further treatment/finishing (Figure 12 and Figure 13). As described in section 2.3.1 it is assumed that long products can largely be assigned to the electric arc furnace route and flat products to the blast furnace route; this is of major relevance for the calculation of energy demand and CO₂-emissions in the following sections. Statistical data on EU 'hot rolled long' and 'hot rolled flat' production as well as on the production of the further different production types stems from the World Steel Association (WSA, 2018).

It is notable that for crude steel, the share of primary steelmaking (~70%) is higher in Germany compared to the EU27+UK (~60%). Following the material flow downstream, the share of flat

¹⁵ Cullen et al. (2011) calculate an iron ore utilization of 1.00 t per tonne direct reduced iron.

products in Germany is slightly higher than on the EU level (+3%). In the case of finished long and flat products the European and German production focus is similar (flat: hot rolled coil, sheet and strip; long: concrete reinforcing bars, wire rod, hot rolled bars, and heavy sections) as shown in Figure 12 and Figure 13.

Table 14: Data used in model to calculate material flows

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence EU27+UK/ Germany
Production data	see Figure 12	see Figure 13	Mt	Statistics	WSA (2018)	WSA (2018); WV Stahl et al. (2016)	High/ high
Iron ore usage BF/BOF	1.37	1.34	kt iron ore/kt steel	Literature	WSA (2019)	WV Stahl et al. (2016); Cullen et al. (2011)	Medium/ medium
Iron ore usage EAF	0.055	0.094	kt iron ore/kt steel	Literature	WSA (2019); WV Stahl et al. (2016); Cullen et al. (2011)	WV Stahl et al. (2016); Cullen et al. (2011)	Medium/ medium
Scrap usage BF/BOF	0.125	0.170	kt scrap/kt steel	Literature	WSA (2019)	WV Stahl et al. (2016)	Medium/ high
Scrap usage EAF	1.101	1.062	kt scrap/kt steel	Literature	WSA (2019); WV Stahl et al. (2016); Cullen et al. (2011)	WV Stahl et al. (2016); Cullen et al. (2011)	Medium/ medium
Limestone usage BF/BOF	0.27	0.27	kt lime-stone/kt steel	Literature	WSA (2019)	WSA (2019)	Medium/ medium
Limestone usage EAF	0.088	0.088	kt lime-stone/kt steel	Literature	WSA (2019)	WSA (2019)	Medium/ medium
Metallurgical coal BF/BOF	0.78	0.78	kt metallurgical coal/kt steel	Literature	WSA (2023)	WSA (2023)	Medium/ medium

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence EU27+UK/ Germany
Sinter usage BF/BOF	0.92	0.88	kt sinter/kt steel	Calculated	WSA (2018), Herbst (2017) based on UNFCCC	WV Stahl et al. (2016)	Medium/high
Coke usage BF/BOF	0.39	0.38	kt coke/kt steel	Calculated	WSA (2018), UN Data	WV Stahl et al. (2016)	High/high

Due to the lack of comprehensive statistical data at the detailed product level, the bottom-up allocation of final products to end-use sectors has been based on the publications by Cullen et al. (2011)¹⁶ and Flint et al. (2020). Cullen et al. (2011) developed inter alia a global steel use matrix, which allocates intermediate steel products to end-use goods using European and international sources. Flint et al. 2020 estimated the shipments of flat steel products to different industry sectors in Europe based on data from a European steelmaking company which has been upscaled on EU level. The estimates of these two sources have been combined in this study to provide a steel use matrix for the EU27+UK and Germany (see Table 15).

The results of our calculations show that in both the EU27+UK and Germany, the sector 'construction and tubes' has the highest share of steel demand (48%/44%) followed by vehicle construction (26%/27%), metal products (16%/18%) and industrial equipment (10%/11%).

Table 15: Steel use matrix [rounded]

	Construction and tubes	Vehicles	Industrial equipment	Metal products	Source	Confidence
Light sections	100%	0%	0%	0%	Cullen et al. (2011)	Medium
Heavy sections	100%	0%	0%	0%	Cullen et al. (2011)	Medium
Railway track material	90%	0%	10%	0%	Cullen et al. (2011)	Medium
Concrete reinforcing bars	100%	0%	0%	0%	Cullen et al. (2011)	Medium
Wire rod	54%	7%	6%	32%	Cullen et al. (2011)	Medium
Hot rolled bars	4%	17%	41%	38%	Cullen et al. (2011)	Medium
Hot rolled plate	46%	13%	29%	12%	Flint et al. (2020)	Medium

¹⁶ Cullen et al. (2011) mapped the global flow of steel from steelmaking to end-use goods. This study identified the WSA as the most comprehensive production statistic, which is why this source was also used as the basis for the present report.

	Construction and tubes	Vehicles	Industrial equipment	Metal products	Source	Confidence
Hot rolled coil, sheet, strip	43%	44%	5%	9%	Flint et al. (2020)	Medium
Other metal coated sheet, strip	29%	50%	9%	12%	Flint et al. (2020)	Medium
Non-metallic coated sheet, strip	72%	6%	13%	9%	Flint et al. (2020)	Medium
Tinmill products	0%	0.6%	0.6%	98.8%	Flint et al. (2020)	Medium
Electrical sheet, strip	20%	26%	27%	27%	Flint et al. (2020)	Medium
Welded tubes	20%	26%	27%	27%	Flint et al. (2020)	Medium
Seamless tubes	61%	21%	18%	0%	Cullen et al. (2011)	Medium
Cast steel	0.0%	0.0%	50%	50%	Cullen et al. (2011)	Medium

Source: own elaboration based on Cullen et al. (2011); Flint et al. (2020)

Table 16: Steel use sector-share comparison

	Construction and tubes	Vehicles	Industrial equipment	Metal products
Eurofer (2016)	44%	22%	15%	19%
EU bottom-up calculation	48%	26%	10%	16%
WV Stahl (2016)	41%	26%	12%	21%
DE bottom-up calculation	44%	27%	11%	18%

Source: own elaboration based on Cullen et al. (2011); Flint et al. (2020); Eurofer (2016); WV Stahl (2016)

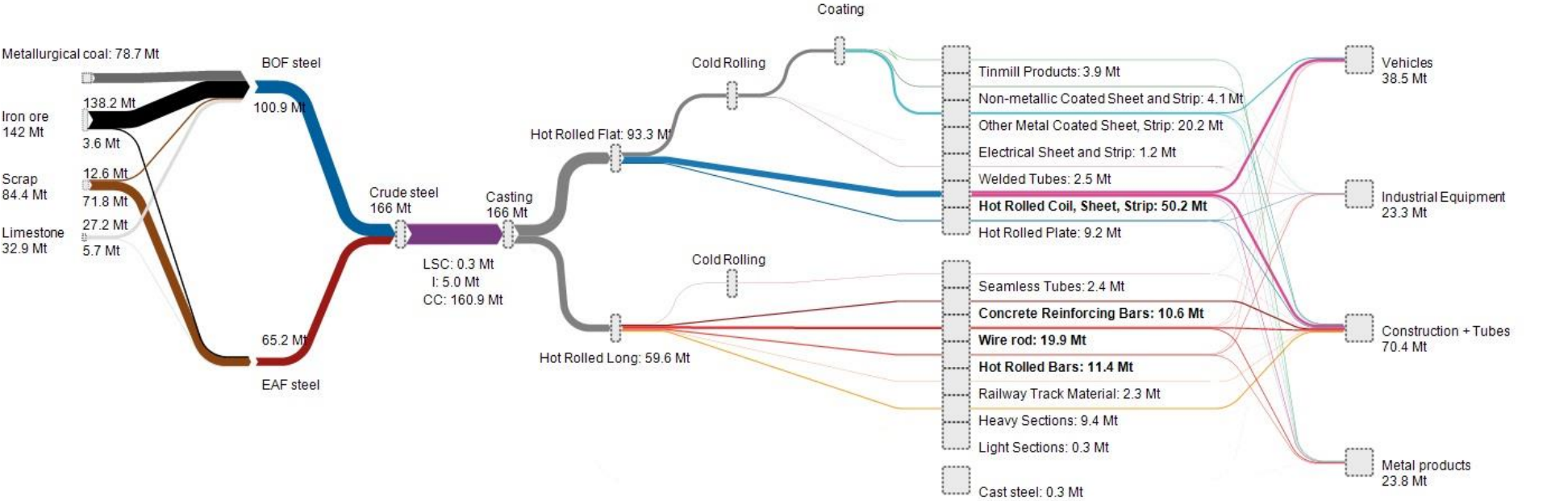
However, these results are subject to the highest uncertainties within this modelling approach due to limited data availability. To address these uncertainties, the bottom-up calculated steel use sector-shares have been compared with data provided by European and national associations (see Table 16). In the case of Germany, the bottom-up calculated values already show a very high accuracy compared to the aggregated data of WV Stahl (2016). The strongest deviation (-3%) can be observed in the demand sector 'metal products'. In the European case, uncertainties are higher as are the deviations from the aggregated statistical data of Eurofer (2016). The deviations range between 3 and 5 percentage points and are strongest for the sector 'industrial equipment'. Reasons for these deviations can be:

- Uncertainty in data basis due to foreign trade affecting the allocation of products to use sectors from the production or demand perspective,

- ▶ Uncertainty in data basis due to downstream processing, e.g. as stated by Eurofer (2018)¹⁷, as steel products partly are consumed in their semi-finished form,
- ▶ Lack of consideration of scrap volumes in the production process,
- ▶ National and regional differences compared to global trends,
- ▶ Lack of detailed statistical data, e.g. concerning production losses in the manufacturing of steel containing products: Cullen et al. (2011) and Flint et al. (2020) also had to make assumptions or use data from individual sources.

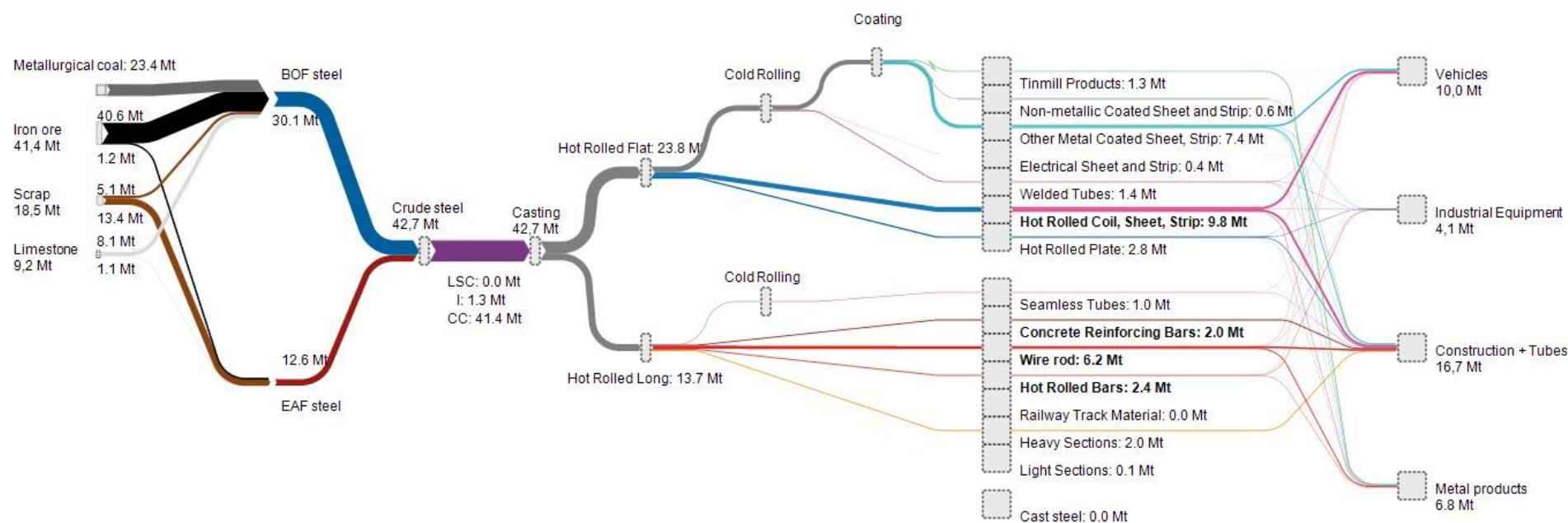
¹⁷ "Downstream processing converts some HRWS into CRF, and some CRF into Hot Dipped and some Hot Dipped into Organic Coated. Downstream processing uses both domestic and imported steel. Production totals may thus not add up precisely." (Eurofer, 2018); HRWS: Hot rolled wide strip, CRF: Cold rolled flat

Figure 12: Modelled material flow steel industry (LSC: liquid steel casting, I: ingot casting, CC: continuous steel casting), EU27+UK 2015



Source: own calculation based on WSA (2018); Cullen et al. (2011); Flint et al. (2020)

Figure 13: Modelled material flow steel (LSC: liquid steel casting, I: ingot casting, CC: continuous steel casting), Germany 2015



Source: own calculation based on WSA (2018); WV Stahl (2016); WV Stahl et al. (2016); Cullen et al. (2011); Flint et al. (2020)

2.3.3.2 Final energy demand

Final energy demand is concentrated in the first two production steps: raw material preparation¹⁸ and steelmaking/casting (see Table 17). With an energy consumption¹⁹ of 12.06 GJ/t (EU27+UK) and 12.62 GJ/t (Germany) primary steel production (BF/BOF steel; for process description see section 2.3.1) is much more energy-intensive than secondary steel production (3.26 GJ/t, EU27+UK; 2.51 GJ/t, Germany). Including the raw material preparation phase (sinter + coke) cumulative final energy demand for primary steel production adds up to 15.53 GJ/t of steel in the EU27+UK and 15.81 GJ/t in Germany (see Table 17). Fuel mix may depend on national influences (fuel prices, etc.), it is, however, dominated by the use of coke for reduction in the primary route.

Table 17: Specific energy consumption (SEC) data used in model to calculate final energy demand (FED)

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
SEC fuels coke	3.2	3.2	GJ/t coke	Literature	Rehfeldt et al. (2017)	Rehfeldt et al. (2017)	Medium
SEC fuels sinter	2.24	2.09	GJ/t sinter	Literature/statistic	Rehfeldt et al. (2017)	WV Stahl et al. (2016)	Medium/high
SEC electricity coke	0.12	0.12	GJ/t coke	Literature	Rehfeldt et al. (2017)	Rehfeldt et al. (2017)	Medium
SEC electricity sinter	0.13	0.13	GJ/t sinter	Literature/statistic	Rehfeldt et al. (2017)	WV Stahl et al. (2016)	Medium/high
SEC fuels BF/BOF	11.46	12.14	GJ/t steel	Literature/statistic	Rehfeldt et al. (2017)	WV Stahl et al. (2016)	Medium/high
SEC fuels EAF	0.98	0.65	GJ/t steel	Literature/statistic	Rehfeldt et al. (2017)	WV Stahl et al. (2016)	Medium/high
SEC electricity BF/BOF	0.60	0.48	GJ/t steel	Literature/statistic	Rehfeldt et al. (2017)	WV Stahl et al. (2016)	Medium/high
SEC electricity EAF	2.28	1.86	GJ/t steel	Literature/statistic	Rehfeldt et al. (2017)	WV Stahl et al. (2016)	Medium/high
SEC fuels rolled steel	2.39	2.39	GJ/t steel	Literature	Rehfeldt et al. (2017)	Rehfeldt et al. (2017)	Medium
SEC electricity rolled steel	0.6	0.6	GJ/t steel	Literature	Rehfeldt et al. (2017)	Rehfeldt et al. (2017)	Medium
SEC bar mill	0.5	0.5	GJ/t steel	Report	Arcelor Mittal (2019)	Arcelor Mittal (2019)	Medium
SEC wire mill	0.7	0.7	GJ/t steel	Report	Arcelor Mittal (2016)	Arcelor Mittal (2016)	Medium

¹⁸ The analysis of the final energy demand during the raw material preparation phase includes the production of sinter and coke.

¹⁹ Comparison with other sources show that these are established orders of magnitude, e.g. Pardo and Moya (2013): Prospective scenarios on energy efficiency and CO₂ emissions in the European Iron & Steel Industry. [Blast furnace - BOF plant + Bloom, slab and billet mill] = [12.309 - 0.853 + 1.783] = 13.239 GJ/t

A detailed data set for was used as the basis for the SEC data (Rehfeldt et al. 2017). For selected processes it was necessary to supplement this with Arcelor Mittal (2019), as these were not covered in the original source. In addition, the aim was to use national values for Germany as the original data set covers the EU. Thus, in some cases, the process-specific values for energy consumption in Germany are derived from the industry association for steel, Wirtschaftsvereinigung Stahl (WV Stahl). Analog to the material flow indicators, WV Stahl provides specific information for Germany about energy consumption for the relevant process steps excluding the coke production (not statistically recorded). No distinction is made for the steel rolling processes (hot and cold). Accordingly, the energy consumption of sinter production, BF/BOF and EAF for Germany can be derived from this data set. In the German statistics, the specific energy consumption for the BF/BOF is with 17.36 GJ/t steel significantly higher than the value reported by Rehfeldt et al. (2017) for the EU (11.46 GJ/t). It is expected that the German value does not correspond to the same accounting logic as in Rehfeldt et al. (2017) (see section 2.3.2 for further information on different accounting options). The value is adapted according to case 3 in section 2.3.2 assuming that the difference between blast furnace/ converter gas production and blast furnace/ converter gas consumption in the steel industry is provided to other end users for electricity generation (credits: 2.92 GJ/t steel). In addition, the internal use of these gases in the blast furnace as well as the energy supply to further process steps (e.g. rolling) is deducted to avoid double counting (1.51 GJ/t) and the energy demand for oxygen supply²⁰ is subtracted (0.79 GJ/t steel) (see Table 17). Even after deducting the above-mentioned variables, the value is higher than at the EU level. Thus, it is not possible to determine whether there is an actual difference in energy demand or differences regarding the consideration of by-product gases. However, compared to the range presented in section 2.3.2, both values are plausible in relation to each other. Additionally, the specific energy consumption of the EAF route varies. The value is lower for Germany compared to the EU (2.51 GJ/t steel compared to 3.26 GJ/t steel). It must be taken into account that there are differences between the input to the EAF route at the EU level and in Germany (see section 2.3.3.1). These differences, as well as the different data sources, justify this discrepancy

The final analysed products listed in Table 18 and Table 19 include different energy uses, each up to the final production step of the product. Data availability on the further processing of steel into final analysed products is very heterogeneous. This is due to the fact that individual plants often form the basis for studies/analyses. However, the constellations can be very different depending on the site under the consideration (European Commission et al., 2022). In following it is assumed for EU27+UK and Germany that the further processing of steel takes place on-site so that no re-heating of the feedstock is necessary (see Table 17). For the calculation of the cumulative energy demand of the final analysed products an input factor of 1.06t/t EAF steel for 'concrete reinforcing bars', 'hot rolled bars' and 'wire rod' has been assumed based on Cullen et al. (2011). For 'hot rolled coil, sheet and strip' a BOF steel input factor of 1.05t/t has been assumed (Cullen et al., 2011). According to the assumption on the allocation of the BF/BOF route to flat and the EAF route to long products, the FED of the respective processes are considered for cumulating the energy demand²¹.

²⁰ It is assumed that the energy demand for the oxygen supply is considered by the other energy carriers.

²¹ Long products: EAF and hot rolling, flat products: sinter, coke, BF/BOF and hot rolling

Table 18: Calculated final energy demand, EU27+UK 2015

Product	ETS-activity	Production [t]	Fuels [GJ]	Electricity [GJ]	Total [GJ]	Total cum. [GJ]	Specific [GJ/t]	Specific cum. [GJ/t]
Sinter	22	92,794,880	207,860,531	12,063,334	219,882,293	n/a	2.37	n/a
Coke	23	39,336,960	125,878,272	4,720,435	130,598,707	n/a	3.32	n/a
BF/BOF steel	24	100,864,000	1,155,901,440	60,518,400	1,216,419,840	1,566,900,941	12.06	15.53
EAF steel	24	65,247,000	63,942,060	148,763,160	212,705,220	212,705,220	3.26	3.26
Concrete reinforcing bars	25	10,608,000	1,856,400	3,182,400	5,038,800	41,829,999	0.48	3.94
Hot rolled bars	25	11,404,000	1,995,700	3,421,200	5,416,900	44,968,827	0.48	3.94
Wire rod	25	19,920,000	2,394,384	11,553,600	13,947,984	83,035,530	0.70	4.17
Hot rolled coil, sheet and strip	25	50,208,000	119,997,120	30,124,800	150,121,920	965,335,665	2.99	19.23

Table 19: Calculated final energy demand, Germany 2015

Product	ETS-activity	Production [t]	Fuels [GJ]	Electricity [GJ]	Total [GJ]	Total cum. [GJ]	Specific [GJ/t]	Specific cum. [GJ/t]
Sinter	22	26,405,000	55,056,891	3,477,600	58,534,491	n/a	2.22	n/a
Coke	23	11,276,000	36,083,200	1,353,120	37,436,320	n/a	3.32	n/a
BF/BOF steel	24	30,054,000	364,855,560	14,436,000	379,291,560	475,262,371	12.62	15.81
EAF steel	24	12,622,000	8,263,931	23,432,400	31,696,331	31,696,331	2.51	2.51
Concrete reinforcing bars	25	1,996,000	349,300	598,800	948,100	6,280,641	0.48	3.15
Hot rolled bars	25	2,368,000	414,400	710,400	1,124,800	7,451,181	0.48	3.15
Wire rod	25	6,222,000	747,884	3,608,760	4,356,644	20,979,425	0.70	3.37
Hot rolled coil, sheet and strip	25	9,838,418	23,513,819	5,903,051	29,416,870	207,671,931	2.99	19.52

2.3.3.3 Emissions

The emissions associated with material processing are calculated building upon the material and energy flow. The model includes indirect emissions generated by electricity use in the production process, direct process related emissions and direct energy related emissions caused by fuel consumption. The energy carrier distribution based on the German data from the WV Stahl et al. (2016) and the use of natural gas for steam generation are assumed. In accordance with the observations made for final energy demand primary production has the highest specific and cumulative emission levels (see Table 21 and Table 22). These emission levels are passed on to the final analysed product 'hot rolled coil, sheet, strip' leading to cumulative emissions of 2.23 t CO₂/t (EU27+UK) considering the required BOF steel input for the production (~1.05 t BOF steel/t 'hot rolled coil, sheet, strip')²². Direct emissions from the production process of 'hot rolled coil, sheet, and strip' are comparatively low 0.30 t CO₂/t (EU27+UK). The remaining final analysed products have lower emission cumulative levels (0.38-0.42 t CO₂/t, EU27+UK) due to their relation to secondary steelmaking and the required EAF steel input of roughly 1.06 t EAF steel/t product (see Table 21 and Table 22)²³.

Table 20 Data used in model to calculate emissions

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Emission factor Fuel Oil	0.074	0.078	t CO ₂ /GJ	Literature	UBA 2016	UBA 2016	High
Emission factor Coal	0.094	0.094	t CO ₂ /GJ	Literature	UBA 2016	UBA 2016	High
Emission factor Coke	0.108	0.108	t CO ₂ /GJ	Literature	UBA 2016	UBA 2016	High
Emission factor Natural Gas	0.056	0.056	t CO ₂ /GJ	Literature	UBA 2016	UBA 2016	High
Emission factor Blast Furnace Gas	0.260	0.260	t CO ₂ /GJ	Literature	UBA 2016	UBA 2016	High
Emission factor Derived Gas*	0.060	0.060	t CO ₂ /GJ	Literature	UBA 2016	UBA 2016	High
Emission factor Electricity	0.109	0.163	t CO ₂ /GJ	Literature	Koffi et al. 2017	Koffi et al. 2017	Medium
*including, but not limited to coke oven and converter gas							

²² Calculation example for cumulated emissions of 'hot rolled coil, sheet, strip' (EU27+UK): 1.05 t BOF steel/t 'hot rolled coil, sheet, strip'*1.85 t cumulated CO₂eq/t BOF steel+0.30 t direct CO₂eq/t 'hot rolled coil, sheet, strip'=2.23 t cumulated CO₂eq/t 'hot rolled coil, sheet, strip' (inaccuracy due to rounding)

²³ Calculation example for cumulated emissions of 'concrete reinforcing bars' (EU27+UK): 1.06 t EAF steel/t 'concrete reinforcing bars'*0.30 t cumulated CO₂eq/t EAF steel+0.06 t direct CO₂eq/t 'concrete reinforcing bars'=0.38 t cumulated CO₂eq/t 'concrete reinforcing bars' (inaccuracy due to rounding)

Table 21: Calculated emissions, EU27+UK 2015

Product	ETS-activity	Production [t]	Process related [t CO ₂ eq]	Direct energy related [t CO ₂ eq]	Indirect energy related [t CO ₂ eq]	Total (incl. indirect) [t CO ₂ eq]	Total Cumulated (incl. indirect) [t CO ₂ eq]	Specific (incl. indirect) [t CO ₂ eq/t]	Specific cumulated (incl. indirect) [t CO ₂ eq/t]
Sinter	22	92,794,880	6,217,257	21,849,675	1,310,213	29,377,146	n/a	0.32	n/a
Coke	23	39,336,960	n/a	32,728,351	512,692	33,241,043	n/a	0.85	n/a
BOF steel	24	100,864,000	1,512,960	116,215,802	6,572,976	124,301,738	186,919,926	1.23	1.85
EHF steel	24	65,247,000	482,828	3,037,094	16,157,345	19,677,267	19,677,267	0.30	0.30
Concrete reinforcing bars	25	10,608,000	n/a	249,076	345,644	594,720	3,998,258	0.06	0.38
Hot rolled bars	25	11,404,000	n/a	267,766	371,581	639,347	4,298,278	0.06	0.38
Wire rod	25	19,920,000	n/a	621,616	1,254,850	1,876,466	8,267,724	0.09	0.42
Hot rolled coil, sheet and strip	25	50,208,000	n/a	11,615,721	3,271,891	14,887,612	130,318,827	0.30	2.23

Table 22: Calculated emissions, Germany 2015

Product	ETS-activity	Production [t]	Process related [t CO ₂ eq]	Direct energy related [t CO ₂ eq]	Indirect energy related [t CO ₂ eq]	Total (incl. indirect) [t CO ₂ eq]	Total Cumulated (incl. indirect) [t CO ₂ eq]	Specific (incl. indirect) [t CO ₂ eq/t]	Specific cumulated (incl. indirect) [t CO ₂ eq/t]
Sinter	22	26,405,000	1,769,135	5,788,573	567,496	8,125,204	n/a	0.31	n/a
Coke	23	11,276,000	n/a	9,381,632	220,810	9,602,442	n/a	0.85	n/a
BOF steel	24	30,054,000	450,810	36,683,042	2,355,753	39,489,605	57,217,251	1.31	1.90
EAF steel	24	12,622,000	93,403	392,517	3,823,840	4,309,759	4,309,759	0.34	0.34
Concrete reinforcing bars	25	1,996,000	n/a	46,866	97,716	144,582	869,648	0.07	0.44
Hot rolled bars	25	2,368,000	n/a	55,601	115,927	171,528	1,031,728	0.07	0.44
Wire rod	25	6,222,000	n/a	194,161	588,899	783,060	3,043,265	0.13	0.49
Hot rolled coil, sheet and strip	25	9,838,418	n/a	2,276,138	963,295	3,239,433	26,360,065	0.33	2.32

2.3.3.4 Uncertainties and limitations of approach

The applied methodology and data inherently show a number of uncertainties that are briefly noted in this section. Firstly, the data used to set up the quantitative model include assumptions and extrapolations from limited data sets.

For example, the data availability concerning the end-use distribution of final analysed products is very limited and statistics like e.g. Eurofer only provide aggregated information on steel use in different sectors which is not further differentiated into detailed product level as needed in this study. To address these uncertainties the bottom-up calculated steel use sector-shares have been compared with data provided by European and national associations showing minor deviations. This is caused by uncertainty, e.g. in the data basis due to foreign trade and downstream processing, e.g. as stated by Eurofer (2018)²⁴ (see section 2.3.3.1 for further information). In addition, due to limited data availability within this study the detailed modelling of scrap and recycling was not taken into account.

Concerning the specific energy consumption, a generic approach based on previous studies, literature and available statistics and company data has been used. It follows that these data do not correspond to individual companies and cannot take into account national differences in fuel composition for all EU countries. However, they provide a European and German average, which is sufficient for the purpose of this study.

Generalised, it has to be stated that this contribution only provides a simplified illustration of material, energy and CO₂ flows for the EU and Germany due to limited resources and time within this study. Especially in the area of end-uses and scrap volumes, there is still a great need for future research in other studies, as there currently exist neither comprehensive nor reliable statistics.

2.3.4 Key economic indicators and cost structure

In the following sections, the key economic indicators, the cost structure and the market prices of the analysed products (Hot Rolled Bars, Concrete Reinforcing Bars, Wire Rod, Hot Rolled Coil, Sheet and Strip) are summarised. The key economic indicators or more precisely the trade relevance is determined from current and historical trade data provided by the European Steel Association Eurofer and the EU commodity statistics Prodcom²⁵ (Eurofer, 2020a; Eurofer, 2020b; Eurostat, 2020b). The consideration of these databases is discussed further in Appendix A. The sources for the cost structure and the market prices are discussed in section 2.3.4.2 and 2.3.4.3.

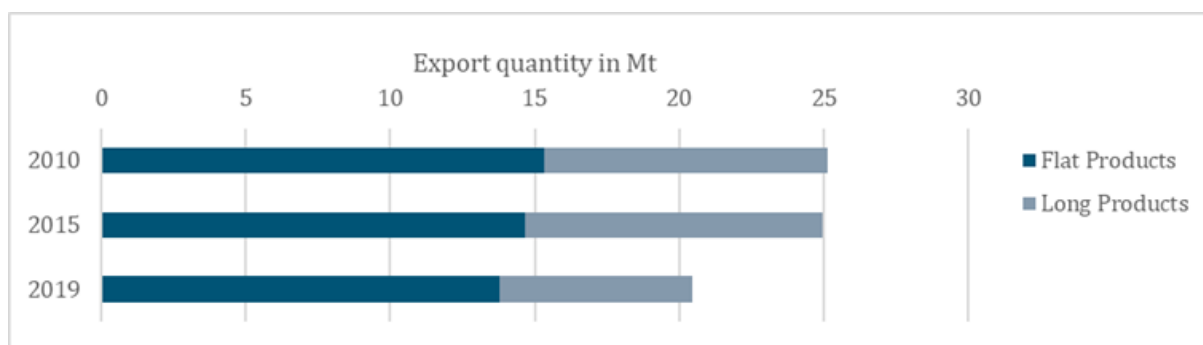
2.3.4.1 Trade relevance

In 2019, 20.5 Mt of finished steel products were exported from the EU. Flat products had with 13.8 Mt the larger share compared to the long products with 6.7 Mt (Eurofer, 2020a). As shown in Figure 14, the exports decreased in 2019 compared to 2010 and 2015.

²⁴ "Downstream processing converts some HRWS into CRF, and some CRF into Hot Dipped and some Hot Dipped into Organic Coated. Downstream processing uses both domestic and imported steel. Production totals may thus not add up precisely." (Eurofer, 2018) ; HRWS: Hot rolled wide strip, CRF: Cold rolled flat

²⁵ Eurofer and Prodcom do not use the same product categories. Assumptions regarding product allocation are indicated in the respective sections.

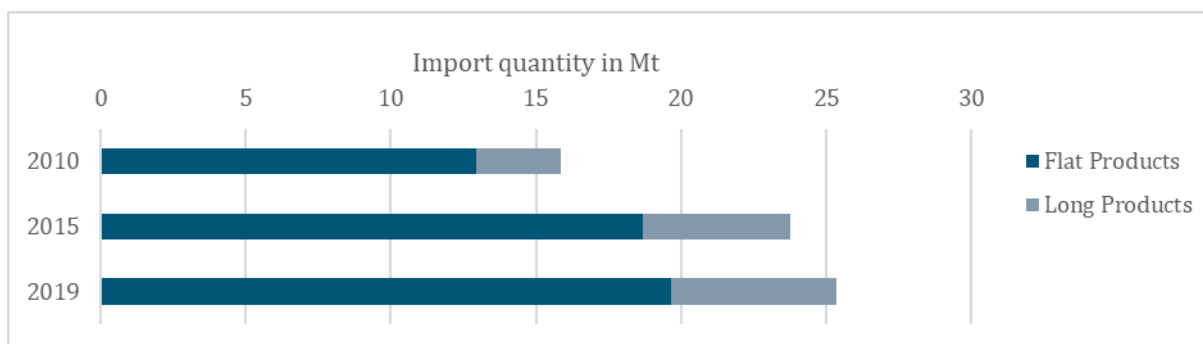
Figure 14: Export of finished steel products, EU27+UK 2010, 2015 and 2019



Source: Eurofer 2020b

Compared to the total imports of 25.3 Mt in 2019 it is apparent that the EU currently is a net importer of finished steel products. Hereby, the flat products account for 19.7 Mt and the long products for 5.7 Mt of the imports. In contrast to the preceding consideration of the exports, the imports in Figure 15 are increasing in the years 2015 and 2019 compared to 2010 (Eurofer, 2020b).

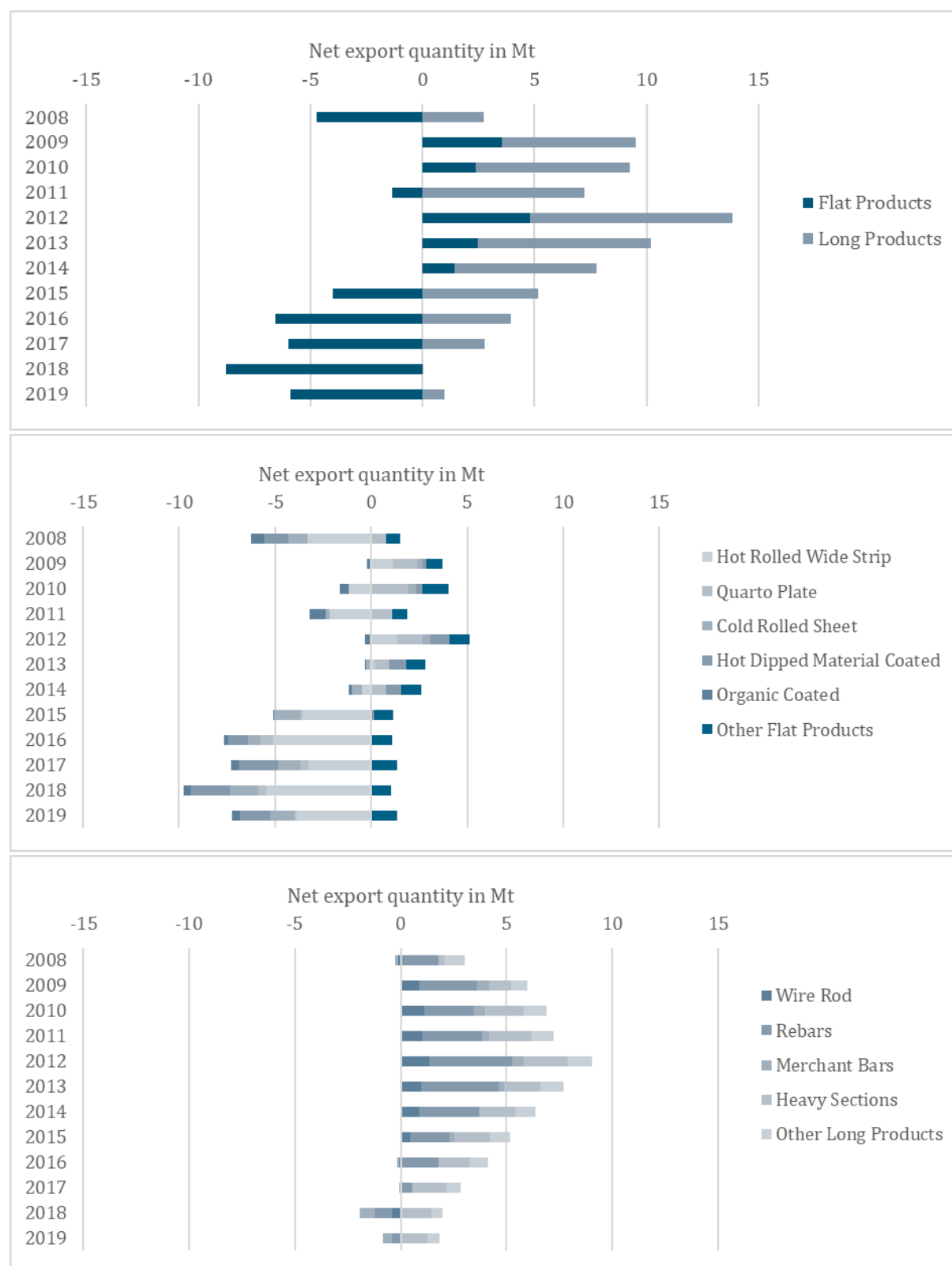
Figure 15: Import of finished steel products, EU27+UK 2010, 2015 and 2019



Source: Eurofer 2020b

For the further assessment of the product-specific trade relevance the net exports of EU are shown in Figure 16. Even though the overall net exports are decreasing since 2014, some product groups are exceptions. Generally, there is a large export surplus for long products, while there is an import surplus for flat products since 2015. Consequently, the EU is a net exporter of long products and a net importer of flat products. Especially, the product Hot Rolled Wide Strip accounts for a large share of the net imports since 2015 (Eurofer, 2020b).

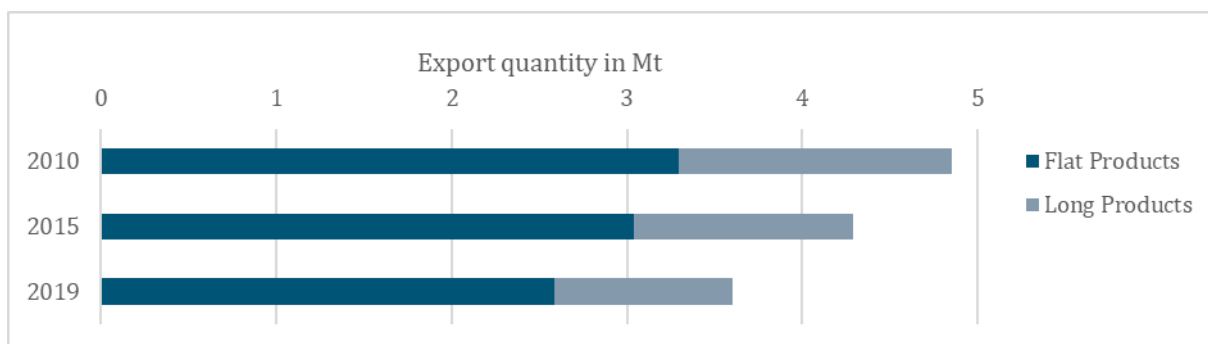
Figure 16: Aggregated and specific net export of flat and long finished steel products, EU27+UK 2008 to 2019



Source: Eurofer (2020b)

In Figure 17, the German finished steel exports are shown. In 2019, 2.6 Mt of flat products and 1.0 Mt of long products were exported from Germany to non-EU countries. The export quantity decreased compared to 2010 and 2015 (Eurofer, 2020b).

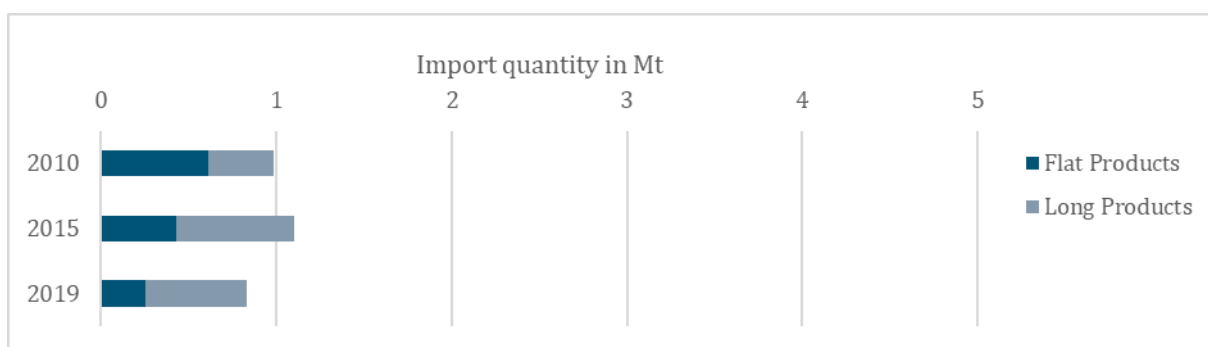
Figure 17: Export of finished steel products, Germany 2010, 2015 and 2019



Source: Eurofer 2020b

In contrast to the export import ratio on the EU level, the imports of finished steel products to Germany are significantly lower (see Figure 18). Consequently, Germany is currently a net exporter of finished steel products. Furthermore, the import quantity decreased compared to 2010 and 2015. In total 2.8 Mt of finished steel products were imported to Germany in 2019 excluding extra-EU-imports (Eurofer, 2020b).

Figure 18: Import of finished steel products, Germany 2010, 2015 and 2019



Source: Eurofer 2020b

Germany's role as net exporter is also displayed in Figure 19 excluding the intra-EU-trade. Despite a decrease since 2017, the net exports remain strongly positive. Especially the high share of flat products is significant in comparison to the EU. Only minor net imports of the product Merchant bar can be repeatedly determined (Eurofer, 2020b).

Figure 19: Aggregated and specific net export of flat and long finished steel products, Germany 2008 to 2019



Source: Eurofer (2020b)

Since the trade data provided by Eurofer is not including the associated monetary values, the EU statistic Prodcum is used to assess the economic trade relevance. Additionally, Prodcum enables the targeted survey of the final analysed products initially mentioned (Hot Rolled Bars, Concrete Reinforcing Bars, Wire Rod, Hot Rolled Coil, Sheet and Strip) and includes the intra-EU-trade on the national level assessment. Hence, the economic indicators for the products are summarised for the year 2015 on the next pages and compared to the values provided by Eurofer (excl. intra-EU-trade on national level). Particular attention should be paid to the average export and import prices in comparison to the market prices 2015 for rebars (443 \$/t, Steelonthenet, 2020c) and hot rolled coil (398 \$/t, Steelonthenet, 2020c)²⁶ and to the RCA which is used to assess the trade importance as described in section 2.3.1.

²⁶ For further information see also section 2.3.4.3

Table 23: Overview of trade indicators, EU27+UK 2015

	Export in Mt	Import in Mt	Net export in Mt	Export in €	Import in €	Net export in €	Average export price in €/t	Average import price in €/t	RCA
Hot rolled bars*	0.93	1.0	-0.26	1,204,760,700	915,081,060	289,679,640	1,288.95	764.36	1.27
Concrete reinforcing bars**	3.51	1.64	1.87	1,423,427,530	637,567,960	785,859,570	405.53	387.61	2.15
Wire rod***	2.37	1.90	0.47	1,408,301,310	940,833,590	467,467,720	595.40	495.65	1.44
Hot rolled coil, sheet and strip****	4.77	9.01	-4.24	2,320,161,820	3,675,764,080	-1,355,602,260	486.42	407.97	0.61

* considered Prodcom codes: 24106230, 24106250, 24106410, 24106430, 24106610, 24106620, 24106630, 24106640, 24106650

** considered Prodcom code: 24106210

*** considered Prodcom codes: 24106110, 24106120, 24106130, 24106140, 24106190, 24106300, 24106510, 24106530, 24106550, 24106570

**** considered Prodcom codes: 24103110, 24103130, 24103150

Source: Eurostat (2020b)

Table 24: Overview of the trade indicators, EU27+UK 2015

	Export quantity in Mt	Import quantity in Mt	Net export quantity in Mt
Hot rolled bars*	1.45	1.25	0.19
Concrete reinforcing bars**	3.51	1.64	1.87
Wire rod	2.37	1.90	0.47
Hot rolled coil, sheet and strip***			

* considered product group: Merchant Bars

** considered product groups: Rebars

*** no equivalent product group available

Source: Eurofer (2020b)

Table 25: Overview of trade indicators, Germany 2015

	Export in Mt	Import in Mt	Net export in Mt	Export in €	Import in €	Net export in €	Average export price in €/t	Average import price in €/t	RCA
Hot rolled bars*	0.95	1.70	-0.75	1,135,108,540	1,326,972,210	-191,863,670	1,190.00	778.43	0.68
Concrete reinforcing bars**	0.75	0.64	0.10	343,510,740	270,483,480	73,027,260	458.99	419.90	1.01
Wire rod***	2.66	1.62	1.04	1,353,060,760	1,036,276,540	316,784,220	509.37	640.11	1.03
Hot rolled coil, sheet and strip****	3.88	4.18	-0.30	1,981,059,280	2,095,590,670	-114,531,390	511.12	501.37	0.75

* considered Prodcom codes: 24106230, 24106250, 24106410, 24106430, 24106610, 24106620, 24106630, 24106640, 24106650

** considered Prodcom code: 24106210

*** considered Prodcom codes: 24106110, 24106120, 24106130, 24106140, 24106190, 24106300, 24106510, 24106530, 24106550, 24106570

**** considered Prodcom codes: 24103110, 24103130, 24103150

Source: Eurostat (2020b)

Table 26: Overview of trade indicators, Germany 2015

	Export quantity* in Mt	Import quantity* in Mt	Net export quantity* in Mt
Hot rolled bars**	0.21	0.27	-0.05
Concrete reinforcing bars***	0.17	0.12	0.05
Wire rod	0.57	0.27	0.30
Hot rolled coil, sheet and strip****			

* intra-EU-trade excluded

** considered products group: Merchant Bars

*** considered product groups: Rebars

**** no equivalent product group available

Source: Eurofer (2020b)

2.3.4.2 Cost structure

For the assessment of the cost structure of the selected final analysed products the costs of primary steelmaking (BF/BOF) and secondary steelmaking (EAF) as well as product specific costs are summarised based on literature research. Due to the complexity of the production processes, proxy products for flat and long products are used in relevant literature and will consequently be used for the assessment in the following paragraphs (Moya et al., 2016; Medarac et al., 2020). Hence, wire rod is used as proxy for long products and hot rolled coil as proxy for flat products. The relative and absolute results are summarised in Table 27. Costs for CO₂, e.g. EU emission allowances (EUA), for the year 2019 are subsummarised under “Other”²⁷ (see Medarac et al. 2020, p. 9). For example, for hot rolled coil (BOF) they amount to only 2% of total production costs (see Medarac et al. 2020, p. 10). In the row 'Confidence', we specify a general (rough) own estimation on the level of confidence.

Table 27: Cost structure by product/process: % of total costs [value]

Product	BF/BOF steelmaking 2020	EAF steelmaking 2020	Wire rod (BOF) 2019	Wire rod (EAF) 2019	Hot rolled coil (BOF) 2019	Hot rolled coil (EAF) 2019
Labour in % of total cost	6 [25 \$]	3 [12 \$]	9 [44 €]	6 [31 €]	9 [36 €]	4 [19 €]
Raw materi- als in % of total cost	88 [363 \$]	78 [300 \$]	68 [352 €]	58 [279 €]	65 [300 €]	65 [316 €]
Energy in % of total cost	12 [50]	12 [45 \$]	11 [56 €]	20 [95 €]	17 [77 €]	15 [71 €]
Credit* in % of total cost	-1 [-5 \$]	n/a	-11 [-55 €]	-1 [-6 €]	-18 [-83 €]	-1 [-7 €]
Other in % of total cost	13 [53 \$]	7 [28 \$]	23 [119 €]	17 [81€]	28 [126 €]	18 [88 €]
Total currency per tonne	413 \$	385 \$	516 €	480 €	458 €	486 €
Source	Steelonthenet 2020a	Steelon- thenet 2020b	Medarac et al. 2020	Medarac et al. 2020	Medarac et al. 2020	Medarac et al. 2020
Confidence	Low/ medium	Low/medium	Medium	Medium	Medium	Medium

* Credit: savings from recycled scrap and self-power generation (Medarac et al. 2020)

²⁷ Considering that the EUA price throughout the year 2019 has been at an average of about 25 €/EUA (see DEHSt 2023), it can be assumed that in the sources used by Medarac et al. only costs on top of (average) free allowance allocations given to firms have been taken into account – i.e., only “monetary costs”, and no opportunity costs, have been accounted for. This would be a plausible assumption for the situation in 2019.

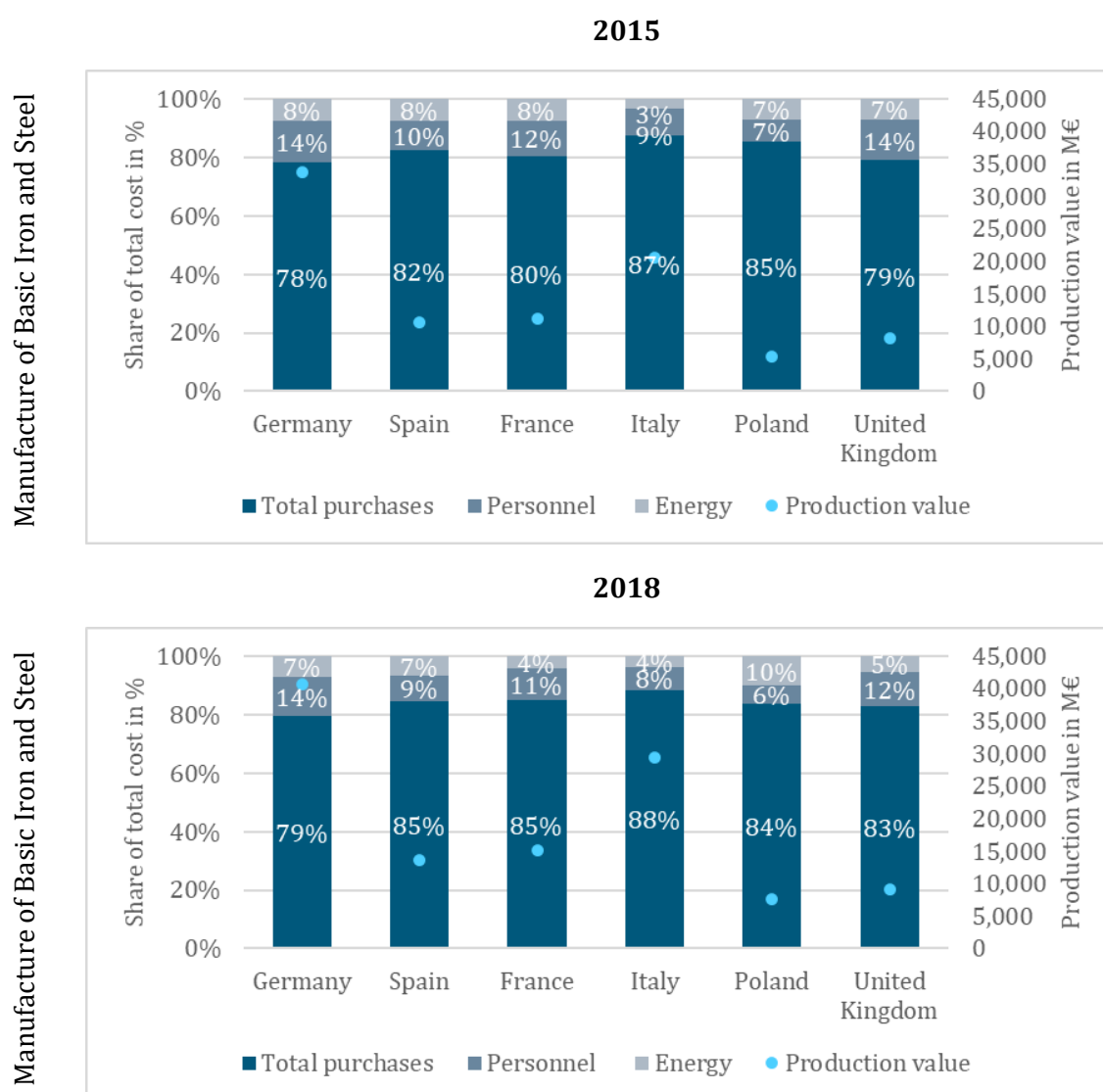
The costs given for the primary crude steelmaking processes (BF/BOF) are representatives for a BF/BOF plant with a yearly capacity of 3 Mt of liquid steel located on the Japanese coast using own coke and sinter plants and importing the required raw materials (Steelonthenet, 2020a). The representative values for the EAF plant consider an annual capacity of 1 Mt production and is located in Japan (Steelonthenet 2020b). As the shown data represents only one specific plant outside the European Union, careful reflection of the values applicability for the assessed region is necessary, as is also stated by Steelonthenet (2020a, 2020b).

The cost structure of Wire Rod and Hot Rolled Coil is based on plant specific data for 31 plants in the EU provided by a cost model run by CRU for the year 2019 (Medarac et al., 2020). Thus, the information is specific for the EU level but does not consider cost differences in the EU individually. The location of the plants is not clearly presented. Medarac et al. (2020) assess the data representativeness by comparing the share of the production route covered by the model and a plant database for the EU provided by World Steel Dynamics. About 80% of the BF/BOF plants in the EU and nearly 30% of the EAF plants are covered by the CRU model (Medarac et al., 2020).

In an earlier version of the Medarac et al. (2020) report, including the cost structures published in 2016, a similar approach had been used but additionally, the product specific representativeness had been determined. Thus, the coverage of the model was relatively high (92-100%) for the products produced from BF/BOF steel, but significantly lower for the production of Wire Rod from EAF steel (70%) and lowest for Hot Rolled Coil produced from EAF steel (34%) (Moya et al., 2016). Both reports conclude that the data representativeness is appropriate for the purpose.

For the further assessment of the data quality regarding the selected products, they are compared with the cost structure provided by the Structural Business Statistics from Eurostat. For the comparison, the major cost components (total purchases of goods and services, personnel costs, purchases of energy products) as well as the total production value of six countries are summarised. The six countries (Germany, Spain, France, Italy, Poland, and United Kingdom) have been selected based on the data availability and to obtain a regional heterogeneity. The illustration differentiates between the base year 2015 and the most current covered year, 2018. The subsector 'Manufacture of Basic Iron and Steel' (including all of the four selected products). The data are summarised in Figure 20.

Figure 20: Cost structure of the iron and steel industry, selected EU countries 2015 and 2018



Source: Eurostat (2021)

2.3.4.3 Market prices

The availability of market price information for the final analysed products in the iron and steel industry is limited. However, the following sections summarize and compare the available information for available proxy products. A comparison of the sources, the covered products, regions, periods and available and generally estimated confidence is given in Table 28.

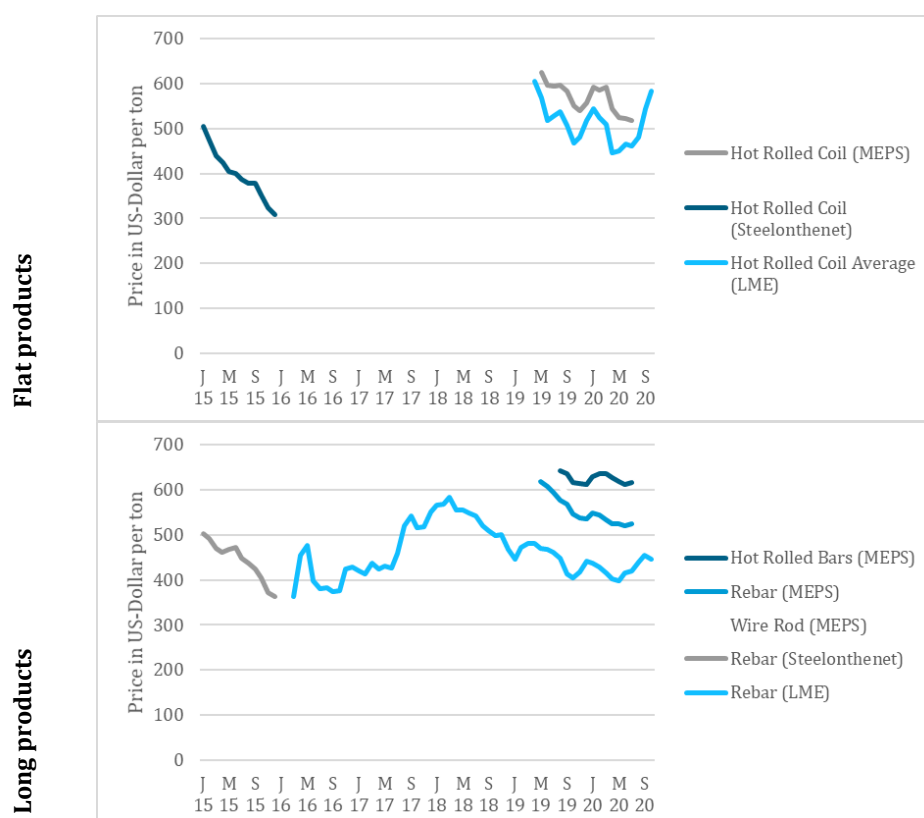
Table 28: Sources for market prices of finished steel products

	Steelonthenet	MEPS	LME
Product	Hot rolled coil, cold rolled coil, hot dip zinc galvanized, organic coated sheet, tinplate, rebar, average for finished steel products	Merchant bar, rebar, wire rod, hot rolled coil	Rebar, hot rolled coil

	Steelonthenet	MEPS	LME
Region	Global	Global, Europe, Asia, North America	Global
Period	January - December 2015	May 2019 - July 2020	March 2016 - October 2020 (rebar), April 2019 - October 2020 (hot rolled coil)
Source	Steelonthenet (2020c)	MEPS (n.d.)	LME (n.d.)
Confidence	Medium	Medium	Medium

An attempt for the comparison of the world average prices provided by the three sources is shown in Figure 21. For this, the following proxy products were selected: Merchant Bar for Hot Rolled Bar, Rebar for Concrete Reinforcing Bar, and Hot Rolled Coil for Hot Rolled Coil, Sheet and Strip.

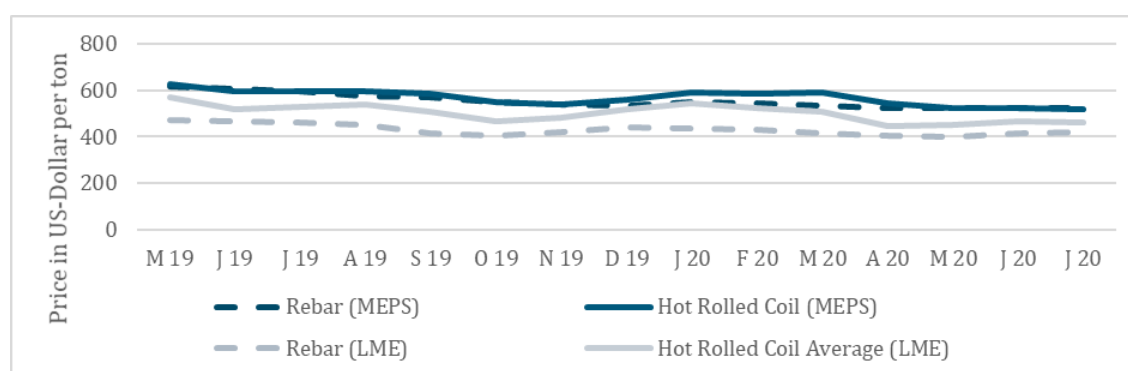
Figure 21: Comparison of market prices for long products (Hot Rolled coil) and flat products (Hot Rolled Bars, Rebar, Wire Rod)



Source: Steelonthenet (2020c), MEPS (n.d.), LME (n.d.)

A direct comparison is possible exclusively for the market prices provided by LME and MEPS for May 2019 until July 2020 for the proxy products Rebar and Hot Rolled Coil. As can be seen, the market prices shown Figure 22 provided by MEPS are higher than those provided by LME, but the prices follow the same trends.

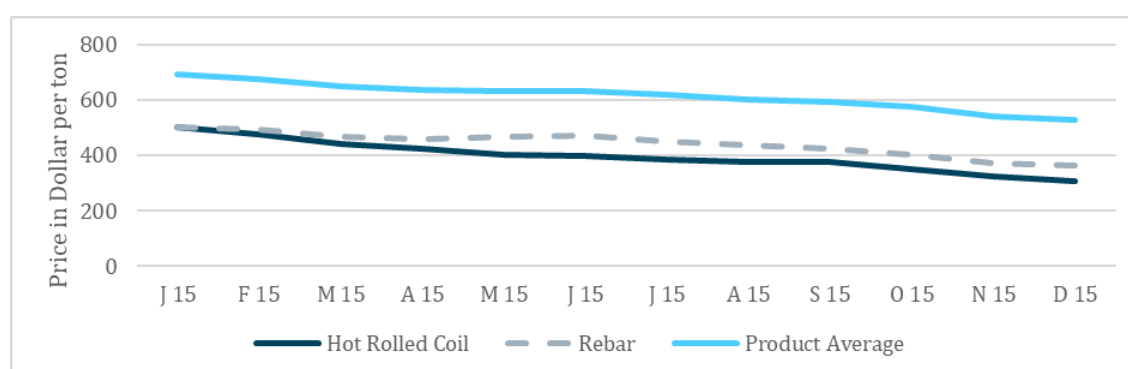
Figure 22: Comparison of market prices of rebar and hot rolled coil



Source: MEPS (n.d.); LME (n.d.)

Particular attention should be paid to the market prices provided by Steelonthenet because those are the only available prices for the year 2015. An overview for the proxy products and for the world average of finished steel products is shown in Figure 23 (the upper line, in blue). The prices are comparable to the prices for 2019 and 2020 provided by MEPS and LME. The price average for finished products is higher than these prices, as further processed products are also included.

Figure 23: Market prices for Rebars and Hot Rolled Coil in 2015



Source: Steelonthenet (2020c)

2.3.5 Summary and conclusions

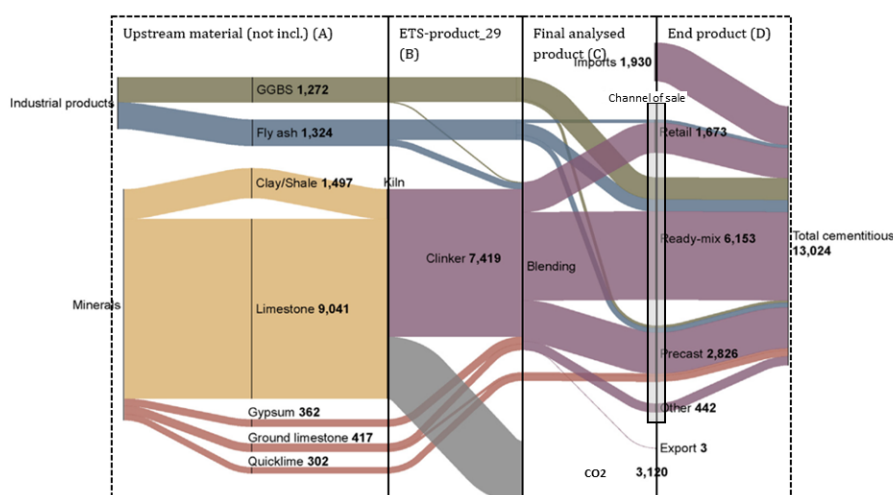
In this section, we developed a simplified material and energy flow model for the steel industry. The four selected final analysed products, hot rolled coil sheet and strip, wire rod, hot rolled bars and concrete reinforcing bars are important products of the sector concerning production and trade volume and reflect the two main production routes in the steel industry (primary and secondary). As expected, especially products who are mainly produced via BF/BOF have significantly higher cumulated specific CO₂-emissions. Compared to the (crude) steelmaking, further processing steps such as e.g. cold rolling, coating are hardly relevant from an energy and emissions perspective. A clear statement that primary production generally leads to higher costs due to higher energy consumption could not be made in this context. Raw material costs are the most important item, followed by energy and other costs. Product type and energy carrier prices, both for electricity and fossil fuels, have an important influence on the results.

2.4 Cement

2.4.1 Production overview

Cement production can be divided in four steps (Figure 24 and Figure 25): raw material preparation, calcination, blending and further processing. The main raw material input for clinker is limestone, which is sintered in a rotary kiln together with shale and clay minerals (and other silicate- and alumina-carriers). **Mining and raw material preparation** (mainly limestone, clay, chalk, also sand and iron ore (VDZ (2002), BDZ & VDZ (2002))) does not produce direct GHG-emissions but requires ~24 kWh/t (Ishak & Hashim, 2015). This production step is not included in the ETS ('A' in Figure 24) and is currently not considered further in this study. The most important and energy intensive process step is the **calcination in rotary kilns**²⁸. Of high importance for product quality, energy demand and GHG-emissions is the material mixture according to Figure 24, which is also influenced by mineral residues of fuels used in the process. The raw meal is heated to around 1450°C in several stages, which releases CO₂ from limestone (and organic components) and sinters the ingredients to clinker. A mass-based share of 44%²⁹ of the limestone input (CaCO₃) is released as CO₂ (3,120 kt/9,041 kt, 42% in Figure 24). These **process-related** emissions are inevitable when limestone is used. Additionally, **energy-related** emissions occur due to fuel combustion to cover the observed 3-4 GJ/t clinker energy³⁰. They are mainly influenced by the fuel mix, which can vary strongly within the EU. The sintered phases of the cement clinker constitute the hydraulic-active parts that constitute the strength of the cement. This process step ('B' in Figure 24) is subsumed under activity 29 in the EU-ETS (European Parliament, 2003). Clinker is thus defined as 'ETS-product' in this study³¹.

Figure 24: Exemplary material flow in cement production (United Kingdom), in kt



Source: Shanks et al. (2019 (edited))

²⁸ Small production capacities of shaft kilns exist. They have a higher specific energy demand.

²⁹ The molar mass of CaCO₃ is 100 g/mol, of CO₂ 44 g/mol.

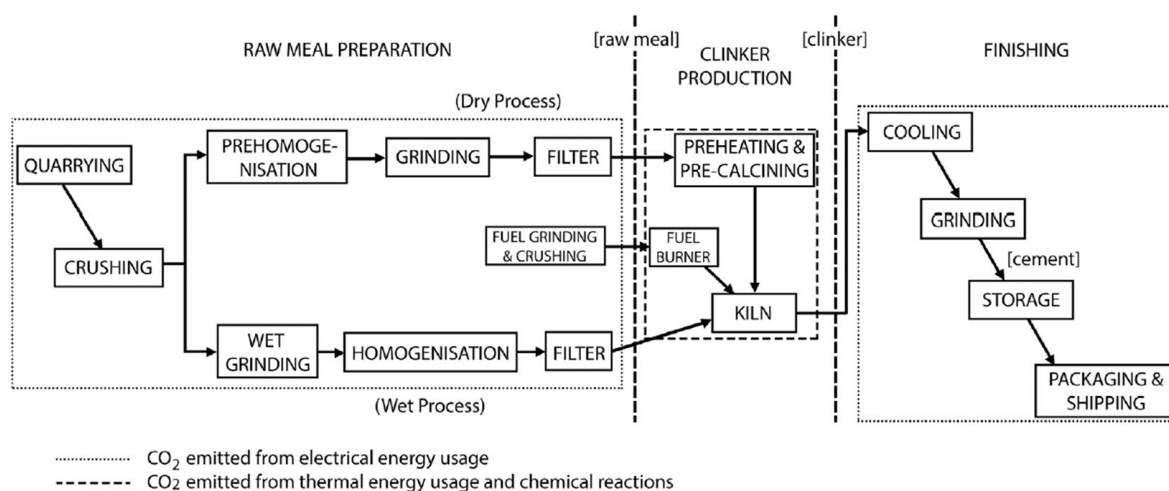
³⁰ Large consensus among several scientific publications (e.g. Ishak & Hashim (2015); Pardo et al. (2011); Rahman et al. (2013); van Ruijven et al. (2016)) and company reports (e.g. Opterra (n.n.), CEMEX (2017), HeidelbergCement (2017)).

³¹ Please note that Figure 25 is given to illustrate the material flow qualitatively. The data represented there are not used in this report. They show the situation for the United Kingdom with varying reference years depending on data source. The reader is referred to the source for closer information.

The clinker is subsequently cooled, ground, and **blended with other materials** (e.g. fly ash from coal-fired power plants, ground-granulated blast furnace slag (GGBS) as well as calcium- and sulphur-carriers which influence the solidification properties) to **form cement** (section 'C' in Figure 24)³². These process steps use electric energy (~45 kWh/t cement³³). According to DIN EN 197-1 five different **main cement types** are distinguished (standard notation: CEM I, CEM II, CEM III-V). They differ in composition and one main differentiation is the clinker share (average DE 2017: 0.71, EU27+UK 2017: 0.77³⁴). The clinker share³⁵ defines the CO₂ emissions attributed to cement production to a high degree. **Further processing** of the cement depends on the form of the end product (ready-mix, pre-cast, retail). The respective shares of these end products in the EU27+UK are similar to the shares observed in Germany³⁶.

The material flows depicted in Figure 25 describe the status in the United Kingdom. They represent the material flow qualitatively, but the actual values of individual flows have relevant variations among the member states of the EU27+UK. For example, the relation of limestone to clinker (in Figure 25: 1.22) is comparable to numbers given by the VDZ for Germany (1.17 (VDZ 2018)). Less so, the overall clinker share (Figure 25: 0.67). To represent the EU27+UK, either data directly supplied for this entity or representatives generated from a share of the total production is used. The values presented in Figure 24 are not used further.

Figure 25: Simplified process steps of cement manufacturing



Source: Ishak & Hashim (2015)

Clinker itself shows only small³⁷ variations of specific emissions and energy demand (e.g. caused by the fuel mix and process efficiency) within the EU27+UK. As tradable product however, **ce-**

³² See e.g. DIN-EN 197-1 for a list of raw materials.

³³ Ishak and Hashim (2015). Small quantities of thermal energy can be used to dry blast furnace slag (VDZ 2002). These are not quantified here but subsumed in the energy demand of the kiln.

³⁴ Average calculated across all main cement types (CEM I-V), excluding export, including import, according to VDZ (2018), WBCSD (2019).

³⁵ Average clinker content in cement products.

³⁶ According to VDZ (2018): Germany 2015: Ready-mix: 56.2%, pre-cast: 28.9%, retail: 5.2%, other: 9.7%.

³⁷ Variations in energy-related emission intensity among EU27+UK countries is about or below 10%. Examples are Germany (69.7 t CO₂/GJ), EU27+UK (74.6 t CO₂/GJ), Spain (77.9 t CO₂/GJ), United Kingdom (72.0 t CO₂/GJ), France (74.9 t CO₂/GJ), Poland (70.8 t CO₂/GJ), all according to WBCSD (2019).

ment shows higher opportunities for meaningful differentiation and is thus defined as '**final analysed product**' in the context of this study ('C' in Figure 24), differentiated by the **main cement types**.

As '**end product**' in the investigated production chain, we analyse the delivery form of cement and concrete. The main types differentiated in available statistics are ready-mix, pre-cast and retail. Ready-mix is either mixed in concrete plants and delivered to construction site in soft state (consistency class C3/F3, Opterra (2015)) or mixed with special equipment at the construction site (but under responsibility of the deliverer). 'Retail' covers bagged cement, which is mixed and used at construction sites without the involvement of concrete plants. Pre-cast concrete elements are mixed, formed and hardened in dedicated plants. The finished element is delivered to the customer. Pre-cast and ready-mix concrete account for the large majority of the market in several important EU countries while retail products represent a smaller market share (Germany 2015: 15%, Italy 2016: 14%, United Kingdom: 17%)³⁸.

The available statistical data are not sufficiently detailed to determine how much e.g. CEM I is used for ready-mix or precast products. The model (see 3.3.2) fills this gap by disaggregating the available data. The delivery type and end use are then allocated to cement types with estimated distributions. This layer of information is thus of lower confidence than other information that can be directly referenced to statistical or literature data. In theory, all cement types laid out in DIN EN 197-1 can be used for all delivery groups. Limitations exist with regard to special environments (exposition classes), e.g. corrosion, increased wear or frost, in which low-clinker cement types are not allowed. However, this only applies to selected sub-groups of CEM II/III cements, while others (e.g. CEM II B/V, with 21-35% fly ash) show the same applicability with regard to exposition as CEM I. We thus use the hardening procedure as main distinction criterion. It is faster for cements with high clinker share and an important economic indicator for pre-cast concrete products. CEM I cements are mostly used for pre-cast concrete elements, where fast hardening increases productivity³⁹. In turn, transport cement⁴⁰ comprises preferably of CEM III. However, for these relations, the CEM-type is merely an indicator, as in principle, all CEM-types may occur in all strength classes (32.5, 42.5, 52.5) and a range of hardening speeds. These relations thus cannot be traced per se by official statistics on a European level, as reporting does not comprise strength classes on a regular basis. Thus, an assumption on the CEM I-share in pre-cast concrete is made (see 3.3.5). It comprises that CEM I (clinker share >95%) is mainly used for pre-cast elements and CEM III (clinker share 5-64%) for ready-mix. CEM II is used for both, the exact share is uncertain. This basic assumption is accompanied by plausibility estimations and calibration based on statistics regarding production and delivery type.

2.4.2 Cement flow model: important concepts

The material flow follows the process description given in 3.3.1 and allocates the available data to the production steps. Here, some important concepts are presented: These are the definition of high- and low-efficiency burning, the process-related emission balance, the CEM-types and the modes of cement use.

Burning efficiency is a concept in the model that differentiates the burning of clinker into processes with high efficiency (HE) and low efficiency (LE), characterized by their specific energy

³⁸ Respective national associations' yearly reports (e.g. Oficemen (n.d.), VDZ (2018)).

³⁹ Personal communication with CEMBUREAU and VDZ (August 2019) and expert interview with a manufacturer of pre-cast concrete elements; Sybertz and Thielen (n.d.).

⁴⁰ Cement used in concrete that is mixed at a concrete manufacturing site and then moved to the construction site. By and large, the closest translation of the German term is ready-mix concrete, although the latter also includes dry delivery to the construction site.

consumption (SEC) per tonne of clinker. The burning in clinker kilns is the most energy-intensive step in the production chain. The differences between the SEC may stem from the type of equipment, its condition and operation or raw material and fuel composition. In most cases, and for the most relevant differences, available raw material is the governing factor. It influences the appropriate technology and energy demand for drying, i.e. when raw material with high water content is used⁴¹. The differentiation thus does not judge in terms of efficiency ambition. It merely presents the distinction between the otherwise not distinguishable intermediate product clinker based on the energy required to produce it. Doing so, it also introduces a possibility to differentiate among countries⁴². The model considers these process designs as LE-burning: dry without preheating (long kiln), semi-dry, semi-wet, wet/shaft kiln. HE burning includes dry processes with preheating (short kilns), both with and without pre-calcination.

Process-related emissions are an important aspect of cement production. In theory, their generation is easy to describe, as the emission of CO₂ from limestone (CaCO₃) can be approximated stoichiometrically. Usually, an emission factor of 0.53 t CO₂/t clinker is estimated, slight variations over time and within and among countries can apply with the presence of magnesium compounds, replacing limestone. These variations are not critical for the model results.

CEM-types describe the standardized composition of the cement used in concrete products. With the main indicator of clinker share in the cement, they are the most important coding for emissions embedded in the product. The model considers three CEM-types, Portland cement (I, 95% clinker), mixed Portland cements (II, minimum 65% clinker) and blast furnace Portland cements mixtures (III, down to only 5% clinker). Further cement types (IV, V) have low market shares (e.g. about 1% in Germany (VDZ 2018)). As some data sources combine CEM III-V, they are treated as aggregate by the model, using the properties of CEM III. Within the CEM-types, additional variations of the clinker share (and its substitutes) apply (coded with A, B, C)⁴³. The model assumes an unweighted average of the sub-types clinker share⁴⁴. Due to this assumption, the actual clinker share of the CEM-types is a relevant sensitivity candidate.

Modes of cement use describe the form of delivery to the final use. The model considers ready-mix (or transport cement), precast (finished elements) and others (non-concrete uses). They are the final product in our analysis⁴⁵. A critical point in the material and emission flow is the allocation of the cement type and the use mode, as it defines the embedded emissions. While no detailed statistical data is available on this link, qualitative information obtained in communication with and publications from cement and concrete user associations allow the assumption, that CEM I is mostly used in precast cement products while CEM III is exclusively used in ready-mix. CEM II may be used in both modes. The model allocates CEM II as a balance of precast and ready-mix after CEM I and CEM III have been assigned to their respective modes. The reason for this allocation is the qualitative information that high-strength cements, often CEM I, are used in precast-operations for their faster hardening, while slow hardening caused by clinker substitutes (in CEM II-III) is preferable in on-site applications.

⁴¹ High water content of the raw material may result in different plant design, e.g. the use of a different kiln (Lepol-kiln) and preheating/drying technologies (in particular not using cyclone-preheater). These "wet" and "semi-wet" processes are mostly replaced by the dry process. In Germany, the dry process with cyclone preheater is used for about 96% of the production (VDZ, 2018).

⁴² For example, Germany (~5%) has a much lower share of low-efficiency burning than the EU27+UK as a whole (~24%).

⁴³ Although qualitative information (Ruppert et al. 2018) hint at CEM III/A as the most relevant sub-type, no quantitative data is available.

⁴⁴ On the European level, no data is available on the sub-type use. Values are available from Spain (Oficemen (n.d.)) and (limited) Germany (VDZ (2018)).

⁴⁵ A further disaggregation by end use in types of construction projects (infrastructure, residential and non-residential buildings) is not possible with the data available in this study.

As the values modelled here are given on a per-tonne-basis, valuable properties of precast building elements are neglected: With appropriate design and dimensioning, they can fulfil the same function and deliver the same service to a building as ready-mix concrete structures but with a smaller mass. This can offset the higher per-tonne emissions. This dimension could not be quantified in this study.

2.4.3 Emission model: important concepts

The emission model follows the material flow and assigns specific emission factors to materials and process steps. It includes emissions from energy use (direct and indirect) and the clinker burning process. The emissions from each source are summed and distributed to the products. Important concepts are the allocation of indirect emissions, embedded emissions of materials entering the material flow during production and the balancing of the final emissions.

Indirect emissions caused by electricity use are considered in the emission model along the production chain starting with the grinding of limestone. Mining of the raw material is, due to the lack of data, excluded from the balance. It is assumed that the energy demand of this step is negligible⁴⁶. The electricity use in the production is distributed to four steps: raw meal preparation, clinker burning, cement grinding and other uses. The specific electricity demand (in total around 116 kWh/t cement (EU27+UK (WBCSD (n.d.)), 112 kWh/t cement (DE (VDZ (2018))), both in base year 2015) is multiplied with an emission factor of electricity generation (see Table 29) and assigned to the respective process step.

Embedded emissions are emissions generated outside the observed system boundary but allocated to materials that enter the system boundary. In this case, this applies to clinker and cement substitutes, additives and aggregates. For these material flows, a uniform emission factor is applied, based on aggregates⁴⁷. They account for about 3% of the total emissions.

The balancing of final emissions involves the transparent representation of differences occurring during the calculation of emissions in different paths. Throughout the model, multiple perspectives are used to account for manufacturing and end use. This includes the interface of CEM types and mode of use. In the bottom-up approach following the emissions of the individual process steps, a difference to the top-down reported emissions (verified emissions tables, VET) occurs (European Commission & DG GROW, 2018). The order of magnitude of this difference is below 6% of the total emissions. It accumulates along the model calculations and has no single cause.

2.4.4 Uncertainties and limitations of model approach

Apart from the uncertainties associated with the input data (see 3.3.5.1), the material flow approach itself imposes limitations. As the structure is rigid, the model is not able to automatically include strong changes to production routes, e.g. due to shifting resource availability or innovative technologies. Trade flows among EU27+UK countries are not considered and international trade only as net balance. Other cement uses are aggregated, and the model does not yield relevant information on those. Overall, though, the proposed material flow model is an adequate representation of the status of cement production and use. Most limitations stem from data availability, around which the model has been designed.

⁴⁶ The total energy demand of mining and quarry operations (including activities other than limestone production) in the EU27 amounts to about 10% (Germany: 5%) of the sector 'non-metallic minerals' (Eurostat, 2018).

⁴⁷ Sufficient data on substitutes and additives have not been found. It is assumed that the order of magnitude is similar to aggregates. However, methodological issues exist, e.g. the allocation of emission to side-products (GGBS, fly ash) of other industrial activities.

The emission model directly sits on top of the material flow model and thus inherits its weaknesses and strengths. Additionally, the emission factors of the material flows add a layer of uncertainty. This is somewhat balanced with the availability of emission data from the EU ETS, which supplies a benchmark of the total emissions, to which the emission model is calibrated. The resulting difference from these statistical values is low (6% EU27+UK, 3% Germany), but mostly depending on the data, not the model structure.

2.4.5 Data basis

The model is informed by several data points (indicators), defining technological properties of manufacturing processes and their energy use. Next to statistics (e.g. energy balances, emission register) and literature, several indicators include estimated values or assumptions. thus includes an estimate of the data point confidence.

Although all of the listed indicators influence the model to some degree, the most important impact on the embedded emissions of the final products (concrete use in precast elements and in transport/other products) is generated by six values: clinker production, cement production, reported emissions, clinker share in cement types, CEM-type use in products and cement share in the products. These data points are described in more detail.

Clinker production is the reported production of clinker in the European Union. It excludes trade balances. The European values are based on the GNR project (WBCSD (n.d.))⁴⁸ and compared to Prodcom. The German values are taken from the national cement association VDZ (2018). The same data sources apply for **cement production**. These indicators are considered to be of high confidence, as long as consistent data series are used.

GHG-Emissions of clinker and cement production are reported in the verified emissions tables (VET) published as part of the EU ETS documentation. These emissions are the basis of the allocation of emission intensity to the final products, as they are distributed to the product dimensions CEM-type and mode of use. It must be noted that, due to the reference to the VET, changes in energy efficiency do not influence the model result on emissions (emissions from energy use are already included). GHG-emissions of biogenic origin are excluded in this and all other GHG-emission figures.

The **clinker share** in cement types is an aggregated value. Based on DIN EN 197-1, it estimates an average share of clinker in the main CEM-types. As no sufficient data on the production of sub-types (e.g. CEM II/A) is available, a simple average of the sub-types is used. It is possible that this assumption slightly underestimates the clinker share in CEM II and CEM III, as some sub-types with very low clinker share might be extremely rare. Sensitivity analyses of the model show that a decrease in clinker share in CEM II by 10% reduces the emission factor for transport concrete by about 5%. The same change for CEM III reduces the emission factor for transport concrete by about 1.5%. Precast concrete is less affected by this relation, as CEM I is mainly used in its production (of which the clinker share is well known). The lowest possible clinker share in CEM II is 65%, the highest 94%⁴⁹ Overall, the error introduced to the results due to the unknown CEM sub-types seems to be low.⁵⁰

As described in 3.3.2, the allocation of **CEM-type use to the final product** is, due to the differing clinker share, an important link between the manufacturing and use stage. No quantitative data

⁴⁸ Self-description of the source yields as meta-data a coverage of 93% in 2015, with 156 Mt cement production covered out of 168 Mt total and 31 companies, 274 plants participating.

⁴⁹ According to the allowed ranges in DIN EN 197-1 (2004).

⁵⁰ However, detailed statistics on cement production, as for example delivered by the Spanish cement association (Oficemen (n.d.)), should be developed in the EU27+UK. They could greatly support analysis of the sector's challenges and opportunities.

are available for this indicator. Qualitative descriptions (Opterra (2015), HeidelbergCement (2016) VDZ (2002), Becke et al. (2014)) however indicate that CEM I (with high strength and fast drying) is the dominant CEM-type in precast elements while CEM II-III is more likely to be used in transport concrete products. This impression has been confirmed in discussions with representatives from cement and concrete associations⁵¹. Based on this information, the model assumes that 80% of the cement demand in precast concrete products is satisfied with CEM I, the rest with CEM II. Sensitivity analyses show that a 10% decrease of the CEM I-use in precast elements (72% CEM I use) changes (decreases) the emission factor for precast elements by 1.7%. It also slightly influences the emission factor of transport concrete products, as any CEM I not used in precast concrete would be used there.

The **cement share in the final products** influences their emission factor, as cement is, compared to the other components (water, air, aggregates), the single most important carrier of embedded emissions. The model assumes that precast concrete products use a higher cement share (0.17 compared to 0.125 in transport concrete)⁵². This emphasises the desired properties of precast concrete (fast hardening/drying) as does the higher clinker share. The latter value assumes a range for mass concrete between 200 and 400 kg cement/m³ concrete (average 300 kg/m³), with a total mass of 2400 kg/m³⁵³. As a broad variety of concrete products exist, these values can vary. Precast concrete assumes a higher cement share (400 kg/m³)⁵⁴.

⁵¹ Communication with VDZ (August 2019), Cembureau (August 2019) and German association for precast concrete elements (Fachvereinigung Deutscher Betonfertigteilbau FDB, November 2019); also communication with manufacturers of pre-stressed concrete ceiling elements (November 2020).

⁵² Based on average composition of normal (as opposed to light) concrete: Opterra (2015) and cement share by strength classes in Becke et al. (2014).

⁵³ This calculation is based on concrete categorizations in DIN 1045-2 (2008), as reported in Opterra (2015) and Schwenk (2013).

⁵⁴ Equivalent to a mix of concrete classes C45/55 and C50/60, with emphasis on the latter.

Table 29: Data used in model of material and emission flows (2015)

Group	Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Energy	SEC heat average	3.73	3.75	GJ/t clinker	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	High
	SEC high efficiency burning	3.59	3.61	GJ/t clinker	Statistics	WBCSD (N.D.)	VDZ (2018)	High
	SEC low efficiency burning	4.13	4.15	GJ/t clinker	Statistics	WBCSD (N.D.)	VDZ (2018)	High
	Share high efficiency burning	0.81	0.95	1	Statistics	WBCSD (N.D.)	VDZ (2018)	High
	Share low efficiency burning	0.19	0.05	1	Statistics	WBCSD (N.D.)	VDZ (2018)	High
	SEC electricity average	116	112.3	kWh/t cement	Statistics	WBCSD (N.D.)	VDZ (2018)	High
	SEC electricity raw meal preparation	19.5	19.5	kWh/t cement	Literature	Ishak & Hashim (2015)	Ishak & Hashim (2015)	High
	SEC electricity burning	27	27	kWh/t cement	Literature	Ishak a& Hashim (2015)	Ishak & Hashim (2015)	High
	SEC electricity cement grinding	23	23	kWh/t cement	Literature	Ishak & Hashim (2015)	Ishak & Hashim (2015)	High
	SEC electricity other uses	46.5	42.8	kWh/t cement	Assumption	Balance	Balance	Medium
	Share biogenic fraction alternative fuels on total energy	0.148	0.213	1	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	High
	Share fossil fuels on total energy	0.569	0.338	1	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	High
	Share non-biogenic fraction alternative fuel on total energy	0.283	0.449	1	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	High

Group	Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Emission	Emission factor cement	0.741	0.614	t CO ₂ /t cement	Calculated ²	-	-	-
	Emission factor clinker	0.93	0.819	t CO ₂ /t clinker	Calculated ³	-	-	-
	Emission factor electricity generation	0.391	0.587	kg CO ₂ /kWh	Literature	Koffi et al. (2017)	Koffi et al. (2017), similar ¹ Icha et al. (2021)	Medium
	Emission factor fuel (average)	0.078	0.078	t CO ₂ /GJ	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	Medium
	Process emissions clinker	0.53	0.53	t CO ₂ /t clinker	Literature	VDZ (2018)	VDZ (2018)	High
	Energy-related emissions from clinker	0.4	0.289	t CO ₂ /t clinker	Calculated ⁴	-	-	-
	Energy-related emissions clinker (HE)	0.385	0.278	t CO ₂ /t clinker	Calculated ⁵	-	-	-
	Energy-related emissions clinker (LE)	0.443	0.32	t CO ₂ /t clinker	Calculated ⁵	-	-	-
	Embedded emissions aggregates	0.005	0.005	t CO ₂ /t	Literature	McGrath et al. (2012)	McGrath et al. (2012)	High
	Embedded emissions substitutes	0.005	0.005	t CO ₂ /t	Assumption	McGrath et al. (2012)	McGrath et al. (2012)	Low
	Embedded emissions additives	0.005	0.005	t CO ₂ /t	Assumption	McGrath et al. (2012)	McGrath et al. (2012)	Low
	Oil emissions factor	0.074	0.074	t CO ₂ /GJ	Literature	Ruppert et al. (2018)	Ruppert et al. (2018)	High

Group	Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Material	Gas emissions factor	0.056	0.056	t CO ₂ /GJ	Literature	Ruppert et al. (2018)	Ruppert et al. (2018)	High
	Total GHG-emissions (excluding biogenic)	116	19	Mt CO ₂	Statistics	European Commission & DG GROW (2018)	European Commission & DG GROW (2018)	High
	Clinker production	125	23	Mt	Statistics	WBCSD (N.D.)	VDZ (2018)	High
	Clinker substitutes/additives (sum)	23	6	Mt	Statistics	WBCSD (N.D.)	WBCSD (N.D.), Ruppert J. et al. (2020)	High
	Cement production	157	31	Mt	Statistics	WBCSD (N.D.)	VDZ (2018)	High
	Cement substitutes (sum)	37	8	Mt	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	Medium
	Limestone use per t clinker	1.22	1.22	t/t clinker	Assumption	BDZ & VDZ (2002)	BDZ & VDZ (2002)	Medium
	Other raw material use per t clinker	0.31	0.31	t/t clinker	Assumption	BDZ & VDZ (2002)	BDZ & VDZ (2002)	Medium
	Clinker factor	0.796	0.75	t clinker/t cement	Calculated ⁶	-	-	-
	Clinker factor CEM I	0.975	0.975	1	Assumption	DIN (2004)	DIN (2004)	Medium
	Clinker factor CEM II	0.75	0.795	1	Assumption	DIN (2004)	DIN (2004)	Medium
	Clinker factor CEM III	0.4	0.295	1	Assumption	DIN (2004)	DIN (2004)	Medium
	CEM I share	0.3	0.308	1	Assumption	Weighted average	VDZ (2018)	Medium

Group	Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
End use	CEM II share	0.51	0.462	1	Assumption	Weighted average	VDZ (2018)	Medium
	CEM III - V share	0.19	0.23	1	Assumption	Weighted average	VDZ (2018)	Medium
	Share of cement in ready-mix concrete	0.125	0.125	1	Assumption	Opterra (2015)	Opterra (2015)	High
	Share of cement in precast concrete	0.17	0.17	1	Assumption	Becke et al. (2014)	Becke et al. (2014)	High
	Share aggregates ready mix	0.675	0.675	1	Assumption	MPA (2018)	MPA (2018)	High
	Share of aggregates in precast	0.63	0.63	1	Assumption	MPA (2018)	MPA (2018)	Low
	Share of air and water in concrete	0.2	0.2	1	Assumption	MPA (2018)	MPA (2018)	Low
	Precast satisfied by CEM I	0.8	0.8	1	Assumption	-	-	Low
	Precast satisfied by CEM II	0.2	0.2	1	Balance	-	-	Low
	Cement as transport concrete	0.562	0.562	1	Assumption	VDZ (2018)	VDZ (2018)	Medium
	Cement as precast concrete	0.289	0.289	1	Assumption	VDZ (2018)	VDZ (2018)	Medium
	Cement as other deliverable	0.149	0.149	1	Assumption	VDZ (2018)	VDZ (2018)	Medium

Group	Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
	Recarbonating factor in buildings	0.001	0.001	1	Assumption	Saulles (2013), Cembureau (2018)	Saulles (2013), Cembureau (2018)	Medium
	Recarbonating in demolition waste	0.003	0.003	1	Assumption	Saulles (2013), Cembureau (2018)	Saulles (2013), Cembureau (2018)	Medium

1: The sources report different values (Koffi et al. (2017): 0.587 kgCO₂/kWh, Icha et al. (2021):0.527 -0.575 kgCO₂/kWh, depending on trade balance consideration). This difference has a low impact on the bottom-up calculated emissions (about 1.6% lower emissions when the lower value is used).

2: Sum of energy- and process-related emissions times clinker ratio.

3: Sum of energy- and process-related.

4: Difference of statistical emission data (VET) and process-related emissions.

5: Energy-related emissions scaled by energy intensity of the process group.

6: Clinker production divided by cement production.

2.4.6 Uncertainties and limitations of model data

The cement model is based on statistical values on production, energy demand and emissions, but includes several individual data points from varying sources to fill in gaps and add details on all three levels (Table 29). These data points are of differing quality. Some are based on national associations' publications and merely assumed to be appropriate for the EU27+UK (though many important values are averaged from a sizeable share of total EU27+UK production). Some rely on technology description in peer-reviewed journals, which are, although well documented, often also based on individual sites. The overall quality is estimated in Table 29 as 'confidence', taking into account the type of the data point (simple transparent value or complex compound data) and the source (transparency, coverage, range of values in the sources).

Due to the comparatively high differentiation of data points, information from statistics and literature are generally assumed to have a high confidence, as they can be found directly in the source and can be checked for plausibility. Examples include total cement production, average specific energy consumption of production processes and the composition of concrete. An exemption is e.g. the use of cement substitutes in concrete, as the definition, which materials are allocated to this group, seems ambiguous in the statistic (with little impact on the value, though).

Other data points rely on assumptions. Either due to severely limited coverage of the value (thus just assuming they are usable) or for the lack of documented values, these are regularly categorised with low or medium confidence. They should be taken as expert judgment. Examples include the limestone use in clinker (taken from a rather old publication for Germany and assumed to be a proxy for the EU27+UK as well), the clinker factor by CEM I-III (as the production by sub-type with varying clinker share is not known in all cases) and the cement use by delivery type (as the value is based on a share of the total production of countries with related statistics (44%, see below, in particular Table 31 for details)).

2.4.7 Key figures cement

2.4.7.1 Material flow

Figure 26 and Figure 27 present the material flow for the EU27+UK and Germany, respectively. They start at the delivery of raw material from the quarry (or other sources) and follow the manufacturing processes over the kiln and cement grinding to delivery of cement in different CEM-types. These are distributed to the final products precast and transport concrete, taking into account substitutes, aggregates, water and air and the trade balance⁵⁵.

The, regarding the following emission calculation, most important material flow (limestone->clinker->cement) is fairly straightforward (here described for the EU27+UK in 2015). From 191 Mt of raw material (of which 153 Mt limestone), raw meal (191 Mt) is prepared for use in high efficiency burning (short rotary kilns in dry process with preheater, 155 Mt) and low efficiency burning (dry process without preheater, semi-dry, semi-wet and wet processes, 36 Mt). It is processed in the kilns to 125 Mt clinker (101 Mt from high efficiency, 24 Mt from low efficiency). The mass difference between kiln input and output is CO₂ (66 Mt), released to the atmosphere as process-related emissions, creating a closed mass balance of the kiln. The clinker is

⁵⁵ The trade balance is based on cement trade data from Eurostat (2019) and consists of the net material flow cross the respective entity (EU27+UK or Germany). The CEM-type is assigned in the model according to the production share of CEM I-III, respectively (thus an assumption, not a statistical value). For the EU27+UK, the trade balance in 2015 shows a net export of 12 Mt, of which the CEM-types I, II and III-V make up for 3.6 Mt, 6.0 Mt and 2.3 Mt, respectively. For Germany, the trade balance in 2015 shows a net export of 5 Mt, of which the CEM-types I, II and III-V make up for 1.5 Mt, 2.3 Mt and 1.2 Mt, respectively.

ground and mixed with additives and substitutes to form the aggregated group of cement production (157 Mt)⁵⁶.

At this point, the model leaves the statistical basis mainly provided by the GNR project (WBCSD 2019) and transitions to national associations' statistics and assumptions on delivery types, CEM-types and end use. The cement group is distributed to CEM-types (Table 30)⁵⁷, which serve as a proxy of clinker share and thus emission intensity. In a net balance, 12 Mt cement are exported, 44 Mt are of CEM I, 74 Mt are of CEM II and 28 Mt are of CEM III-V⁵⁸. Sources for the national values in the following Tables 30, 31, 32 are national statistics. For Germany, VDZ (2018), for Belgium, Febelcem (2018), for the United Kingdom, mpa (2015, 2018, 2019), for Spain, Oficemen (2016, n.d.), for Italy, AITEC (2017a, 2017b) and for Poland, spc (2015-2017).

Table 30: Data basis for allocation of CEM-types

Country	Cement production [kt]	Share production on EU	CEM I	CEM II	CEM III	Rest
Belgium	6,100	4%	0%	47%	53%	0%
UK	10,200	6%	60%	34%	0%	6%
Germany	31,200	20%	30%	46%	22%	2%
Spain	12,900	8%	33%	57%	3%	7%
Italy	20,800	13%	14%	70%	3%	13%
Poland	15,600	10%	44%	42%	13%	1%
SUM	96,800	62%	30%	51%	14%	5%

The cement is mixed with aggregates (565 Mt), cement substitutes (32 Mt) and water and air (171 Mt) to form concrete (values for EU27+UK in 2015, referring to Figure 26). This happens in different delivery types: precast concrete and transport concrete. Other uses of cement products are used as balance item, their value is thus highly uncertain but of no further interest for the material flow.

Precast concrete elements mainly use high-clinker cement types, as these harden faster, allowing for more economical operations⁵⁹. The share of CEM I used in precast concrete (rest of 20% is CEM II) is assumed to be 80% but may be even higher⁶⁰. In this case, the material flow results to 34 Mt CEM I, 7.9 Mt CEM II, 49 Mt water and air and 153 Mt aggregates to produce 243 Mt precast concrete. Transport concrete includes concrete mixed at construction sites and concrete delivered in a mixed state and uses 10 Mt CEM I, 66.2 Mt CEM II, 27.6 Mt CEM III, 122 Mt water and air and 412 Mt aggregates for a production of 647 Mt. The differentiation by delivery type is

⁵⁶ A remaining difference of other uses and statistical/model differences remains, which is represented in Figure 26 to Figure 29 "other uses (difference)". It amounts to 28 Mt (3% of concrete material flow to the construction sector).

⁵⁷ The presented data points are the whole data set of information for the respective category available to and used in this study.

⁵⁸ CEM III dominates in this group, individual categories for CEM IV and CEM V have not been considered due to their low importance and their similar clinker share as CEM III.

⁵⁹ The cast elements must reach a specific early hardness to be removed from the mould. Faster hardening increases throughput. There are additional differentiations of cement properties (fast hardening 'R', normal hardening 'N'), but the clinker content is a major criterion for this property.

⁶⁰ Full splits for EU27+UK as modeled: 157 Mt cement production, export of 12 Mt. Of the remaining 145 Mt, 33.5 Mt are CEM I in precast, 10.1 Mt are CEM I in ready-mix, 7.9 Mt are CEM II in precast, 66.2 Mt are CEM II in ready-mix and 27.6 Mt are CEM III-V in ready-mix and other uses.

based, similar to the one by CEM type, on national associations' statistics, where they were available (Table 31).

Table 31: Data basis for allocation of delivery type

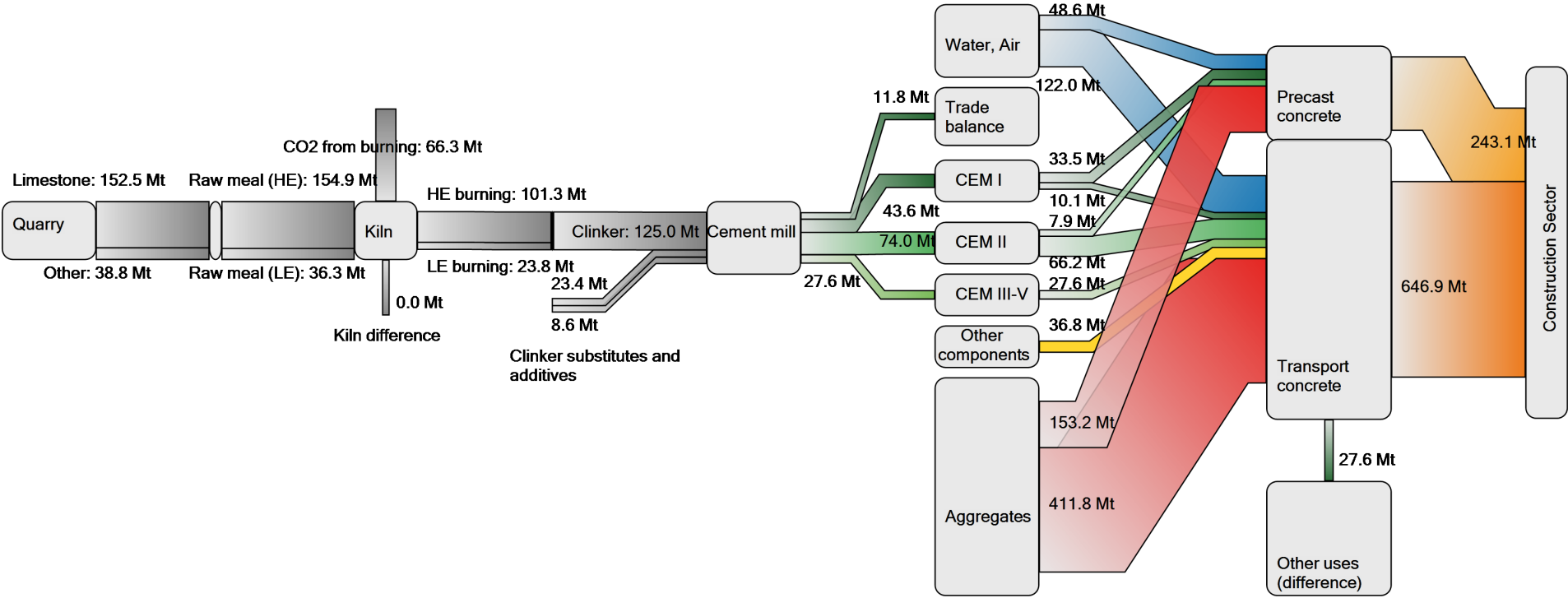
Country	Cement production [kt]	Share production on EU	Ready-mix (transport cement)	Pre-cast	Others
Belgium	6,100	4%	59%	20%	21%
UK	10,200	6%	52%	23%	25%
Germany	31,200	20%	56%	29%	15%
Italy	20,800	13%	51%	9%	40%
SUM	68,300	44%	54%	21%	25%

The total concrete use can also be allocated to its end use (residential, non-residential and infrastructure, Table 32). However, this level of information is not available as intersection with delivery type. While it can be assumed that most precast concrete is used in buildings, the differentiation is ambiguous. As the data basis for this differentiation is smaller (accounting for only 28% of EU27+UK production in two countries), this dimension is not included in the material flow.

Table 32: Data basis for allocation of end use

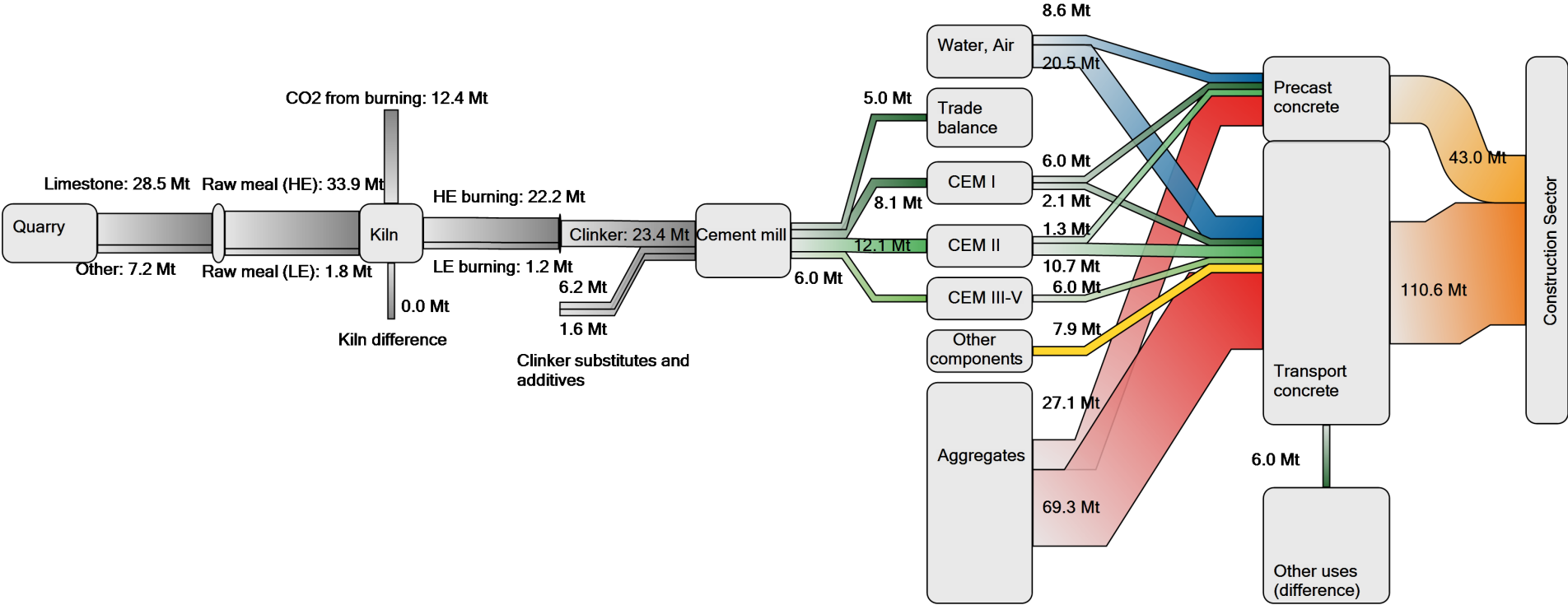
Country	Cement production [kt]	Share production on EU	Residential	Non-residential	Infrastructure
Germany	31,200	20%	32%	34%	35%
Spain	12,900	8%	25%	21%	54%
SUM	44,100	28%	30%	30%	40%

Figure 26: Modelled material flow cement, EU27+UK 2015



Source: own calculation

Figure 27: Modelled material flow cement, Germany 2015⁶¹



Source: own calculation

⁶¹ "Kiln difference" checks the mass balance of the kiln, consisting of raw material, clinker and CO₂-streams for gaps. "Other components" combine limestone, slag, fly ash, other puzzolana and gypsum used in concrete mixing that complete the mass balance. The values given here represent the model results, as they are given in the text and as they form the basis for the result tables (Table 30, Table 30).

2.4.7.2 Final Energy Demand

The energy demand of material processing is concentrated in the primary manufacturing steps: raw material preparation, clinker burning and cement grinding (Table 33)⁶². The main energy demand occurs during clinker burning, hence the CEM types carry different energy demand loads based on their clinker content (Table 34 and Table 35). Differences in grinding effort (governing electricity use) are not included, as these could not be quantified.

Table 33: SEC data used in model to calculate FED

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
SEC heat average	3.730	3.750	GJ/t clinker	Statistics	WBCSD (N.D.)	VDZ (1028)	High
SEC high efficiency burning	3.590	3.610	GJ/t clinker	Statistics	WBCSD (N.D.)	VDZ (1028)	High
SEC low efficiency burning	4.130	4.150	GJ/t clinker	Statistics	WBCSD (N.D.)	VDZ (1028)	High
Share high efficiency burning	0.810	0.950	1	Statistics	WBCSD (N.D.)	VDZ (1028)	High
Share low efficiency burning	0.190	0.050	1	Statistics	WBCSD (N.D.)	VDZ (1028)	High
SEC electricity average	116.0	112.3	kWh/t cement	Statistics	WBCSD (N.D.)	VDZ (1028)	High
SEC electricity raw meal preparation	19.5	19.5	kWh/t cement	Literature	Ishak & Hashim (2015)	Ishak & Hashim (2015)	High
SEC electricity burning	27.0	27.0	kWh/t cement	Literature	Ishak & Hashim (2015)	Ishak & Hashim (2015)	High
SEC electricity cement grinding	23.0	23.0	kWh/t cement	Literature	Ishak & Hashim (2015)	Ishak & Hashim (2015)	High
SEC electricity other uses	46.5	42.8	kWh/t cement	Assumption	Balance	Balance	Medium
Share biogenic fraction alternative fuels on total energy	0.148	0.213	1	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	High
Share fossil fuels on total energy	0.569	0.338	1	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	High

⁶² The values given are only based on the production steps until (including) cement grinding and processing (e.g. packaging). Additional energy demand for pre-cast elements could not be defined. An estimate, based on an expert interview and a single installation (pre-stressed concrete ceiling), yields about 0.09 GJ natural gas and 7 kWh electricity per tonne of pre-cast concrete.

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Share non-biogenic fraction alternative fuel on total energy	0.283	0.449	1	Statistics	WBCSD (N.D.)	WBCSD (N.D.)	High

The different products listed in Table 34 and Table 35 include different energy uses, each up to the final production step (and material flow) of the product: Clinker only reflects the electricity use for raw material preparation and fuel and electricity for the rotary kiln, CEM I-V additionally include electricity use for grinding and the trade balance. The concrete delivery types include the same balance room as cement but exclude other cement uses. In total, about 17% of the fuel and 16% of the electricity used for cement production does not contribute to the investigated delivery types transport/precast concrete (Germany: 20% fuel, 19% electricity). This energy use is net exported in products or used for other applications.

Table 34: Calculated final energy demand, EU27+UK 2015

Product*	ETS-activity	Production [kt]	Specific fuels [GJ/t]	Specific electricity [kWh/t]	Fuels [TJ]	Electricity [TWh]	Source
Clinker	29	125,000	3.73	47	466,250	5.81	Model results
CEM I	-	43,553	3.64	116	158,393	5.05	Model results
CEM II	-	74,041	2.80	116	207,129	8.59	Model results
CEM III-V & other uses	-	27,584	1.49	116	41,155	3.20	Model results
All CEM	-	157,000	2.59	116	406,677	18.21	Model results
Transport concrete	-	646,914	0.30	15	192,676	9.38	Model results
Precast concrete	-	243,117	0.59	20	143,369	4.79	Model results

* Difference in allocated fuel demand between CEM and clinker due to cement trade balance (net export of 11.8 Mt cement). Difference in allocated electricity demand due to electricity use after clinker (e.g. grinding). Difference in total fuel/electricity use for concrete delivery types due to other cement uses.

Table 35: Calculated final energy demand, Germany 2015

Product*	ETS-activity	Production [kt]	Specific fuels [GJ/t]	Specific electricity [kWh/t]	Fuels [TJ]	Electricity [TWh]	Source
Clinker	21	23,355	3.75	47	87,581	1.09	Model results
CEM I	-	8,057	3.66	112	29,459	0.90	Model results

Product*	ETS-activ-ity	Production [kt]	Specific fuels [GJ/t]	Specific electricity [kWh/t]	Fuels [TJ]	Electricity [TWh]	Source
CEM II	-	12,086	2.98	112	36,031	1.35	Model results
CEM III-V & other uses	-	11,017	1.86	112	20,450	1.23	Model results
All CEM	-	31,160	2.76	112	85,941	3.49	Model results
Transport concrete	-	110,586	0.30	14	32,928	1.55	Model results
Precast concrete	-	43,007	0.60	19	25,745	0.82	Model results

* Difference in allocated fuel demand between CEM and clinker due to cement trade balance (net export of 5 Mt cement). Difference in allocated electricity demand due to electricity use after clinker (e.g. grinding). Difference in total fuel/electricity use for concrete delivery types due to other cement uses.

2.4.7.3 CO₂-Emissions

The emissions associated with material processing are building upon the material and energy flow. The model includes indirect emissions generated by electricity use in the production process (raw meal and cement grinding, other uses in the production process), direct process related emissions in the kiln and energy related emissions caused by fuel consumption. These emissions are allocated to the material flow and transported through the production chain, until they reach the final product stage (Figure 28 and Figure 29). Trade is considered as a balance, thus implicitly assuming the same (domestic) emission factor for imported and exported material. For the total cumulated emissions (Table 36 and Table 37), the emissions of the trade balance are included as well as emissions from other (non-CEM I-V) products, whose use is unclear (balanced as difference in the material flow). The allocation of these materials and emissions to the delivery types and cement types includes ambiguity and thus the resulting sums (e.g. total emissions⁶³) and indicators (e.g. t CO₂/t clinker and t CO₂/t cement) are not exactly those one would expect from the aggregated statistical values. They are, however, close to them⁶⁴.

The specific emissions of pre-cast concrete are higher than those of transport concrete (by 30 - 50%). This is caused by a higher clinker share (mostly CEM I and CEM II is used). In total, the modelled emissions sum up to 121.25 Mt for the EU27+UK and 20.53 Mt for Germany in 2015 (Table 36 and Table 37).

The emission model starts along the material flow with emission-free raw materials (Table 29). The emissions actually embedded at this stage due to transport and quarry activity is unknown but expected to be negligible⁶⁵. The model calculations yield the following values in the respective processing steps: The processing of the raw material to raw meal causes indirect emissions from electricity use of 1.5 Mt CO₂eq, of which 1.2 Mt CO₂eq are proportionally allocated to high-efficiency and 0.3 Mt CO₂eq to low-efficiency burning. The bulk of the emissions (117.2 Mt

⁶³ For example, the total direct emissions from cement production (appearing only in clinker, 19,299 kt) in Germany deviate by 168 kt from the publications of the VDZ for 2015 (19,131 kt).

⁶⁴ If only direct emissions are considered, the value for Germany changes to 0.62 tCO₂/t cement (VDZ reports 0.61), the EU27+UK value changes to 0.75 t CO₂/t cement (from production and verified emissions, the result is 0.74).

⁶⁵ For example, the fuel use in the entire mining and quarrying subsector in Germany sums to about 2.5 TWh (2015), consisting mainly of natural gas and lignite. This results in emission <1Mt CO₂eq

CO₂eq) occur in the burning process, of which HE burning accounts for 93.8 Mt CO₂eq and LE burning for 23.4 Mt CO₂eq. The LE burning has, specifically, slightly higher emissions due to higher fuel use. Overall, the difference between the burning efficiencies amounts to 6% (~5% in Germany). The added embedded emissions from additives and clinker substitutes are negligible (0.16 Mt CO₂eq). The grinding of clinker to cement causes indirect emissions due to electricity consumption (3.3 Mt CO₂eq for a subtotal of 120.5 Mt CO₂eq). Of those, 8.4 Mt CO₂eq are (net) traded outside the system and the rest (114.1 Mt CO₂eq) is distributed to the CEM-types (CEM I: 43.5 Mt CO₂eq, CEM II: 57.1 Mt CO₂eq and CEM III-V: 11.5 Mt CO₂eq). The CEM-types are distributed to the delivery types, adding indirect emissions by electricity use for other uses (e.g. packaging). The precast delivery type consists of 34 Mt CO₂eq for CEM I use, 6.2 Mt CO₂eq for CEM II use and 0.8 Mt CO₂eq for embedded emissions in aggregates. The transport concrete (ready-mix cement) delivery type consists of 10.3 Mt CO₂eq for CEM I use, 52.2 Mt CO₂eq for CEM II use, 12 Mt CO₂eq for CEM III-V use and 2.2 Mt CO₂eq for embedded emissions in aggregates⁶⁶. The total emissions of the delivery type pre-cast concrete elements (41.1 Mt CO₂eq) and transport concrete (76.7 Mt CO₂eq) are finally flowing to the construction sector for a total of 117.8 Mt CO₂eq⁶⁷.

⁶⁶ The supply of water is not considered as relevant emission source, the related energy demand is assumed to be negligible (pre-cast concrete elements) or out of bounds (construction site).

⁶⁷ This constitutes a difference to the official statistics (VET, European Commission (2017)) of 1.5 Mt CO₂eq, when indirect and embedded emissions from aggregates are excluded.

Table 36: Calculated emissions, EU27+UK 2015

Product	ETS-activity	Production [kt] ¹	Process related [kt CO ₂ eq] ²	Direct energy related [kt CO ₂ eq] ³	Indirect energy related [kt CO ₂ eq] ⁴	Total (incl. indirect) [kt CO ₂ eq]	Total (excl. indirect) [kt CO ₂ eq]	Total cum. (incl. indirect) [kt CO ₂ eq] ⁵	Specific (incl. indirect) [t CO ₂ eq/t] ⁶	Specific cum.(incl. indirect) [t CO ₂ eq/t] ⁷	Confidence
Clinker	21	125,000	66,250	48,664	2,273	114,914	117,187	117,187	0.94	0.94	High
CEM I	-	43,553	0	0	1,184	0	1,184	46,706	0.03	1.07	High
CEM II	-	74,041	0	0	2,012	0	2,012	61,780	0.03	0.83	High
CEM III-V & other uses	-	27,584	0	0	750	0	750	12,770	0.03	0.46	Medium
All CEM	-	157,000	0	0	3,945	0	3,945	121,257	0.03	0.77	Medium
Transport concrete	-	646,914	0	0	1,470	0	1,470	80,059	0.00	0.12	Medium
Precast concrete	-	243,117	0	0	751	0	751	42,908	0.00	0.18	Medium

1: Production amount as reported in Figure 26, including trade balance.

2: Process related emissions caused in the respective process.

3: GHG-emissions caused by fuel use ("Direct energy related") calculated as difference between total (excl. indirect) and process-related emissions.

4: Indirect emissions caused by electricity use, calculated as electricity use times emission factor of electricity generation.

5: Total cumulated emissions (sum of lines). E.g. the value for "all CEM" is the sum of CEM I, CEM II and CEM III. Values for transport and precast concrete are model results based on their share of CEM and delivery type.

6: Emissions (total incl. indirect) divided by production.

7: Cumulated emissions (total cumulated incl. indirect) divided by production.

Table 37: Calculated emissions, Germany 2015

Product	ETS-activity	Production [kt] ¹	Process related [kt CO ₂ eq] ²	Direct energy related [kt CO ₂ eq] ³	Indirect energy related [kt CO ₂ eq] ⁴	Total (incl. indirect) [kt CO ₂ eq]	Total (excl. indirect) [kt CO ₂ eq]	Total cum. (incl. indirect) [kt CO ₂ eq] ⁵	Specific (incl. indirect) [t CO ₂ eq/t] ⁶	Specific cum.(incl. indirect) [t CO ₂ eq/t] ⁷	Confidence
Clinker	21	23,355	12,378	6,283	637	18,662	19,299	19,299	0.83	0.83	High
CEM I	-	8,057	0	0	311	0	311	7,700	0.04	0.96	High
CEM II	-	12,086	0	0	467	0	467	9,553	0.04	0.79	High
CEM III-V & other uses	-	11,017	0	0	426	0	426	3,280	0.04	0.30	Medium
All CEM	-	31,160	0	0	1,204	0	1,204	20,532	0.04	0.66	Medium
Transport concrete	-	110,586	0	0	347	0	347	13,696	0.00	0.12	Medium
Precast concrete	-	43,007	0	0	184	0	184	6,818	0.00	0.16	Medium

1: Production amount as reported in Figure 27, including trade balance.

2: Process related emissions caused in the respective process.

3: GHG-emissions caused by fuel use ("Direct energy related") calculated as difference between total (excl. indirect) and process-related emissions.

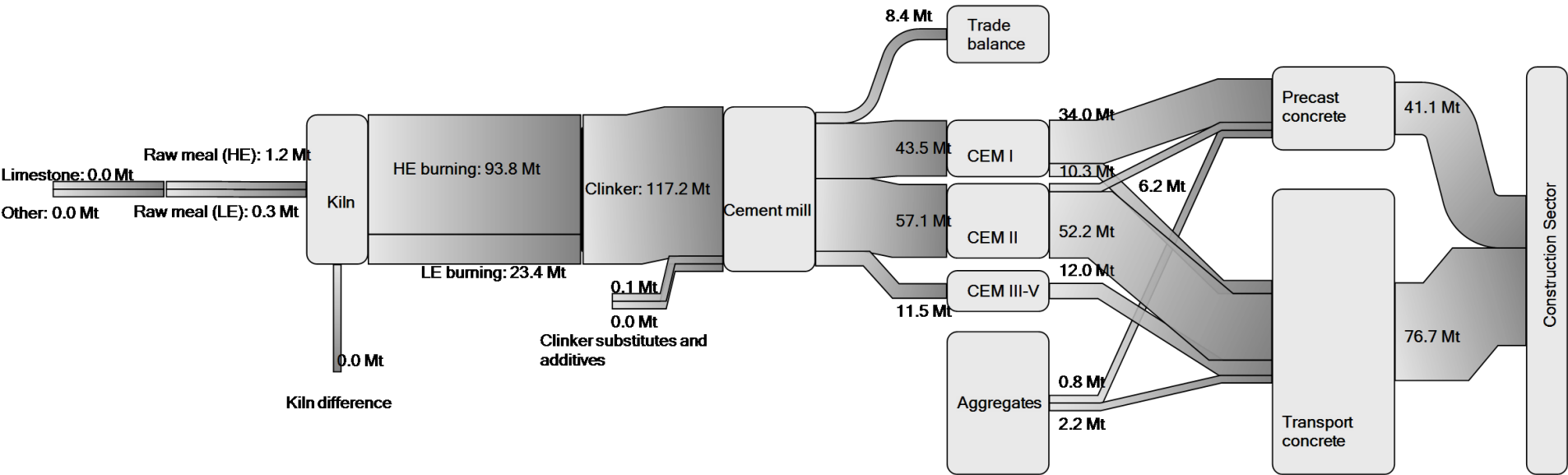
4: Indirect emissions caused by electricity use, calculated as electricity use times emission factor of electricity generation.

5: Total cumulated emissions (sum of lines). E.g. the value for "all CEM" is the sum of CEM I, CEM II and CEM III. Values for transport and precast concrete are model results based on their share of CEM and delivery type.

6: Emissions (total incl. indirect) divided by production.

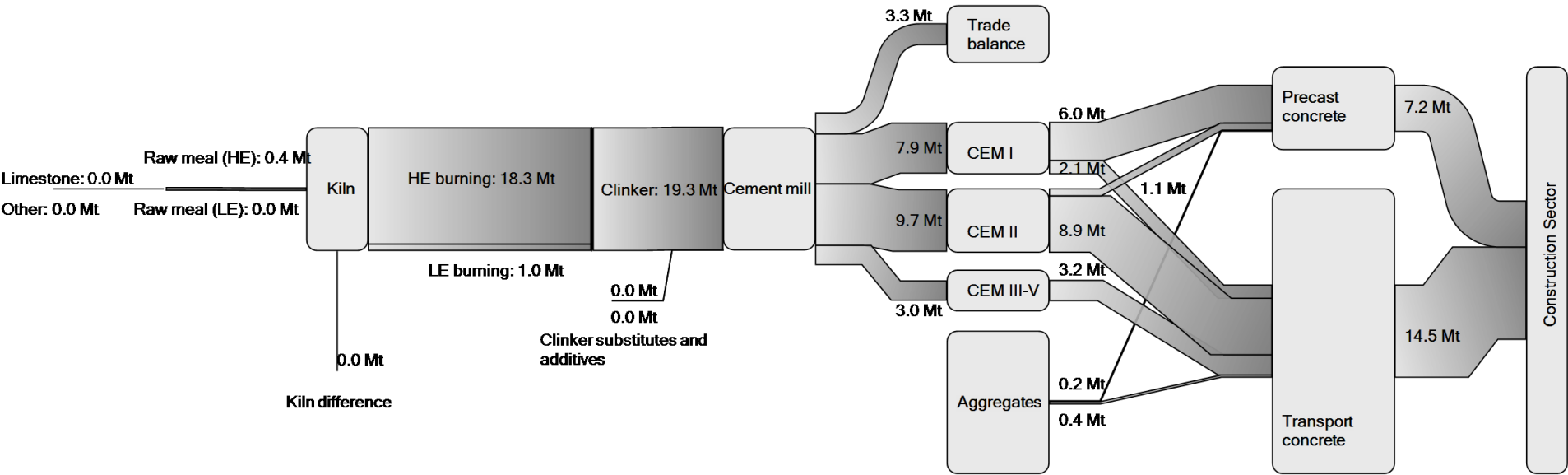
7: Cumulated emissions (total cumulated incl. indirect) divided by production.

Figure 28: Modelled CO₂-emission flow cement, EU27+UK 2015



Source: own calculation

Figure 29: Modelled CO₂-emission flow cement, Germany 2015



Source: own calculation

2.4.7.4 Limits to interpretation of emissions figures in this report regarding the delivery types of concrete

The interpretation of the results regarding the specific emissions of the concrete delivery types requires, on the level of detail utilized in this study, careful consideration. While it is clear that a tonne of pre-cast concrete has a significantly higher GHG burden than one tonne of transport concrete (Wünschmann 2018), any conclusions must consider the actual use in buildings. However, this study is focused on the effects of the EU ETS and is thus restricted to products within it (or close to it). In addition, the applications of concrete in buildings are diverse. It was thus not possible to quantify these effects in this study. A qualitative analysis of the advantages of pre-cast concrete elements has been done at the example of pre-stressed concrete ceilings.

The main argument in favour of using these pre-cast elements over transport concrete is their increased material efficiency (in addition to a high quality and shorter construction time). Estimates range from 12% (DW Systembau (2019)) to 40% (Kämereit (2019)⁶⁸ reduction in GHG-emissions, mostly driven by reduced material use (steel and concrete). Wünschmann (2018) showed, that even within the group of pre-cast ceiling elements, the actual design can influence the global warming potential (GWP) by 40% (and more, depending on the variation). Within the scope of this study, these results could not be confirmed but they show that evaluation must include the use in buildings.

We thus conclude that the insights gained in this study regarding the use of pre-cast or transport concrete cannot give an answer to the question which of the two products is more sustainable even only in terms of GHG-emissions. It should be followed by detailed analyses of the application in buildings.

2.4.8 Key economic indicators and cost structure

In the following sections the key economic indicators, the cost structure and the market prices of the analysed products (Clinker, CEM I, CEM II, CEM III-V, Precast Concrete, Transport Concrete) are summarised. The key economic indicators or more precisely the trade relevance is hereby determined from current and historical trade data provided by the EU commodity statistics from Prodcom (Eurostat, 2020b). On the national level the data are supplemented by information from the national industry association Verein Deutscher Zementwerke e.V. (VDZ). The VDZ retrieves and aggregates the information from the German commodity statistics provided by Destatis (VDZ, 2020; Destatis, 2021b). The information on cost structure and the market prices are presented and discussed in section 2.4.8.2 and 2.4.8.3.

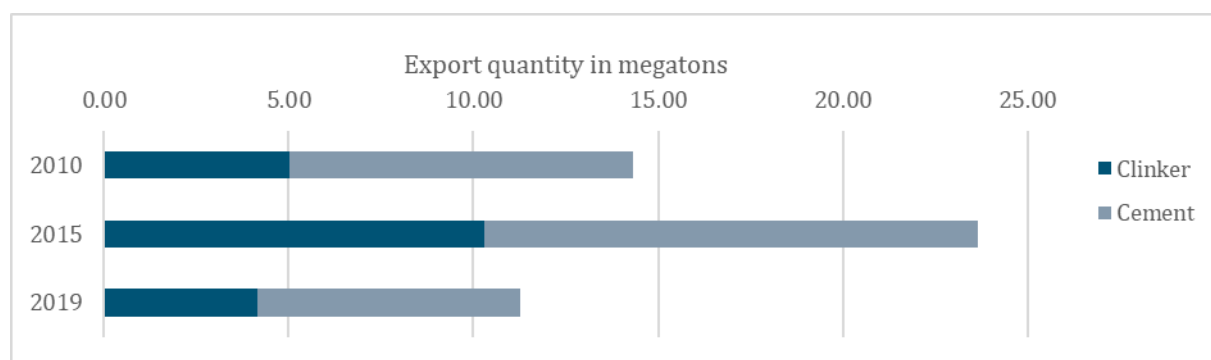
2.4.8.1 Trade relevance

In 2019, more than 7.1 Mt cement and more than 4.1 Mt clinker were exported from the EU⁶⁹. As shown in Figure 30 this is a significant decrease in comparison to 2015 (13.4 Mt cement and 10.3 Mt clinker). The cement and clinker exports were increasing until they reached their maximum in 2014 (Eurostat, 2020b).

⁶⁸ For specific applications and assuming a dedicated design approach.

⁶⁹ In 2015, 157 Mt cement and 125 Mt clinker were produced in the EU27+UK (see Figure 26).

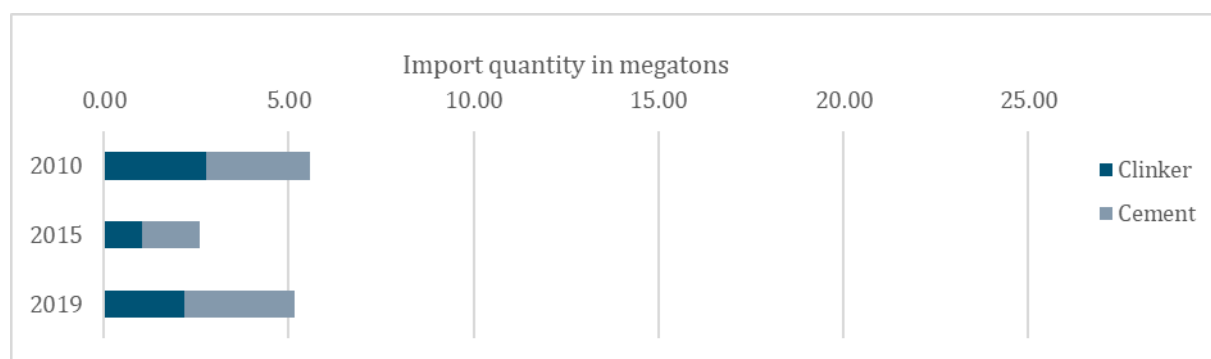
Figure 30: Export of the cement industry, EU28 2010, 2015 and 2019



Source: Eurostat 2020b

Compared to the imports of 3.0 Mt cement and 2.2 Mt clinker in 2019, it is apparent that the EU is currently a net exporter. Furthermore, an inverted development of the imports in comparison to the exports can be assessed (see Figure 31). The minimum of imports was reached in 2014. Since then, the imports are increasing (Eurostat, 2020b).

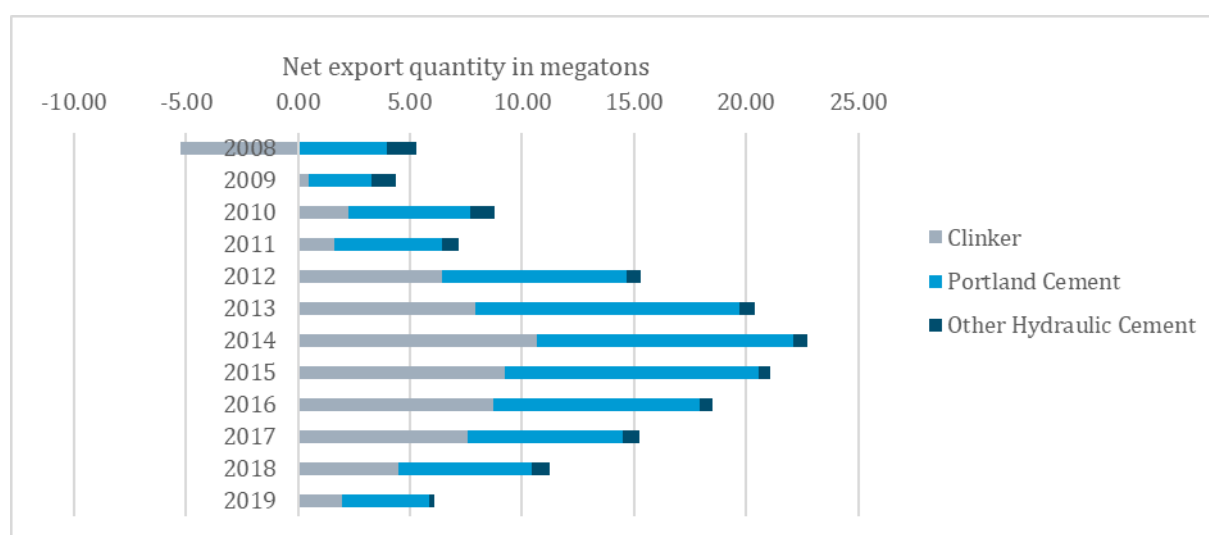
Figure 31: Import of the cement industry, EU28 2010, 2015 and 2019



Source: Eurostat (2020b)

For the further assessment of the trade relevance of cement and clinker, the net exports are displayed in Figure 32. As shown below, the EU has been a net exporter of cement and clinker in the last decade. In general, more Portland Cement than Other Hydraulic Cement is traded in the EU (Eurostat, 2020b).

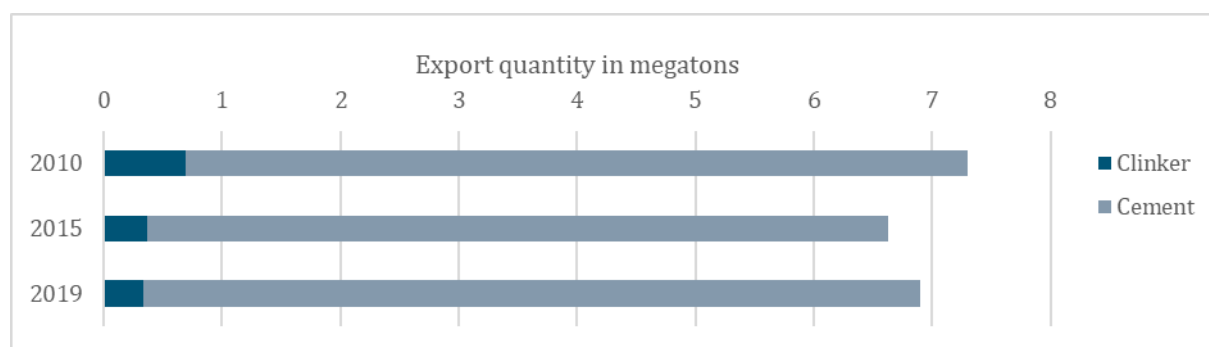
Figure 32: Net export of the cement industry, EU28 2008 to 2019



Source: Eurostat (2020b)

In Figure 33 the exports of the German cement industry covering the products clinker and cement are displayed. Further information about the down-stream products is not provided by the VDZ. Due to the variety of these products, exclusively the trade relevance of the selected products will be outlined in the sections below. In 2019, 0.3 megatons clinker and 6.6 megatons cement were exported from Germany. Even though the export quantity increased compared to 2015, the export quantity in 2010 were highest (Destatis, 2021b).

Figure 33: Export of the cement industry, Germany 2010, 2015 and 2019

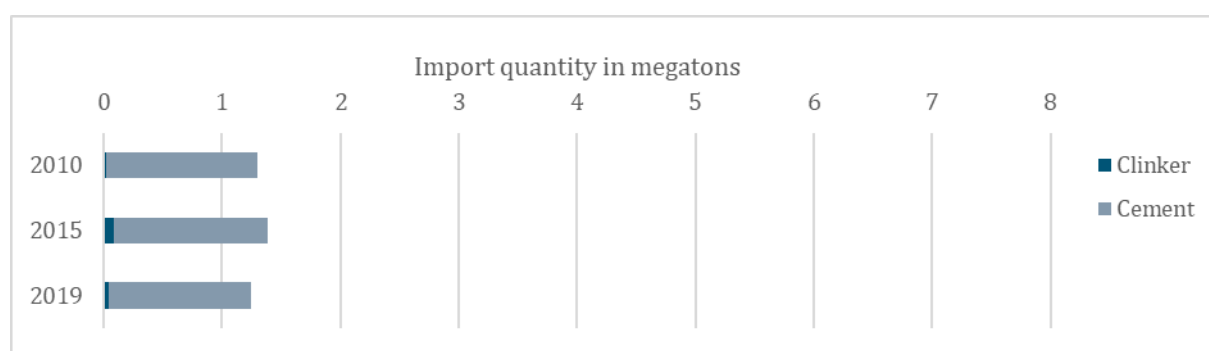


Source: Destatis (2021b)

The imports of cement and clinker are significantly lower than the exports as shown in Figure 34. Consequently, the German cement industry is currently a net exporter of clinker and cement. Additionally, it is apparent the imports were highest in 2015 and lower in 2010 and 2019⁷⁰. In 2019, about 0.1 megatons clinker and 1.2 megatons cement were imported (Destatis, 2021b).

⁷⁰ In 2015, 31.2 Mt cement and 23.4 Mt clinker were produced in Germany (see Figure 27).

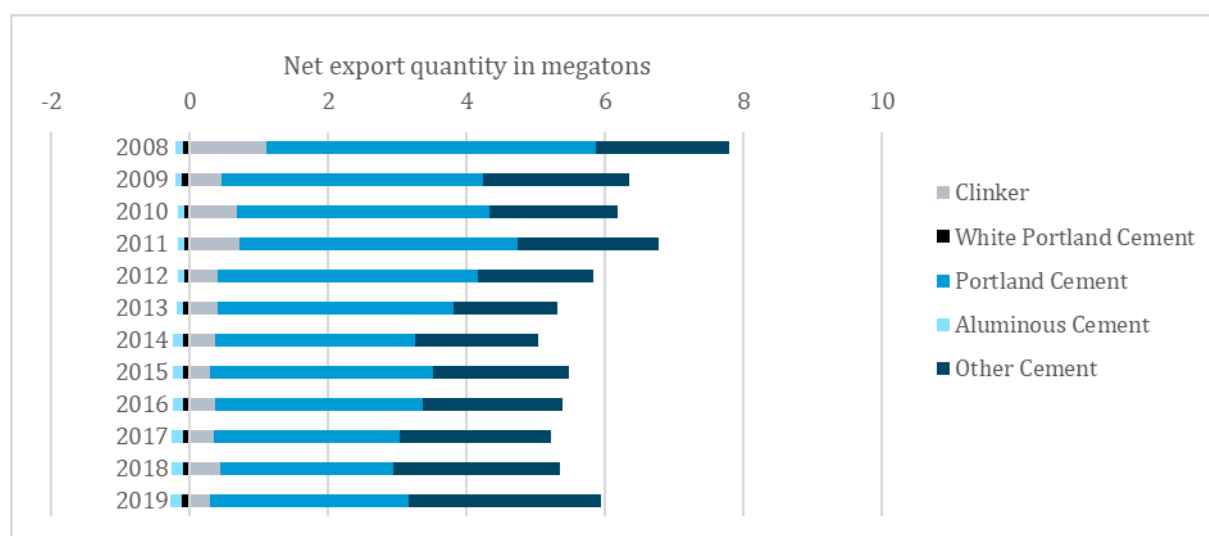
Figure 34: Import of the cement industry, Germany 2010, 2015 and 2019



Source: Destatis (2021b)

The net exports of the German cement industry for clinker and different cement types are additionally displayed in Figure 35. Despite smaller fluctuations, the overall trade balance is declining slightly since 2008. Exclusively for White Portland Cement and Aluminous Cement marginal net imports can be observed continuously. In comparison to the EU, clinker has a lower net export relevance (Destatis, 2021b).

Figure 35: Net export of the cement industry, Germany 2008 to 2019



Source: Destatis (2021b)

To establish a common base for the assessment of the economic relevance of the selected products the EU statistic Prodcom is used. This ensures comparability with the key economic indicators of iron and steel in section 2.3.4. Furthermore, this enables the more specific addressing of the relevant products (Clinker, CEM I, CEM II, CEM III-V, Precast Concrete, Transport Concrete). However, the allocation of the cement types covered in Prodcom to the cement types CEM I, CEM II and CEM III-V used in the material flow model is not possible (European Commission & DG GROW, 2018). Hence, the economic indicators for Cement Clinker, Portland Cement, Other Hydraulic Cement, Precast Concrete and Transport Concrete are summarised for the year 2015 on the next pages. Particular attention should be paid to the average export and import prices in comparison to the market prices in section 2.4.8.3 and to the revealed comparative advantage (RCA). Positive RCA values indicate specialization advantages, negative RCA values specialization disadvantages (see section 2.3.1 for further information).

Table 38: Overview of trade indicators, EU27+UK 2015

	Export in Mt	Import in Mt	Net export in Mt	Export in €	Import in €	Net export in €	Average export price in €/t	Average import price in €/t	RCA
Cement Clinker	10.28	1.04	9.24	426,842,200	77,147,460	349,694,740	41.53	74.39	5.33
Portland Cement	12.79	1.45	11.34	671,782,710	103,689,950	568,092,760	52.51	71.55	6.24
Other Hydraulic Cement	0.58	0.10	0.48	103,900,670	20,514,840	83,385,830	179.09	206.73	4.88
Precast Concrete*	0.70	0.09	0.61	208,183,700	30,136,460	178,017,240	297.42	333.73	6.66
Transport Concrete**	0.52	0.01	0.51	25,700,460	864,590	24,835,870	49.16	103.41	28.65
*considered product group: Prefabricated Structural Components									
**considered product group: Ready-mix Concrete									

Source: Eurostat (2020b)

Table 39: Overview of trade indicators, Germany 2015

	Export in Mt	Import in Mt	Net export in Mt	Export in €	Import in €	Net export in €	Average export price in €/t	Average import price in €/t	RCA
Cement Clinker	0.37	0.08	0.28	17,116,360	4,153,280	12,963,080	46.73	50.65	3.27
Portland Cement	4.12	0.99	3.13	288,495,700	71,871,960	216,623,740	70.10	72.75	3.18
Other Hydraulic Cement	2.15	0.32	1.83	160,515,110	87,871,970	72,643,140	74.79	274.38	1.45
Precast Concrete*	1.16	0.77	0.40	297,416,750	120,544,370	176,872,380	255.94	157.22	1.96
Transport Concrete**	0.66	0.10	0.56	22,151,340	4,456,930	17,694,410	33.58	46.62	3.94
*considered product group: Prefabricated Structural Components									
**considered product group: Ready-mix Concrete									

Source: Eurostat (2020b)

Table 40: Overview of the trade indicators, Germany 2015

	Export in Mt	Import in Mt	Net export in Mt	Export in Euro	Import in Euro	Net export in Euro
Cement Clinker	0.37	0.08	0.28	17,118,000	4,150,000	12,968,000
Portland Cement*	4.12	0.98	3.13	288,491,000	71,863,000	216,628,000
Other Hydraulic Cement**	2.15	0.32	1.83	160,513,000	87,875,000	72,638,000
*considered product groups: White Portland Cement and Portland Cement						
**considered product groups: Aluminous Cement and Other cement						

Source: Destatis (2021b)

2.4.8.2 Cost structure

For the assessment of the cost structure of the selected products (Clinker, CEM I, CEM II, CEM III-V, Precast Concrete, Transport Concrete) the costs of the cement industry are summarised based on a literature research. This research has shown that product-specific data are hardly available. Hence, an overview of the available data will be given and compared. This is the foundation for assumptions about the cost structure of the selected products.

An earlier version of the report providing the information about the cost structure of the selected steel products (see section 2.3.4.2) includes information about the cost structure of the cement industry in the EU in 2012 as well (Moya et al., 2016). About 94% of the cement production of plants in the EU are considered in this cost assessment. Thus, specific information for the EU is provided neglecting country specific differences. While the costs of the clinker production are not mentioned specifically, they are considered as raw material cost. Nevertheless, Moya et al. (2016) focus on an ex-factory assessment, thus, neglecting capital costs. Furthermore, production costs for Precast Concrete and Transport Concrete are not mentioned (Moya et al., 2016). A more current assessment of the cost structure in the EU cement industry has been made in a study of the European Commission in 2018. To assess the competitiveness of the cement sector 17 cement producers were surveyed regarding their production costs. Again, the clinker production costs were considered as raw material costs and the costs of further processing were not evaluated. In contrast to Moya et al (2016), financing costs were considered in this analysis (European Commission & DG GROW, 2018). Both studies are compared in Table 41.

Table 41: Cost structure of the cement industry in the EU: % of total costs [value per ton]

	Cement industry, EU 2012	Cement industry, EU 2017
Labour and other in % of total cost	49 [23.70 €/t]	62*
Raw materials in % of total cost	15 [7.20 €/t]	14
Energy in % of total cost	36 [17.10 €/t]	24
Total in % of total cost	100 [48.00 €/t]	100
Source	Moya et al. (2016)	European Commission & DG GROW (2018)
Confidence	Low/ medium	Low/ medium

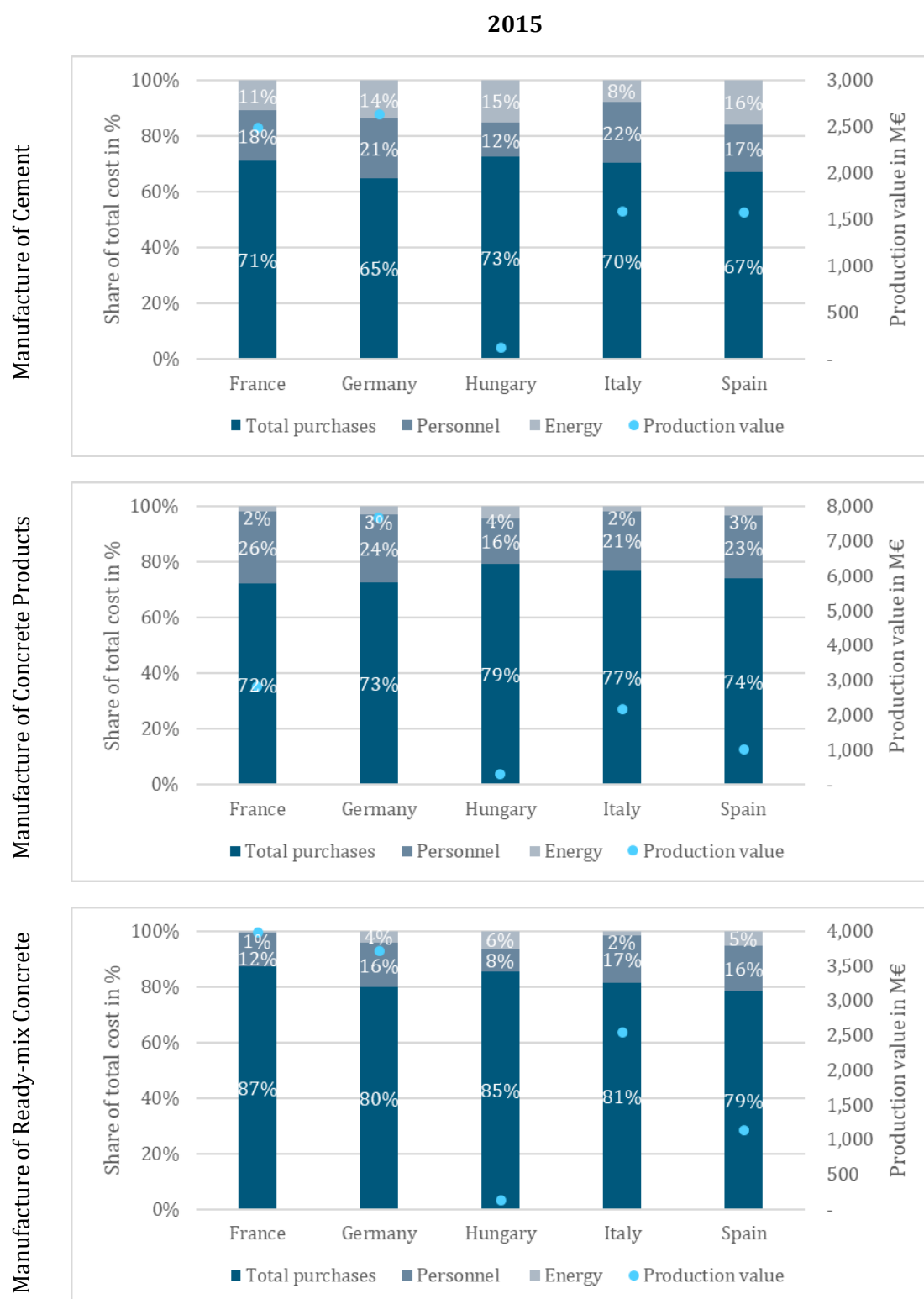
*including maintenance cost, other material cost, financing cost and other cost

For the further assessment of the data quality of both sources, they are compared with the cost structure provided by the Structural Business Statistics from Eurostat. For the comparison, the major cost components (total purchases of goods and services, personnel costs, purchases of energy products) as well as the total production value⁷¹ from five EU Member Countries are summarised. The five countries (France, Germany, Hungary, Italy, and Spain) have been selected based on the data availability and to obtain a regional heterogeneity. Similar to Moya et al. (2016), the capital costs are not covered by this analysis. The illustration differentiates between the base year 2015 and the most current covered year, 2018. The subsectors Manufacture of Cement (incl. clinker and cement), Manufacture of Concrete Products for Construction Purposes

⁷¹ According to the Structural Business Statistics from Eurostat, the total production value is defined as the amount actually produced. For this, the profit is deducted from the turnover of an industry (Eurostat, 2021).

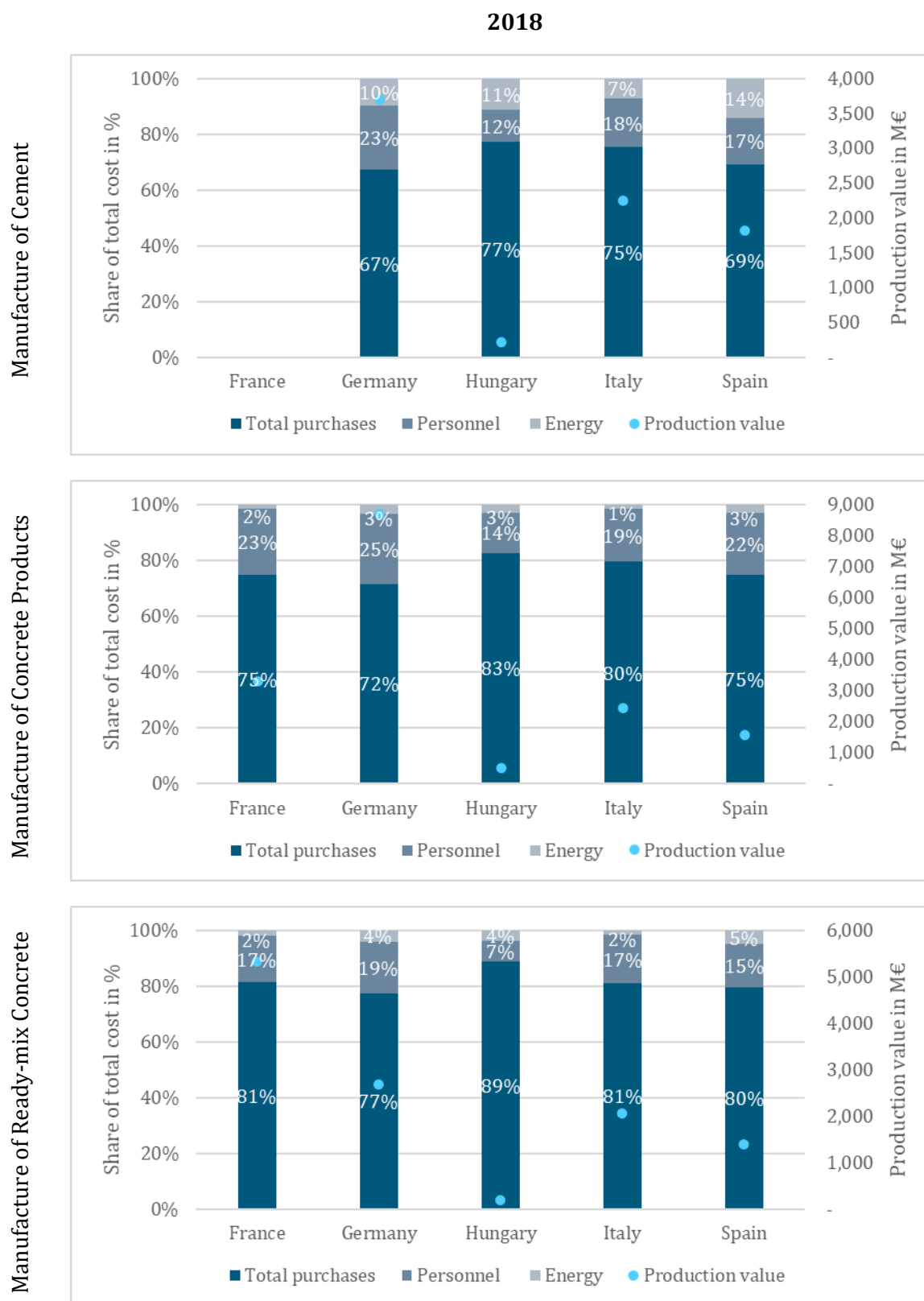
(incl. precast concrete) and Manufacture of Ready-mix Concrete (incl. transport concrete) are covered. The data are summarised in Figure 36 and Figure 37.

Figure 36: Cost structure of the subsectors in the cement industry, selected EU countries 2015



Source: Eurostat (2021)

Figure 37: Cost structure of the subsectors in the cement industry, selected EU countries 2018 (no data available for Manufacture of Cement in France)



Source: Eurostat (2021)

2.4.8.3 Market prices

Similar to the iron and steel industry the availability of information about the market prices of the selected products (Clinker, CEM I, CEM II, CEM III-V, Precast Concrete, Transport Concrete) is limited. However, the following section summarizes and compares available sources. Different methodological approaches on the EU and the national level are applied for this assessment.

For an initial assessment of the price scale, the same two reports providing information about the cost structure of the cement industry contribute estimates for the price of clinker and cement on the EU level. Moya et al. (2016) are indicating an average clinker price of 20.50 EUR per tonne and an average cement price of 73.30 €/t in 2012. The European Commission & DG GROW (2018) provides exclusively a cement price of 60.00 €/t in 2017. The last report underlines that this is a rough estimate since the sales prices are confidential and vary significantly across the EU. Thus, the EU level and the national level will be assessed separately in the following.

For the evaluation of the available data on the EU level, the average export and import prices (incl. intra- EU trade) as well as the ratio of production value and production quantity derived from Prodcom can be compared with the prices for clinker and cement. Additionally, this information can be generated for the products Precast Concrete and Transport Concrete⁷². An overview for the years 2012 and 2017 as well as the base year of this report, 2015, is given in Table 42.

Table 42: Price estimates for the cement industry, EU27+UK 2012, 2015 and 2017

	2012	2015	2017
<i>Clinker</i>			
Average export price in €/t	39.68	41.53	34.78
Average import price in €/t	67.64	74.39	64.67
Average product value in €/t	39.39	40.65	35.76
<i>Portland Cement</i>			
Average export price in €/t	55.01	52.51	52.25
Average import price in €/t	69.18	71.55	68.50
Average product value in €/t	74.27	72.78	70.99
<i>Other Hydraulic Cement</i>			
Average export price in €/t	146.05	179.09	129.97
Average import price in €/t	260.00	206.73	287.48
Average product value in €/t	80.01	81.80	80.11
<i>Precast Concrete</i>			
Average export price in €/t	276.72	297.42	309.78

⁷² Precast Concrete and Transport Concrete are represented by the Prodcom products Prefabricated Structural Components (PRC code 23611200) and Ready-mix Concrete (PRC Code 23631000).

	2012	2015	2017
Average import price in €/t	310.30	333.73	273.97
Average product value in €/t	136.67	187.50	166.67

Transport Concrete

Average export price in €/t	36.01	49.16	44.80
Average import price in €/t	64.12	103.41	137.85
Average product value in €/t	33.12	33.54	32.88
Source	Eurostat 2020b	Eurostat 2020b	Eurostat 2020b
Confidence	Medium	Medium	Medium

Prodcom provides the same information on the national level. Based on the data availability the base year 2015 and the most current year 2019 are assessed in Table 43.

Table 43: Price estimates for the cement industry, Germany 2015 and 2019

	2015	2019
--	------	------

Clinker

Average export price in €/t	46.73	46.47
Average import price in €/t	50.65	85.15
Average product value in €/t	36.98	40.75

Portland Cement

Average export price in €/t	70.10	74.42
Average import price in €/t	72.75	76.44
Average product value in €/t	66.03	70.33

Other Hydraulic Cement

Average export price in €/t	74.79	70.35
Average import price in €/t	274.38	276.45
Average product value in €/t	68.59	67.66

Precast Concrete

Average export price in €/t	255.94	252.85
Average import price in €/t	157.22	171.13
Average product value in €/t	No data available	153.17

	2015	2019
<i>Transport Concrete</i>		
Average export price in €/t	33.58	38.80
Average import price in €/t	46.62	48.81
Average product value in €/t	No data available	No data available
Source	Eurostat 2020b	Eurostat 2020b
Confidence	Medium	Medium

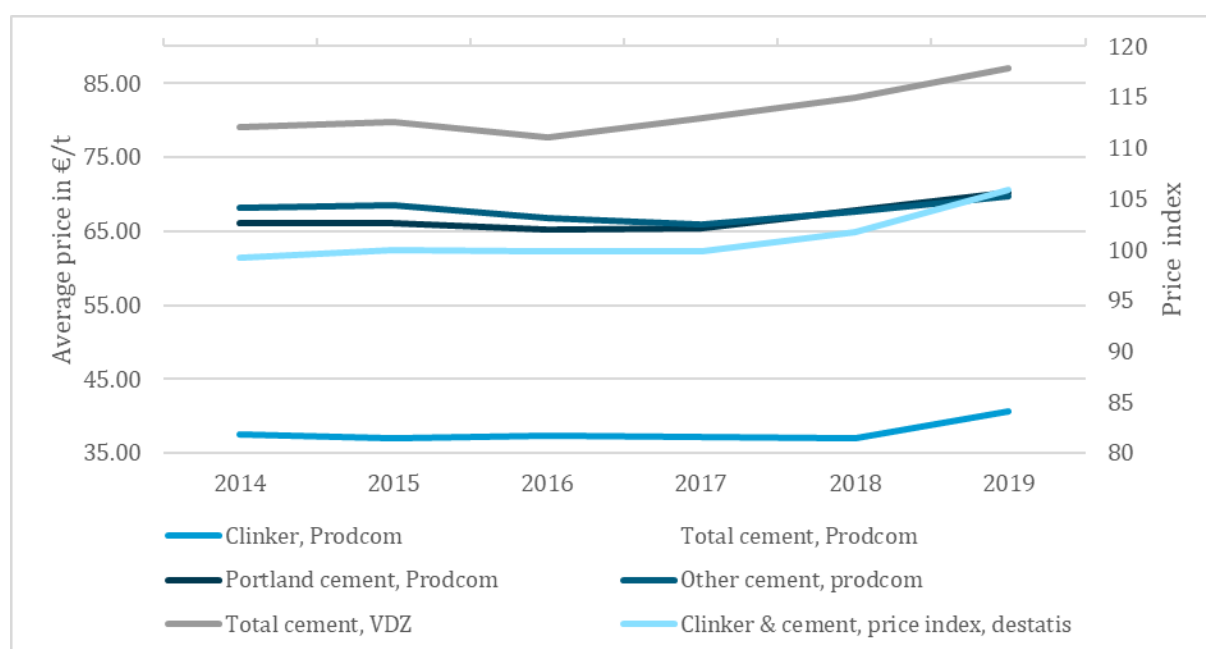
These price estimates can be compared with average sales per tonne provided by the industry association VDZ and BTB. Information about Clinker prices as well as the price for Precast Concrete is not provided by the associations. Additionally, the cement types are aggregated. An overview is given in Table 44.

Table 44: Price estimates for the cement industry, Germany 2015 and 2019

	2015	2019
<i>Clinker</i>		
Average sales in €/t	No data available	No data available
<i>Cement</i>		
Average export price in €/t	79.85	87.11
<i>Precast Concrete</i>		
Average export price in €/t	No data available	No data available
<i>Transport Concrete</i>		
Average export price in €/t	68.98	77.59
Source	BTB 2020; VDZ 2020	BTB 2020; VDZ 2020
Confidence	medium	medium

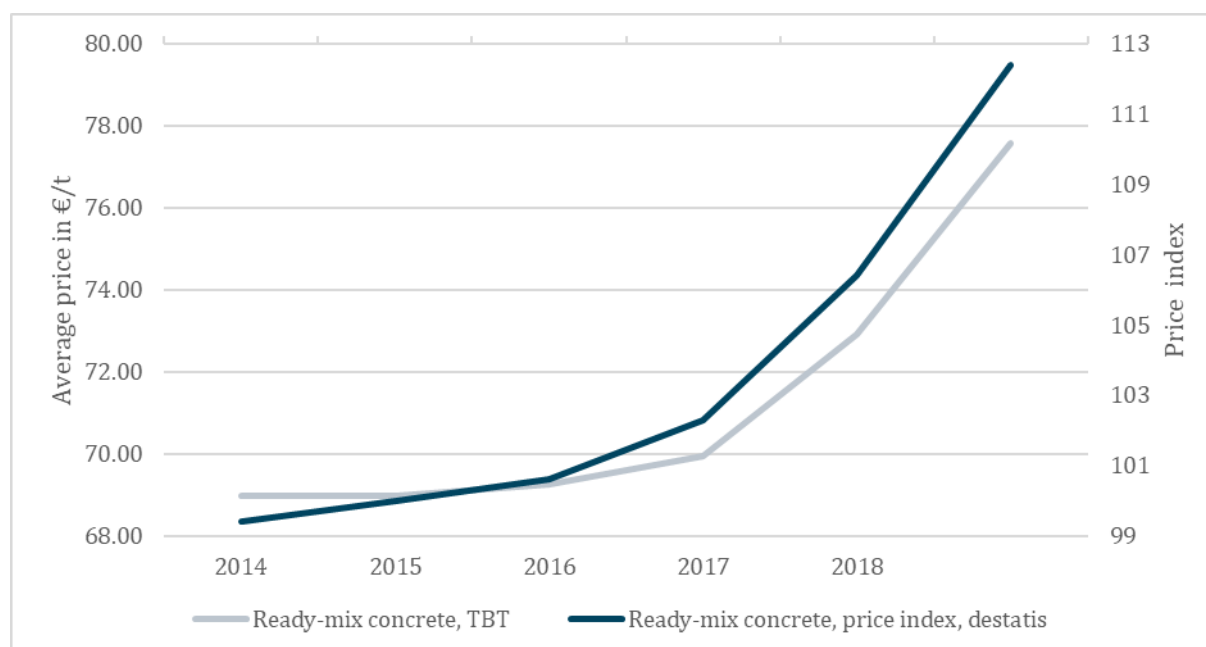
For a better classification of the price estimates, they can be compared with the general price development in the year 2014 to 2019. For this purpose the price index of the subsectors Manufacture of Cement and Manufacture of Ready-mix Concrete as well as the price estimates for the relevant product groups derived from Prodcom, the VDZ and the BTB are shown in Figure 38 for Clinker and Cement and in Figure 39 for Transport Concrete. As expected, the price estimates based on sales provided by the industry associations correspond with the price index.

Figure 38: Price estimates and price index for clinker and cement, 2014 to 2019



Source: Eurostat (2020b); Destatis (2021b); Destatis (2021a)

Figure 39: Price estimate and price index for transport concrete, 2014 to 2019

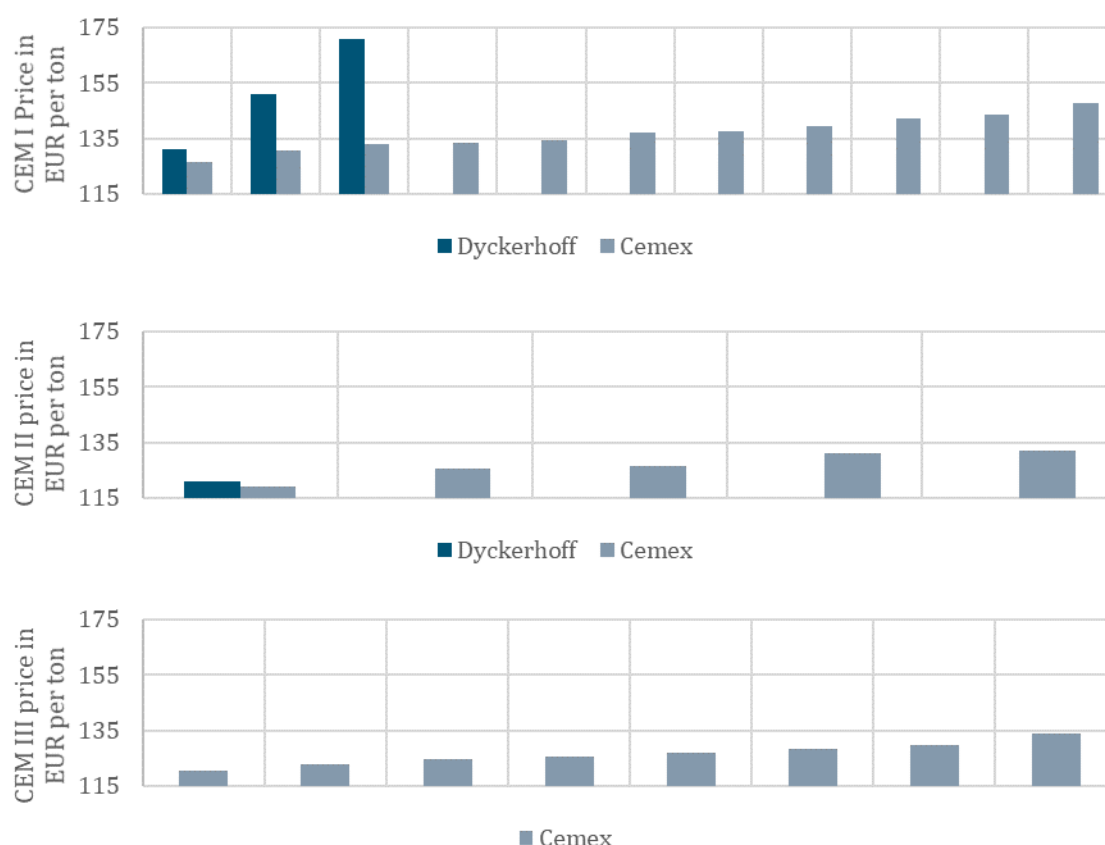


Source: BTB (2020); Destatis (2021a, 2021b)

Additional information can be derived from supplier price lists. For this purpose, the availability of price lists from the six cement producers with the highest sales share in Germany are assessed. Again, no information about the clinker prices were available. A single price list for pre-cast concrete supports our conclusion above in the cost structure assessment, determining significant variations depending on the actual use case (Bundeskartellamt, 2017). Thus, 28 cement prices covering three different cement types (CEMI, CEMII, CEMIII) from two producers

(Dyckerhoff, Cemex) as well as 89 prices for a proxy Transport Concrete⁷³ from six producers (HeidelbergCement, Holcim, Schwenk, Dyckerhoff, Opterra, Cemex) are assessed. Due to the data availability the years 2020 and 2021 are considered. The cement prices are displayed in Figure 40, where each bar represents a different price for a cement type within the CEM I-CEM III categories. For example, the prices for CEM I from Dyckerhoff vary between 131 €/t and 171 €/t and from Cemex between 126.50€ and 147.50 €/t.

Figure 40: Supplier prices for Cement, Germany 2020 and 2021.

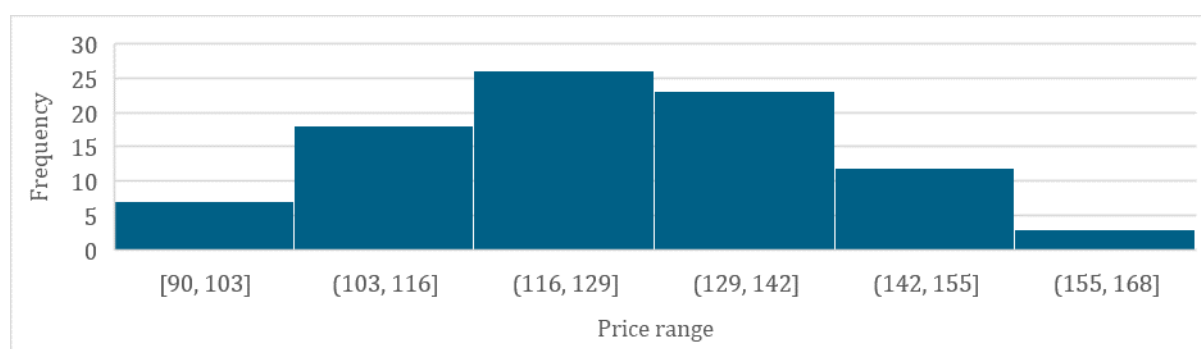


Source: see Annex B

It is apparent that the prices for cement vary. This is particularly the case for CEM I. A detailed review of the price lists has shown a possible reasoning: the regionalization of prices. This has also been confirmed during an investigation by the German Federal Cartel Office in 2017. The same is assessed for Transport Concrete (Annex B). The distribution of the prices of Transport Concrete in 2020 and 2021 is shown as a histogram in Figure 41. Most significant in the comparison of the statistical price estimates listed above, and the supplier prices is that the supplier prices are significantly higher - both for Cement and for Transport Concrete.

⁷³ XC1/XC2 C20/25 F3 32 M or similar

Figure 41: Supplier prices for transport concrete, Germany 2020 and 2021



Source: see Annex B

2.4.9 Summary and Conclusions

We find a (non-surprising) high relevance of clinker production and clinker share in cement and specific emission factors (Table 36 and Table 37). The clinker share in the final products (differentiated by CEM-type and, related, by end use) thus strongly impacts the embedded GHG-emissions in mass-equivalent concrete end uses. With the data used in this analysis, we find a 40-50% higher emission factor for pre-cast compared to transport concrete. This is mainly caused by the higher clinker share in pre-cast concrete (coded in the use of CEM I rather than CEM II and CEM III) and higher cement share in the concrete. While the higher clinker share is also used to increase hardening and thus throughput of pre-cast element production, it effectively increases the service the product provides in buildings. The results presented here do not justify the conclusion that the use of pre-cast should be reduced to reduce emissions. For such an assessment, it would be necessary to investigate the actual applications in buildings and determine whether the increased specific strength and other advantages (see 3.3.6.4) outweigh the higher specific emissions per tonne of concrete. In this respect, even a GHG emission related assessment would have to address the use, and end-of-life phases within the respective applications in addition to the production phase, as undertaken in this report. These considerations would have to be combined with a general evaluation of the available and suitable building materials as concrete is a carbon-intensive one in any case.

The results derived from the model are largely confirmed with indicators (e.g. emissions per tonne of cement) from public statistics. However, due to several uncertainties caused by data availability and heterogeneous uses of cement products, relevant differences to statistics remain. While the general methodology to disaggregate the available statistics thus proved to be successful, a better and more reliable picture of the industry could be achieved with more detailed, complete and harmonized statistics.

2.5 Non-ferrous metals

The non-ferrous metals manufacturing industry is a very diverse industry that processes different materials such as copper, aluminium, lead, nickel, magnesium, zinc, but also precious and other minor metals. It provides solutions for various important sectors such as electronics, automobile industry, transport equipment, energy production, construction, and batteries. Aluminium and other non-ferrous metals are widely used for their specific properties, such as the absence of magnetism, resistance to corrosion, recyclability and durability. In this study, the focus of the research lies solely on Aluminium production.

Non-ferrous metals have a production chain that begins with the extraction of the ore at the mines and the preparation of concentrates. This is followed by smelting and refining, where the

concentrates are treated with the aim of separating the pure metals. Then, the metals are processed into semi-finished and finished products. In addition, the cyclicity of the metals must be considered: after the use phase they can be collected, treated and refined into secondary raw material (Wyns & Khandekar, 2019).

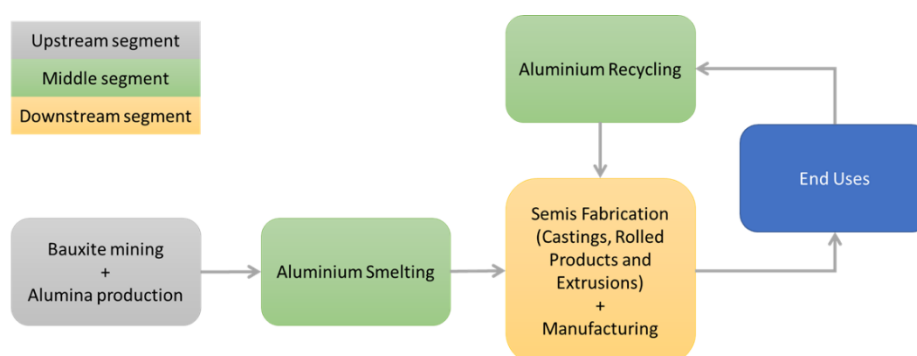
The non-ferrous metals extraction industry is small in Europe, therefore metal production depends largely on imports of the minerals as the raw material, importing around 84% for aluminium (bauxite), 82% for copper, 78% for tin, 71% for zinc (concentrate), 48% for cobalt. As an exemption, lead imports only 18% of their raw material. However, in the European context, bauxite is the most extracted material (Wyns & Khandekar, 2019).

2.5.1 Production overview

Aluminium is, after steel, the most used metal. It is highly used because it contributes to weight reduction in transportation vehicles, as a building material with a long life, and because it is a highly recyclable light metal (density of 2.7 kg/dm³ at room temperature) with good corrosion properties. It can be re-melted and reused with only little degradation times without losing its properties (density, conductivity, formability, durability, permeability). In the aluminium production industry, there are 600 plants (small and medium sized companies) all over Europe. This industry employs more than 1 million people and generates about 40 billion € annually.

The aluminium production can be summarised in three large segments (see Figure below) according to the OECD (2019): the upstream segment, which comprises the extraction of bauxite ending with its refining into alumina; the middle segment, which involves the production of primary aluminium and secondary aluminium (aluminium scrap recycling); and the downstream segment, which comprises the production of semi-fabricated aluminium products ('semis') and their use in the manufacturing of products, such as automotive, construction, packaging or consumer goods.

Figure 42: The aluminium production chain: stages of processing



Source: Bertram et al. (2017 (simplified))

Only primary aluminium production involves refined bauxite ore into alumina (aluminium oxide), and the subsequent conversion of alumina into pure aluminium. To produce one tonne of aluminium, 2 t alumina derived from 4 to 5 t of bauxite are required (Wyns & Khandekar, 2019). The Bayer's process is the most common for producing alumina from bauxite. The Hall-Heroult process is the subsequent electrochemical process to produce primary aluminium from alumina. The Hall-Heroult process, generates most of the direct GHG emissions from all aluminium production (see section 2.5.3.3). It is also the stage that requires the most energy. About 14.79 MWh of electricity are needed to produce one tonne of primary aluminium from alumina (Claisse, 2016).

On the other hand, the production of secondary aluminium (aluminium scrap recycling) requires no alumina and needs 95% less energy when compared to the production of primary aluminium; moreover, scrap-based production tends to cost less than primary production (IEA n.d.). In addition, the recycling process produces only 5% of the GHG generated during primary material production (BVSE, 2019). Although everything made of aluminium can be recycled in principle, what is currently recycled the most are beverage cans. For the latter, a complete and efficient circularity of the material (it takes 60 days to recycle the material based on soda cans) is achieved (Rosenhagen & Höbelmann, 2020). Other products made from aluminium have much longer lifetimes, i.e., the material is much longer bound in stocks.

It should be also considered that during recycling, the quality of the given aluminium scrap can be downgraded but might be also upgraded into very pure products using for example laser induced breakdown spectroscopy, depending on the separation made from scrap aluminium and the alloys⁷⁴ it contains. In the downstream segment, the basic material (primary or recycled aluminium) is processed into semi-finished aluminium products, also called 'semis'. This processing can be carried out through extrusion, rolling or casting and depend on the final uses to which the semi-finished products are destined (Sauvage, 2019).

The main uses and shares of aluminium flows by weight can be structured as follows: Transport (22%); Packaging (23%); Aluminium foil (18%); Construction (11%); Technical application (8%); Consumer goods (4%); and Stockists (15%) (European Aluminium, 2021).

2.5.2 Aluminium flow model: Important concepts

Categorisation of downstream products / intermediates

As shown in the categorisation for Aluminium in section 2.5.1, it is suggested to differentiate further the downstream products including an aggregation of different products in the following categories: flat rolled aluminium products, extruded and casted products. The CO₂ emissions attributable to these products were assessed by assigning common process steps to produce them in Europe.

In this regard, the following assumptions were made: Semis are produced both from primary and secondary metal, available as inputs mostly in the form of aluminium ingots or bars, slabs and billets. These are obtained by downstream companies to produce semis meant for the needs of final use sectors such as automotive, transportation, building and constructions, mechanics, furniture etc.

For the categorisation of the semis, we consulted directly with the European Aluminium Association, resulting in the following specific product classification:

Extrusions: Rods, sections, bars, tubes (and pipes);

Flat-Rolled Products: Sheets, strips, foil;

Castings: Unwrought aluminium alloys;

Others: Powder and flakes, hollow ware, cables, wire and others.

⁷⁴ Aluminium alloys are made by mixing aluminium with various other metals (the so-called alloying elements). Some increase the strength of aluminium, others make it denser, still others change its heat transmission properties, etc. Common alloying elements include boron, iron, silicon, magnesium, manganese, copper, nickel, lead, titanium, chromium, zinc, zirconium, lithium, scandium, silver, and others. In addition, aluminium alloys can include dozens of other alloying elements such as strontium, phosphorous and others, so the total number of possible alloys is very impressive. Today, over 100 aluminium alloys are used in industry (Aluminium Leader, n.d.),

Extrusion means that a solid aluminium cylinder (a billet) is forced by mechanical compression into profiles for use primarily as construction materials (e.g., window and doorframes) or as vehicle components, or processed into wire for the energy sector (e.g., as transmission wires and cables, instead of copper). For this category of products, it was assumed that 60% of primary aluminium is required to produce extrusions, according to experts from the industry. It follows that 40% of extrusions are made from secondary aluminium.

Flat rolling processes basic material aluminium forms into sheets, plates and foils that are subsequently used in the automotive industry (e.g., chassis, car frames and boat hulls), in the aircraft industry (e.g., airplane fuselages), in construction (e.g., roofing) and in beverage and food packaging (e.g., flexible packaging and cans). Flat rolled products are assumed to be produced from similar shares (each 50%) of primary and secondary aluminium. This was discussed with flat rolling experts.

Casting is a manufacturing process in which liquid aluminium is pressed or squeezed under high pressure to produce high-strength parts that can also be used to give aluminium products a number of intricate properties and shapes, for example, for use as wheel rims or as components of small appliances such as lawn mowers and coffee machines (OECD, 2019). Casting products are assumed to be produced from both basic aluminium from primary and secondary aluminium routes at the same share (50:50), according to interviewed experts from the industry.

Alumina and Primary Aluminium

The Bayer process is used for the bauxite refining process. For this, the ore is first crushed and dissolved in hot sodium hydroxide. Then the iron and other oxides are removed as insoluble 'red mud'. The solution is precipitated and goes through a calcination process to produce alumina. The Bayer process is not reflected in the model and the resulting data in this study.

The production route for primary aluminium from alumina is the Hall-Heroult process, an electrolytic process using carbon anodes in the pot lines. The alumina is first dissolved in a cryolite bath, which serves as a eutectic to lower the required melting temperature for the process. The molten bath is subjected to very large amounts of electrical current, reducing the alumina (aluminium oxide) to form liquid aluminium at the bottom of the cell or pot, which is then collected and usually melted down again so it can be brought to its first form for further treatment, i.e. ingots.

The production of primary aluminium is very energy intensive due to the electrolytic process. In average, in Europe the production of Alumina needs 8,977 MJ/t of thermal energy and 141 kWh/t of electricity. The specific CO₂ intensity for the production of Alumina is 542 kg CO₂eq per ton. Primary aluminium production has a very high electricity consumption of 14.79 MWh/t, and a specific CO₂ intensity of ca. 1,638 kg CO₂eq per tonne of liquid metal (European Aluminium, 2021).

Secondary Aluminium

Secondary aluminium production begins with material recovery (aluminium scrap). Here, it is necessary to mention that there are different sources where scrap appears and can be collected: at the manufacturing of semi-finished products, at the manufacturing of final products and when End-of-Life (EOL) of the products is reached. However, as, according to Bertram et al. (2017), it is very difficult to differentiate statistically each of these sources, they will be grouped under the concept of 'old and new scrap' (Bertram et. al., 2017). Once the scrap is collected, it must be classified and separated according to its quality and characteristics. For the material melting process, there are reverberatory and induction furnaces and emerging technologies such as rotary arc and plasma furnaces. The respective choice for one of these furnace types depends on the

characteristics of the input material. The amount of energy used in all these processes, however, is significantly less than that used to produce primary aluminium. In the case of secondary aluminium, the use of electricity per tonne of aluminium produced is 0.12-0.34 MWh/t and specific CO₂eq emissions sum up to 653 kg CO₂eq per tonne (Wyns & Khandekar, 2019).

2.5.3 Key figures of the aluminium industry

2.5.3.1 Material Flow

The objective of the material flow analysis (MFA) for the aluminium industry in Europe and in Germany is manifold. The analysis includes the representation of the production of primary aluminium, secondary aluminium and downstream product categories such as casting, flat rolled products and extrusion. For this study, the following products were identified together with UBA:

1. Castings: unwrought aluminium alloys
2. Flat-Rolled Products: sheets, strips and Foil
3. Extrusions: Rods, sections, bars, tubes and pipes

The category others comprise the following products but are not part of the products considered in this study: Powder and flakes, hollow ware, cables, wire and others. For the year 2015 and for Europe the following data sources were used for our MFA model for Aluminium:

1. Eurostat Production Data (NACE Rev. 2) and Eurostat PRODCOM Data,
2. World Metal Statistics (2017), and Data from the European Aluminium Association,
3. The statistics of the European foundry association (CAEF),
4. Data from Gesamtverband der Aluminium Industrie (GDA) in Germany,
5. The Secondary raw materials (waste streams) report in Germany.

The following Table 46 summarizes the aluminium production, imports and exports for primary and secondary aluminium as well as the downstream/intermediate products selected in this study as classified above. The values are shown for EU27+UK and for Germany for the year 2015 indicating the source as well as the confidence on the data. Table 46 also indicates the end-consumer sectors for products, both for flat-rolled and extruded products.

Interviews and discussions on data available for modelling as well as on the specifics of the products and the scrap market were conducted with the following institutions and experts listed in Table 45.

Table 45: Interviews on aluminium data

Name	Institution
Bob Lamrechts, Djibril René	European Aluminium
Dr. Andreas Postler	GDA, German Aluminium Association
Tobias Renning, Dr. Fynn-Willem Lohe	BD Guss und CAEF
Linlin Wu, Marlen Bertram, Nadine Faldo	World Aluminium

Source: IREES (2020)

Table 46: Data used for the aluminium material flow model

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Primary	2,155	541	kt	P	GDA	GDA	High
Primary	6,926	2,190	kt	I	WBMS	WBMS	High
Primary	3,271	324	kt	E	WBMS	WBMS	High
Secondary	5,292	446	kt	P	WBMS	WBMS	High
Secondary	1,599	1,039	kt	I	WBMS	WbMS	High
Secondary	2,034	398	kt	E	WBMS	WBMS	High
Castings	2,916*	1,059*	kt	P	CAEF	GDA	High
Castings	n/a	n/a	kt	I	-	-	n/a
Castings	n/a	n/a	kt	E	-	-	n/a
Flat rolled	4,799*	1,841*	kt	P	EUSTAT	GDA	High
Flat rolled	3,733	1,363	kt	I	WBMS	WBMS	High
Flat rolled	3,045	1,415	kt	E	WBMS	WBMS	High
Extrusions	2,953*	595*	kt	P	EUSTAT	GDA	High
Extrusions	1,890	573	kt	I	WBMS	WBMS	High
Extrusions	1,660	287	kt	E	WBMS	WBMS	High
Scrap back-flow fr. production	2,259	413	kt	P	Assumption	WBMS	Medium/High
Flat rolled transport	1,207	393	kt	P	EU Alumin.	EU Alumin.	High
Packaging	1,207	393	kt	P	EU Alumin.	EU Alumin.	High
Foilstock	988	322	kt	P	EU Alumin.	EU Alumin.	High
Construction	604	197	kt	P	EU Alumin.	EU Alumin.	High
Technical appliances.	439	143	kt	P	EU Alumin.	EU Alumin.	High
Consumer goods	219	72	kt	P	EU Alumin.	EU Alumin.	High
Stockists	823	268	kt	P	EU Alumin.	EU Alumin.	High
Other	-	-	kt	P	EU Alumin.	EU Alumin.	High
Extrusion transport	764	211	kt	P	EU Alumin.	EU Alumin.	High
General Engineering	318	88	kt	P	EU Alumin.	EU Alumin.	High

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Electrical Engineering	127	35	kt	P	EU Alumin.	EU Alumin.	High
Construction	1,241	344	kt	P	EU Alumin.	EU Alumin.	High
Consumer goods	127	35	kt	P	EU Alumin.	EU Alumin.	High
Stockists	446	123	kt	P	EU Alumin.	EU Alumin.	High
Other	159	44	kt	P	EU Alumin.	EU Alumin.	High
Old scrap	3,193	300	kt	P	Assumption	WBMS	Medium/High

P: Production, E: Export, I: Import, WBMS: World Metal Statistics (2017), CAEF: The European Foundry Association (2020), GDA: Gesamtverband der Aluminiumindustrie (n.n.), EUSTAT: Eurostat (2020b), EU Alumin.: European Aluminium (2021), *: Values adjusted, normalized based on primary/secondary aluminium production

For the year 2015, the imports of primary aluminium were 3.2 times as high as the EU production, and the exports of primary aluminium were 1.5 times as high as the domestic production, which means that, in a net balance, primary imports are used as trade goods. In Germany, the imports share of primary aluminium was over 4 times higher than the production in Germany, while exports represented 60% of the produced amount in Germany.

The production of secondary aluminium in Europe approached the 5.3 Mt mark for EU27+UK and over 440,000 t for Germany in the year 2015. The imports of secondary aluminium to the EU amounted to 1.6 Mt while for Germany this number was 1 Mt. Secondary aluminium exports from the EU amounted slightly over 2 Mt.

The products for this study are grouped in three product bundles, as described above: castings, flat rolled products and aluminium extrusions. The numbers from the table above show the following: Castings' production in Europe slightly goes over 2.9 Mt, while in Germany castings' production surpasses 1 Mt in 2015. The production of flat rolled products represents the highest quantity in Europe for the analysed product groups with 4.8 Mt while in Germany it amounts to 1.8 Mt. The manufacturing of aluminium extrusion products has been estimated to be 3.0 Mt in Europe and almost 600,000 t for Germany. Unfortunately, data on casting imports and exports has not been found in Europe or in Germany. Therefore, the respective flows are not represented in the material flow analysis. Exports of flat rolled products are two times higher in Europe (3 Mt) when compared to Germany (1.4 Mt). The imports from extrusion in Europe reached 1.9 Mt in 2015 and for Germany almost 575,000 t, slightly below the amount produced in Germany. Exports in Europe amounted up to 1.7 Mt of extrusions while almost 290,000 t of exports for Germany.

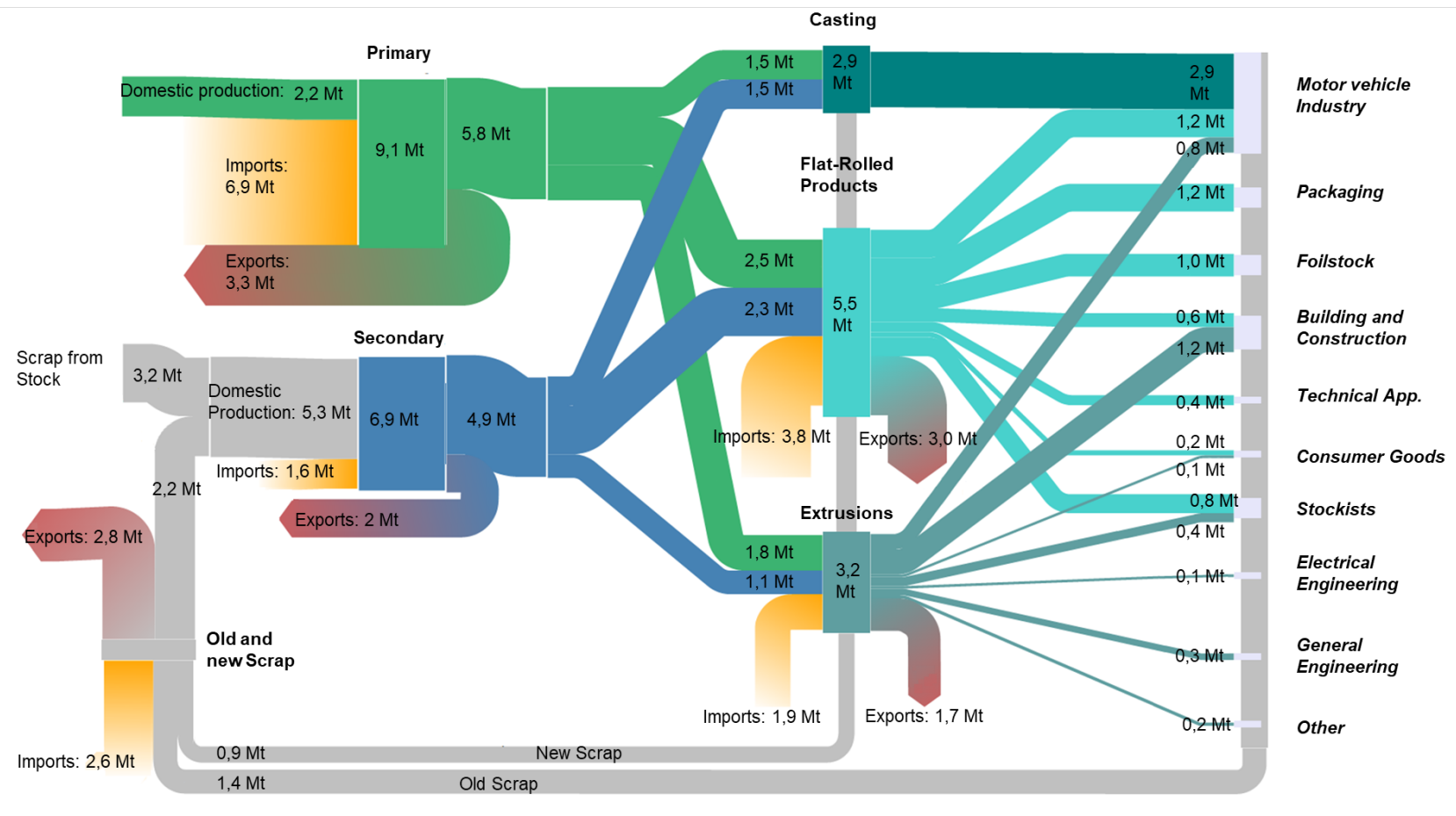
The main results of the material flow analysis are presented in the figures below. The material flow for aluminium in the EU27+UK as of 2015 (see Figure 43) and in Germany (see Figure 44) display the domestic production and the inputs and outputs of imports and exports along the aluminium value chain including primary, secondary, intermediate products and the final consumer sectors. As different sources had to be used for relevant data for this material flow analysis, all flows have been normalized on the basis of quantities for primary and secondary production to ensure consistency of the material flows. This comes along with uncertainties. When balancing the total quantities of the basic material produced with imports and exports, there is a total of 5.8 million tons primary aluminium plus nearly 4.9 million tons of secondary aluminium

available in the EU to produce ETS downstream products. These 10.7 million tons of basic aluminium available, according to the material model, are allocated to the production of product groups as follows for the case of the EU27+UK in 2015: castings 27.3%, flat rolled products 45% and extrusions 27.7%. Primary aluminium alone is allocated as follows: castings 26%, flat rolled products 42.7% and extrusions 31.3%. For secondary aluminium alone, the allocation is as follows: castings 29%, flat rolled products 47.7% and extrusions 23.3%. To derive these allocations, the sources regarding material volumes given in Table 46 were used, weighted with an assumption for typical usage of primary and secondary aluminium for the production of the respective intermediates, and then normalised using the import/export balance for primary and secondary aluminium, respectively.

To produce secondary aluminium, both for the EU27+UK and for Germany, the flows of scrap from the production of semi-finished products (new scrap) and from end uses (old scrap) were considered and differentiated. When balancing the imports and exports of secondary aluminium (scrap remelting) with internal production, an assumption had to be made regarding the existence of an additional flow from a scrap stock, which is considered as an extra input of scrap to the flow of material available in the market.

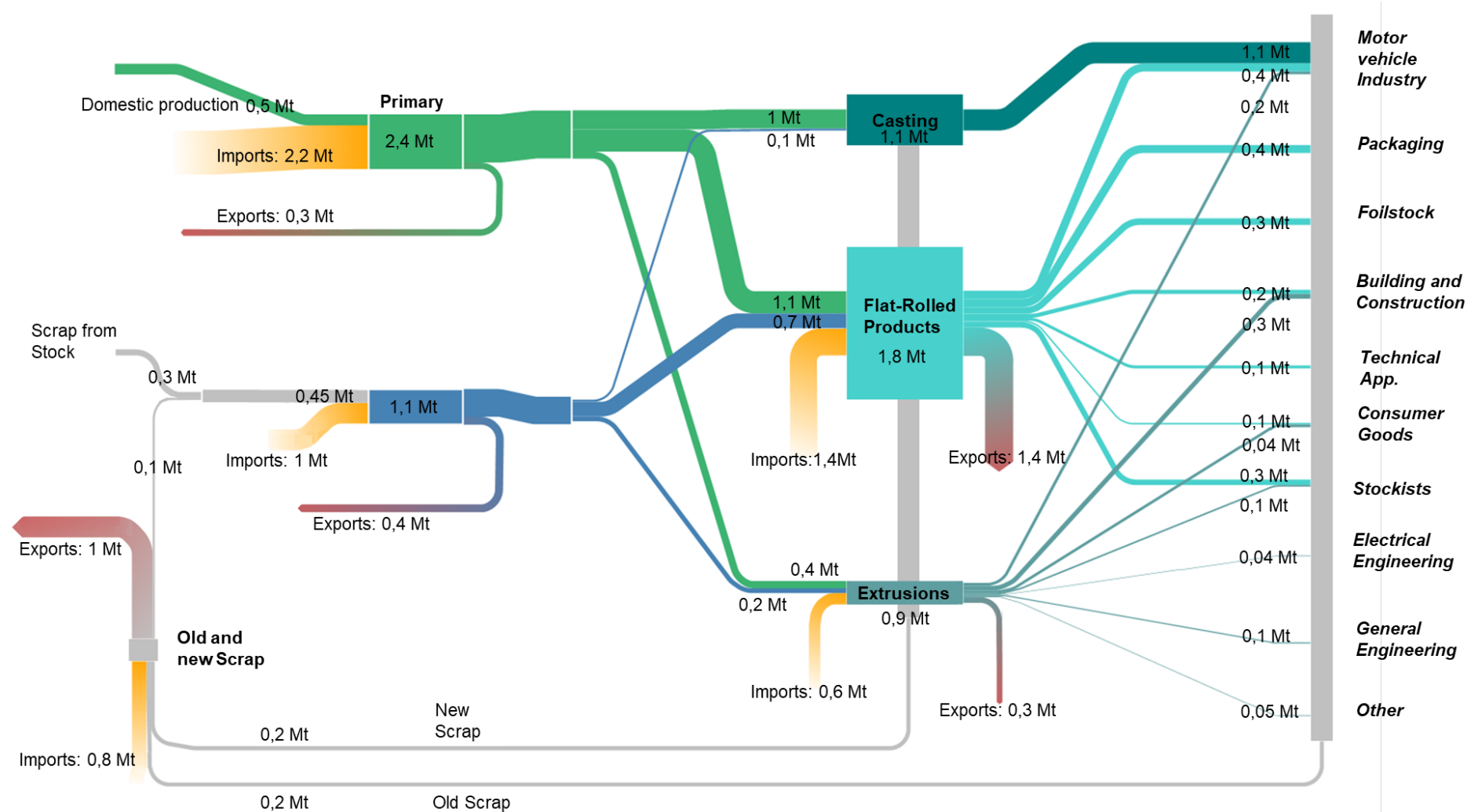
In the case of the EU27+UK, a percentage close to 1% is recovered from the production of semi-finished products and a percentage close to 10% from final uses, which amounts to 2.2 Mt of scrap. The flows of imports and exports are nearly cancelling out each other and the main entry is that of the stock of scrap, which amounts up to 3.2 Mt. In the case of Germany, a percentage close to 6% is recovered from the production of semi-finished products and the same percentage from final uses, which adds up to 0.4 Mt. The flows of imports and exports leave a negative balance, the main entry of material being that of the assumed additional stock of scrap, which is 0.3 Mt. In both cases, as for the EU27+UK and Germany in 2015, the end uses of castings are mainly concentrated in the automotive industry segment. The same is true for flat-rolled products: the flow of material is mainly distributed among the motor vehicle industry, packaging, foils and warehousing. Finally, extrusions, the main use being construction and, to a lesser extent, the motor vehicle industry and warehouses according to the estimations of the European Aluminium Association and the German Aluminium association.

Figure 43: Modelled material flow aluminium, EU27+UK 2015



Source: own calculation

Figure 44: Modelled material flow aluminium, Germany 2015



Source: own calculation

2.5.3.2 Final energy demand

In accordance with the expert interviews with the EU Aluminium and German Aluminium associations, the best available data for the average production conditions along the complete aluminium value chain are the updated environmental and life cycle inventories for the EU from February 2018, related to the conditions of the production in Europe for products including the ones considered here, as well as for other products containing aluminium. The 2018 update also includes the various environmental and LCA inventories databases related to the aluminium production processes in Europe, which are representative for the datasets used for this study.

It is important to note that EU Aluminium data is being prepared for their members and their own process steps. This data have been updated in 2018 to the most up-to-date average data available for these processes, and EU Aluminium have recommended us to use this data for this EU wide analysis. Older literature data should be disregarded, as they may not represent the current status quo of the industry due to technological improvements, progress in operating performance, changes with regard to raw materials or waste treatment etc. (European Aluminium 2018).

The LCA report is targeting mainly LCA practitioners (e.g. policy consultants and database providers), companies along the aluminium value chain (aluminium producers, customers or suppliers), research entities (universities, environmental agencies) or any other stakeholders interested to have accurate environmental data related to aluminium industry performance in Europe.

Table 47: Production data used in the model to calculate final energy demands.

Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Primary	2,155	541	kt	P	EU Alum./GDA	GDA	High
Secondary	5,292	446	kt	P	WBMS	WBMS	High
Castings	2,916	1,059	kt	P	CAEF	GDA	High
Flat Rolled	4,799	1,841	kt	P	EUSTAT	GDA	High
Extrusions	2,953	595	kt	P	EUSTAT	GDA	High
Scrap flows fr. production	2,259	413	kt	P	Assumption	WBMS	Medium/High
Scrap fr. stock	3,193	300	kt	P	Assumption	WBMS	Medium/High

The production of all the defined products for the analysis has been addressed above. The table above provides the boundaries of the data found and used in this report, mostly in accordance with the assumptions done in the LCA EU Aluminium study and EU average values but adjusted in some cases to ensure consistency of material flows, as already mentioned above.

The consumption of certain inputs such as energy or raw material are related to the aluminium produced in Europe available for LCA datasets to produce 1 t of aluminium ingots from primary aluminium, considering the value chain from mining bauxite up to the sawn aluminium ingot ready for delivery. The resulting dataset presented below for final energy demand includes the

energy and environmental aspects of the production processes and required raw materials used to deliver 1 tonne of *sawn primary ingot produced* by the European smelters.

The most important result from this step is that the electricity consumption is the major contributor to the energy demand for the production of primary aluminium. Besides primary aluminium, the highest energy demand is required to produce castings, followed by extrusions and flat rolled products.

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The most important result from this step is that the electricity consumption is the major contributor to the energy demand for the production of primary aluminium. Besides primary aluminium, the highest energy demand is required to produce castings, followed by extrusions and flat rolled products.

The databases with the information regarding the analysed products or 'semis' include information on production processes (casting, extrusion, foils or sheets) which reflect the transformation of aluminium ingots into the semis, which are, at the end of the process ready to be delivered to the final producing steps. The datasets also include the recycling of so-called new scrap and chips generated during the process including recycling. The specific energy and material values correspond to the production of 1 t of semi-finished product (casting, extrusion and flat rolled products). The values include the average value for producing these products based on the year 2015 and were also provided by specialized associations (foil association, etc.). The secondary aluminium route and datasets also indicates average values for EU remelting plants for new and old scraps to produce wrought alloy ingots for 2015 in Europe.

Table 48 and Table 50 show the results for the final energy demand calculations along the material flows modelled, for the EU27+UK and Germany, respectively. Calculation of fuel and electricity demand for each production step/product is straightforward by multiplying production quantities with demand factors from literature. The latter are depicted in the last two columns in both tables. The total cumulated energy demand for the three product groups castings, flat rolled, and extrusions has been calculated by allocating shares of primary and secondary aluminium energy demand to these product groups considering the material flows in the model. For this, only domestic energy demands of the domestic primary and secondary aluminium production have been considered, i.e., high exports and low imports lead to a higher specific allocation, and vice versa. This must be kept in mind when comparing cumulated energy demands for different balance limits / definitions of "domestic production".

Table 48: Calculated domestic final energy demand for the analysed aluminium flows, EU27+UK 2015

Product	ETS-activity	Production [kt]	Fuels [TJ]	Electricity [TJ]	Total [TJ] ⁷⁵	Total cum. [TJ] ⁷⁶	Spec. fuels ⁷⁷ [GJ/t]	Spec. elect. ⁷⁸ [MWh/t]	Source
Primary	26	2,155	5,172	114,741	119,913	119,913	2.4	14.79	European Aluminium /Calculation
Secondary	27	5,292	8,746	1864.7	10,610	10,610	1.6	0.095	European Aluminium /Calculation
Castings	28	2,916	20,414	13,648	34,063	68,267	7	1.3	European Aluminium /Calculation
Flat rolled	28	4,799	4,571	5,343	9,915	66,199	0.95	0.31	European Aluminium /Calculation
Extrusions	28	2,953	12,022	967	12,989	53,024	4.1	0.091	European Aluminium /Calculation

Table 49: Calculated domestic final energy demand for the analysed aluminium flows, Germany 2015

Product ⁷⁹	ETS-activity	Production [kt]	Fuels [TJ]	Electricity [TJ]	Total [TJ]	Total cum. [TJ]	Spec. fuels [GJ/t]	Spec. elect. [MWh/t]	Source
Primary	26	541	1,299	28,825	30,125	30,125	2.4	14.79	European Aluminium /Calculation
Secondary	27	446	716	153	869	869	1.6	0.095	European Aluminium /Calculation

⁷⁵ Total FED for the respective production step

⁷⁶ Total cumulated FED for the respective production quantity, taking into account respective shares of downstream primary/secondary aluminium production for Castings, Flat Rolled, and Extrusions

⁷⁷ SEC for fuels and energy refer to the energy demand for the respective production step only. To calculate "cumulated SEC" for respective product group, divide "Total cum." by production quantity.

⁷⁸ SEC for fuels and energy refer to the energy demand for the respective production step only. To calculate "cumulated SEC" for respective product group, divide "Total cum." by production quantity.

⁷⁹ For this table, the same footnotes apply as for the analogous table for EU27+UK

Product ⁷⁹	ETS-activity	Production [kt]	Fuels [TJ]	Electricity [TJ]	Total [TJ]	Total cum. [TJ]	Spec. fuels [GJ/t]	Spec. elect. [MWh/t]	Source
Castings	28	1,059	7,411	4,955	12,367	24,364	7	1.3	European Aluminium /Calculation
Flat rolled	28	1,841	1,753	2,050	3,803	18,159	0.95	0.31	European Aluminium /Calculation
Extrusions	28	595	2,422	195	2,617	7,256	4.1	0.091	European Aluminium /Calculation

The processing of alumina into primary aluminium through electrolysis is a highly energy-intensive operation, whereby a high electric current is passed through an electrolyte in which alumina has been dissolved. Competitive and reliable electricity is therefore critical to aluminium smelting: energy can represent up to 40% of the costs of production for primary aluminium, depending on local power prices (Norsk Hydro, 2013).

Energy costs are the most significant source of variation in the total cost of aluminium production across countries and regions, and by some estimates account for about 70% of that variability (Nappi, 2013). Energy costs can vary greatly depending on the energy source, its availability, and countries' energy and environmental policies so that geography and resource endowments play an important role. Aluminium smelting also needs petroleum coke to prepare the carbon anodes that enable the process of electrolysis, with the combustion of these anodes emitting significant quantities of CO₂. Additionally, the purchase strategy of electricity by aluminium producers also influences the productions costs and therefore their respective competitiveness future. The stringency and enforcement of environmental policies can constitute another important factor affecting competitive conditions in the aluminium industry.

2.5.3.3 Direct and indirect Emissions related to the analysed aluminium material flows

Direct and indirect emissions were assessed based on the production quantities reflected in the material flow model and the respective energy demands presented above. Additionally, information on non-energetic process emissions, occurring at primary aluminium production (PFCs and anode consumption), were taken from European Aluminium (2017).

To derive emissions from specific energy demand factors and production quantities, the same emission factors as stated above in Table 20 were used. Some specific energy demand quantities were only denominated as "fuel" or "steam" in the respective sources. For these, it was assumed that the emission factor of natural gas can be used as an approximation.

For the allocation of GHG emissions incurred from domestic primary and secondary aluminium production to the domestic production quantities of the addressed product groups castings, flat rolled products, and extrusions, the same method as described above for the allocation of energy demand was applied.

In Table 50 and Table 51, the respective results of the emissions' assessment for the EU27+UK and Germany in 2015 are shown. Here, indirect emissions refer to the use of electricity. The

dominating role of indirect emissions incurred by primary aluminium processing is clearly visible. Embedded emissions from primary aluminium in the three analysed downstream product groups dominate their respective specific cumulated emissions. This points to the exceptional role of primary aluminium production when decarbonisation measures for the aluminium industry are being discussed. Comparing results for the EU27+UK and Germany for 2015, some differences are visible; for example, specific primary aluminium emissions were yet higher than for the bloc, which is due to the specifically high grid emission factor of Germany.

Table 50: Calculated emissions, EU27+UK 2015

Product	ETS-activity	Production [kt]	Direct fuel Emissions [Mt CO ₂ eq]	Direct process Emissions [Mt CO ₂ eq]	Indirect Emissions [Mt CO ₂ eq]	Total Emissions [incl. indirect] [Mt CO ₂ eq]	Total cum. Emissions [incl. indirect] [Mt CO ₂ eq]	Specific Emissions [incl. indirect] [t CO ₂ eq /t]	Specific cum. Emissions [incl. indirect] [t CO ₂ eq /t]	Confidence
Primary	26	2,155	0.32	3.45	12.46	16.23	16.23	7.53	7.53	Medium
Secondary	27	5,292	0.49	-	0.20	0.69	0.69	0.13	0.13	Medium
Casting	28	2,916	1.14	-	1.48	2.62	7.04	0.90	2.41	Medium
Flat rolled	28	4,799	0.26	-	0.58	0.84	8.10	0.17	1.69	Medium
Extrusion	28	2,953	0.67	-	0.11	0.78	6.02	0.26	2.04	Medium

Table 51: Calculated emissions, Germany 2015

Product	ETS-activity	Production [kt]	Direct fuel Emissions [Mt CO ₂ eq]	Direct process Emissions [Mt CO ₂ eq]	Indirect Emissions [Mt CO ₂ eq]	Total Emissions [incl. indirect] [Mt CO ₂ eq]	Total cum. Emissions [incl. indirect] [Mt CO ₂ eq]	Specific Emissions [incl. indirect] [t CO ₂ eq /t]	Specific cum. Emissions [incl. indirect] [t CO ₂ eq /t]	Confidence
Primary	26	541	0.08	0.87	4.70	5.65	5.65	10.43	10.43	Medium
Secondary	27	446	0.04	-	0.02	0.07	0.07	0.15	0.15	Medium
Casting	28	1,059	0.41	-	0.81	1.22	3.46	1.15	3.27	Medium
Flat rolled	28	1,841	0.10	-	0.33	0.43	3.06	0.23	1.66	Medium
Extrusion	28	595	0.14	-	0.03	0.17	1.02	0.28	1.71	Medium

2.5.3.4 Uncertainties and limitations of the approach

The production of Aluminium in Europe in 2015 and in Germany takes place at least in 26 smelters (including EFTA) and at least four plants in Germany, Italy, France and the UK (before Brexit) recently closed, changed their capacities available in Europe, or their imports and exports quantities. That shows that an analysis of aluminium flows and their respective interconnections are generally a snapshot in time.

The secondary aluminium production can be differentiated by the use of new and old scrap flows. New scrap is available for instance after the production of semis or products according to our model approach and stems from several plants across Europe. For example, there are more than 75 aluminium rolling mills in the EU, with 70% of these concentrated in less than 10 companies, and more than 300 aluminium extrusion plants across the EU. The approach used in the model to estimate the available new scrap data leads therefore to a variable with a higher degree of uncertainty, as there are no centralised data collection databases for it. Furthermore, an unknown share of this amount stays at the plants of origin and is reprocessed there.

Unfortunately, there is not much reliable data available, with the exemption of expert assessments, concerning usable quantities of new and old scrap. The new scrap is available mostly at the production facilities for the aggregated product categories. Closed loop sorting and collection methods might increase the efficiency of recyclability in the future. Old scrap data is non-existent and expert assessments and preliminary estimations were used to build up the model for this study. The availability of old and new scrap requires more data collection efforts, e.g. through surveying, in the future. At best in a way that suits subsequent aggregation of scrap flows to the product group's extrusion, casting and rolling.

Old scrap amounts are also not completely certain for the EU. For Germany, some statistics on the waste streams containing aluminium were available. These were partially used to define the material streams. Other assumptions for Europe were derived from the world aluminium association's material flows for Europe and the world.

Different sources were consulted to establish the aluminium production quantities for each phase of the material flow model. However, that led to inconsistencies between the input and output material flow in some process steps. These inconsistencies were corrected by normalizing all flows on the basis of primary and secondary aluminium quantities. This seems to be a reasonable approach, as basic materials' production, at least primary aluminium production, is responsible for most of the energy demand and GHG emissions incurred along the aluminium material flows.

2.5.4 Key economic indicators and cost structures

2.5.4.1 Trade relevance

Aluminium is a versatile metal with multiple final uses in a wide range of industrial branches, including construction and buildings, engineering, automotive industry, and packaging, among others. No other metal except for steel is more widely used around the world, which makes Aluminium a global commodity.

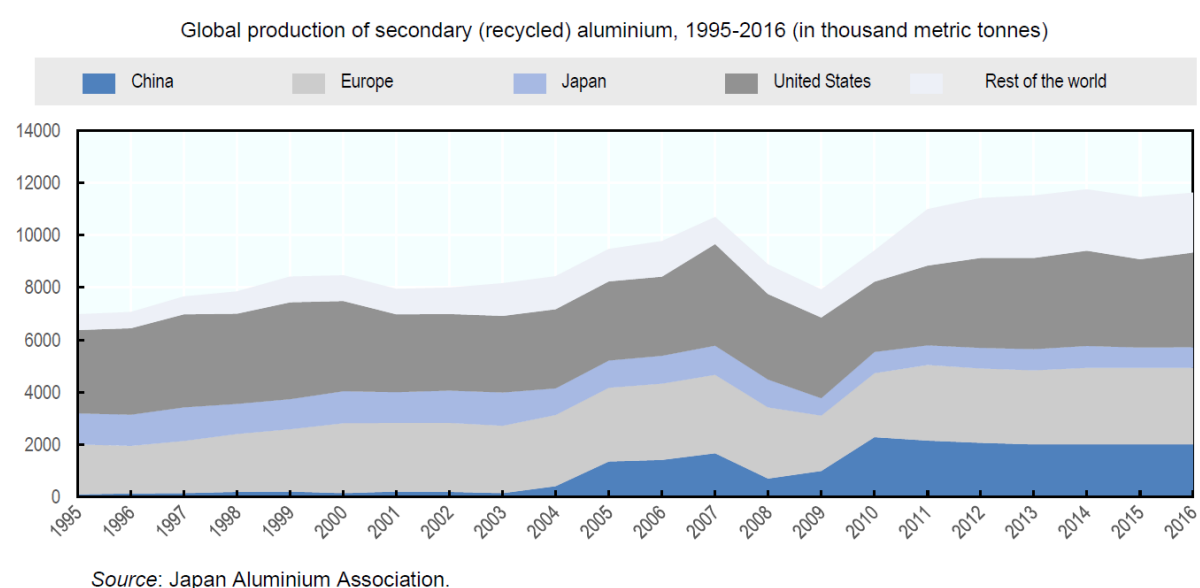
Worldwide, the production of primary Aluminium is currently close to 60 Mt/year with an increasing production prospect especially dominated by developing and transitional countries. The most prominent case is China as a major driver for aluminium products demand, and accounts for more than 70% increase in production during the last 10 years. This means that approximately 60% of the primary aluminium production occurs in China.

Products from the complete aluminium value chain, as well as scrap metal are traded internationally, and the European Union is a major importer aluminium used in different industries. Under this perspective, there is an increasing attention for further strengthening of recycling and circularity based on global trade aspects.

Metal waste and scrap are generated either as a by-product of manufacturing (new scrap) or from recycled goods (stock scrap, e.g. beverage cans, automobiles, wires, and cables). The equivalent of 26 Mt is estimated globally to be supplied in form of new and old scrap according to Bertram et al. (2017). These volumes include relevant shares of forming and fabrication scrap, which also circulates in the primary production route. This is a confirmation that circularity is very well advanced in the sector.

New and old scrap takes different forms: either as mixed and casting scraps, or packaging scrap, or scrap from flat rolling or from extrusion. The recycling of aluminium is differentiated worldwide and rather centred in OECD countries, due to their established waste collection and sorting systems.

Figure 45: Global production of secondary aluminium, 1995 to 2016



Source: OECD (2019) based on Japan Aluminium Association (2017)

As indicated above for primary and secondary aluminium as well as for EU ETS aluminium products selected for this study, the EU imports approximately 50% of their aluminium requirements. One of the aspects is the trade within the European Economic Area where the EU imports primary aluminium from Norway and Iceland (European Aluminium, 2021). The EU also imports from other major countries including China, Russia, the United Arab Emirates and Mozambique (European Aluminium, 2021; WBMS, 2017).

The trade analysis for aluminium products was performed for the following 16 tradable aluminium commodity groups in the EU27+UK, based on the Prodcom database as consulted in 2019 and 2020.

Table 52: Aluminium commodities for trade analysis

Commodity Code	Commodity Name
76	Aluminium and articles thereof
7601	Aluminium; unwrought
7602	Aluminium; waste and scrap
7603	Aluminium; powders and flakes
7604	Aluminium; bars, rods and profiles
7605	Aluminium wire
7606	Aluminium; plates, sheets and strip, thickness exceeding 0.2 mm
7607	Aluminium foil (whether or not printed or backed with paper, paperboard, plastics or
7608	Aluminium; tubes and pipes
7609	Aluminium; tube or pipe fittings (e.g. couplings, elbows, sleeves)
7610	Aluminium; structures (excluding prefabricated buildings of heading no. 9406) and parts
7611	Aluminium; reservoirs, tanks, vats and the like for material (not compressed or liquefied
7612	Aluminium casks, drums, cans, boxes etc. (including rigid, collapsible tubular containers),
7613	Aluminium; containers for compressed or liquefied gas
7614	Aluminium, stranded wire, cables, plaited bands and the like, (not electrically insulated)
7615	Aluminium; table, kitchen or other household articles and parts thereof, pot scourers
7616	Aluminium; articles n.e.c. in chapter 76

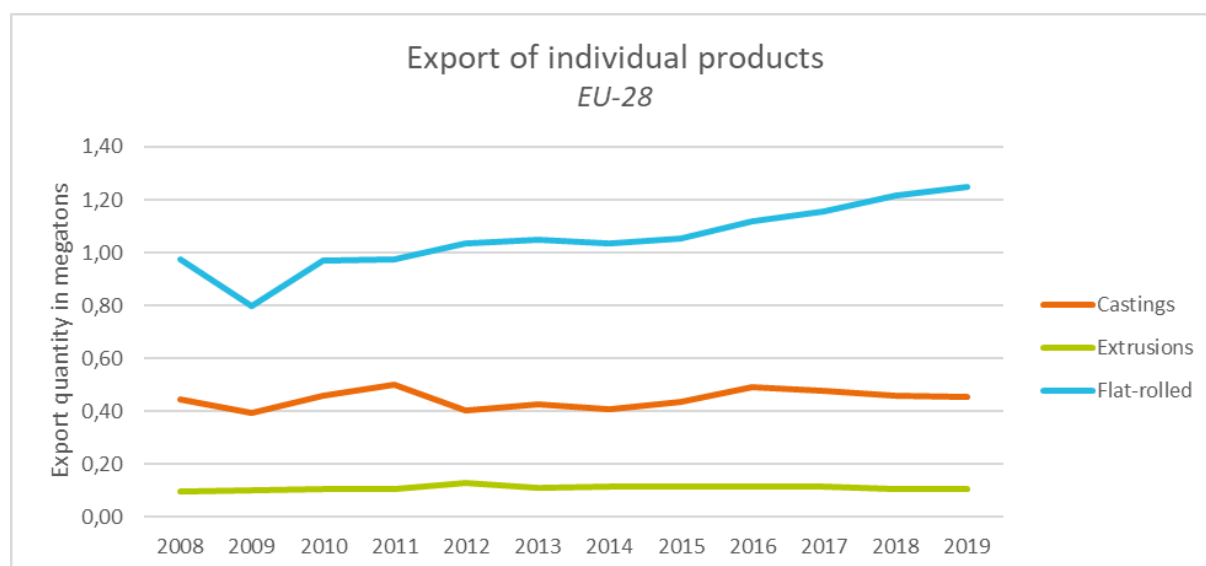
Source: Eurostat 2020b

According to Prodcom, the imports of all tradable aluminium commodities amounted to 9.8 Mt in 2018, i.e., it almost doubled when compared to the 5.1 Mt for the year 2000. The same increase is observed for the trade value, reaching 48 million € in 2018 (25 million in 2000). 90% of the imports correspond to the aluminium commodity groups 7601, 7602, 7604 (incl. primary aluminium bars), 7605 and 7606.

The average price for these commodities in 2018 reaches 1,940 €/t, however, aluminium products such as plates, sheets and strips with a thickness exceeding 0.2 mm reaches almost 3,000 €/tonne while aluminium rods and profiles display lower prices, just over 1,300 €/tonne (see figures below). Average prices were calculated using data for the physical volumes and corresponding revenues given for the respective product groups in the Prodcom database.

The EU27+UK exports of aluminium are dominated by flat-rolled products and have increased approximately 38.3% since 2008, especially for flat rolled products, while the volumes of the other two categories analysed remained almost unchanged.

Figure 46: Export of aluminium products, EU27+UK EU 2008 to 2019

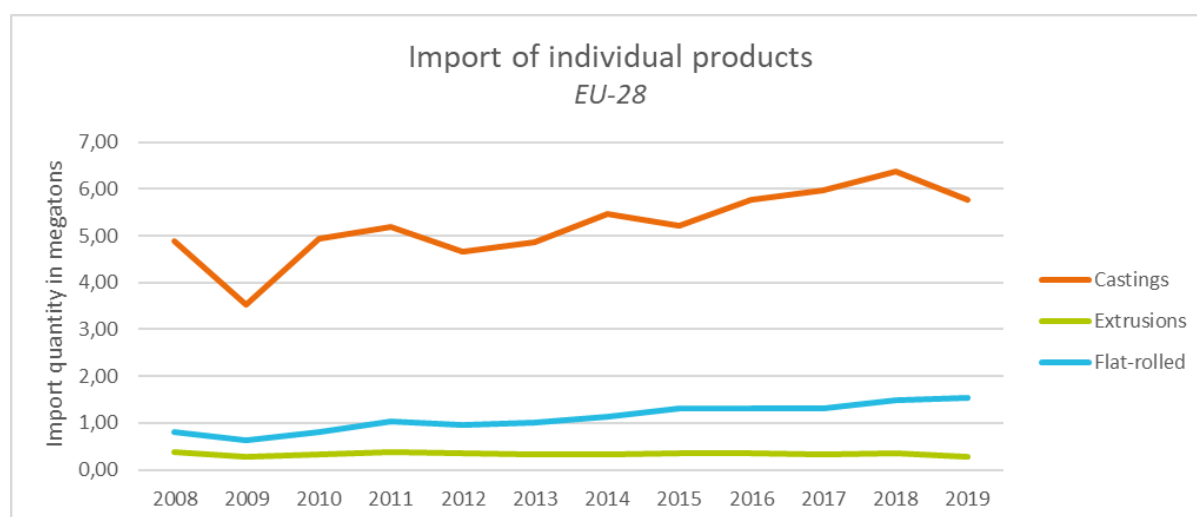


Source: Eurostat (2020b)

The EU27+UK aluminium imports are dominated by unwrought aluminium (castings) with a 76% share in 2018, followed by flat-rolled (commodity group 7606).

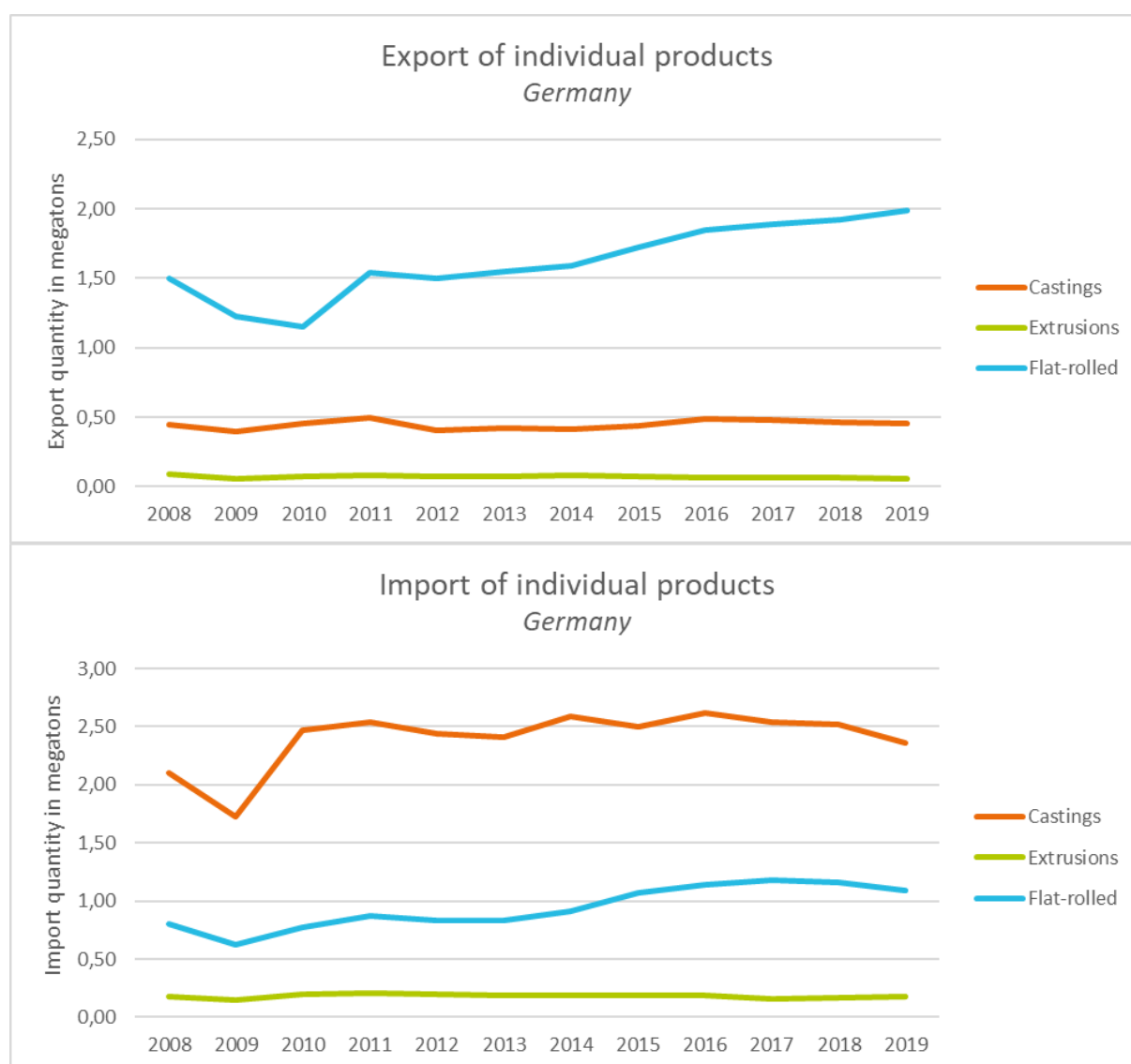
As shown in the following figure, from 2008 until 2019 the change in castings imports was about 18% regarding physical quantities. It is interesting to see that imports are dominated by castings, while exports are dominated by flat rolled products. A possible explanation is that some imported unwrought products are processed further to e.g. flat-rolled products with higher value added. However, this could not be further investigated in the course of this study.

Figure 47: Import of aluminium products, EU27+UK 2008 to 2019. S



Source: Eurostat (2020b)

Figure 48: Export and import of aluminium products, Germany 2008 to 2019



Source: Eurostat (2020b)

As Figure 48 shows, the export and import structure for Germany is quite similar to the EU27+UK. Castings represent the dominant import of semis, while flat-rolled products dominate the exports. Also, the trends for the respective product groups between 2008 and 2019 are much alike. The economic downturn due to the financial crisis in 2009 is reflected both in export and import values.

In the EU and for 2019, 88% of exports correspond to flat-rolled products and extrusions. Half of these exports correspond to aluminium foil, plates, sheets and strips with thickness over 0.2 mm. The average export price for flat-rolled products in 2019 was 3,613 €/t, while the average import price was 2,771€/t. For extrusions, the average export price in 2019 was 5,543 €/t and the average import price 2,982 €/t. For castings, the average export price in 2019 was 1,966 €/t and the average import price 1,840 €/t.

The graphs below depict the development of import and export prices in €/t for the three product categories. All following numbers relate to the 2008 to 2019 period. For flat rolled products, the average export price remained nearly unchanged (-1.5%) during the whole period, while the average import price fell (-11.2%). Casting export prices exhibited a decrease on average (-

8.1%), the same holds true for casting import prices, but prices fell by a slower degree (-4.8%). The average export prices for extrusions rose by 11.6%, while import prices also rose by a comparable degree (13.1%).

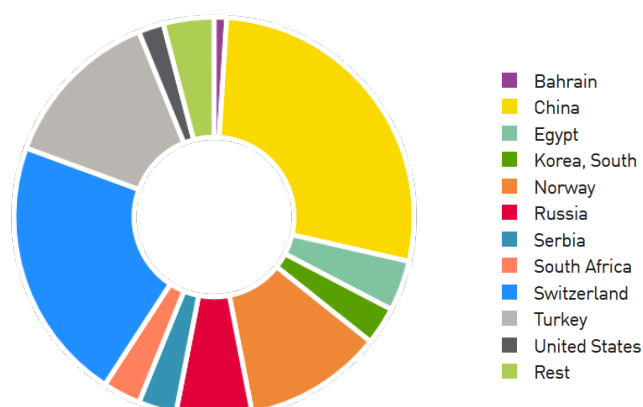
Figure 49: Average export and import prices. EU-28 2008 to 2019



Source: Eurostat (2020b)

The imports of flat rolled and casting products in the EU has increased, especially regarding imports from China, which amounted to over 27% in 2019 for flat rolled products and to 37% for extrusions (Figure 50). Interestingly, Switzerland is also a major contributor to EU flat rolled imports.

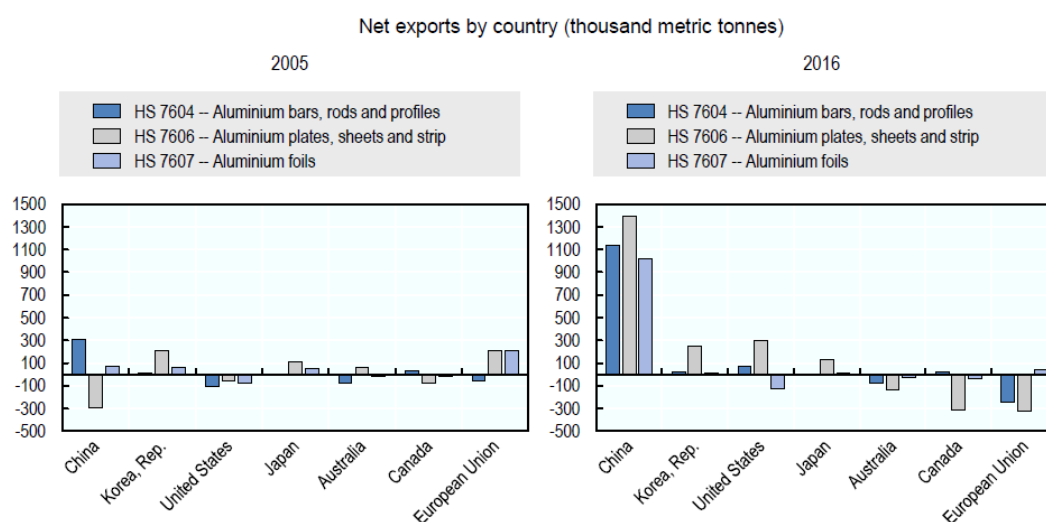
Figure 50: Import shares for flat rolled products to the EU in 2019, country of origin



Source: European Aluminium (2021)

Within 15 years, China has become the largest producer and exporter of semis (Aluminium plates, sheets, strip under commodity group 7606, bars, rods and profiles under 7604, and foils under 7607) worldwide and to the EU. This poses a large challenge for European producers as China is not necessarily sticking to all rules of a market economy, and large subsidies from the Chinese government were observed in the past, which puts the international level playing field for EU competitors at risk (OECD, 2019). Over the same period, only India, Mexico, and the Russian Federation saw significant increases in their output, though far below that of China (OECD, 2019).

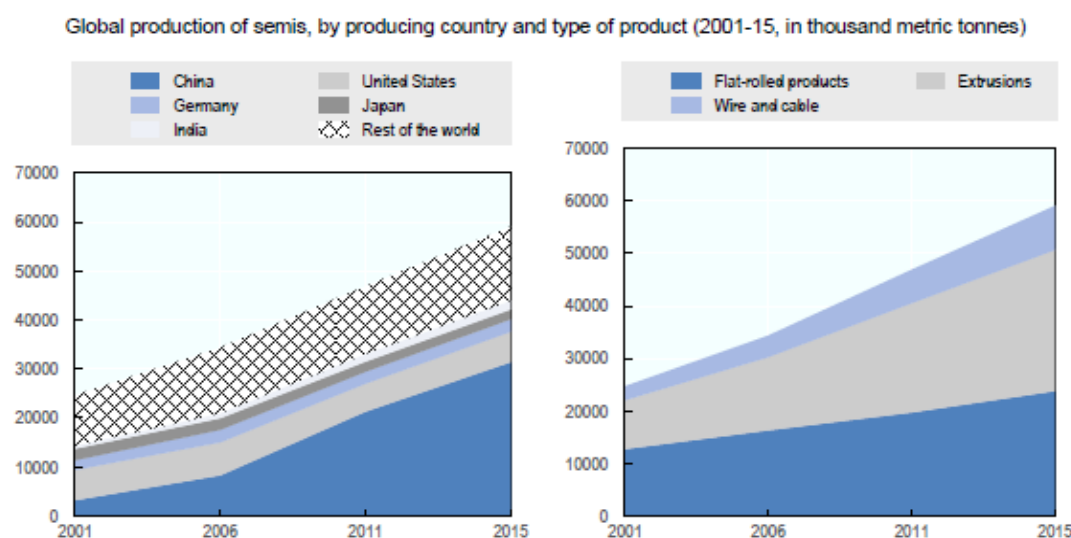
Figure 51: Net exports by country and commodities, 2005 and 2016



Source: OECD (2019)

The production of semis in China is dominated by extrusions, presumably due to the heavy infrastructure and housing boom, producing 64% of the global total. A similar pattern is observed in India, increasing their production threefold between 2001 and 2015 (from 600.000 tons to 1.8 million tons). China also shows a continuous increase in flat rolled products, and overtook USA in less than 10 years.

Figure 52: Global production of semis, 2001 to 2015



Source: OECD (2019)

2.5.4.2 Cost structure

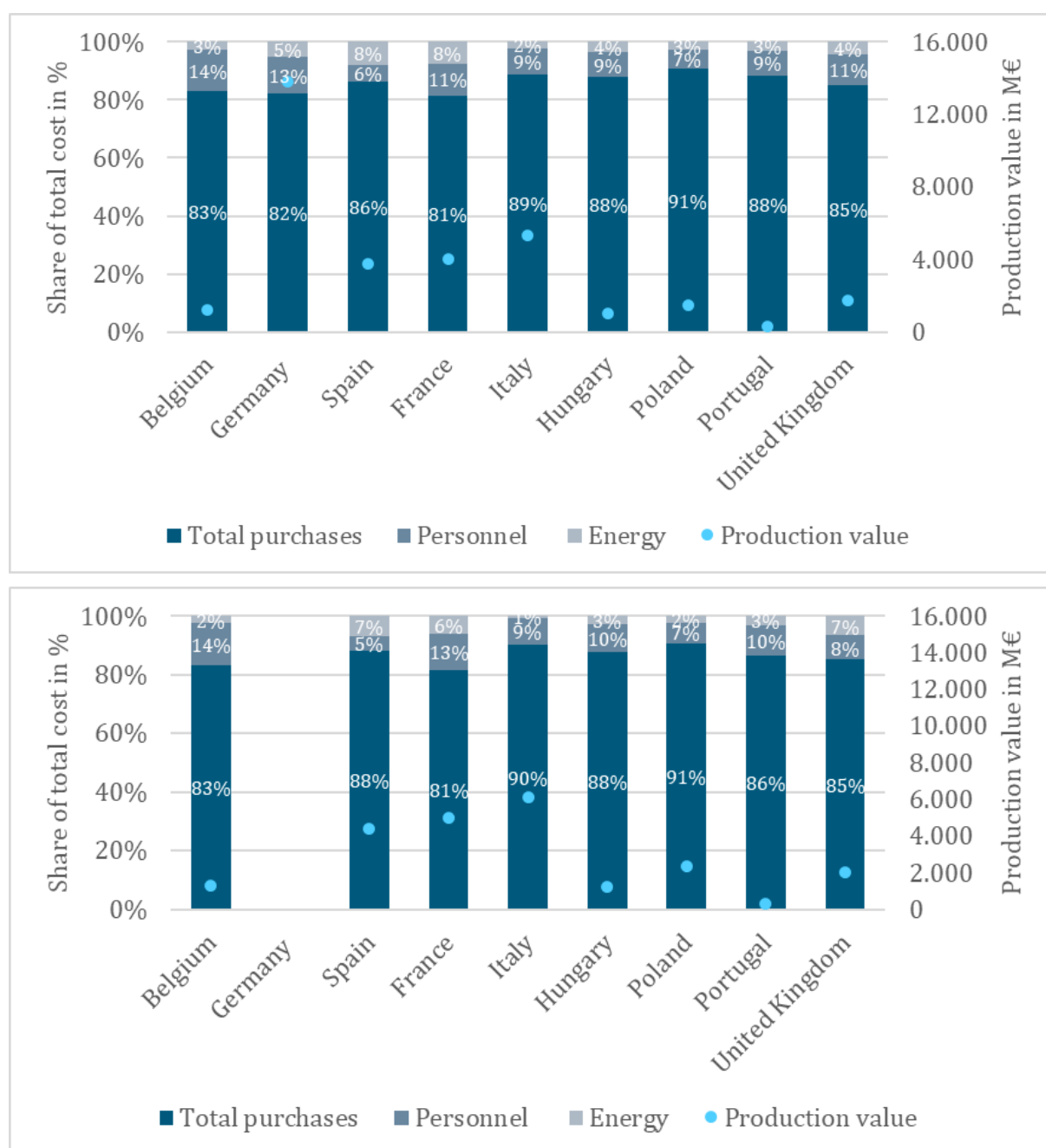
The cost of producing castings, flat-rolled products and extrusions is largely determined by the costs of the raw material for primary aluminium. Following examples are noted:

- ▶ For flat rolled products: The cost of raw (primary and secondary) aluminium accounts for 75-86% of average business costs in 2015.
- ▶ The costs for the smelting are also important
- ▶ The energy used and costs for re-melting represent a significant part of the costs of processing primary aluminium into semis.
- ▶ This led to the decision in China or the Middle East for certain producers of Semis to locate their facilities close to the smelter, in order to save energy costs.
- ▶ In Europe, for instance semis plants are rather located close to the customers (automotive industries) in order to save shipping costs.

The concentration of the semis industries is lower than other segments of the aluminium value chain. Producers can range from local, specialised small companies providing products to a single customer (e.g. car manufacturer) to large, vertically integrated multinational companies.

The cost structure of the aluminium production is taken from the Structural Business Statistics from Eurostat. Here, aluminium production does not include the production of precursors (alumina) and the costs for their respective inputs. For comparison, the major cost components (total purchases of goods and services, personnel costs, purchases of energy products) as well as the total production value of nine countries are summarised. The nine countries (Belgium, Germany, Spain, France, Italy, Hungary, Poland, Portugal and United Kingdom) have been selected based on the data availability and to obtain a regional heterogeneity within the EU27+UK in 2015. The illustration differentiates between the base year 2015 and the most current covered year, 2018. The data are summarised in Figure 53. It can be clearly concluded that aluminium production costs in the EU are dominated by material costs. Energy plays a significant role, but, as energy intensity drops for production processes further down the value chain, it is not the most important issue of concern for corporations, but still of major relevance.

Figure 53: Cost structure of the aluminium industry, selected EU countries 2015 (top) and 2018 (bottom)



Source: Eurostat (2021)

2.5.5 Summary and conclusions

Aluminium is a young metal with a very complex material flow model structure in Europe starting by the local production of primary and secondary routes. In OECD countries and in the EU, there is a high share of recycling for some of the uses, demonstrating that it can be recycled many times without affecting the material's properties. This allows aluminium to play an important role regarding the climate mitigation targets for 2030 and 2050 in the EU and in Germany, as far as scrap availability is given to allow for secondary production to replace primary aluminium production.

Many uses are in important markets such as transport, automobile industry (including e-mobility), construction and renovations as well as packaging, renewable energy technologies and machines construction. Worldwide, the demand for Aluminium is projected to increase by 40%, also for secondary routes, whereas in Europe a saturation point is likely to be reached in the near future.

The demand for aluminium semis or products is very diverse as observed in the resulting material flows, and this reduces the volatility of these markets. The industry is expected to increase production volumes in all three product categories driven by a complex set of factors. These range from e.g. higher relevance of packaging to technological developments of the construction, automotive or engineering fields, such as lightweight requirements for the construction of cars, which benefits aluminium compared to other materials such as steel

The role of secondary flows is very important for the future efficiency of the aluminium industry, and for contributions to the reduction of material use, energy demand and GHG emissions. Half of the intended growth worldwide could be met by recycling and secondary aluminium.

The total metal available in Europe for recycling is projected to grow from 27% until 55% in 2050 and therefore, this increases the importance of supporting a competitive secondary production, also in view of high installed capacities in China. There is still room to improve and increase current recycling practices in the EU, and changes in waste management legislations are required to take into account difficult aspects such as extraction from vehicle machines or constructions.

More information is required with respect to the internal recycling of new scrap. This is an uncertainty that might be turned into a research and development project that involves different disciplines and could be coupled to the issue of increasing material efficiency in producing companies.

Challenges with respect to alloy recyclability should be further discussed with several stakeholders, as that might open the spectrum to reuse several casting alloys that would become available for circularity. Furthermore, only around 20% of end-of-life scrap is turned into wrought aluminium, even though wrought products account for two-thirds of all aluminium in use. Europe and North America have already reached the point where there is 'excess scrap' – i.e., scrap that exceeds domestic requirements for cast aluminium, but which is too mixed or highly alloyed to be used again as basic material for other product categories. However, this is not sustainable in the long term. As noted above, the amount of post-consumer scrap is growing globally. At some point, it will exceed the demand for casting alloys, even with extensive trade across regions. Unless post-consumer scrap can be used for wrought products, more primary aluminium will be required.

2.5.6 Critical discussion of uncertainties in model results of Aluminium

For the aluminium material flow model, the amount of scrap available was aggregated in two flows (old and new scrap from production in the value chain) which are provided to the scrap remelting plants. In Europe, there are over 220 plants that remelt at least 2.2 Mt and handle over 5 Mt of scrap (including assumed quantities of scrap from stock) to produce castings, flat rolled products and aluminium extrusions. Limitations of data consistency were observed when balancing the amounts of primary and secondary aluminium produced, imported, and exported, with scrap flows. This inconsistency led us to assume that the production of secondary aluminium needs an additional flow from a stock of scrap. This was done in order to estimate the necessary amounts for 2015 under extrusion, casting and rolling aluminium products.

An additional uncertainty of the model relates to the estimation of the produced quantities of semi-finished products as compiled in the three product categories. There was no agreed amount across different data sources and there is not an official data for these products in the EU. There were different sources indicating different production ceilings for each of the three groups of products (extrusion, castings and rolling). After discussing with the experts as indicated above from industrial associations, research and companies, the authors agree to estimate the sum of available castings, flat rolled products and extrusions including imports and export flows to be 11.6 Mt. This results from normalizing domestic production quantities for the three product categories to the primary and secondary aluminium balances. Imports and exports from flat rolled products and extrusions were available in the statistics, but not for castings. The total production of castings in Europe was obtained from the foundry's association in Europe and Germany.

For the decarbonisation of the aluminium production and the reduction of electricity needed for the production of aluminium, the role of the secondary market and available quantities is important as most of the material losses, leading to primary production to substitute these losses, happen when aluminium products reach their end-of-life. Technologies towards decarbonisation of the aluminium industry includes possibilities to substitute current fuels such as the use of renewable energy, green hydrogen, and electrification. Several technologies are currently in R&D in this respect. Furthermore, the increase of an energy efficient production is an important aspect, using tools, technologies and methods such as: energy management systems, energy efficiency networks, waste heat utilization technologies, sensible and latent heat storages, etc. Moreover, the use of higher shares of secondary aluminium and also closed loop recycling and reduced demand and material efficiency increases competitiveness (Toro, 2020). The core of the circular economy opportunity for aluminium is to make the best use possible of metal that has already been produced. This requires minimising losses and expanding the secondary production to meet as much of the demand for aluminium as possible. However, many aluminium applications are very long-lasting, especially in buildings. This is a constraint for the further development of secondary production.

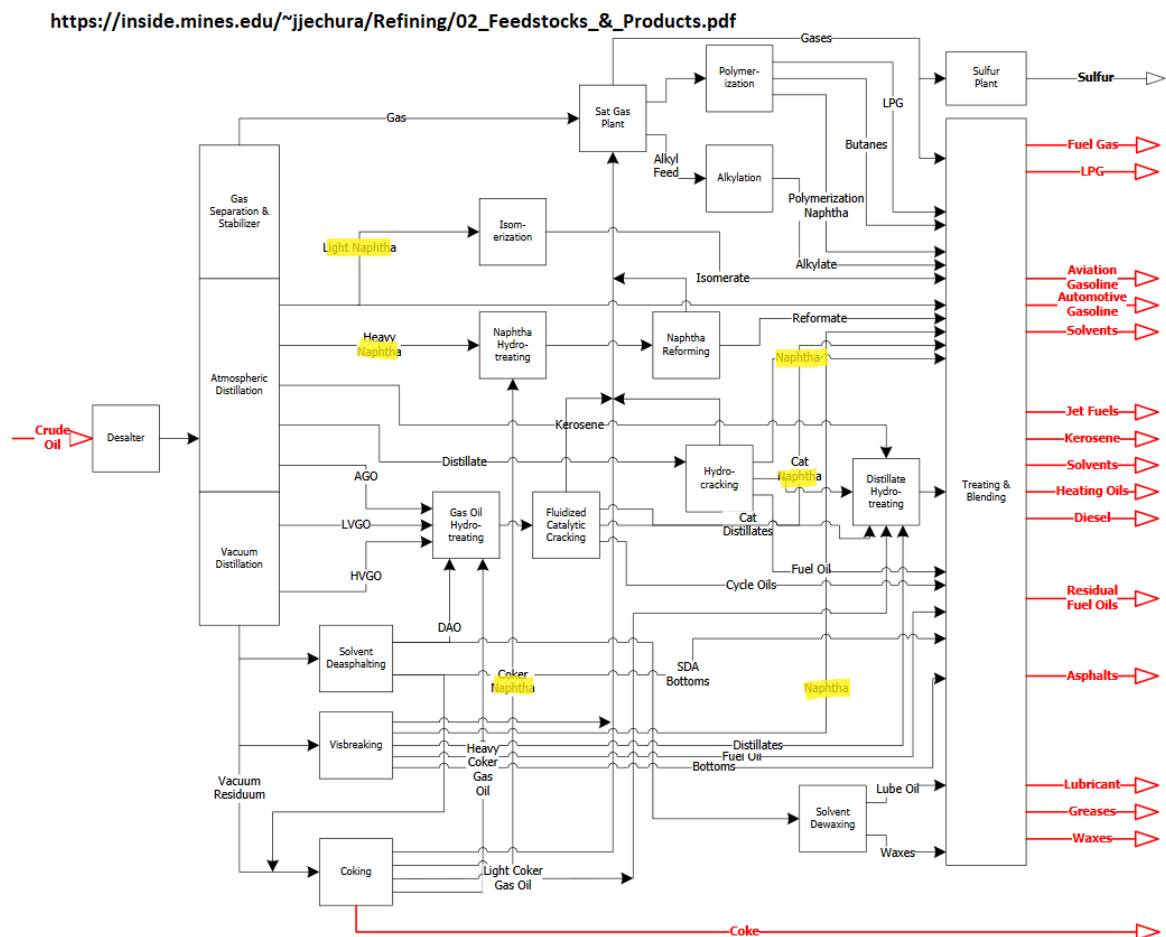
As to the large number of plants for the different products in Europe and Germany, an additional moderate uncertainty arises. The specific material and energy demands as well as specific emission factors were researched and the best average figures from 2018 from the European Aluminium association were used in this study; however, these average figures cannot account for the diversity of efficiency levels of the large number of plants and facilities.

2.6 Refineries

2.6.1 Production Overview

Refineries are extremely complex production systems with a broad variety of products based on crude oil as raw material input. The product structures consist of mixtures of hydrocarbons, which are rather defined according to their use than to their exact chemical structure, where the need to adjust the latter depends on the requirements of the appliances and products downstream. A typical structure (process-units with flows of intermediates and final products) for a crude oil refinery is shown in Figure 54. Potential occurrences of naphtha, as the chosen products for this assessment, are highlighted. The figure represents very well the complexity of the network of individual process units setting up a mineral oil refinery.

Figure 54: A typical process-focused refinery structure



Source: Jechura 2018

In 2015, according to the World Refinery Survey 2017 (Oil and Gas Journal, 2017), 98 crude oil refineries were operating in the EU27+UK. These refineries can be further categorized, e.g. according to their complexity regarding to the present processing units. As shown in Figure 55, four different types, here named complex 1-4, can be distinguished according to literature, where complexity in general increases from complex 1 to complex 4. Complexity level 1 includes, in addition to the basic facilities of atmospheric and vacuum distillation, only thermal conversion units. For complexity 1, the conversion rate of heavy fractions is limited. This results in a high remaining proportion of fractions grouped under 'heavy fuel oil'. In complexity level 2, the focus lies on the production of gasoline. For this purpose, a fluid catalytic cracking unit (FCCU) is used, which splits the heavy fractions from vacuum distillation to produce more valuable light fractions. This also produces gasoline fractions, which are a potential source of naphtha. Complexity stage 3 replaces the catalytic cracking unit with a hydrocracker (HCU), which allows a further increased yield of light fractions by adding hydrogen. This process allows a more flexible selection of product fractions but is also more complex and expensive than using the FCCU unit. The highest, fourth, degree of complexity results from the combination of FCCU and HCU, which again increases the flexibility of the product composition and further reduces the proportion of heavy fractions.

Figure 55: Characterisation of refineries according to their process-unit focused complexity

Categories	Process units	Characteristics
Complex 1	CDU+RF+DSU	This refinery type has CDU as primary process and treatment for its products. The quality of the products is constricted to the quality of its crude oil source.
Complex 2	CDU+RF+DSU+FCCU	This refinery type adds a FCC unit to the complex 1 type. It is geared toward maximising the production of gasoline.
Complex 3	CDU+RF+DSU +HCU	This refinery type adds a HCU to complex 1 type. It is more energy intensive and expensive than complex 2 and suitable for producing good quality of diesel at a higher share.
Complex 4	CDU+RF+DSU +HCU +FCCU	This refinery type adds both FCC and HCU to the complex 1. It is characterized by its flexibility on demand. The gasoline/diesel ratio is in between complex 2 and complex 3.

Note. CDU- Crude distillate unit, RF- Reformer, DSU- Desulfurization unit, VDU- Vacuum distillate unit, FCCU- Fluid catalytic cracking unit, HCU- Hydro cracking unit. Adapted from Reinaud (2005).

Source: adapted from Reinaud (2005)

Choosing naphtha as refinery product to be assessed – Occurring complexities

Naphtha was chosen as the object of study in the refinery sector. Even though naphtha is not a major final product of refineries, when looking at the final product structure, it has a high importance as a feedstock in the value chain of olefins (steam cracking) and plastics production. As the assessment of plastics is also part of this work, and moreover represents a material use of crude oil, naphtha seems to be of special interest.

Naphtha, however, is not a very well-defined product. The chemical structure, i.e., the mixture of hydrocarbons constituting the product naphtha, varies in a rather broad range. While so-called straight-run naphtha stemming directly from crude distillation units (CDU) lies typically in the range of C₄-C₆/C₇ hydrocarbons, naphtha won from other fractions or residues with cracker or coker units (as shown in Figure 55) may be composed quite different.

Adding to complexity, not only the chemical composition of naphtha varies, but the different technical means (i.e., different combinations of process units leading to naphtha as a product) to produce naphtha can also be varied in certain degrees according to production priorities regarding the total final product structure of the individual refinery, which in the end is driven by relative margins of the respective product structure. Moreover, naphtha can be used as an intermediate internally or sold as a product, e.g., as raw material for basic chemicals, leading to a further degree of freedom for the operation of the refinery.

The possible relative shares of naphtha stemming from different combinations of process units is restricted by the type of crude oil used, as the relative share of distillation residues depends on the type of crude oil. The authors were able to speak with representatives of refineries regarding this issue, which already shed light on the broad range of crude oil actually used. While one refinery uses mainly crude oil from Russia, with a medium-range share of residues, another uses relevant shares of regionally available oil with high shares of residues.

As to these circumstances, defining 'typical' material-flow based figures for GHG-emissions, energy demand for production, and costs / added value for naphtha as a refinery product, is a task with an enormous complexity as to the very high number of parameters and variables, which,

ideally, needed to be defined in detail and assessed. Moreover, ideally, these parameters and production variables would need to be assessed for each individual refinery, and dynamically over a certain course of time. However, this would be way beyond the scope of this work. According to one of the refinery representatives interviewed, a mass-flow approach to assess refinery GHG emissions does not exist yet.

As to this, a practicable approach needs to be defined, which on the one hand simplifies the problem to a degree which is feasible, while at the other hand leads to results which at least reflect the fact that there is no such thing as a single and homogenous product naphtha. In the following, this idea, based on the CWT-approach and the aforementioned characterization of refineries in different complexities, will be presented and used to establish key figures for naphtha.

2.6.2 Methodological approach and data basis to establish naphtha key figures

The complexity weighted tonne (CWT) approach is a methodology to establish refinery-specific GHG emissions for purposes of setting the product benchmark and to determine free allocation of emission certificates in the ETS-framework. It has been developed and established by Solomon Associates and CONCAWE (CONCAWE, 2012). The methodology is process-unit specific, i.e., to each process-unit, a factor is assigned which represents the unit's typical CO₂ emissions relative to the CDU, the latter therefore having a factor equal to 1. Of course, operating parameters of the respective units are standardized for that purpose. The total CWT of a specific refinery is the activity factor for establishing that refineries total GHG emissions and is the sum of the respective units' total throughputs weighted with the unit-specific CWT-factor. It is therefore an activity function representing both the magnitude of the activities (plant throughputs) as well as their complexity. For each refinery, an indicator CO₂/(cumulative) CWT is established, and the average of the 10% most carbon efficient refineries in the ETS-system is defined as the benchmark value for certificate allocation purposes. The benchmark is therefore lower than the average value. For the 2007-2008 baseline, used for the third ETS trading period (2013-2020), the benchmark was established as 0.0295 t CO₂/CWT, and the average value for all European refineries as 0.037 t CO₂/CWT (CONCAWE, 2012). For the approach presented further below, the average value shall be used, as the key figures should represent average values, too.

While there is no current mass-flow based approach to disaggregate refinery GHG emissions to single refinery fractions or 'products', the CWT-methodology opens up a possible solution. If it is possible to define 'typical' bandwidths for the relative share of naphtha stemming from the respective process-units capable of producing naphtha, a linear function for each of the aforementioned refinery complexities 1-4 and each of the naphtha production lines therein can be defined. This then leads to complexity and refinery (due to different production capacities for the same types of production units) specific emission and energy use factor for the complexity-specific naphtha product. As the four refinery complexities vary according to their process-unit structure, and as these process units differ in terms of their CWT-factor and their SEC according to Worrell & Galitzky (2004), this seems to be a reasonable approach. The refinery specific indicators can be aggregated to complexity-specific figures by forming a weighted average, considering the different production capacities of the individual refineries and their assignment to one of the four complexities, which can be directly deduced from Oil and Gas Journal (2016). The typical naphtha-output from each naphtha-producing process-unit is multiplied with the respective CWT-factor for this process-unit, then these individual results are added up for each refinery complexity. Therefore, this would define a kind of 'mass-flow weighted CWT for naphtha', which can be multiplied with the average CO₂/CWT performance index for EU27+UK refineries (third ETS-period, as analysed year is 2015) to end up with a naphtha-specific emission factor.

The same approach can be used to establish naphtha-specific energy consumption figures, differentiated according to refinery complexities I-IV, using the same simplified naphtha-production lines and CWT-factors, while using process unit specific SEC factors from literature (Worrell & Galitzky, 2004).

It is important to note that this approach does not allow to differentiate between direct (on-site) and indirect (imported) emissions, e.g., regarding imported electricity. This is due to the methodology of defining the CO₂/CWT performance index presented in CONCAWE (2012), which is based on a consumer benchmark approach, i.e., refinery benchmarks are defined according to energy consumption irrespective of where the actual energy conversion process emitting GHG takes place. Therefore, the CO₂/CWT performance index includes, e.g., the own electricity consumption of the refineries, calculated as 'import plus own production minus export'.

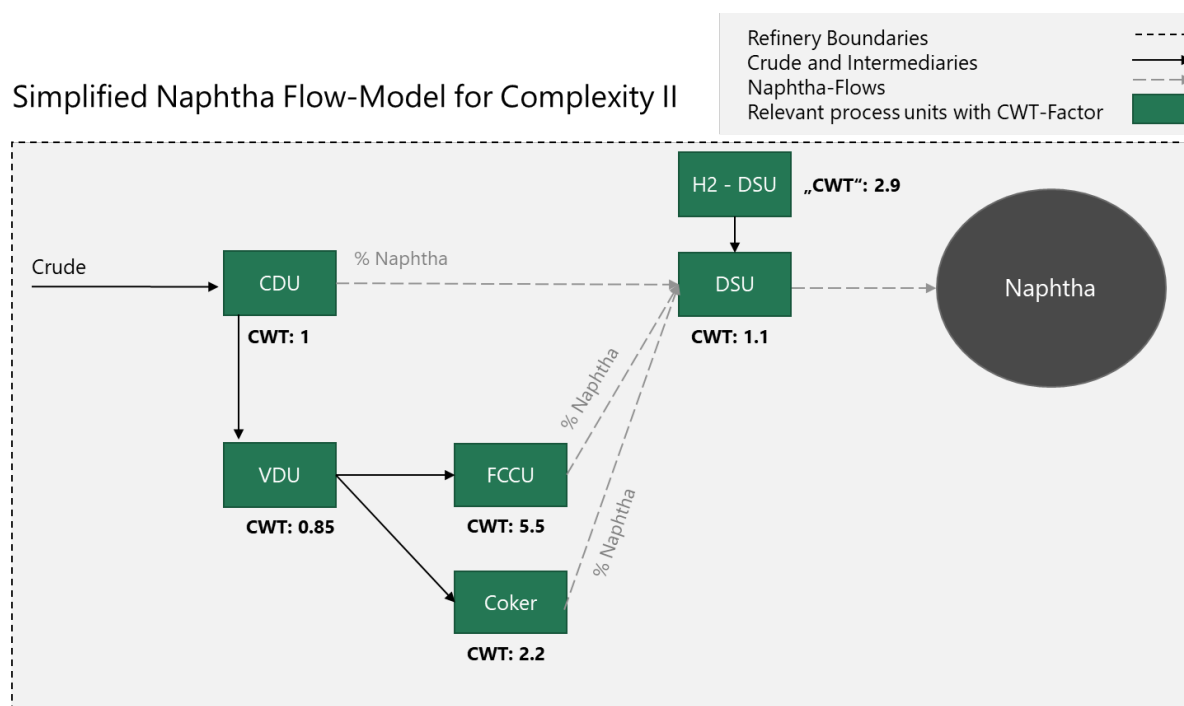
To assess typical (and simplified) naphtha-production lines for each of the four complexities as well as the typical bandwidth for the respective naphtha-shares produces from the relevant production units, a series of interviews with refinery representatives was conducted. As to data protection, neither the corporation nor the individual representatives interviewed can be mentioned here. Unfortunately, only a rather small number of refineries responded positively to our inquiry for interviews. As to this, we were not able to gather data concerning naphtha production shares for complexities I and IV. Therefore, in the following, the application of the methodological approach is presented for complexities II and III only.

Naphtha producing processes: simplified naphtha flow-models

Based on information from interviews with refineries, simplified flow models for naphtha production for complexity II and complexity III were developed. Both models assume that internal naphtha production stems from a small range of process unit types: in the case of complexity II, naphtha is part of the output of CDU, FCCU and the coker (or visbreaker) units. In the case of complexity III, naphtha stems from CDU and coker (or visbreaker) units, too, but a FCCU is not present. Instead, the complexity is characterised by the presence of HCU units. Both models look quite similar in terms of their structure, as shown in Figure 56 and Figure 57. This is caused by the fact that in both cases, the cracking units (HCU or FCCU) are fed with the VDU distillate, while coker/visbreaker units are used for further treatment of VDU residues. In both figures, for ease of illustration, DSU is shown as the last process step as it is common to all naphtha flows, even if desulphurisation takes place at different positions in the actual mass flow through the refinery.

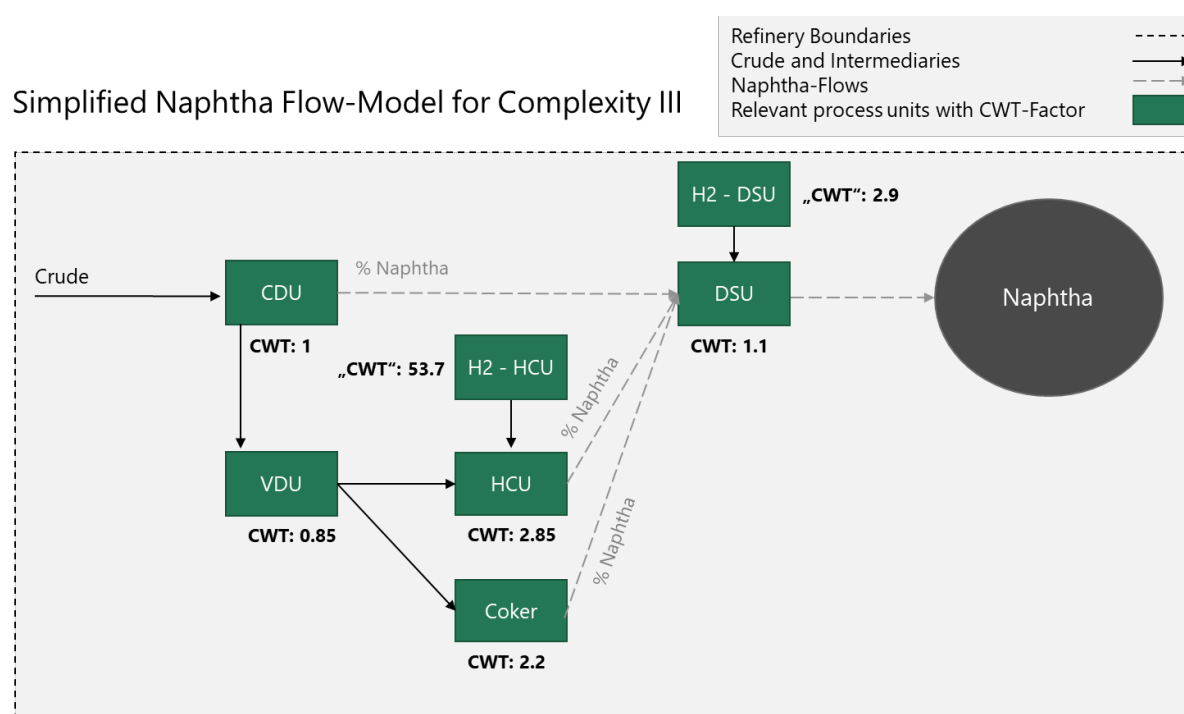
The two flow models differ in terms of reflecting hydrogen use. Hydrogen is considered for desulphurisation in the DSU unit and for hydrocracking in the HCU. A different hydrogen 'CWT' Factor was calculated for both applications, based on a product specific hydrogen CWT factor and on specific hydrogen demands per unit of feedstock, as described further below.

Figure 56: Simplified naphtha flow-model for complexity II



Source: own depiction

Figure 57: Simplified naphtha flow-model for complexity III



Source: own depiction

It must be pointed out that the production volumes analysed to determine specific emissions and specific energy consumption per tonne of naphtha are not to be confused with production volumes actually sold by the refineries. These production volumes are rather gross quantities before internal conversion. This is in line with the approach to assess average naphtha emission

and energy figures according to the differentiation between refinery complexities. To assess which share of the respective individual internal naphtha flows is further treated and converted to other final tradeable products to end up with a consideration of net naphtha production quantities would add to complexity and to uncertainty of the results.

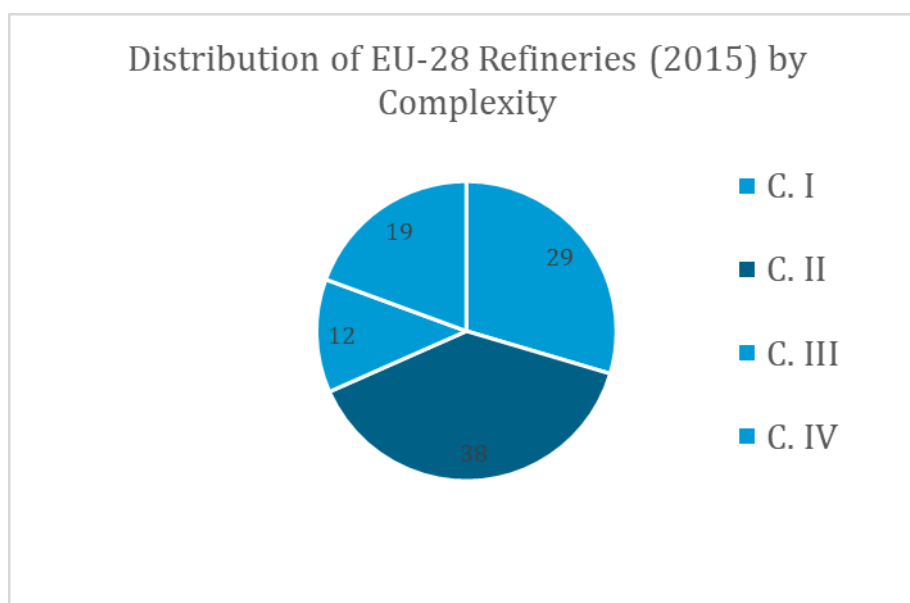
For complexity II, gross naphtha production is split into three different and independent internal naphtha flows:

- ▶ CDU naphtha (straight-run naphtha);
- ▶ FCCU naphtha;
- ▶ Coker naphtha.
- ▶ For complexity III, also three different and independent naphtha flows were identified and considered:
- ▶ CDU naphtha (straight-run naphtha);
- ▶ HCU naphtha;
- ▶ Coker naphtha.

Calculating key figures with the data basis

The distribution of the 98 EU27+UK refineries according to the complexities I-IV in 2015 is shown in Figure 58. Therefore, as to the limitation of unavailable information regarding complexities I and IV, in total 50 (38 C. I and 12 C. III) out of 98 refineries were addressed with the presented approach.

Figure 58: Distribution of refineries by complexity, EU27+UK 2015



Source: Oil&Gas Journal 2017

Given the individual CWT factors for the considered process units, the following CWT factors for the aforementioned naphtha-flows were deduced:

Table 53: Cumulated CWT-factors for individual naphtha-flows

	CDU naphtha	Coker naphtha	HCU naphtha	FCCU naphtha
Complexity II	5.0	8.0	n/a	11.3
Complexity III	5.0	8.0	59.5	n/a

It must be pointed out that these cumulated CWT-factors include the use of hydrogen, both for hydrotreating, which is relevant for all naphtha flows and therefore part of all cumulated CWT-factors, and for the special case of the HCU where hydrogen is used to crack and purify input process feedstock. The cumulated CWT factor for the HCU stands out for this reason in Table 53. For hydrogen production in refineries, an individual CWT factor is determined in the delegated regulation EU 2019/331 (EU Commission (2019)), but, contrary to the other CWT factors used herein, not based on process throughput but on product output. In refineries, hydrogen is also produced as by-product from the reformer. By using figures from literature for the specific hydrogen demand for desulphurisation (Hermann et al. (2014)) and hydrocracking (Worrell & Galitzky (2004) per process throughput, the hydrogen CWT factor was rebased.

To assess GHG-emissions on the basis of the presented approach, besides the cumulated CWT-factors shown in Table 53, unit-specific annual throughputs for all refineries allocated to a certain complexity are needed, to consider the relative weight of the aforementioned naphtha-flows. These throughputs can be deduced from capacity data for all 98 EU27+UK (2015) main-stream refineries which are available from the World Refinery Survey 2017 (Oil and Gas Journal (2016) by multiplying, for each individual refinery, unit capacities with refinery-wide but refinery-specific utilisation rates which were taken from BP (2016). In the interviews with representatives from different refineries, we were informed that it is plausible to transfer the refinery-specific utilization rates to the individual processes, since no significant deviations are to be expected here. It must be pointed out that in Oil and Gas Journal (2016) no Coker capacities were available, which led to the need of using an approximation based on a Coker capacity value available for a complexity II refinery from an interview, and on the assumption of equal relationships of VDU and Coker capacities for all refineries.

Multiplying the cumulated CWT factors for the identified naphtha flows with the sum of the process unit specific throughputs (for EU27+UK or Germany, respectively) yields a CWT value for each naphtha flow. The CWT values of the naphtha flows for the respective complexity are again summed to obtain the CWT value specific to that complexity. Multiplication by the average performance index of 0.037 t CO₂/CWT (CONCAWE (2012)) then yields the absolute GHG emissions attributable to 2015 naphtha production by refineries of each complexity. If the absolute GHG emissions determined in this way are related to the determined gross naphtha production volume, the result is the specific GHG emission per tonne of naphtha for the respective complexity. It is possible to consider both the EU27+UK and Germany, and the resulting results for complexities II and III are shown below.

Table 54: Process unit specific energy intensities used for calculation of naphtha figures

	CDU	VDU	FCCU	HCU	Hydrotreater (DSU)	Coker	HCU-H ₂	DSU-H ₂
Energy intensity (GJ/t tp)	1.07	0.97	0.60	2.33	1.53	0.90	27.73	1.49
Fuel	49%	38%	74%	45%	35%	100%	98%	98%

	CDU	VDU	FCCU	HCU	Hydrotreater (DSU)	Coker	HCU-H ₂	DSU-H ₂
Steam	48%	60%	0%	35%	54%	0%	0%	0%
Electricity	3%	2%	26%	20%	11%	0%	2%	2%
Total	100%	100%	100%	100%	100%	100%	100%	100%

The final energy demands, absolute and specific, are determined almost analogously. Process-specific final energy intensities per tonne of throughput are available as a starting point, as shown in Table 54. These data are largely taken from Worrell & Galitzky (2004), and with regard to the data for the Coker, information from one of the interviews conducted was used as no data for this unit was available in Worrell & Galitzky (2004). Data for H₂-DSU and H₂-HCU (Hydrogen produced in the refinery and used for DSU or HCU, respectively) have been estimated by the authors using information from Worrell & Galitzky (2004); Hermann et al. (2014); Matthes et al. (2020). First, the absolute final energy demand is determined for the individual naphtha flows per complexity by multiplying the process-specific values by the respective determined naphtha production quantities of the individual naphtha flows, differentiated according to the process chain of each naphtha flow. By referring to the naphtha production quantities of each flow, the specific final energy demand per naphtha flow is obtained. To arrive at the absolute and specific energy demand quantities for each complexity, the flow-related quantities are again summed. Here again, both the EU27+UK and Germany can be considered.

2.6.3 Uncertainties and limitations of the methodological approach and data basis

The uncertainties and limitations of the methodological approach and the used database are manifold. On the one hand, it must always be considered that the derivation of specific emission and energy demand figures for refinery products always represents a certain point in time. As a co-product, naphtha is always dependent on the processes used and the overall product structure of the refineries considered. If this changes over time, for example due to a decreasing relevance of fuel production, this will also have an influence on the key figures for individual fractions or products such as naphtha.

The internal naphtha sources represented in Figure 56 and Figure 57 are simplifying with regard to the interlinking of the individual process units and can only represent the individual complexity of the individual refineries in a generalized way. For the quantity-based weighting of the individual naphtha streams to derive average key figures, on the one hand, the data on the relative shares of naphtha production regarding the throughput of the naphtha sources are decisive. On the other hand, with regard to the balance area to which the key figures refer (EU27+UK or Germany, 2015), the data on the production capacities and utilisation rates of the process units are relevant for the quantity-based weighting. For the first point, the question arises as to the transferability of the (few) relative naphtha production shares data obtained via interviews in the course of this study to other refineries. These also depend on a whole range of other factors, including in particular the type of crude oils used. This can result in significant short-term fluctuations as well as long-term trends that affect the relative naphtha shares produced from the assumed internal naphtha sources. For the second point, variations over time can result from plant closures, restructuring, or relining.

Other uncertainties arise from the use of CWT factors to determine GHG emissions on the one hand and the use of literature data for the specific energy intensities of individual processes on the other. It is true that the same simplifying production structure for the internal naphtha sources is assumed for both indicators and the same throughput data is used, i.e., to this extent

the two indicators follow the same approach. However, certain energy requirements of these process units, which are typical for EU refineries, are used to determine the process-specific CWT factors relative to the CDU. However, these are not transparent, which is why other literature data on specific energy intensities had to be used here. These data from Worrell & Galitzky (2004) were in turn determined as typical values for U.S. refineries. Therefore, the consistency between emission and energy key figures is limited.

Moreover, using the average performance index of 0.037 t CO₂/CWT is at least questionable, as not the complete refinery population used to derive this figure is analysed for establishing key figures, but divided into sub-populations (according to complexities I-IV, and separate analysis for Germany) (CONCAWE, 2012). This is unavoidable, as it is the central idea of the presented approach to differentiate between different kinds of 'naphtha products' according to different internal refinery sources for naphtha. It is relatively clear that the smaller the sub-population of refineries considered gets, the more the average performance index of this sub-population might deviate from that of the total population. However, as performance indices for individual refineries are not available, this uncertainty cannot be resolved.

In addition, the capacity data from Oil and Gas Journal (2016) was not complete, which required another generalizing assumption for Coker capacities that also contributes to uncertainty. In addition, also, since the capacity data in the Oil and Gas Survey is not available, the presence of a Coker assumed in the modelling, for both complexity I and complexity II, is ultimately an assumption. It seems very plausible that each refinery would have a facility to process the VDU residuals, however, this unit may also be a Visbreaker, which has a slightly different CWT factor than the Coker (Coker: 2.2; Visbreaker: 1.4) and ultimately, according to one result of the interviews, serves the same purpose as the Coker.

The necessity to work with literature data for demand parameters needed to converse the product-based hydrogen CWT factor given in European Commission (2019) to process-based 'CWT'-factors for the DSU and HCU hydrogen applications leads to additional uncertainties, as energy demand for SMR depends presumably on facility factors such as facility specific energy efficiency and use of by-products such as steam. In addition, demand for hydrogen in both applications depends on the chemical composition of feedstock and products.

2.6.4 Key figures for naphtha as result of the methodological approach

In the following, the key figures for naphtha based on the methodological approach presented above for complexity II and complexity III are given.

Complexity II

For naphtha as defined as a product of complexity II refineries, Table 55 shows the resulting specific emissions, for the case of EU27+UK and Germany in 2015, respectively.

Table 55: Assumptions, intermediate figures and specific emissions for naphtha from complexity II refineries

C.II naphtha	EU27+UK (2015)				Germany (2015)			
	CDU-naphtha	FCCU-naphtha	Coker-naphtha	Total C.II	CDU-naphtha	FCCU-naphtha	Coker-naphtha	Total C.II
Throughputs (kt)	249,282.8	61,864.8	29,734.1	50,6086.7	40,134.6	12,408.9	5,325.3	92,221.4
Assumed naphtha share /unit	20%	45%	10%	-	20%	45%	10%	-
Gross naphtha production (kt)	49,856.6	27,839.2	2,973.4	80,669.1	8,026.9	5,584.0	532.5	1,4143.5
Cumulated CWT-factor	5.0	11.3	8.0	-	5.0	11.3	8.0	-
CWT naphtha (kt)	248,664.0	315,629.1	23,899.1	58,8192.1	40,035.0	63,309.1	4,280.3	107,624.3
CWT offsites for naphtha (kt)				26,766,7				4,796.0
t CO ₂ /CWT (kt)				37.0				37.0
Total emissions (t CO ₂) for gross production				22,753,477				4,159,552.0
Specific emissions (t CO ₂ /t C.II naphtha)				0.282				0.294

By applying the simplified mass flow models and the specific energy demand values presented in Table 54, the following absolute and specific energy consumption has been calculated for C.II naphtha (Table 56):

Table 56: Resulting C.II naphtha energy consumption figures

C.II naphtha	EU27+UK (2015)	Germany (2015)
Total energy consumption for total naphtha production [PJ]	374.89	67.63
SEC per tonne C.II naphtha [GJ/t]	4.65	4.78

As a plausibility check for these specific GHG emission and energy consumption figures, two indicators have been used (Table 57). First, specific emissions per tonne of C.II naphtha can be related to specific energy consumption per tonne of C.II naphtha. This relation is relevant, as these two key figures are derived with two different approaches, as described in 3.5.3. The resulting value fits well in the range of natural gas and refinery gas, which are dominant refinery energy carriers. This leads to the conclusion that, while not being absolutely consistent, using two different approaches for establishing the two dependent key figures seems feasible and leads to plausible results. Second, specific energy consumption per tonne of naphtha is related to the

lower heating value of crude oil (AG Energiebilanzen, 2021). The result shows that only a fraction of the crude oil LHV is used to refine it and win C.II naphtha. Therefore, at least the magnitude of the derived figure seems reasonable.

Table 57: Plausibility checks for derived C.II naphtha figures

Plausibility checks for C. II naphtha EU27+UK	
SGHG/SEC [kg CO ₂ /GJ]	60.69
For comparison: Natural gas	55.9
For comparison: Refinery gas	61.2
SEC naphtha / LHV crude oil	10.9%
LHV crude oil [GJ/t]	42.5
SEC naphtha [GJ/t]	4.6

Complexity III

For naphtha as defined as a product of complexity II refineries, Table 58 shows the resulting specific emissions, for the case of EU27+UK and Germany in 2015, respectively.

Table 58: Assumptions, intermediate figures and specific emissions for naphtha from complexity III refineries

C.III naphtha	EU27+UK (2015)				Germany (2015)			
	CDU-naphtha	HCU-naphtha	Coker-naphtha	Total C.III	CDU-naphtha	HCU-naphtha	Coker-naphtha	Total C.III
Throughputs (kt)	86,050.6	22,329.5	10,689.5	119,069.6	23,142	5,596.8	3,312.9	32,051.7
Assumed naphtha share / Unit	10%	30%	25%	-	10%	30%	25%	-
Gross naphtha production (kt)	8,605.1	6,698.9	2,672.4	17,976.3	2,341.2	1,679	828.2	4,821.5
Cumulated CWT-factor	5.0	59.5	8.0	-	5.0	59.5	8.0	-
CWT naphtha (kt)	42,918.5	398,826.3	21,479.4	463,224.2	11,542.3	99,963.6	6,656.9	11,8162.8
CWT offsites for naphtha (kt)				11,485.6				3,189.4
t CO ₂ /CWT (kt)				37.0				37.0
Total emissions (t CO ₂) for gross production				175,64261.9				4,490,029.2

C.III naphtha	EU27+UK (2015)				Germany (2015)			
	CDU-naphtha	HCU-naphtha	Coker-naphtha	Total C.III	CDU-naphtha	HCU-naphtha	Coker-naphtha	Total C.III
Specific emissions (t CO ₂ /t C.III naphtha)				0.977				0.931

By applying the simplified mass flow models and the specific energy demand values presented in Table 54, the following absolute and specific energy consumption has been calculated for C.II naphtha (Table 59):

Table 59: Resulting C.III naphtha Energy consumption figures

C.III naphtha	EU27+UK (2015)	Germany (2015)
Total energy consumption for total naphtha production [PJ]	276.4	70.9
SEC per tonne C.III naphtha [GJ/t]	15.4	14.7

Again, the same plausibility checks as presented above have been conducted, the results are presented in Table 60. Again, specific GHG emissions related to the SEC shows a plausible number comparable to the specific GHG emissions of natural gas and refinery gas as dominant energy carriers. The quotient of SEC to LHV of crude oil is much higher, though, compared to C.II naphtha. However, this still seems not unrealistic, as to the high energy intensive hydrogen production. Uncertainty arises, as described in 3.5.3, due to hydrogen demand in the HCU, which might vary considerably between individual refineries.

Table 60: Plausibility checks for derived C.III naphtha figures

Plausibility checks for C. III naphtha EU27+UK	
SGHG/SEC [kg CO ₂ /GJ]	63.54
For comparison: Natural gas	55.9
For comparison: Refinery gas	61.2
SEC naphtha / LHV crude oil	36.2%
LHV crude oil [GJ/t]	42.5
SEC naphtha [GJ/t]	15.4

Comparing results for complexity II and complexity III

The results for complexity II and complexity III naphtha show clear differences, which will be briefly discussed here. Both the specific emissions and the specific energy demand per tonne of naphtha are significantly higher for complexity III than for complexity II. Considering the EU27+UK, the specific emissions for complexity III are higher by a factor of 3.5, the specific energy demand by a factor of 3.3. This can clearly be attributed to the high hydrogen demand as well as the high specific emissions and the high specific energy demand of hydrogen production,

which is expressed in the very high cumulative CWT factor of 59.5 for HCU. This shows that the refinery production structure, represented by the existing naphtha-producing plants, plays a significant role for a material flow-based determination of key figures.

A look at the naphtha production figures determined for the EU27+UK and for Germany shows that the production volumes of C.II naphtha are significantly higher in total than those of C.III naphtha. For the EU27+UK, the C.II quantity was 4.5 times as high as the C.III quantity, for Germany this factor was just under 3. This ratio appears plausible in view of the distribution of refineries among the defined complexities (Table 60). It should be emphasised once again that these are gross production quantities, determined with the methodology described here, not actually empirically determined or sales quantities of the refineries. Due to the significantly higher specific emissions and energy requirements for C.III naphtha, the ratio of the absolute attributable emissions and energy requirements deviates significantly from the ratio of the gross production quantities. For the EU27+UK in 2015, based on the methodology described here, 1.3 times as many emissions were caused by C.II naphtha compared to C.III naphtha at 4.5 times the production volume. For Germany, this value is around 0.9, which means that C.III naphtha caused higher emissions than C.II naphtha despite a significantly lower production volume. The ratio looks quite similar for the relation of specific energy requirements, for the EU27+UK the factor C.II/C.III is 1.4, for Germany 0.95.

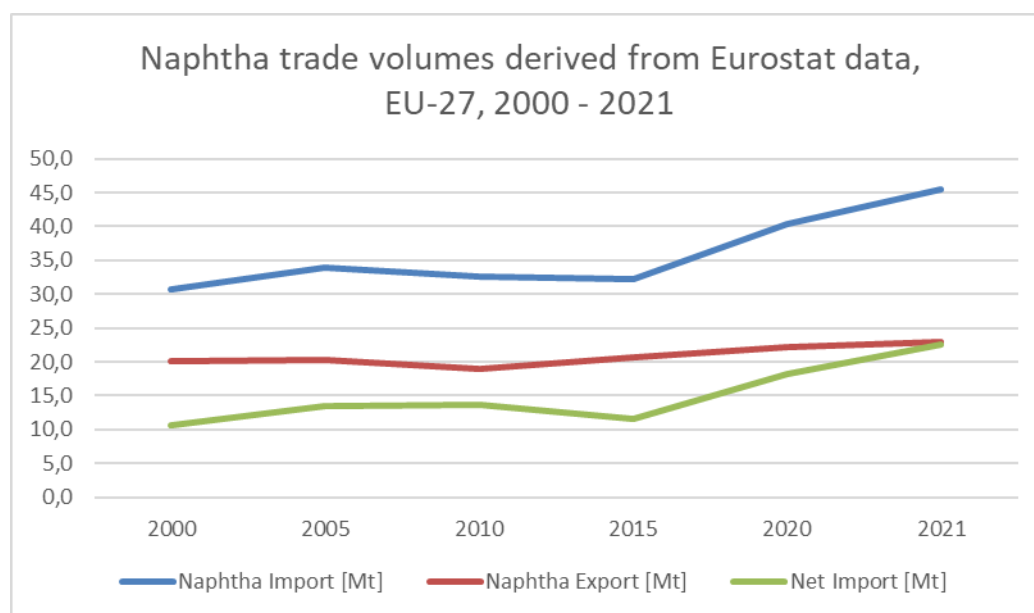
2.6.5 Key economic indicators and cost structure

Specific information on naphtha trade volumes is not available in the Comtrade database; see further below for more general information on trade volumes regarding the oil and refinery industry.

However, Eurostat energy statistics provides data on imports and exports for the EU-27 and individual member states, including Germany (Eurostat, 2023a; Eurostat, 2023b). These data are presented in the following. However, the data provided by Eurostat is given in energy units. To translate these to physical quantities, the heating value for naphtha given by the AG Energiebilanzen has been used.

Figure 59 shows the resulting naphtha trade volumes for the EU-27 from 2000 to 2021. Clearly, naphtha imports have always been higher in this period than exports, resulting in a net import of naphtha. The amounts are quite significant and since 2015, higher imports can be seen. From 10.6 million tons in 2000, net imports rose to 22.6 million tons in 2021, which is an increase of more than 100% in 20 years. Physical petroleum products trade quantities

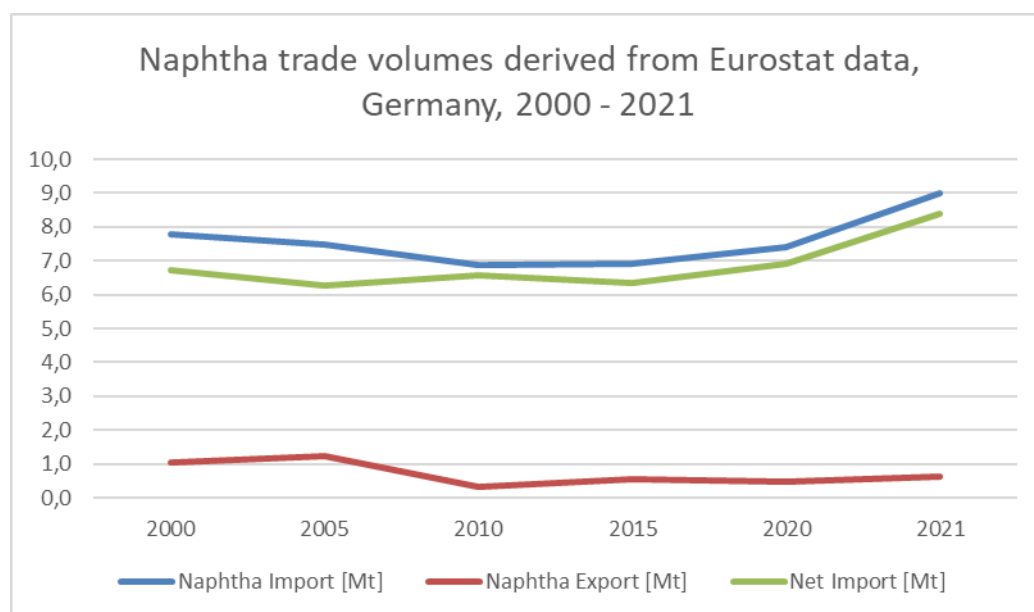
Figure 59: Naphtha trade volumes for the EU-27, 2000 - 2021



Source: Eurostat (2023a); Eurostat (2023b)

Figure 60 gives the respective trade numbers for the case of Germany. As for the EU, imports have always been higher in this period, but the relation of imports to exports is even higher than for the EU in total. However, the relative increase of net imports in this period was not as high as for the EU-27 and reached 24.2%, up from 6.7million tons in 2000 to 8.4 million tons in 2021. From that, it can be concluded that other EU-27 member states must be responsible for the step increase of naphtha imports in that timeframe.

Figure 60: Naphtha trade volumes for Germany, 2000 - 2021



Source: Eurostat 2023a; Eurostat 2023b

Additionally, in the Comtrade trade database, some aggregated data on the oil and refining industry can be found, which includes naphtha, but of course also many other products. The fol-

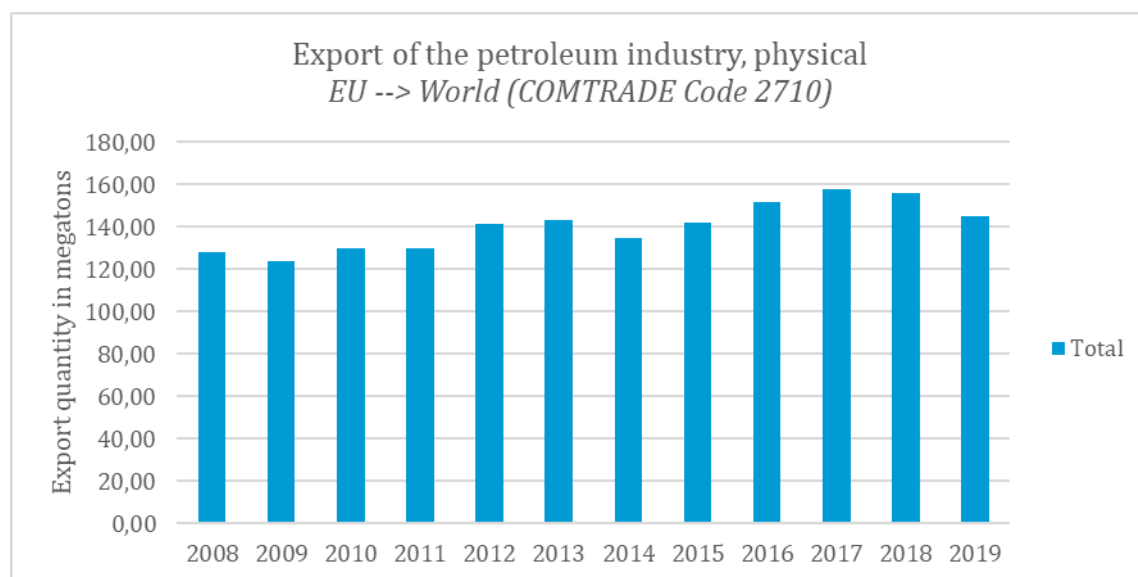
lowing is an analysis of the data of Comtrade code HS (harmonized system) 2710, which includes: 'Petroleum Oils, oils from bituminous minerals, not crude; preparations n.e.s containing less than 70% petroleum oils, oils from bituminous minerals; these being the basic constituents of the preparations'. Unfortunately, there is no further information on the exact commodities covered, but the other four-digit level HS27 codes suggest that 2710 covers all petroleum products excluding crude oil (which would be 2709).

Physical petroleum products trade quantities

As the following graphs (Figure 61, Figure 62, Figure 63) show, petroleum product imports and exports in physical quantities grew in the last years since 2008, adding to ~15% higher imports in the 2008-2019 and ~30% higher exports in the same period. Imports and Exports are in similar magnitudes, resulting in rather small net trade volumes (EU27+UK $\leftrightarrow$ World) between 10 and 25 Mt net exports. Looking only at net trade flows, considerable fluctuations can be seen.

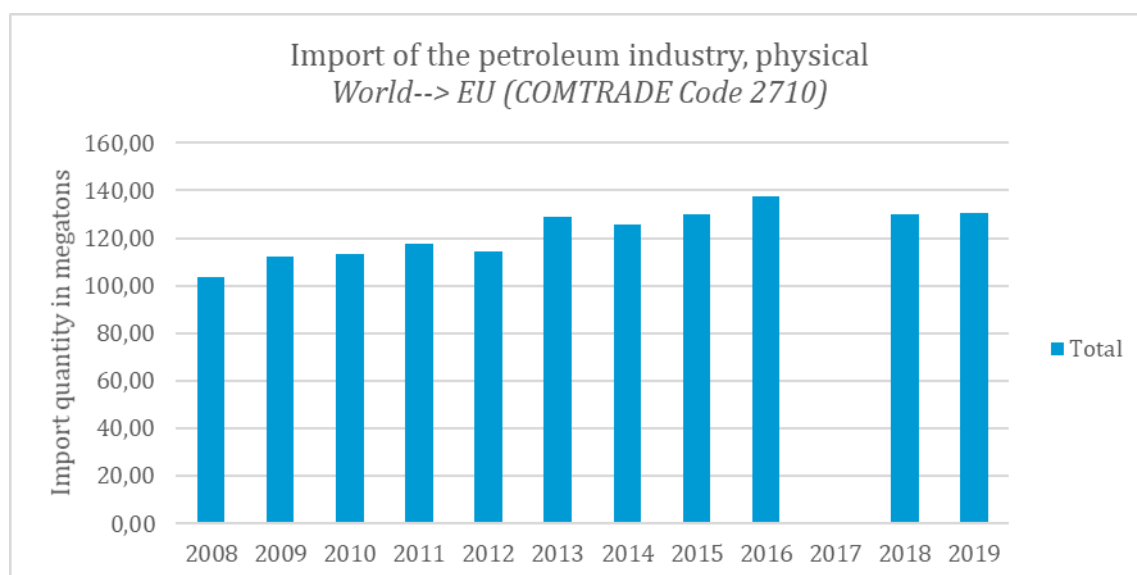
Interestingly, Germany's net trade volumes were partly higher than EU27+UK trade volumes, but that can be attributed to trading within the EU (Figure 64). Germany net trade volumes were more stable in recent years than the ones for the EU27+UK in total.

Figure 61: Export of the petroleum industry (physical quantities), EU27+UK 2008 to 2019



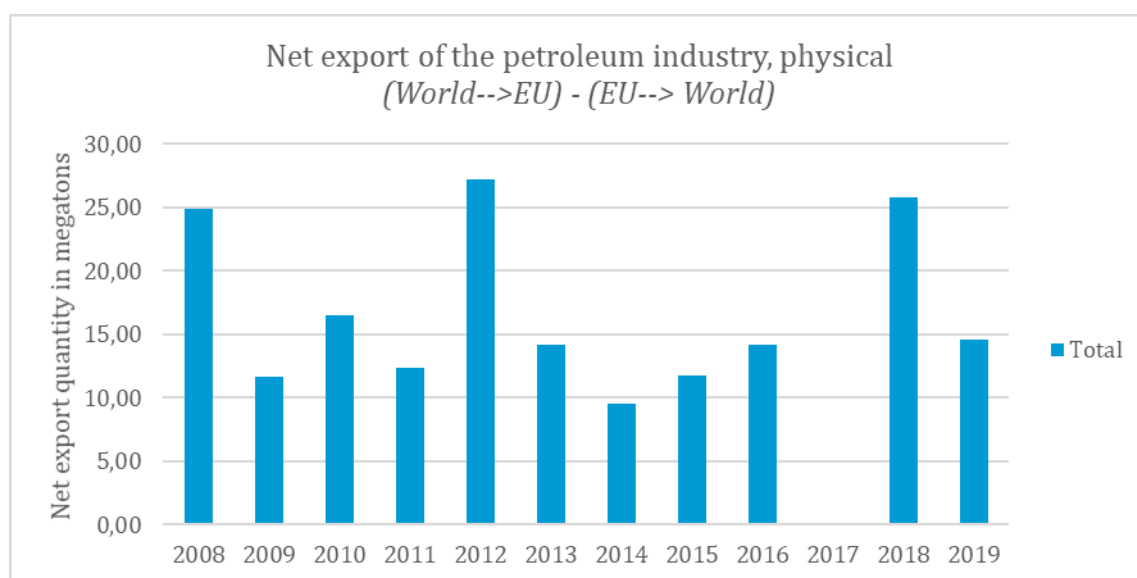
Source: Eurostat (2020b)

Figure 62: Import of the petroleum (physical quantities), EU27+UK 2008 to 2019



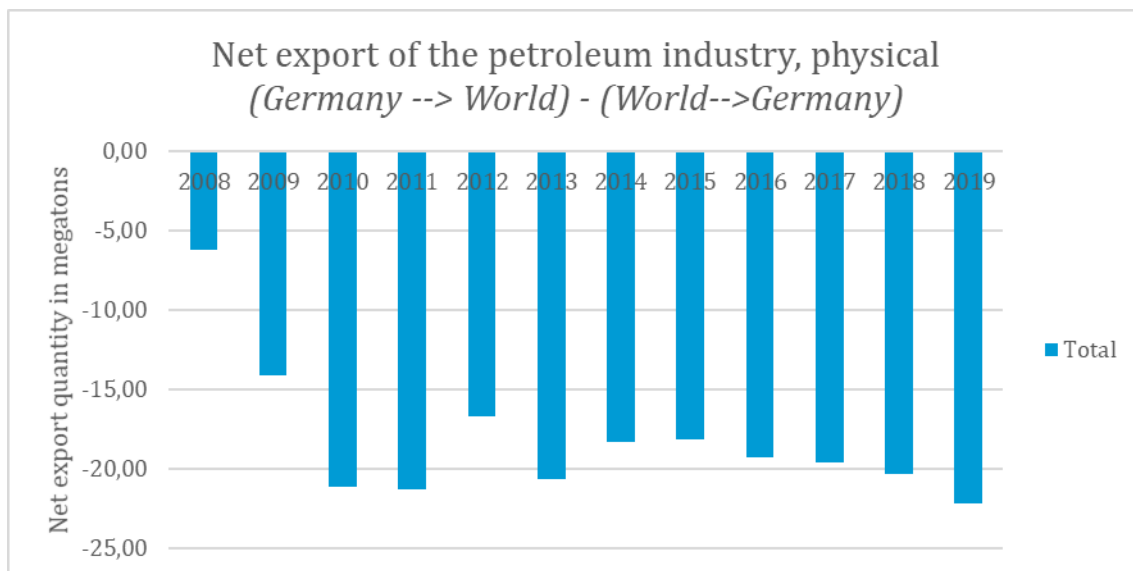
Source: Eurostat (2020b)

Figure 63: Net export of the petroleum industry (physical quantities), EU27+UK 2008 to 2019.



Source: Eurostat (2020b)

Figure 64: Net export of the petroleum industry (physical quantities), Germany 2008 to 2019.

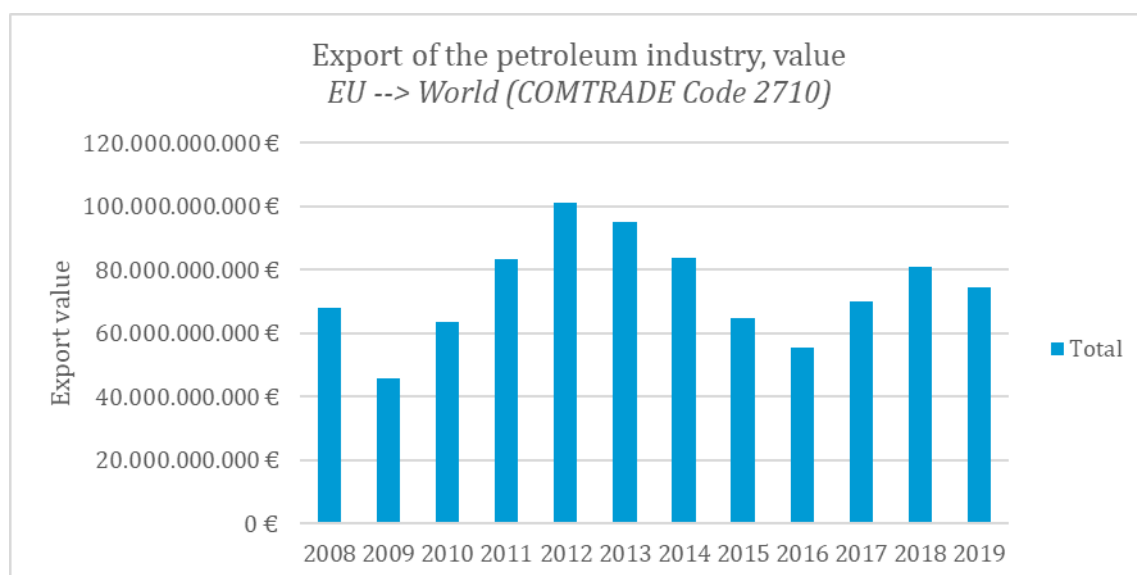


Source: Eurostat (2020b)

Trade value of petroleum products trading

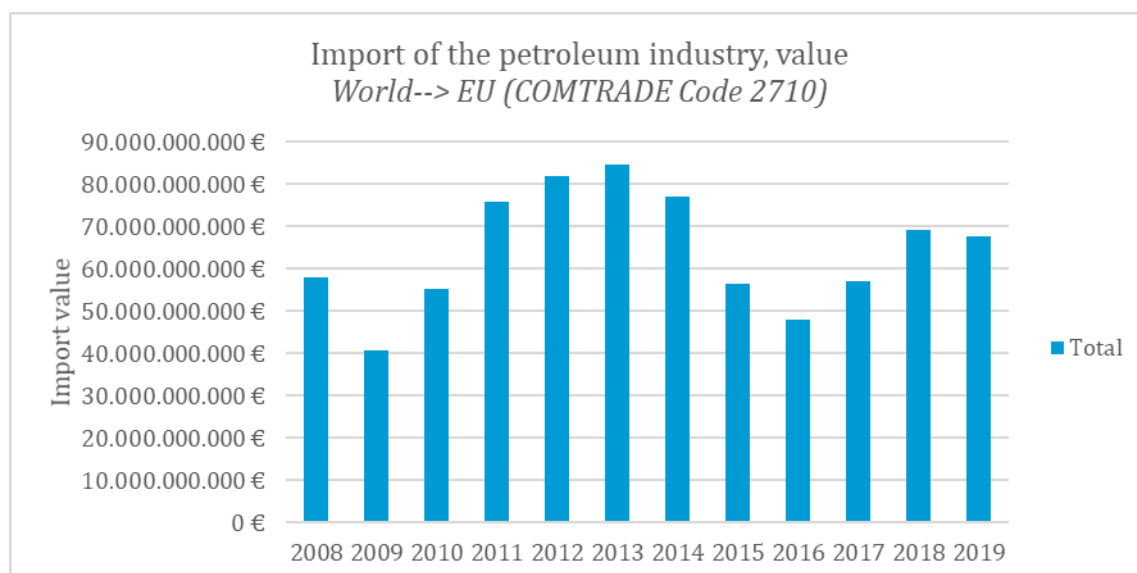
The figures representing the monetary trade values (Figure 65, Figure 66, and Figure 67) show an interesting picture. Obviously, the trade value of both imports and exports fluctuates with the same periodicity. Therefore, it can be assumed that these are not shifts in the traded product structure. It is reasonable to assume that these values reflect business cycles in the petroleum industry, which are reflected in fluctuating product margins, because such fluctuations are not visible in the figures of physical trade values shown above. The assumption that business cycles are the decisive factor here is supported by the discernible declines in monetary trade volumes from 2008 to 2009. While for the EU27+UK as a whole the net trade balance was always positive throughout the period under consideration here, the opposite is true for Germany (Figure 68), reflecting the respective situation for the physical trade quantities.

Figure 65: Export of the petroleum industry (monetary value), EU27+UK 2008 to 2019



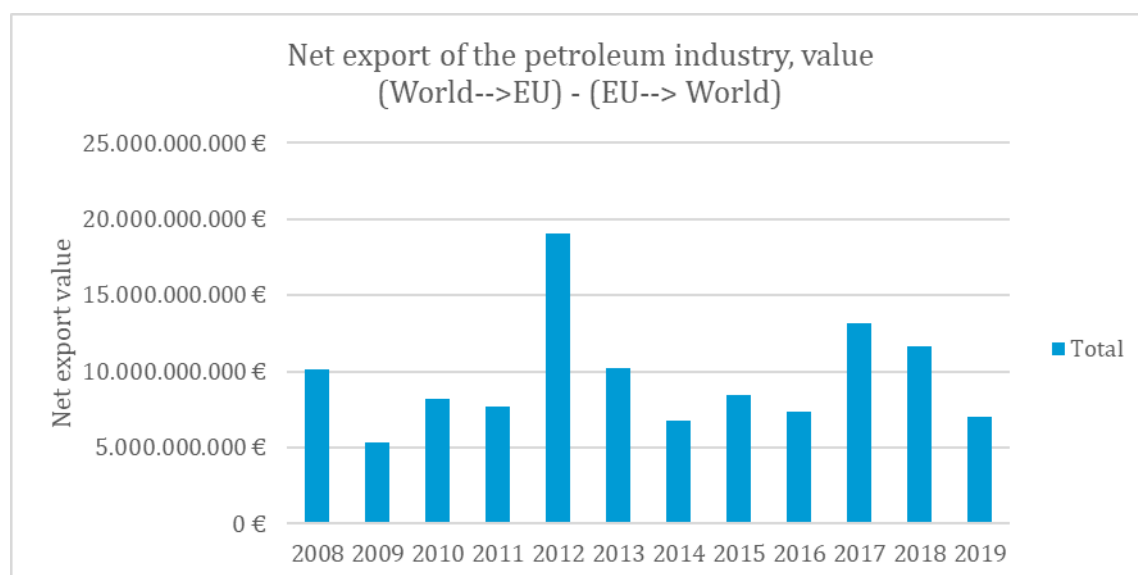
Source: Eurostat (2020b)

Figure 66: Import of the petroleum industry (monetary value), EU27+UK 2008 to 2019



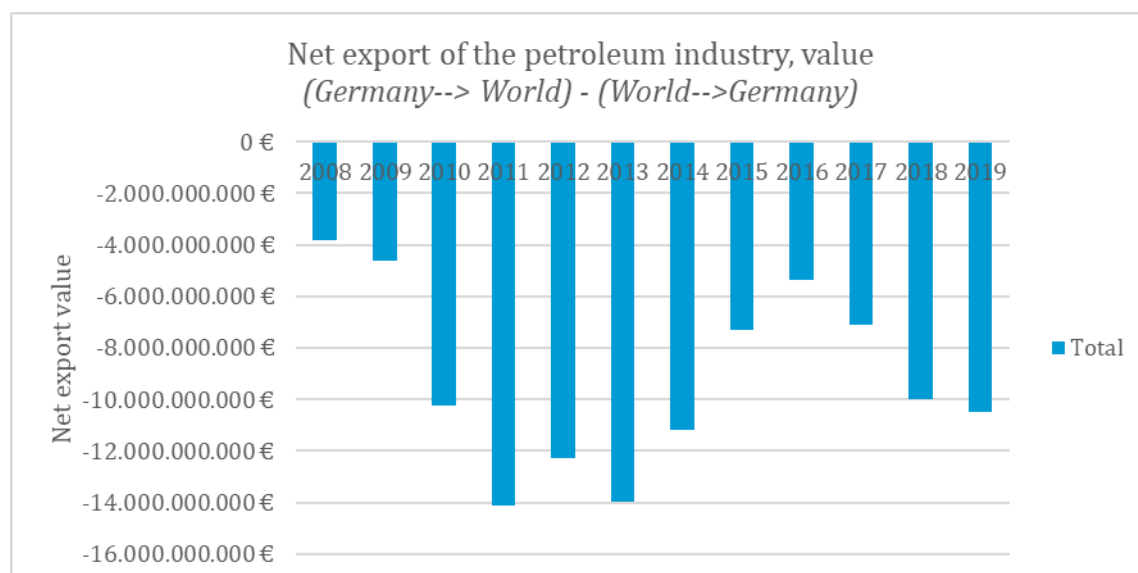
Source: Eurostat (2020b)

Figure 67: Net export of the petroleum industry (monetary value), EU27+UK 2008 to 2019



Source: Eurostat (2020b)

Figure 68: Net export of the petroleum industry (monetary value), Germany 2008 to 2019



Source: Eurostat (2020b)

Typical refinery cost structure

As for trade volumes and values, no naphtha-specific data on cost structure could be retrieved. However, it seems plausible to assume that the general structure of costs does not deviate considerably between different petroleum products, as costs are dominated by crude oil. If process-specific CAPEX where available, it might be possible to define a simplified cost-structure model similar to the model presented above to derive key figures depending on refinery complexity. In the following, a typical breakdown of refinery operating costs is shown, which is taken from literature (Robinson, 2007). It becomes clear that crude oil is very dominant with 85% of the OPEX.

Table 61: Typical OPEX-structure of a refinery

Item	% of 'Other' OPEX	% of Total OPEX
Crude oil and blend stocks	-	85
Other OPEX, and thereof:		15
Fuels	40,7	
Electricity	5,3	
Maintenance	23,3	
Operations	18	
Catalysts and chemicals	12,7	
Totals	100	100

2.6.6 Summary and conclusions

In particular, the analysis presented herein highlights the challenges and limitations of attempting to determine material flow-based key figures for GHG emissions and energy consumption for refinery products. Specifically, the attempt was made to analyse a certain refinery product, namely naphtha, depending on the production structure, and to derive corresponding key figures. The first step was to categorise the refineries of the EU27+UK (2015) according to the complexity of the existing production and conversion units. Subsequently, the internal naphtha sources of the respective complexity were identified, and a simplified material flow model was developed for these sources. Based on interviews with refinery representatives, the model was then parameterised, in particular with regard to the respective 'typical' naphtha shares of the production units considered. With the model and the naphtha shares, it was possible to link to the established CWT approach for establishing process unit specific key figures and to derive product specific key figures. Unfortunately, due to limited response to interview requests, data was only available for two of the four defined complexities, so that the key figures could only be determined for complexity II and complexity III. The results show considerable differences with regard to the specific GHG emissions and the specific energy consumptions that can be assigned to the respective naphtha production. This can be attributed in particular to differences in hydrogen consumption. Despite the many uncertainties and limitations to which the methodological approach developed is inevitably subject (small database and generalization of individual refinery data, use of 'typical' values from literature, clear simplification of the real complex refinery structures), the result is that the production structure of the refineries has a considerable influence on the emissions and energy consumption that can be attributed to a particular refinery product. It seems advisable to refine the present approach and to place it on a more reliable data basis through surveys. However, it should be emphasised that this analysis is also a snapshot. Since naphtha, like all refinery products, is a co-product, changes in the production structures resulting, for example, from changes in the demand markets (trend towards e-mobility leads to declining fuel demand, to name one) lead to changes in the key figures determined here.

2.7 Basic chemicals

2.7.1 Production overview

Polyethylene (PE) and polypropylene (PP) are selected to be investigated as examples of products from basic chemicals. PE and PP belong to the group of polyolefins and are produced by the polymerisation of the monomers ethylene and propylene.

Polyethylene is produced according to two different methods, the high-pressure and the low-pressure process (Caseri et al. 2009). The resulting products are therefore frequently referred to as high-pressure polyethylene or low-pressure polyethylene. They differ mainly in their degree of branching and thus in their degree of crystallinity and density. The high-pressure process produces branched polyethylene with lower densities (approx. 0.915-0.935 g/cm³), known as LDPE (low density polyethylene) or LLDPE (linear low-density polyethylene). The macromolecules of polyethylene from low-pressure processes are largely linear and unbranched. These so-called HDPE (high-density polyethylene) have densities of approx. 0.94-0.97 g/cm³.

Polypropylene is mainly produced using the gas phase polymerisation process. This is initiated with Ziegler-Natta catalysts and, increasingly, metallocene catalysts. The technically used polypropylenes are mostly arranged in the same chain structure (isotactic) and are therefore highly crystalline. However, depending on the catalyst used, less crystalline or amorphous polypropylenes can also be produced, which results in a wide range of material properties. By copolymerisation of propene and ethylene, also elastomers can be produced (EPM).

2.7.2 Key figures for selected basic chemicals

2.7.2.1 Material flow

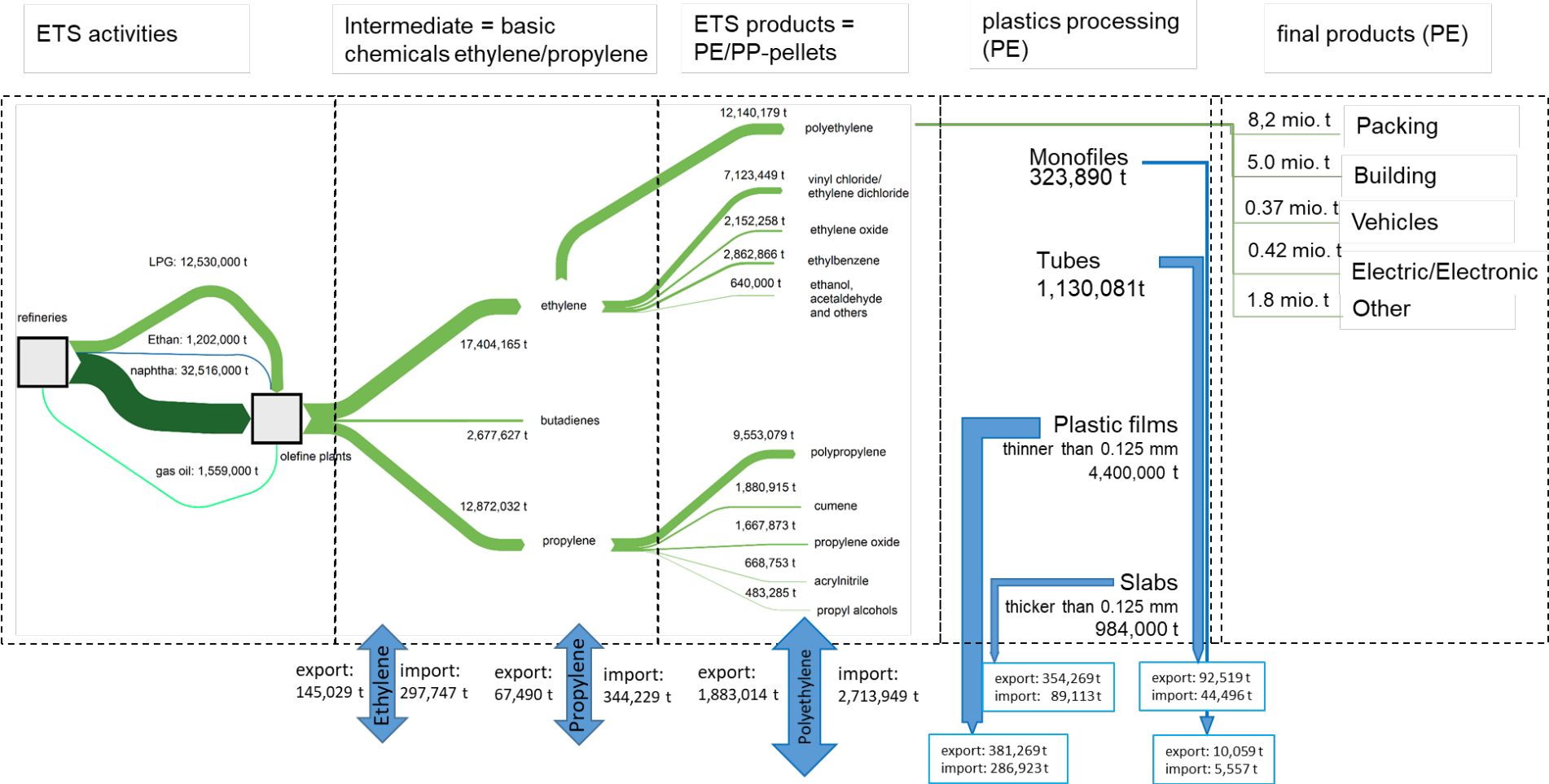
The material flow for the production and use of polyethylene and polypropylene is shown in the following figures. Figure 69 and Figure 70 show the flows in the EU27+UK, Figure 71 and Figure 72 the flows for Germany in 2015.

Steam cracking is the process by which both propylene and ethylene are produced. Therefore, the left part of the graphs is identical for polyethylene and polypropylene. Afterwards, the ethylene or propylene is converted into various products. Among them is polyethylene or polypropylene, which is then further processed into plastic products like foils for packing or tubes for buildings. This processing is done by thermal forming such as injection moulding, extrusion, stretch blow moulding a. o. Of course, this illustration is very simplified: Among other things, there are co-polymers of ethylene/propylene and various additives (e.g. pigments) are used in polymerisation, which quantities are not shown here. Foreign trade is shown in Figure 69 to Figure 72 in the blue arrows at the bottom of the graphs. There is foreign trade at all levels of the value chains. The volumes are smaller for gaseous ethylene/propylene and significantly higher for polyolefin pellets that can be easily transported in bags. The data used for the material flows are given in Table 62.

Table 62: Data used in model to calculate material flows

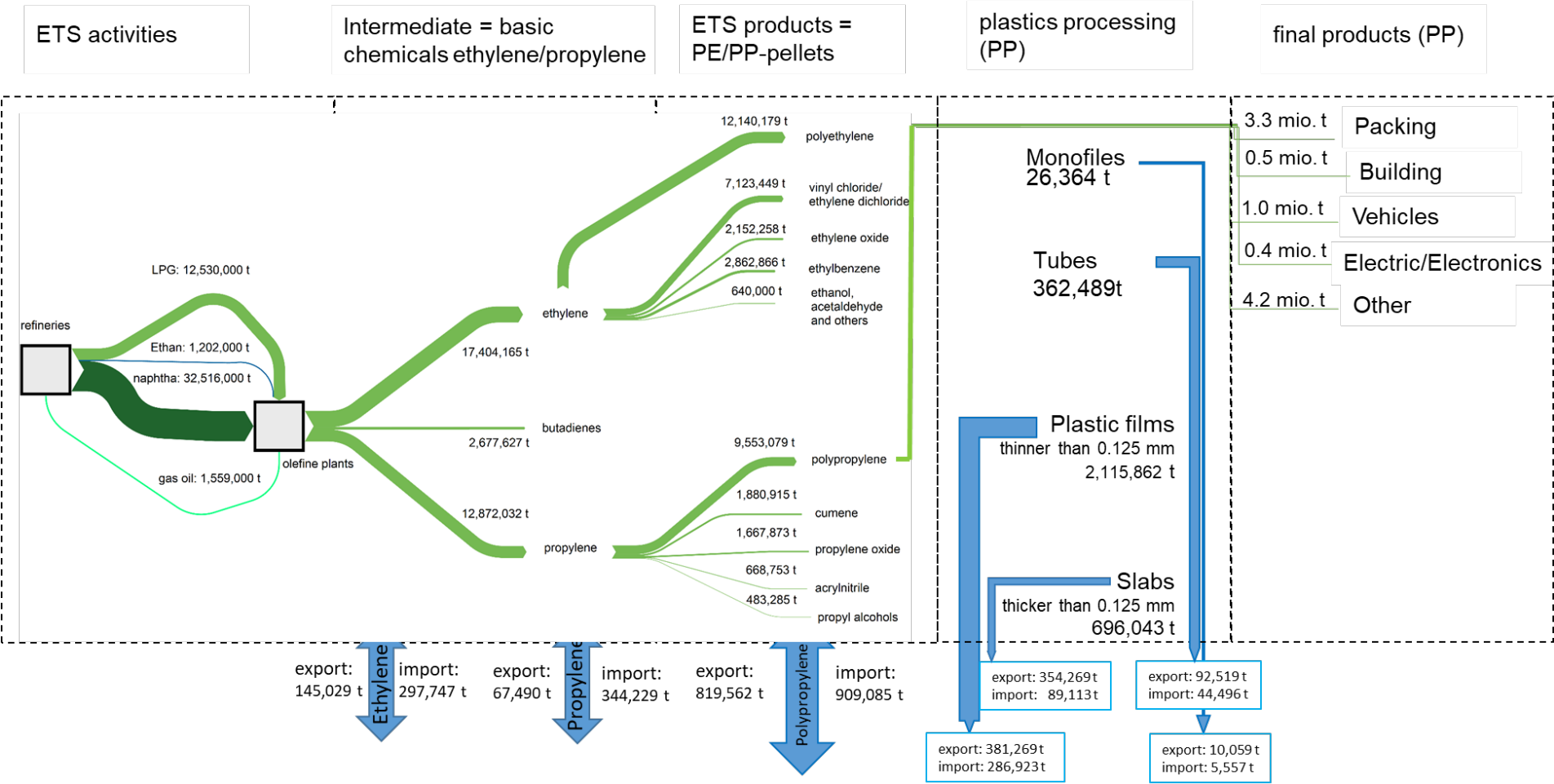
Indicators	Value EU27+UK	Value Germany	Unit	Type	Source EU27+UK	Source Germany	Confidence
Production data	see Figure 69, Figure 70	see Figure 71, Figure 72	t	Statistics	Prodcom (2018)	Destatis (2020), VCI (2018)	high
Foreign trade data	see Figure 69, Figure 70	see Figure 71, Figure 72	t, €	Statistics	Prodcom (2018)	Destatis (2016)	high
Final products	see Figure 69, Figure 70	see Figure 71, Figure 72	Mt	Literature	Kawecki et al. (2018)	Consultic (2016)	medium/high

Figure 69: Modelled material flow polyethylene (PE), EU27+UK 2015



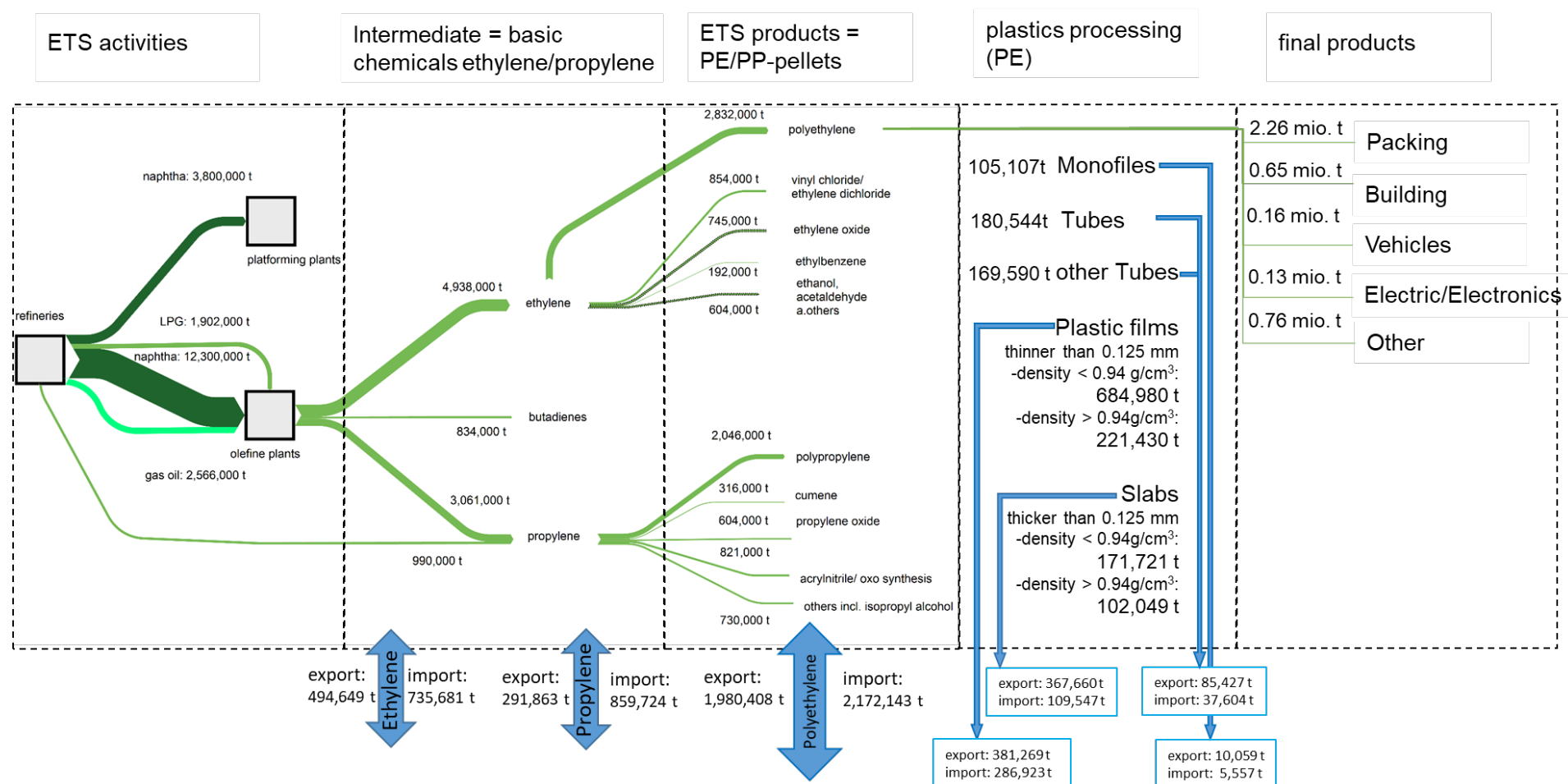
Source: own calculation based on data sources presented in Table 62

Figure 70: Modelled material flow polypropylene (PP), EU27+UK 2015



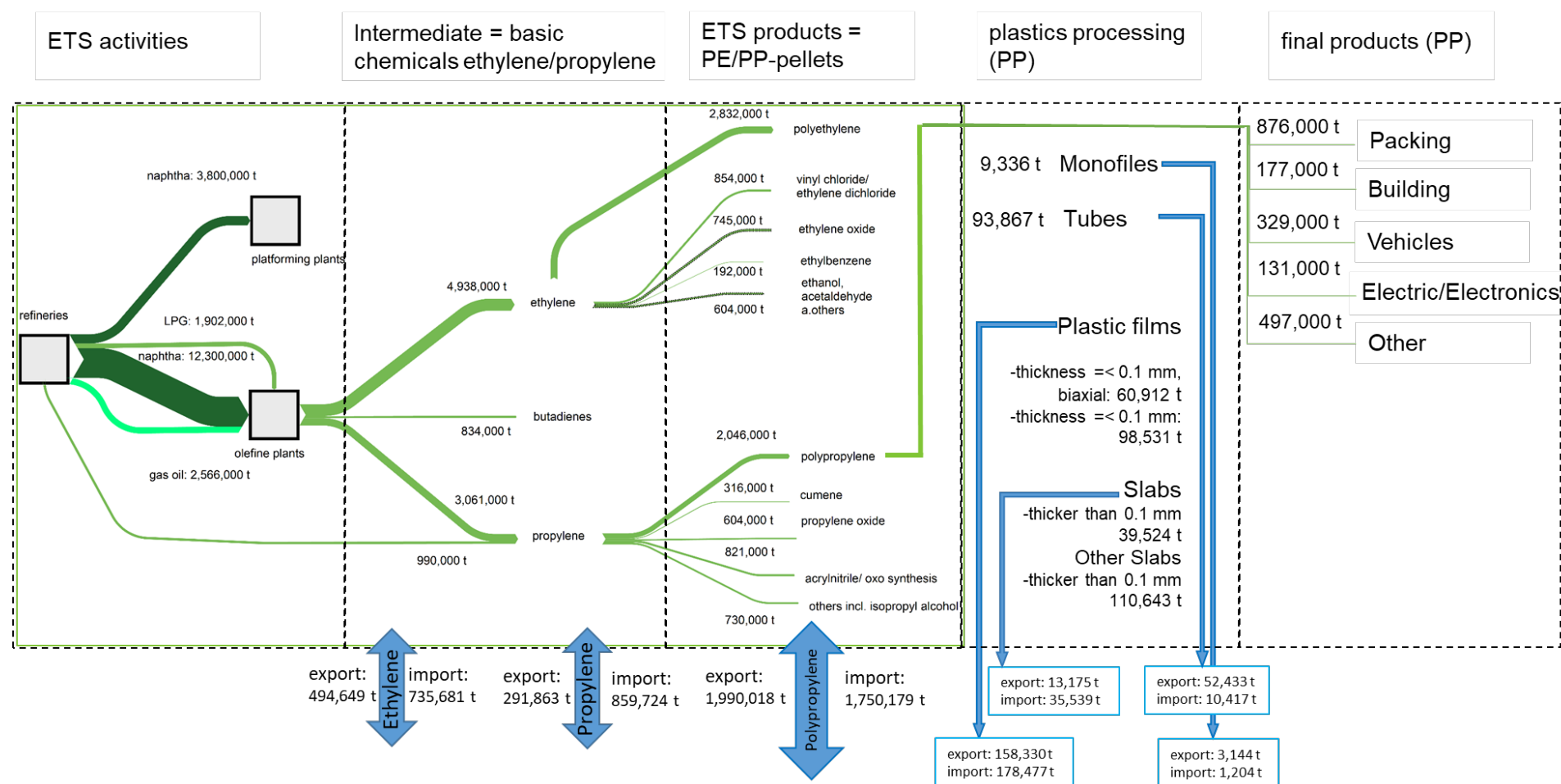
Source: own calculation based on data sources presented in Table 62

Figure 71: Modelled material flow polyethylene (PE), Germany 2015



Source: own calculation based on data sources presented in Table 62

Figure 72: Modelled material flow polypropylene (PP), Germany 2015



Source: own calculation based on data sources presented in Table 62

2.7.2.2 Final energy demand

Looking at energy demand in the value chain for the production of polyethylene and polypropylene, the most energy is used for the production of the monomers ethylene and propylene in the steam cracker. In addition, the energy for the production of the steam cracker feedstock (especially naphtha, LPG and ethane) must also be taken into account. The specific energy consumption of producing the polymers polyethylene and polypropylene from the monomers ethylene and propylene is comparatively low (see the tables on next page), as is the plastics processing at the end of the value chain.

Steam cracking is the only large-scale process currently available for the production of the entire range of short-chain olefins. Worldwide, 98% of ethylene and 70% of propylene are produced in steam crackers. The remaining propylene is mainly produced by catalytic cracking of higher boiling fractions in refineries. Short-chain olefins are also obtained in smaller quantities from refinery gas. Butadiene is also obtained almost exclusively in steam crackers. The aromatics are also mostly produced in steam crackers (approx. 70% for benzene) (Hassan 2013).

Steam cracking consists of several steps, described e.g. for the BASF steamcracker: The naphtha is first mixed and evaporated with water vapour. It is then heated in giant ovens for a fraction of a second to around 840°C, which causes the naphtha to break down into smaller components. The hot gas is rapidly cooled immediately afterwards. This prevents the cleavage products from breaking down further. Finally, the products contained in the mixture formed are further separated by distillation, the products of which include primarily ethylene, propylene, butadiene, pyrolysis gasoline and hydrogen (BASF n.d.). Modern steamcrackers can produce up to 1.5 million tons of ethylene per year and 600,000 t of propylene per year (Linde 2020).

Steam crackers use different feedstock and can produce a different range of products, depending on residence times and reaction temperatures. The different feedstocks for crackers in Germany and the EU27+UK for 2015 are shown in Table 63. While figures from the German chemical association (VCI) were available for Germany, the share of the various feedstock in Europe has to be calculated from the energy balance data for the EU27+UK. The composition of the feedstock in Germany and Europe differ: While mainly naphtha and gasoil were used in Germany, their share was lower in the EU. More LPG and ethane were used instead.

Table 63: Feedstock used in steamcracker 2015

[%]	Germany	EU27+UK
Naphtha	74	67
LPG	11	27
Gas Oil	14	3
Ethane		3
Source	VCI 2018	Eurostat 2020a
Confidence	High	Medium

Depending on the feedstock and the mode of operation of the crackers, but also on the reference product, different energy consumptions for the steam cracker are given in the literature. Within the framework of European emissions trading, so-called high value chemicals (HVC) have be-

come established as a reference. HVC products include ethylene, propylene, butadiene, acetylene, benzene, toluene, xylenes, ethyl benzene, styrene and purified hydrogen (European Commission 2019). Table 64 gives an overview of published energy consumption in steam crackers.

Table 64: Energy consumption and emissions in steamcracker

Fuel	Specific energy consumption	Specific emission	Source
Naphtha	16.5 GJ/ t HVC (BPT* 12GJ/ t HVC)	0.76 t CO ₂ eq/t HVC	Bazanella et al. 2017
	18 – 25.5 GJ/ t ethylene		Ren et al. 2006
	25 – 40 GJ/ t ethylene 14 – 22 GJ/ t HVC		Enviros Consulting 2006
Ethane	15 – 18 GJ/ t ethylene 12.5 – 21GJ/ t HVC		Enviros Consulting 2006
Gas oil	40 – 50 GJ/ t ethylene 18 – 23 GJ/t HVC		Enviros Consulting 2006
Benchmark		0.702 t CO ₂ eq/t HVC	EU 2011

*Best practice technology

In the following tables, the final energy consumptions in the steam crackers for ethylene and propylene are calculated based on the specific fuels demand from Bazanella & Ausfelder (2017) and the production data from VCI (2018). In addition, the values for transforming them into polyethylene and polypropylene are presented, obtained from the ISI model. During the polymerisation of ethylene, steam is produced, therefore the values for the energy consumption of fuels are negative.

Table 65: Calculated final energy demand, EU27+UK 2015

Product	ETS-activity	Production [kt]	Specific fuels [GJ/t]	Specific electricity [GJ/t]	Fuels [TJ]	Electricity [TJ]	Source
Ethylene (naphtha steamcracker)	42	17,404	16.5*		287,166		Bazanella & Ausfelder (2017)
Propylene (naphtha steamcracker)	42	12,872	16.5*		212,388		Bazanella & Ausfelder (2017)
Polyethylene (polymerisation)	42	12,140	-0.2	2.7	-2,400	32,800	ISI Model
Polypropylene (polymerisation)	42	9,553	1.2	2	11,460	19,100	ISI Model

* Specific Fuel demand in [GJ/t HVC]

Table 66: Calculated final energy demand, Germany 2015

Product	ETS-activity	Production [kt]	Specific fuels [GJ/t]	Specific electricity [GJ/t]	Fuels [TJ]	Electricity [TJ]	Source
Ethylene (naphtha steamcracker)	42	4,938	16.5*		81,500		DECHE MA
Propylene (naphtha steamcracker)	42	3,061	16.5*		50,500		DECHE MA
Polyethylene (polymerisation)	42	2,832	-0.2	2.7	-570	7,600	ISI Model
Polypropylene (polymerisation)	42	2,064	1.2	2	2,480	4,130	ISI Model

* Specific Fuel demand in [GJ/t HVC]

2.7.2.3 Emissions

Also in the following tables, the values for HVC from Table 64 are used for the CO₂ emissions for ethylene and propylene. The results are also shown in the Figure 73 and Figure 74.

For the calculation of the CO₂ emissions for the naphtha production in refineries 0.977 t CO₂/t naphtha for Europe and 0.931 t CO₂/t naphtha is used for Germany. These are the values for a complex refinery, see chapter 2.6.4. The quantities are taken from the Figure 69 and Figure 71.

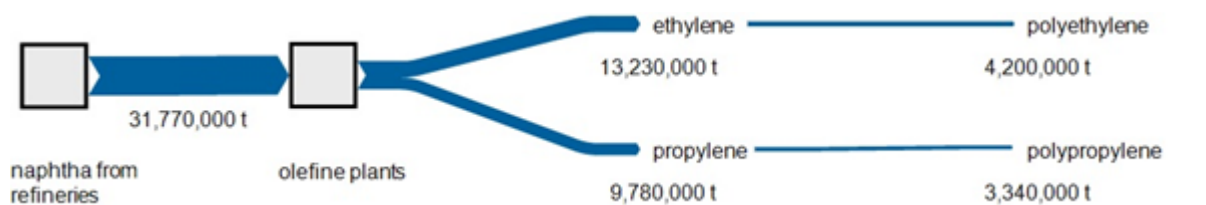
Table 67: Calculated emissions, EU27+UK 2015

Product	ETS-activity	Production [kt]	Specific energy related [t CO ₂ eq/t HVC]	Specific indirect energy-related [t CO ₂ eq/t HVC]	Specific total [incl. indirect] [t CO ₂ eq/t HVC]	Direct energy related [kt CO ₂ eq]	Indirect energy related [kt CO ₂ eq]	Total [excl. indirect] [kt CO ₂ eq]	Confidence
Ethylene (naphtha steamcracker)	42	17,404			0.76	-	-	13,230	Medium
Propylene (naphtha steamcracker)	42	12,872			0.76			9,780	Medium
Polyethylene (polymerisation)	42	12,140	-0.014	0.36	0.35	-170	4,370	4,200	Medium
Polypropylene (polymerisation)	42	9,553	0.08	0.27	0.35	760	2,580	3,340	Medium

Table 68: Calculated emissions, Germany 2015

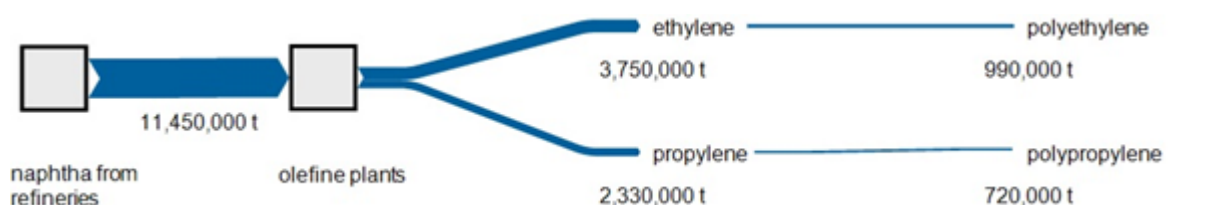
Product	ETS-activity	Production [kt]	Specific energy related [t CO ₂ eq/t HVC]	Specific indirect energy related [t CO ₂ eq/t HVC]	Specific total [incl. indirect] [t CO ₂ eq/t HVC]	Direct energy related [kt CO ₂ eq]	Indirect energy related [kt CO ₂ eq]	Total [excl. indirect] [kt CO ₂ eq]	Confidence
Ethylene (naphtha steamcracker)	42	4,938			0.76	-	-	3,750	Medium
Propylene (naphtha steamcracker)	42	3,061			0.76			2,330	Medium
Polyethylene (polymeri- sation)	42	2,832	-0.014	0.36	0.35	-40	1,020	990	Medium
Polypropylene (polymeri- sation)	42	2,064	0.08	0.27	0.35	165	555	720	Medium

Figure 73: Modelled CO₂-emissions for the production of PE and PP, EU27+UK 2015



Source: own calculation

Figure 74: Modelled CO₂-emissions for the production of PE and PP, Germany 2015



Source: own calculation

2.7.2.4 Uncertainties and limitations of approach

For production volumes and foreign trade, it was possible to draw on statistical data, the quality of which is generally good. The data on specific energy consumption and emissions come from publications, often without further differentiation, so that their data quality must be classified as medium.

2.7.3 Key economic indicators and cost structure

2.7.3.1 Cost structure

For the assessment of the cost structure of the selected final analysed products polyethylene and polypropylene in statistics, the cost structure of companies which produce polymers in primary forms is published. However, these statistics also include companies that do not produce polyethylene and polypropylene, but also other polymers such as PVC or polyamides.

At EU level, data on cost structures are not published in detail (Eurostat 2021), but only for the major cost components (total purchases of goods and services, personnel costs, purchases of energy products). In addition, for reasons of confidentiality, data are not published for some countries, which means that even the aggregated figures for the EU27+UK are not complete. Therefore, seven countries were selected (Belgium, Germany, France, Italy, Hungary, Netherlands, Portugal) based on the data availability and to obtain a regional heterogeneity. Their cost structures are shown in Table 69. The share of personnel and energy costs varies and is lowest in Hungary and Portugal. However, the shares are in the same order of magnitude across Europe.

Table 69: Cost structure for the production of plastics, selected European Countries 2015

C2016 Manufacture of plastics in primary forms	Belgium	Germany	France	Italy	Hungary	Netherlands	Portugal	Average
Production value - million €	6,184	23,533	8,165	8,168	3,102	9,143	1,500	
Total purchases of goods and services - million €	4,840	20,938	7,140	6,767	2,789	8,312	1,336	
Total purchases of goods and services -%	82%	81%	86%	89%	94%	90%	91%	85%
Personnel costs - million €	719	3,585	819	723	104	702	69	
Personnel costs -%	12%	14%	10%	9%	3%	8%	5%	11%
Purchases of energy products - million €	351	1,237	355	134	81	242	61	
Purchases of energy products -%	6%	5%	4%	2%	3%	3%	4%	4%

Source: Eurostat (2021)

The relative and absolute results for the cost structure in Germany 2015 are summarised in Table 70 (Destatis 2017).

Table 70: Cost structure for the production of plastics in primary form for Germany 2015

WZ 20.16 Production of plastics in primary forms	[1,000 Euro]	[%]
Gross production value	26,760,348	100.0
Use of materials, use of traded goods, costs for contract work	16,976,018	63.4

WZ 20.16 Production of plastics in primary forms	[1,000 Euro]	[%]
Of which material costs	13,024,087	48.7
Energy costs among the material costs	1,220,485	4.6
Net production value	9,784,331	
Personal costs	3,529,527	13.2
Costs for loan workers	72,539	0.3
Costs for other services	626,114	2.3
Tax costs	105,209	0.4
Rentals and leases	226,750	0.8
Other costs	2,758,187	10.3
Depreciations	891,827	3.3
Interest on borrowings	393,780	1.5
Source	Destatis 2017	
Confidence	Medium/high	

Source: Destatis (2017)

2.7.3.2 Trade relevance

As shown in the Figure 69 to Figure 72, there is foreign trade on all levels of the value chain of polyethylene and polypropylene. For the export/import of ethylene and propylene, the EU27+UK values are lower than respective values for the Germany. This is due to the good inter-connection of the European chemical sites, which, among other things, use a common ethylene pipeline in Germany, Belgium and The Netherlands (ARGK 2021). On the basis of polymers, there is a lot of foreign trade. In 2015, for example, the EU27+UK produced 12 Mt of polyethylene, imported an additional 2.7 Mt and exported 1.9 Mt. These are of course highly aggregated figures: the properties of the various polyethylene summarised here are different.

Table 71: Overview of trade indicators, EU27+UK 2015

	Export in Mt	Import in Mt	Net export in Mt	Export in €	Import in €	Net export in €	Average export price in €/t	Average import price in €/t	RCA80
20165130 - Polypropylene, in primary forms	0.82	0.91	-0.09	1,089,773,400	1,055,505,170	34,268,230	1,330	1,161	0.99
20161035 - Linear PE < 0,94 g/cm3	0.20	0.90	-0.70	304,540,560	1,097,682,870	-793,142,310	1,503	1,222	0.27
20161039 - PE < 0,94 g/cm3 (excluding linear)	0.82	0.58	0.24	1,139,345,400	703,670,400	435,675,000	1,393	1,216	1.56
20161050 - PE >= 0,94 g/cm3	0.86	1.24	-0.37	1,128,371,610	1,456,436,900	-328,065,290	1,308	1,177	0.75
Sum of polyethylene	1.88	2.71	-0.83	2,572,257,570	3,257,790,170	-685,532,600	1,366	1,200	0.76

Source: Eurostat (2020b)

⁸⁰ For information on the RCA see chapter 2.3.1

Table 72: Overview of trade indicators, Germany 2015

	Export in Mt	Import in Mt	Net export in Mt	Export in Euro	Import in Euro	Net export in Euro	Average export price in Euro per t	Average import price in Euro per t	Revealed comparative advantage
WA29012200 - Polypropylene, in primary forms	1.23	0.80	0.43	1,482,112,000	1,025,655,000	456,457,000	1,210	1,288 €	1.15
WA39011010 - Linear PE < 0,94 g/cm3	0.27	0.35	-0.07	378,847,000	494,982,000	-116,135,000	1,394	1,433 €	0.61
WA39011090 - PE < 0,94 g/cm3	0.71	0.81	-0.10	964,536,000	1,090,114,000	-125,578,000	1,359	1,348 €	0.70
WA39012010 - PE < 0,958 g/cm3	0.00	0.01	0.00	5,643,000	7,829,000	-2,186,000	1,267	1,318 €	0.57
WA39012090 - PE >= 0,94 g/cm3	0.99	1.01	-0.02	1,254,825,000	1,289,738,000	-34,913,000	1,262	1,275 €	0.77
Sum of polyethylene	1.98	2.17	-0.19	2,603,851,000	2,882,663,000	-278,812,000	1,315	1,327 €	0.72

Source: Destatis (2020)

2.7.3.3 Prices for polyethylene and polypropylene

There are different types of prices for chemicals available: contract prices, spot prices, trade prices (prices for imported chemicals, for exported chemicals and the mass-weighted export and import prices for 2015) or a price calculated from production value and production tonnes see Table 73.

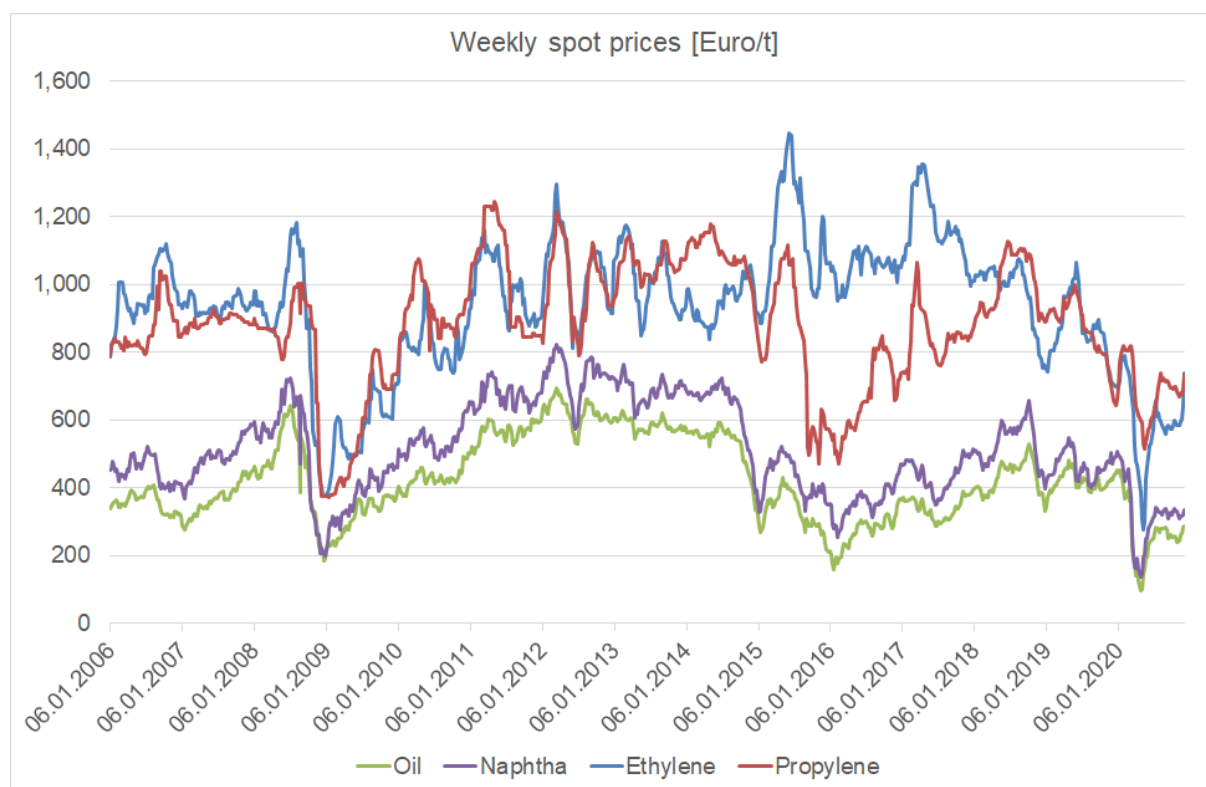
The European contract prices for ethylene and propylene are fixed in advance at the beginning of the respective price period (usually shortly before the beginning of the month or quarter) between supplier and buyer. Around 90 percent of European polymers are produced on the basis of contracted monomer volumes (Kunststoff Information n.d.). Non-contracted, freely saleable monomer quantities are traded in spot transactions. They are reported in Europe on a weekly basis on the basis of trading in the Amsterdam-Rotterdam-Antwerp (ARA) region.

As shown in Table 73 and in Figure 75, the various prices differ from each other, sometimes significantly. The mean foreign trade price, which will be used for the further calculations, lies well within the mean of the price range. The price calculated from the PRODCOM statistics (production value, divided by production amount) is always significantly lower than the other prices.

Table 73: Prices for PE, PP and intermediates, 2015 [€/t]

Product	Contract [mean]	Contract [min/ max]	Spot ARA [mean]	Spot ARA [min/ max]	Trade price GER [mean]	Trade price EU27+UK [mean]	Trade price EU27+UK [import price]	Trade price EU27+UK [export]	Prodcom EU27+UK [value]
Naphthal			422	357 501					
Ethylene	961	810 1,105	1146	911 1,419	819	862	899	787	697
Propylene	850	670 1,030	817	556 1086	831	764	825	452	596
Polyethylene (film quality)	1522	1200 1765			1,321	1,268	1,200	1,366	955
Polypropylene (injec. mould.)	1394	1150 1650			1,240	1,241	1,161	1,330	985
Source	Kunststoff Information n.d.	Kunststoff Information n.d.	Kunststoff Information n.d.	Kunststoff Information n.d.	Destatis 2019	Eurostat 2020b	Eurostat 2020b	Eurostat 2020b	Eurostat 2020b

Figure 75: Weekly spot prices of intermediates, 2006 to 2020



Source: Kunststoff Information n.d.

2.7.4 Summary and conclusions

Polyethylene and polypropylene, the two selected commodities of the chemical industry, are important products of the chemical industry. This applies to their production volume, their production value and their foreign trade. Steam cracking for the production of monomers involves high energy consumption and corresponding CO₂ emissions.

In contrast to the other products investigated in this study, polyolefins being hydrocarbons consist of fossil carbon (non-energy use). This is released as CO₂ at the end of the life cycle, even though it may take a long time, e.g. in the case of old sewage pipes. The consideration of this carbon dioxide is also provided for in the GHG Protocol in SCOPE 3⁸¹, so that these emissions are also considered in more recent studies on the chemical industry (Geres, et al. 2019). Another important point is the emission of macro and micro plastics into the environment which pose a threat to the ecosystem. Consequent recycling can prevent both CO₂ emissions and littering.

⁸¹ In the GHG Protocol Corporate Accounting and Reporting Standard scope 3 Emissions arise from of the activities of a company or organization but occur from sources not owned/controlled by the company (scope 1) or from purchased electricity (scope 2). Some examples of scope 3 activities are extraction and production of purchased materials and the use of sold products and services.

3 Case studies for estimating the CO₂ cost shares at the stages of further processing

The aim of this chapter is to determine and quantify the CO₂ emissions and the cost shares caused by these emissions through the ETS along the value chain of individual final consumer products. The CO₂ cost shares for materials up to the final product are considered. On the basis of chapter 2, two passenger cars, a combustion engine and a battery electric vehicle respectively, as well as a selection of plastic products are systematically analysed to determine energy use along the value chain.

3.1 Material flow cost accounting

The analysis of the CO₂ cost shares for these case studies is based on the method of material flow cost accounting (MFCA) according to ISO 14051. This method is generally used to evaluate complex material and energy flows in companies and enables companies to identify monetary savings potential by mapping the production structure; using the software, the true costs of manufacturing a product can be fully determined (Schmidt, 2017). In addition, the software enables the visualisation of the corresponding flows by means of Sankey diagrams on the one hand and the balancing of product specific GHG emissions on the other. The concrete modelling of the corresponding material and CO₂ cost flows of the case studies is carried out using the software "bw!MFCA" (iPoint, 2018). The methodological analysis of cost and material flows of the case studies is divided into:

1. Evaluation of the production process(es)
2. Development of mass and material balance
3. Calculation of the total energy demand and GHG emissions
4. Analysis of CO₂ and material cost shares

The emission factors from Table 74 are used to calculate the greenhouse gas emissions from the production of passenger cars and plastic products.

Table 74: Emission factors to calculate emissions

Indicators	Value EU27+U K	Unit	Value EU27+U K	Unit	Type	Source EU27+UK	Confidence
Fuel Oil	0.074	tCO ₂ /GJ	0.266	tCO ₂ /MWh	Literature	UBA (2016)	High
Coal	0.094	tCO ₂ /GJ	0.346	tCO ₂ /MWh	Literature	UBA (2016)	High
Coke	0.108	tCO ₂ /GJ	0.388	tCO ₂ /MWh	Literature	UBA (2016)	High
Natural Gas	0.056	tCO ₂ /GJ	0.202	tCO ₂ /MWh	Literature	UBA (2016)	High
Electricity	0.109	tCO ₂ /GJ	0.275	tCO ₂ /MWh	Literature	Koffi et al. (2017)	Medium
Blast furnace gas	0.072	tCO ₂ /GJ	0.260	tCO ₂ /MWh	Literature	UBA (2016)	High
Derived gas	0.016	tCO ₂ /GJ	0.060	tCO ₂ /MWh	Literature	UBA (2016)	High
Naphtha	0.074	tCO ₂ /GJ	0.266	tCO ₂ /MWh	Literature	UBA (2016)	High

3.2 Assessment of the CO₂ cost share flows in the production of passenger cars

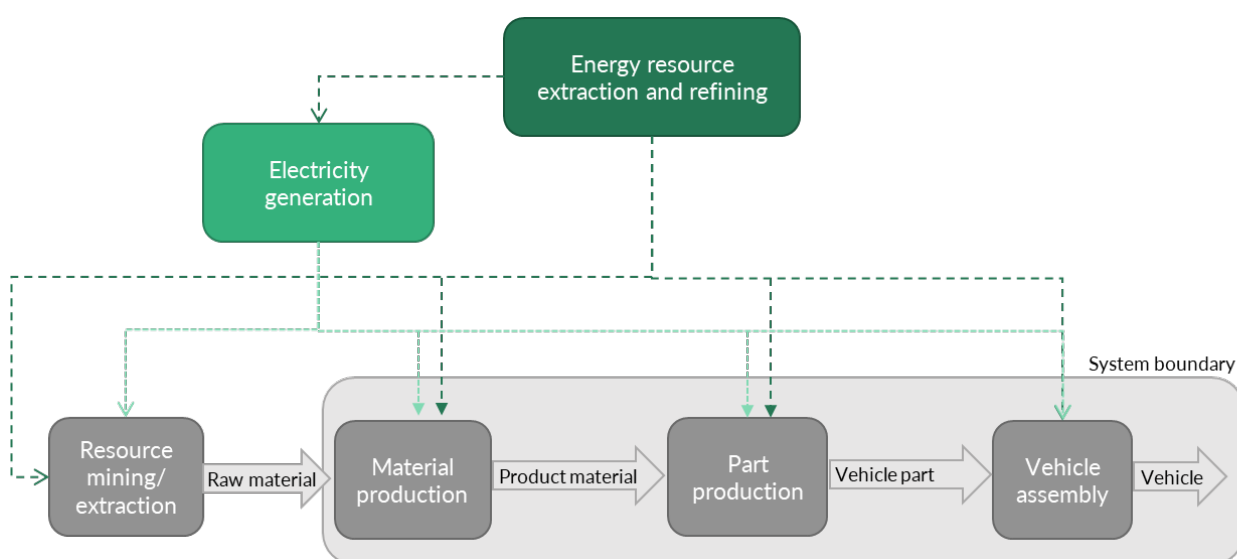
In this chapter, the CO₂ cost share flows in the production process of a combustion engine and a battery electric vehicle are analysed. In 2019, 4.6 million passenger cars were produced in Germany (VDA, 2021). In Europe, about 14.1 million passenger cars were produced in 2019 (ACEA, 2021a). Of these, 75.5% are combustion engine vehicles and 10.5% are electric vehicles. Hybrids account for 11.9% of total passenger car sales (ACEA, 2021b). Although the application of light-weight construction is making progress in the automotive industry, steel is still the most important material in the construction. In Germany, about 11 million tons of crude steel were used in automotive construction in 2016 (Lösch, et al. 2018). In Europe, about 19% of the total steel consumption were used in the automotive industry in 2019 (Statista, 2021). Apart from that, a variety of materials is used, e.g., aluminium, glass, copper, rubber, and textiles. As most materials depend on emission intensive materials, passenger cars are highly relevant to climate policy and ETS. Moreover, the automotive industry is a key factor of European, and even more pronounced German, economy. Therefore, passenger cars are very suitable to derive case studies for this analysis.

3.2.1 General methodology and assumptions

Assumptions

The assessment and calculations are based on a generic medium car produced in Europe. The vehicle is basically inspired by a Golf VI but supplemented by components of other medium cars found in the literature. The underlying vehicle is a simplified representation as certain assumptions are made, which is inevitable for modelling. The varnish is only considered in form of its energy use in the vehicle production but not as a material, as its share of the total inventory is very small. Moreover, materials in the inventory with a share below one per cent are cut-off and joining technologies like screws and rivets are not considered.

Figure 76: System boundary of the analysis



Source: own compilation based on Sato & Nakata (2020)

Figure 76 shows the process and system boundary used for this case study. In the analysis, energy use and GHG emissions in the material production (e.g. steel coils or steel in other forms),

parts production (e.g. body, brakes) and vehicle assembly are considered, whereas the production and extraction of raw materials is excluded. Among the term materials, products at different stages of processing are summarised. Some products (such as zinc) enter the system as materials in their original form, some as prefabricated intermediate products (such as steel coils).

As no transport is considered, it is assumed that the production of materials, parts and components takes place at the same location.

Methodology

In order to illustrate the CO₂ cost shares for the production of a passenger vehicle, it is necessary to analyse the value chain and to develop a material and energy balance. For the compilation of the material balance of the underlying vehicle and the energy balance for the production process, a bottom-up approach is used. That is, the materials used in a passenger car are identified based on the components and parts of the generic medium car. The energy balance and resulting GHG emissions are then calculated based on the materials used as well as on the production and manufacturing processes applied to those materials.

Table 75 shows the hierarchy of the vehicle structure applied in the analysis.

Table 75: Applied hierarchy of the vehicle structure

Dimension	Description
Component group	This dimension describes the main parts of a vehicle (body, chassis, drivetrain)
Components	This dimension describes the single modules like e.g., Engine, Seats
Parts	This dimension describes single parts of components like e.g., Airbag
Materials	This dimension describes the materials used for the construction of the vehicle, like e.g., steel and aluminium

In order to compile the material balance of the generic vehicle, the mass balance is developed in several steps. As a first step, the general weight distribution of a Golf VI is used to identify the individual weight of the respective component groups of a medium car. Due to the similarity of the vehicle models in terms of bodywork and equipment, in the next step, the component groups are complemented by data from Polo V. For remaining components, for which the main material cannot be clearly identified, further literature sources are used to determine the materials of single parts. As the materials are allocated to the parts and components, the material balance can be consolidated.

The total energy demand consists of the energy used in vehicle assembly as well as material and part production. For the vehicle assembly, the energy demand of the Volkswagen plant in Wolfsburg is considered, as the generic medium car is quite similar to the Golf. For the energy demand of material and part production, literature and databases are used. Furthermore, the chemical, steel, and aluminium products from chapter 2 are allocated to the parts and components of the vehicle and are to be complemented by a production process -e.g. stamping, forming and construction of the steel coils to form a car body; processing of other steel products, aluminium and plastics products to produce the engine or the brakes. The GHG emissions are then calculated based on the energy demand and respective emission factors.

Afterwards, the GHG emissions by materials are integrated in the modelling software Umberto and the CO₂ and material cost shares are calculated.

Finally, the CO₂ cost shares in total production costs are calculated. Therefore, the cost for energy and GHG emissions are calculated for all materials used in the vehicles for material and part

production as well as the production and assembly of the vehicle. For the products analysed in chapter 2, also the cost for labour and material are considered.

The base year of the calculations is 2015. To assess the influence of higher prices for fossil fuels, the calculation is also done for 2021 and 2022. For 2015, the prices from Projektionsbericht 2021 for the year 2015 are used. The calculation is based on wholesale prices. This is because different industries and sectors are involved in the production of vehicles with different taxes and levies and no detailed calculation along the value chain can be performed. Moreover, the energy prices of industrial customers with energy needs of OEM (original equipment manufacturer, basically car manufactures) are almost the same as the wholesale price anyway. Moreover, for production steps *using* the materials analysed in chapter 2, which are addressed in this chapter 3, energy costs only account for a small share of the relevant costs. For 2021 and 2022, the energy prices from the research project “ARIADNE”⁸² are used.

For Naphtha, the management report from BASF is used for 2015 and 2021. For 2022, the same price as for 2021 is assumed, as prices decreased since March 2022⁸³.

Table 76: Energy prices for the calculation of the CO₂ cost shares

€/MWh	2015	2021	2022
Electricity	31	92	220
Natural gas	21	51	114
Oil	47	52	70
Solid fuels	8,5	17	34
Naphtha	32.7	63.7	63.7

Source: BASF (2015); BASF (n.d.); Energiedaten (2022); Repenning et al. (2021)

With regard to ETS, different prices are used. For 2015 and 2021, the statistical values of 7.68 and 53.24 per t CO₂eq are used. For 2022, a price of € 80 per t CO₂eq is assumed to assess the impact. Mass and material balance of generic medium car.

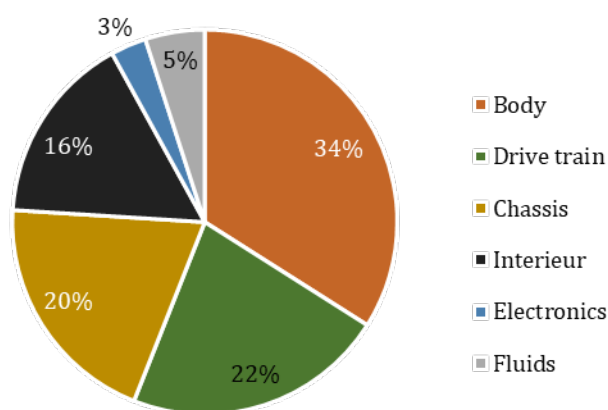
3.2.1.1 Methodology

The mass balance of the generic medium car in this case study is based on the weight distribution by the component groups of a Volkswagen Golf VI with a total weight of 1,405 kg. Figure 77 shows the weight distribution of the component groups for a Golf VI. With a weight of 479 kg, the body is the heaviest part of the vehicle, followed by the drive train with 309 kg and chassis with 279 kg. Together they account for three-quarters of the whole vehicle. The interior of the underlying Golf VI amounts to 228 kg, electronics to 45 kg and fluids (including fuel) to 65 kg.

⁸² <https://ariadneprojekt.de/>

⁸³ See <https://tradingeconomics.com/commodity/naphtha>

Figure 77: Weight distribution of the Golf VI by component groups



Source: own compilation based on Göbbels et al. 2011

Figure 78 shows the weight distribution within each component group represented in Figure 77. Regarding the body of the vehicle, the body-in-white (which means the body without varnish) accounts for more than half of the whole body. Closures and attachments sum up to 23%, others account for 19%. Looking at the drivetrain, the engine accounts for 50% of the total weight of this component group. Another 25% is allocated to the gearbox. The rest is split up into fuel tank, battery, transmission, and others.

The chassis consists of dynamics, subframe, brake and steering system, and wheels. Transverse and vertical dynamics are the heaviest parts of the component group, followed by wheels with 32%. Regarding the interior, seats and interior lining are predominant in the component group and account for more than 60% of the total weight. Besides that, safety devices, peripheral equipment, heating system and acoustics are summed up in this component group.

The electronics of the vehicle consist of lighting, peripheral equipment and operating elements, considering that the peripheral equipment (wire harness) has the highest weight. For a further breakdown of the component groups into more detailed components, a mass balance from a Polo V is used. Therefore, to keep the analysis consistent, the mass balance from Polo V and its components are scaled to the total weight of the Golf VI of 1,405 kg and its weight distribution according to Figure 77. The complete mass balance based on Fuchs (2014) is shown in Appendix C.1. As an example, the mass balance of the components of the body is shown in Table 77. On the basis of the mass balance of Polo V, it is possible to identify the mass and material of some components (e.g., the weight and material of fender).

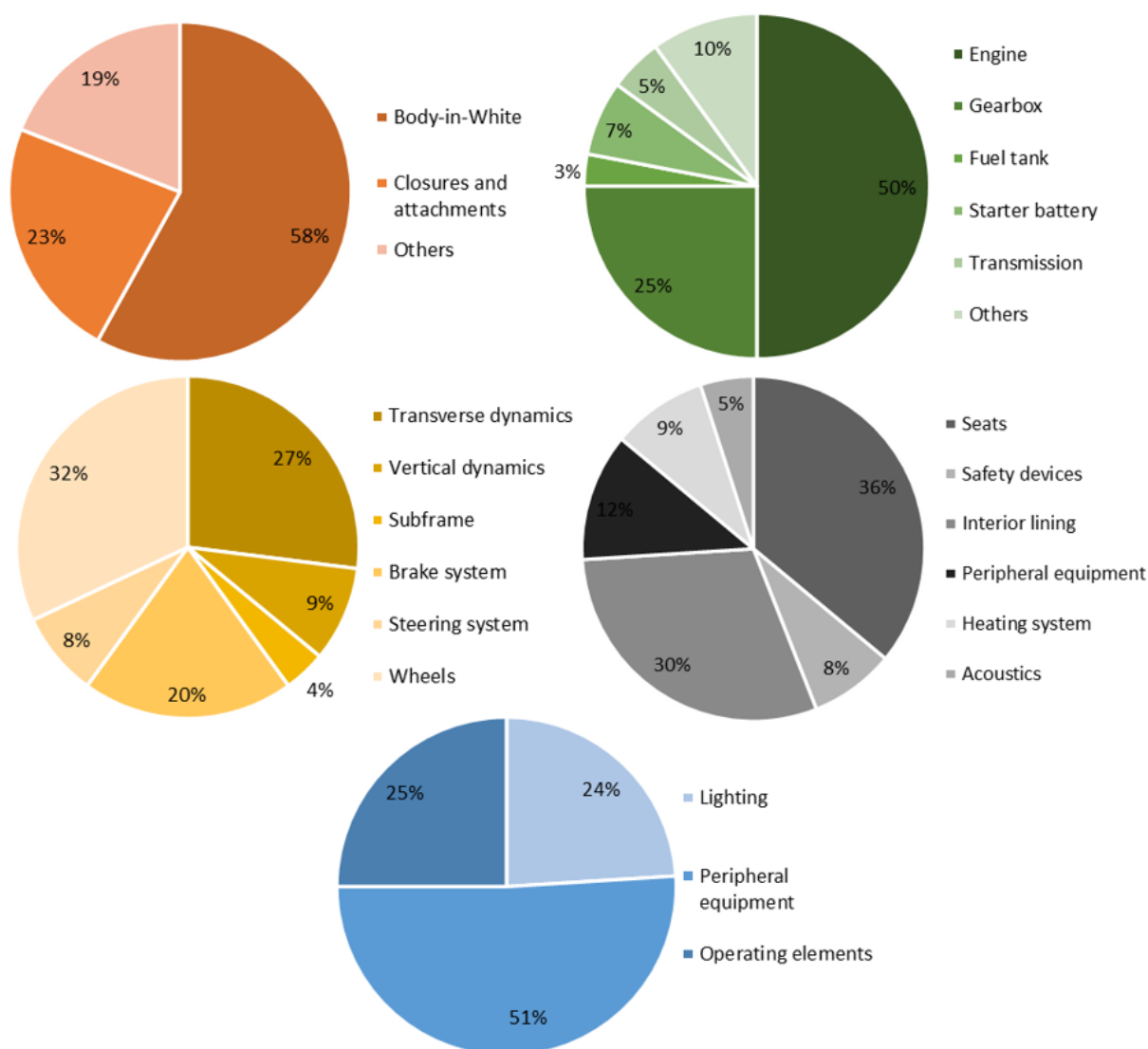
Table 77: On the basis of the mass balance of Polo V, it is possible to identify the mass and material of some components (e.g., the weight and material of fender and bonnet)

Component	Relative share	Weight [kg]
Body-in-White	53%	252.03
Fenders	2%	9.90
Doors	18%	99.24
Bonnet	3%	12.94
Hatchback	3%	14.12

Component	Relative share	Weight [kg]
Wipers	1%	4.81
Bumper	3%	14.42
Mirrors	1%	2.45
Windshield	3%	14.22
Side-window	1%	5.79
Rear side-window	1%	4.31
Back window	1%	5.98
Insulation / acoustics	3%	12.45
Crash system	7%	31.28
Others	1%	5.39
Total		489.36

Source: Fuchs (2014)

Figure 78: Weight distribution within each component group of Golf VI



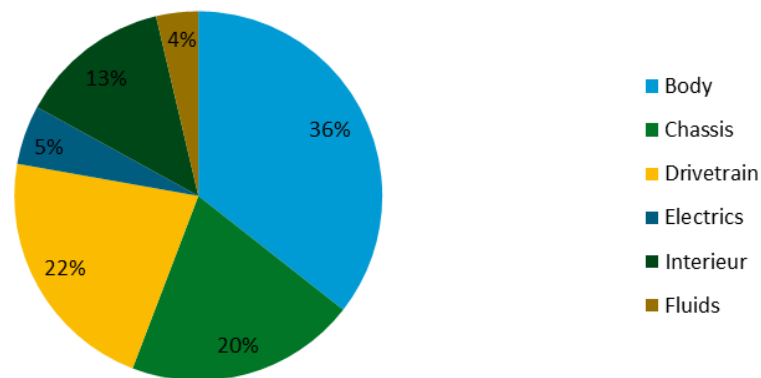
Source: Own compilation based on Göbbels et al. (2011)

After the previous steps, some components could already be identified by their main parts and materials. For other components, like engine and transmission, a more detailed analysis is necessary for an exact definition of materials and energy use. Therefore, an analysis of the components and parts is conducted. To do so, literature analysing single components is used. Components, consisting of only one main material, are excluded from this step. Assumptions regarding materials were made for parts where no literature could be retrieved.

3.2.1.2 Results

The final generic medium car has a weight of 1,311 kg, of which 466 kg are distributed to the body, 265 kg to the chassis, 288 kg to the drive train, 175 kg to the interior, 68 kg to the electrical system and another 48 kg to fluids. Figure 79 shows the weight distribution of the final analysed vehicle. It can be seen that the weight distribution is quite similar to that for the Golf VI.

Figure 79: Weight distribution of the underlying generic medium car



Source: own calculation

The following tables give an overview of the mass balance by materials of the different component groups. Due to the chosen approach it needs to be considered that the data has a different level of detail. Depending on available literature, some components are displayed more in detail whereas some remain on the level of components, as literature could only be found for this level.

Table 78 shows the mass balance and the utilised materials of the body of the vehicle. For the body, mostly aluminium and steel is used. With 278 kg, the structure is the heaviest part in the vehicle.

Table 78: Mass balance of body [kg]

Components		Weight	Flat glass	Aluminium	Steel	Plastics	Rubber
Body-in-White	Structure	278			278		
	Fender	10			10		
Doors and closures	Doors front	47		19	12	15	
	Doors back	47		19	12	15	
	Bonnet	13		13			
	Hatchback	14		12		2	
Exterieur	Windscreen wiper	4		0.35	2		1
	Bumper	14				14	
	Mirrors	2	0.10			2.35	
Windows		32	32				
Others	Retaining plate	5			5		

Sources: Fuchs (2014); Göbbels et al. (2011); Lotus Engineering Inc (2010); Notter et al. (2010); Wurzer (2016); Zottler (2014)

Table 79 shows the mass balance of the chassis. The chassis consists mostly of aluminium and steel, whereby more aluminium is used due to lightweight reasons.

Table 79: Mass balance of chassis [kg]

Component		Weight	Aluminium	Steel	Plastics	Filling compound	Rubber
Transverse and vertical dynamics	Transverse links	16	10	6			
	Wheel carriers	10		12			
	Wheel bearing	10	4	4			
	Stabilizer	6		6			
	Steering knuckle	16.8	16.80				
	Rubber bearings	5.8					5.8
	Dampers	26.37		26.37			
Subframe		19.80	19.80				
Brake system		46.10	3.23	40.11	2.77		
Steering system		19.40	6.25	10.93	2.23		
Wheel	Tyres	8.50		5.93		11.86	16.21
	Wheel rim	13.81	55.25				

Sources: European Aluminium Association (2011); Fuchs (2014); Göbbels et al. (2011); Goodyear (n.d.); Heißing et al. (2011); Lotus Engineering Inc (2010); Notter et al. (2010); Wiesinger (n.d.)

Table 80 shows the inventory of the drivetrain. In this component group, engine and gearbox are the heaviest components. They consist mostly of steel and aluminium, but also iron and plastics. In the literature used to quantify the single parts, non-ferrous metals (except aluminium) are included (Maurer, 2013). As a simplification, these non-ferrous metals used are considered to be zinc, as it is used for coating to prevent corrosion in engines and gearboxes (Benavides et al., 2015). Materials summarised as Others (column) consist of 3.5 kg water, 2.2 kg sulfuric acid, 7.6 kg of lead oxide, 5.4 kg of lead and 0.2 kg of antimony as parts of the starter battery.

Table 80: Mass balance of drivetrain [kg]

Component		Weight	Glass	Alu	Steel	Iron	Zinc	Plastics	Others
Engine		122.00		44.60	59.03	12.44	5.25	13.12	
Gearbox		92.69		26.39	14.82	48.98	1.00	1.50	
Fuel tank		9.27						9.27	
Starter battery		21.63	0.65					2.16	18.82
Others									
	Fuel system	4.4			4.4				
	Exhaust system	22.5			22.5				
	Cooling system	8.8		4.4	4.4				
	Ventilation	6.8						6.8	

Sources: Eval (n. d.); Fuchs (2014); Göbbels et al. (2011); Lotus Engineering Inc (2010); Maurer (2013); Notter et al. (2010); Wurzer (2016)

In Table 81, the mass balance of the interior is displayed. The interior consists mostly of different types of plastics, which are presented more in detail in Figure 80.

Table 81: Mass balance of interior [kg]

Component		Weight	Alu	Steel	Plastics
Seats		64.76		44.09	20.67
Safety devices		18.40		6.44	11.96
Interior lining		38.95			38.95
Peripheral equipment		22.86		9.25	13.61
	Centre console	2.5		2	0.5
	Cockpit	20.36		7.25	13.11
Heating		18.25	3.49	0.82	13.95
Acoustics		11.39			11.39

Sources: automotiveplastic (n.d.); Fuchs (2014); Göbbels et al. (2011); Wurzer (2016)

Table 82 shows the inventory of the electronic components of the vehicle. In the electronic parts, copper and zinc are found. Besides that, plastic is used. In Others, 1.1 kg of LED is included in the

lights, 0.9 kg of brass is included in the operating elements, and the electronic control unit (ECU) contains 1 kg of epoxy resin and 1.1 kg of glass fibre.

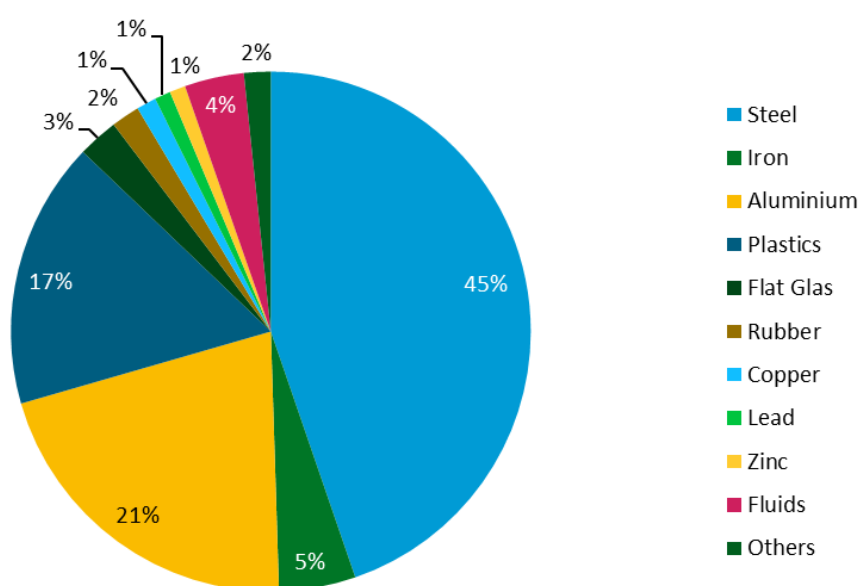
Table 82: Mass balance of electronics [kg]

Component	Weight	Alu	Steel	Iron	Zinc	Copper	Plastics	Others
Lighting								
Cables	3.25					1.63	1.63	
Lights	1.1							1.1
Alternator	4.38	0.96	1.65	1.1		0.65	0.02	
Headlights	3.11						3.11	
Cable harness	22.97					11.49	11.49	
Operating elements	11.24	0.79	0.79		6.74		1.91	0.9
Electronic control unit	22.18	15.65	0.30			2.36	1.73	2.15

Sources: Göbbels et al. (2011); Notter et al. (2010); Schau et al. (2012); Swedish Life Cycle Center (n. d.); Wurzer (2016)

Figure 80 shows the final material balance of the generic medium car. Steel is by far the most widely used material in the vehicle, followed by aluminium. Steel, aluminium and plastics, which are the materials considered in chapter 2, sum up to 87% of the total material balance.

Figure 80: Material balance of the generic medium car



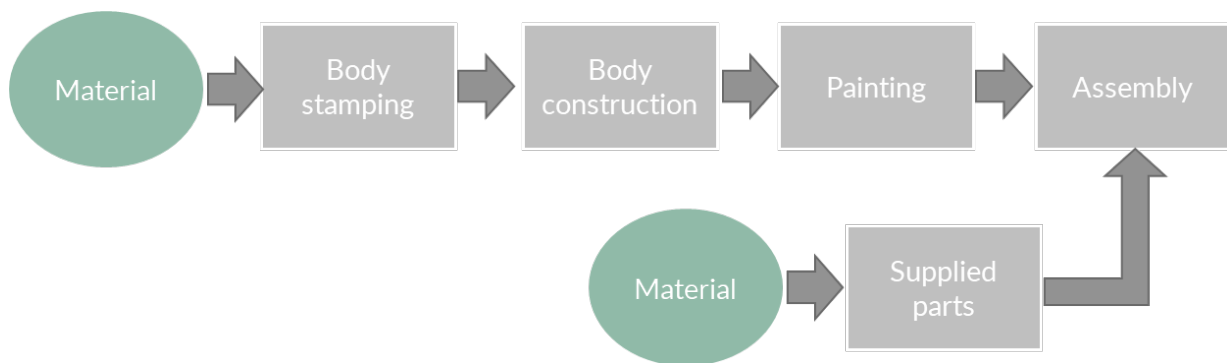
Source: own calculation

3.2.2 Energy demand for the production of the generic medium car

For the calculation of the total energy demand and the resulting GHG emissions, the energy demand to produce materials and components and for assembling is needed. The analysis is split in two chapters: 3.2.2.1 addresses the energy use from the car manufacturer's activity as such. As shown in Figure 81, these include the body stamping and construction, painting of the body and assembly of the parts and components. Chapter 3.2.2.2 then analyses the energy demand that is "embedded" in the material (e.g., the coils) of the car body, as well as parts and components acquired by the car producer (called "Supplied parts" in Figure 81), i.e., the chemical, iron, steel, and aluminium products from chapter 2 are allocated to these parts and components of the generic medium car. Furthermore, the energy demand is calculated for the production of parts and components consisting of materials not included in chapter 2.

Figure 81 shows the production process from the manufacturer's point of view. However, it should be noted that the total energy demand for the production of all parts and components significantly exceeds the energy demand of the car manufacturer.

Figure 81: Production process of vehicles



Source: Volkswagen (2019)

3.2.2.1 Energy demand from car manufacturer's activity

The modelled generic medium car is similar to the construction of a Golf. Therefore, data from Volkswagen is used for the calculation of the energy demand for vehicle assembly. In the environmental report of the plant in Wolfsburg, where the model Golf is mostly produced, the total energy demand of 2018 amounts to 1,909 GWh. Space heating is not considered in the analysis, as it cannot be directly assigned to the production process. Therefore, a final energy demand of 1,359 GWh remains, which is allocated 69% to electricity, 13% to process heating and 19% to fuel gases⁸⁴.

To calculate the energy demand for the production of one Golf, it is necessary to break down the total energy demand. For the purpose of this study, it is assumed that the energy demand is distributed according to the tonnes of vehicles produced (i.e., we assume identical energy demand per kg across all vehicles in the following Table 83, and furthermore an identical split between electricity and fuel use for all these vehicles. Table 83 shows the distribution of produced vehicles in Wolfsburg by tonnes and pieces. The Golf has a share of 30% of the total weight of vehicles produced in Wolfsburg. Thus, it is assumed that all Golf produced have a share of 30% of the total energy demand.

⁸⁴ Fuel gases consist of combustible compounds like hydrocarbons, hydrogen (H₂), and carbon monoxide (CO), which are the source of energy, and of incombustible compounds like helium (He), nitrogen (N₂), and carbon dioxide (CO₂), which decrease the specific energy content. (Müller 2005)

Table 83: Produced vehicles by model at Volkswagen plant in Wolfsburg

Model	Vehicles [t]	Vehicles [pcs.]	Relative share of tonnes produced
Golf	334,340	238,415	30%
Golf Sportsvan	87,387	60,591	8%
Golf GTE Hybrid	13,249	8,029	1%
e-Golf	22,188	13,539	2%
Touran	149,706	90,995	14%
Tiguan	490,887	286,352	45%
Seat Tarraco	4,935	2,660	0,4%
Total	1,102,692	700,581	

Source: Volkswagen 2019

Table 84 shows the energy demand of all Golf produced, per kg of Golf produced, and the energy demand of the generic medium car of 1,311 kg analysed in this study. Based on the above-mentioned simplified assumption of identical energy demand per kg across vehicles (Table 84), the total energy demand for the production of all Golf in Wolfsburg amounts to 412,033 MWh. Thus, for one kg of Golf produced 1.2 kWh of energy is demanded.

For the generic medium car of 1,311 kg, a final energy demand of 1.62 MWh results, which is distributed to 1.11 MWh electricity, 0.2 MWh process heating and 0.3 MWh fuel gases.

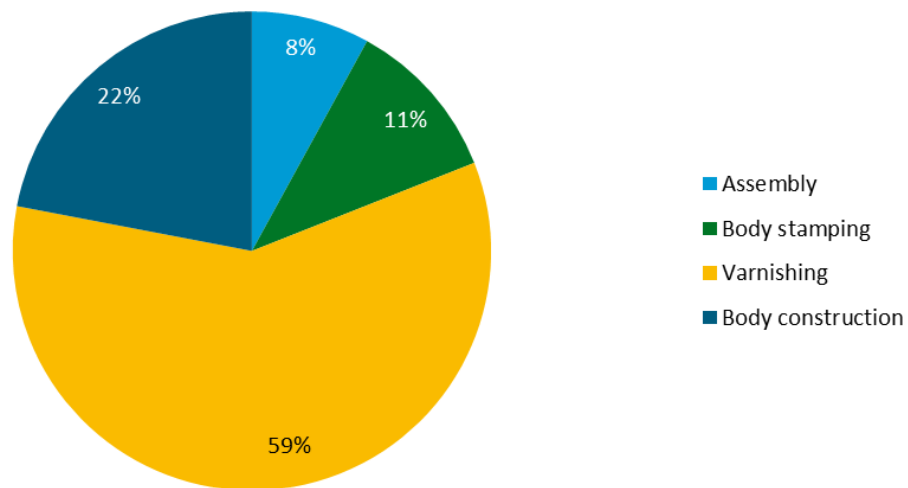
Table 84: Calculation of the energy demand for the production of generic medium car

	Energy demand for all Golf produced in Wolfsburg [MWh]	Energy demand per kg Golf produced in Wolfsburg [MWh]	Energy demand of generic medium car of 1,311 kg [MWh]
Total	412,033	0.0012	1.62
Electricity	283,379	0.0008	1.11
Process heating	51,560	0.0002	0.20
Fuel gases	77,094	0.0002	0.30

Source: own compilation based in Volkswagen (2019)

In a production plant for combustion engine vehicles, energy is needed for body stamping, body construction, varnishing, and assembly of the final car. Figure 82 shows the allocation of the total energy demand to these applications. More than half of the total energy demand is consumed in the process of varnishing the vehicle. Another 22% is needed in the body construction (Klüger, 2011). Energy needed for the preassembly and production of components is not included.

Figure 82: Total energy demand in the production of combustion engine vehicles by process.



Source: Klüger (2011)

Finally, Table 85 shows the energy demand for the assembly, body stamping, construction, and varnishing of the generic medium car of 1,311 kg by production process and energy source. As stated above, in total, 5,817 MJ (= 1.62 MWh) of energy are needed, thereof 4,000 MJ (= 1.11 MWh) of electricity and 1,816 MJ (= 0.5 MWh) of fuels.

Table 85: Energy demand for the generic medium car by process and source

Process	Total [MJ]	Electricity [MJ]	Process heating [MJ]	Fuel gases [MJ]
Assembly	465	320	58	87
Body stamping	640	440	80	120
Varnishing	3,432	2,360	429	642
Body construction	1,280	880	160	239
Total	5,817	4,000	728	1,088

3.2.2.2 Energy demand for materials, parts, and components: Allocation of relevant products from chapter 2 to the generic medium car

Energy use and GHG emissions associated with the production of the materials, parts and components account for the main share of total energy use and GHG emissions for of the generic ICEV vehicle. To identify the energy demand for the production of materials, parts and components consisting of steel, aluminium and plastic, the relevant products from chapter 2 are allocated to the developed mass balance. All relevant materials and products from chapter 2 are shown in Table 86.

Table 86: Relevant materials and products from chapter 2

Material	Product
Steel	Hot rolled coils
Steel	Hot rolled bars
Aluminium	Casting
Aluminium	Extrusion
Aluminium	Flat rolled
Chemical	Polyethylene
Chemical	Polypropylene

For the allocation of the plastic products in chapter 2 to parts and components in the generic medium car, different literature is used. As a consequence of lightweight construction, the amount of plastic in passenger vehicles is rising. According to a market research from Ceresana, polypropylene is the most important plastic in the automotive industry (Ceresana, 2016). In the Golf VII, Acrylonitrile Butadiene Styrene (ABS), Polypropylene (PP), Polyamide (PA) or Nylon, Polycarbonate (PC), Polyurethane (PUR), Polyethylene (PE), Acrylonitrile styrene acrylate (ASA), Polyethylene terephthalate (PET), Polymethyl methacrylate PMMA and Polyvinylchloride (PVC) are used. As simplification, only the materials with the highest share are considered for this case study (Plastics, 2013). Furthermore, it is assumed, that all components containing fabric are made from synthetic yarn. Table 87 shows the types of plastic considered by their area of application.

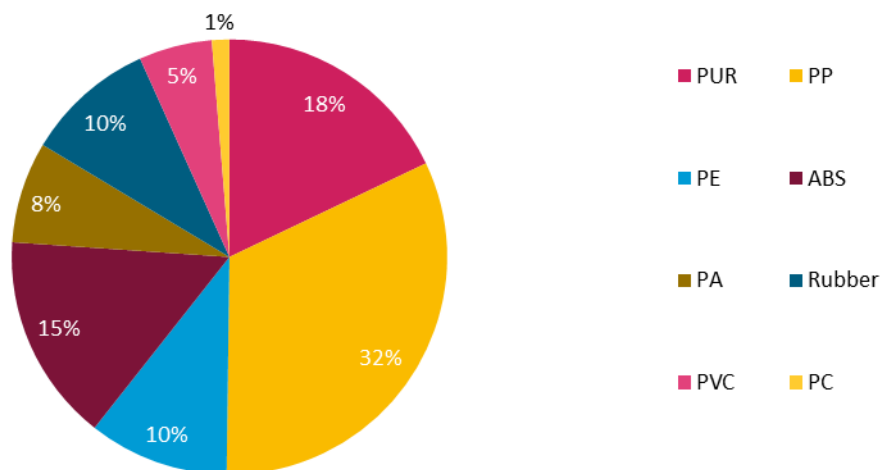
Table 87: Type of plastics used in the case study by their area of application

Type	Area of application
PP	Fender, bonnet, hatchback, bumper
PE	Engine, gearbox, fuel tank, coverings
ABS	Instrument panels, doors, consoles, wipers, brakes
PVC	Cable insulation
PC	Headlights
PA/Nylon	Airbags, seat cover and seat belt, steering wheel
PUR	Insulation, upholstery, steering wheel

Sources: Khemka (2020); Aurora Kunststoffe GmbH (2014); automotiveplastic (n.d.); Ceresana (2016); Emilsson et al. (2019); Maurer (2013); Notter et al. (2010); Plastics (2013); PlasticsEurope (2021); Wurzer (2016)

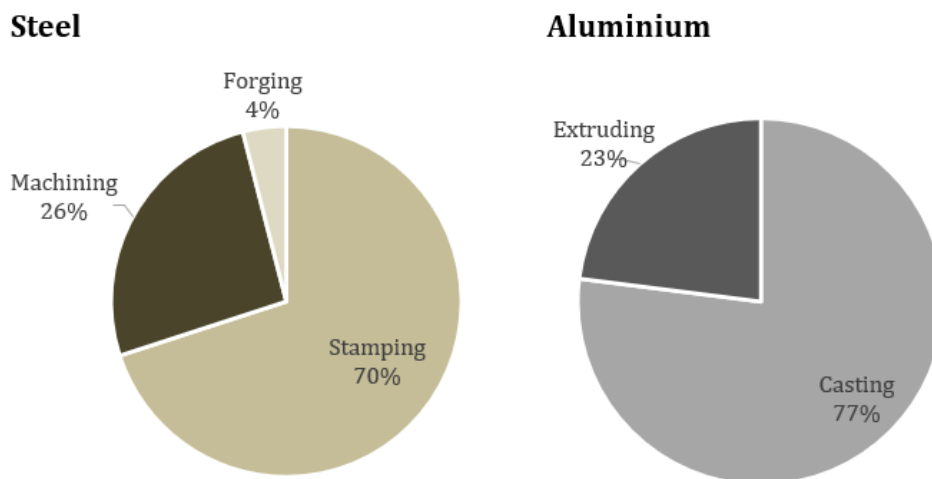
Figure 83 shows the shares of the plastics used in the generic medium car. With 32%, PP is the most used type of plastic, followed by PUR and ABS. As PC is only for the headlights in the vehicle, its total share is very low.

Figure 83: Plastic products and rubber used in the generic medium car



The steel and aluminium products of chapter 2 are allocated to the parts and components in the vehicle based on the appropriate processing and the allocation made by Sato & Nakata (2020). Figure 84 shows the principal part production processes in passenger cars concerning the materials aluminium and steel. Regarding steel, the principal production processes are stamping (70%), machining (26%) and forging (4%). The principal production processes for aluminium used are casting (77%) and extruding (23%).

Figure 84: Principal part production process of aluminium and steel in the automotive industry.



Source: Sato & Nakata (2020)

Transferred to the analysis carried out, the following shares of production processes result. In total, 586 kg of steel is used in the vehicle (see Table 89). From the bottom-up compilation of the material balance results (see Table 78), that 317 kg of steel are used in the body of the vehicle. Hot rolled coils enter the production process at the manufacturer's site and are stamped (referring to hot rolled coils (preassembly) in Table 89). The rest of the steel used, is distributed following Sato et al. This means that 25 kg of steel is forged, 150 kg of steel is machined, and in total 412 kg is stamped, including the hot rolled coils entering the production site. Using the products from chapter 2, it is assumed that hot rolled coils are stamped, and bars are forged and machined.

In addition, 276 kg of aluminium is used in the vehicle. About 64 kg of aluminium is entering the body stamping process of the production (see Table 77). The rest of the aluminium is allocated based on Sato et al., which means that about 163 kg aluminium is casted, and 49 kg is extruded. As the aluminium products from chapter 2 are already processed products, no further manufacturing is necessary). The rest of the aluminium is allocated based on Sato et al., which means that about 163 kg aluminium is casted, and 49 kg is extruded. As the aluminium products from chapter 2 are already processed products, no further manufacturing is necessary.

In the next step, the calculation of the energy demand for the production of the parts and components of the vehicle is described. Therefore, the materials and ETS-products from chapter 2 as well as the other materials are considered. Table 88 shows the cumulated energy demand and the GHG emissions resulting from the production of the relevant products taken from chapter 2.

Table 88: Cumulated energy demand and GHG emissions of products in chapter 2

Material	Product	kg CO ₂ e/kg	MJ/kg
Steel	Hot rolled coils	2.6	20.90
	Hot rolled bars	0.38	3.94
Aluminium	Casting	0.51	40.5
	Flat rolled	0.48	30.9
	Extrusion	0.49	38.6
Chemicals	Ethylene (naphtha steamcracker)	0.35	16.5
	Propylene (naphtha steamcracker)	0.76	16.5
	Polyethylene (polymerisation)	0.35	2.5
	Polypropylene (polymerisation)	0.76	3.2

To identify the part production processes of the materials glass, copper, rubber, and iron, also the paper from Sato et al. 2020 is used. According to this, 80% of the iron used in vehicles is casted and 20% forged. Moreover, flat glass is formed, rubber compression moulded, and copper drawn.

To calculate the energy demand of the remaining materials, the database GREET, but also data from Ecoinvent, PlasticsEurope and other literature is used. The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technology model) database calculates emissions resulting from the transportation life cycle and contains data about electricity, fuels, and vehicle components. The database gives information about the on-site energy demand and resource input for each production process of vehicle components (Argonne National Laboratory, 2016).

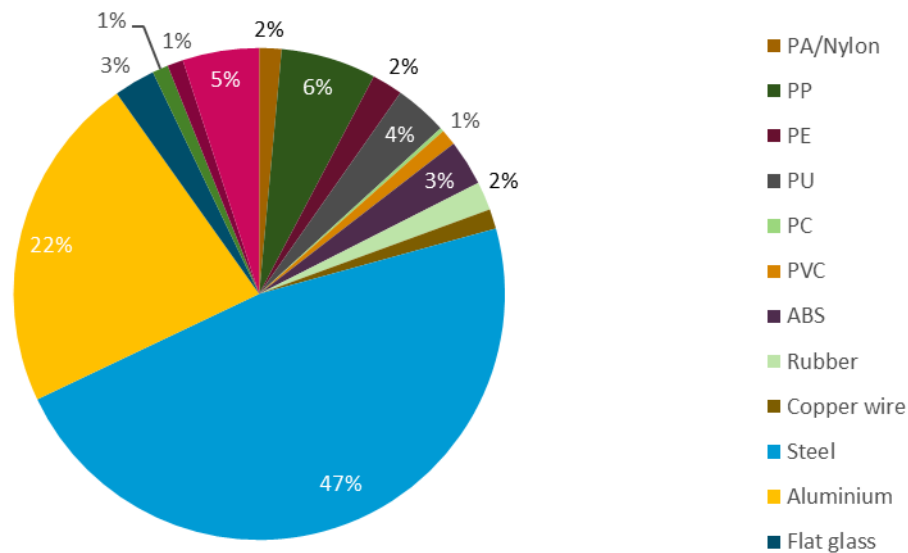
Regarding the plastic products, the GREET database contains data about each manufacturing process and their relative share in vehicle production for each type of plastic. As a simplification for each type of plastic, the most relevant manufacturing process is taken. Concerning zinc and lead, also data from GREET is used. As lead is part of a lead-acid battery, also the assembly process in GREET is considered. In vehicles, mostly recycled lead is used.

3.2.3 Assessment of the CO₂ cost share flows in the production of combustion engine vehicles

3.2.3.1 Mass and material balance of combustion engine vehicle

Due to the cut-off criterion of 1% not all materials are considered in the further analysis of the combustion engine vehicle. Figure 85 shows the final material balance for the combustion engine vehicle. Fuels are excluded because they are allocated to the use phase of a passenger car. The calculation of the energy demand and GHG emissions in the next chapter is therefore based on a total weight of 1,242 kg.

Figure 85: Material balance of a combustion engine vehicle



Source: own calculation

3.2.3.2 Energy demand and GHG emissions for the production of combustion engine vehicles

Table 89 gives an overview of the energy used in the production of materials and parts of the generic medium car. The relevant manufacturing process is named. The table contains the weight, the total and specific energy demand by material production and manufacturing process, and the total and specific GHG emissions for each material.

Energy demand in the activities at the manufacturer's site are therefore excluded. Hot rolled coils are listed twice, as position 9 of the table is processed at the manufacturer's site (body construction) and position 10 further processed as supplied parts. That is why for position 9 no part production process is named.

The emissions associated with material processing are calculated upon the material and energy flow. The model (see 3.1) includes indirect emissions generated by electricity use in the production process, direct process related emissions and direct energy related emissions caused by fuel consumption.

Table 89: Energy demand and GHG emissions of products by energy source and production process of combustion engine vehicle

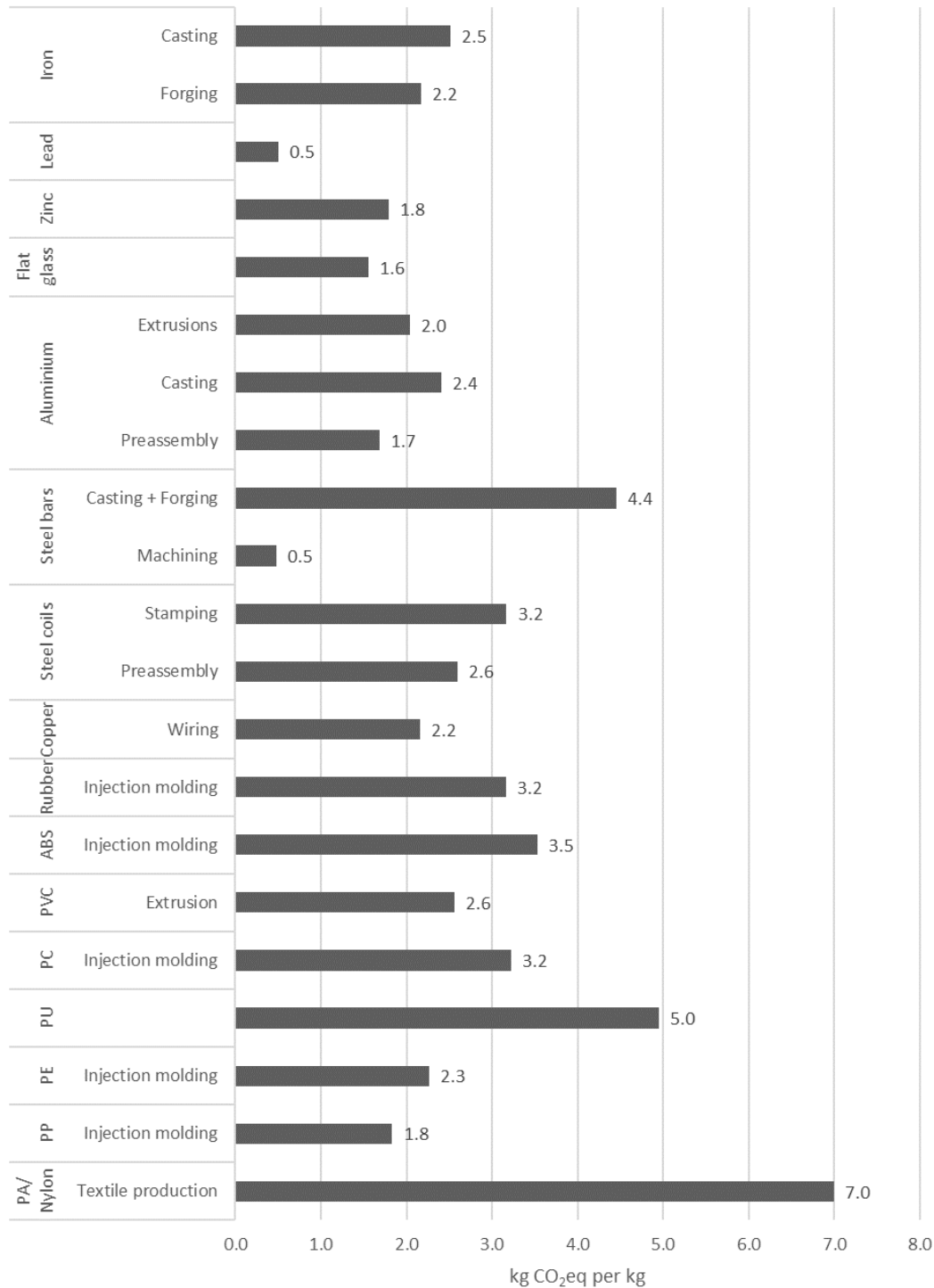
Material No.	Material/ Product	Weight [kg]	Total energy demand [MJ]			GHG emissions [kg CO ₂ eq]			Part production process
			Total	Material production	Part production	Total	Material production	Part production	
1	PA/Nylon	18	1,190	23	1,167	127	2	125	Textile production
2	PP	78	1,767	1,533	233	143	117	25	Injection molding
3	PE	25	654	478	176	57	38	19	Injection molding
4	PU	43	2,754	2,754		214	214	0	
5	PC	3	149	140	9	10	9	1	Injection molding
6	PVC	13	538	511	26	34	31	3	Extrusion
7	ABS	37	2,049	1,937	112	132	119	12	Injection molding
8	Rubber	23	1,106	929	177	74	61	13	Injection molding
	Steel	586					0	0	
9	Hot rolled coils (preassembly)	317	6,634	6,634		824	824	0	Stamped in Body stamping
10	Hot rolled coils stamping	95	2,531	1,985	546	301	247	54	Stamping
11	Hot rolled bars machining	150	684	590	94	72	62	10	Machining
12	Hot rolled bars forging	25	1,140	98	1,042	111	10	101	Casting+Forging
	Aluminium	276							
13	Stamping (preassembly)	64	132	132		108	107.8	0	
14	Casting	163	1,904	1,904		393	393	0	

Material No.	Material/ Product	Weight [kg]	Total energy demand [MJ]			GHG emissions [kg CO ₂ eq]			Part production process
			Total	Material production	Part production	Total	Material production	Part production	
15	Extrusions	49	215	215		100	100	0	
16	Flat glass	34	740	157	583	53	15	38	Melting and refining, forming, annealing, tempering, and laminating
17	Zinc	13	222	222		23	23	0	
18	Copper wire	16	418	370	48	35	30	5	Wiring
19	Lead (recycled)	13	104	65	39	7	4	3	
	Iron (recycled)	63					0	0	
20	Forging	13	464	18	446	27	1	26	Forging
21	Casting	50	1,321	71	1,250	126	5	120	Casting
	Sum		26,716	20,766	5,950	2,967	1,985	555	

Source: Argonne National Laboratory (2020); Sato & Nakata (2020); Van Der Velden et al. (2012)

Figure 86 shows the resulting emissions factors for the materials with the associated part production process. Polyamid/Nylon used for the production of seats have the highest specific emissions due to the energy intensive spinning and weaving process (Van Der Velden et al., 2012).

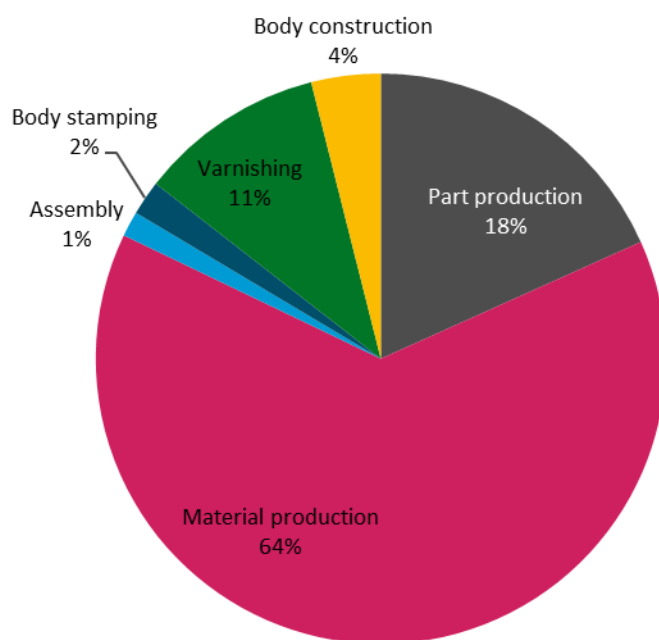
Figure 86: Emission factors by material for the combustion engine vehicle



Source: own calculation

The total energy demand, for material and part production (see 3.2.2.2) and car manufacturer's activities (see 3.2.2.1) amounts to 32,533 MJ. Per kg of vehicle produced this corresponds to 26.2 MJ. Most of the energy demand (64%) is used for material production (including the materials for both the body and the other car parts). Another 18% of the energy demand is used for the part production itself. Varnishing accounts for 11% of the total energy demand. In total, 6% of the energy demand is used for body stamping and construction. The final assembly of the vehicle consumes only 1% of the total energy used. With reference to Figure 81, the energy demand for the individual processes is shown in Figure 87.

Figure 87: Energy demand in vehicle production by productive phase for combustion engine vehicle

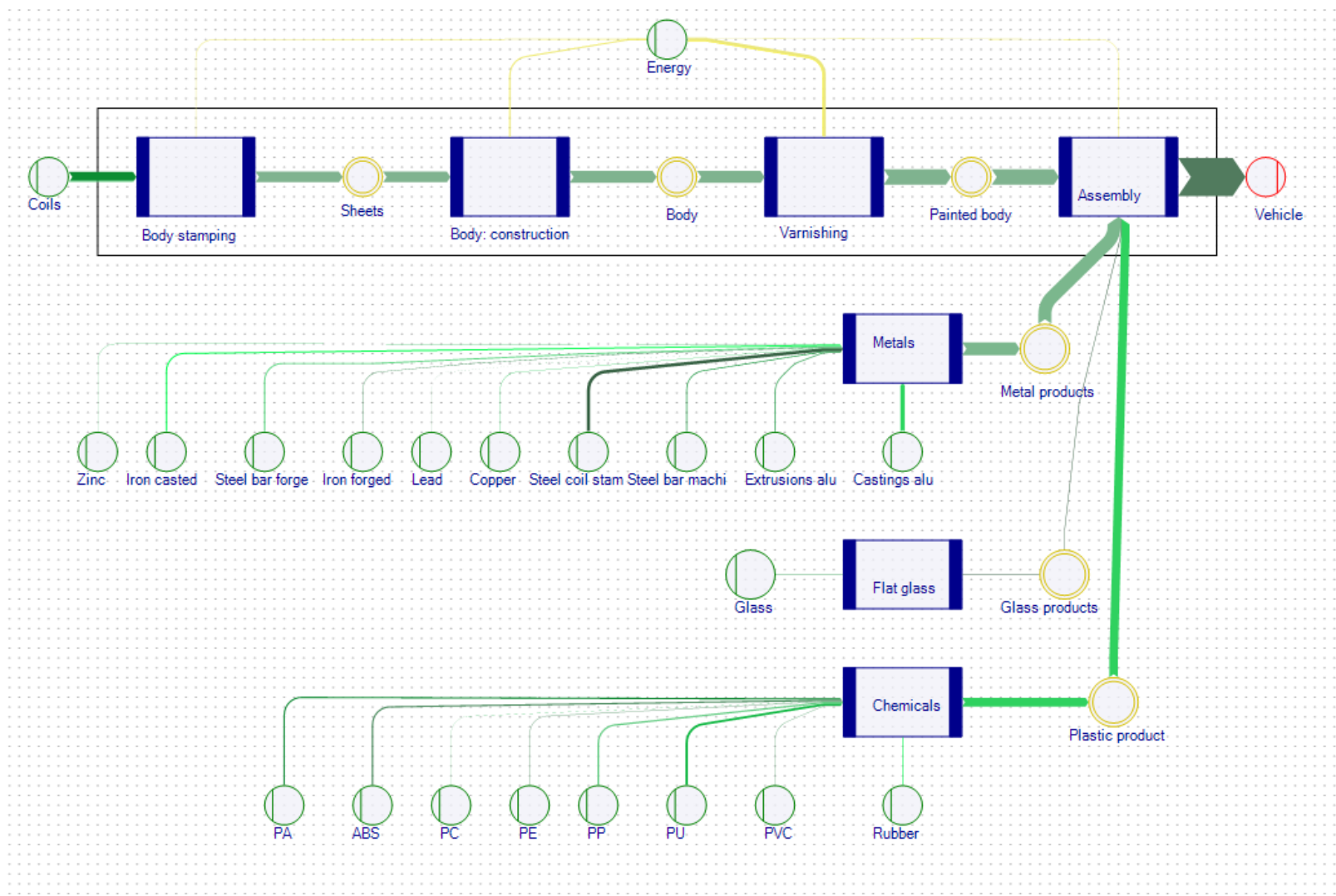


Source: own calculations based on chapter 2, Argonne National Library (2020), Sato & Nakata (2020), Van der Welden et al. (2012)

Based on Figure 81, Figure 88 shows the simplified production process of this case study and the GHG emissions resulting from the productive phases. The green lines represent the GHG emissions. These are added up over the entire process and attributed to the final product, the vehicle. The figure shows the manufacturing of the body of the vehicle, the processed materials entering the assembly and the final assembly of the vehicle.

In total, 3,505 kg CO₂eq are emitted for the production of a passenger car with a combustion engine with a weight of 1,242 kg. The figure shows that the manufacturing of the body and especially the application of the paint has a relevant share of the GHG emissions. Body stamping, body construction and varnishing are responsible for 1,422 kg CO₂eq. However, the coils used in the stamping of the body already amount to 932 kg CO₂eq. The energy used in the production process itself has a minor responsibility regarding GHG emissions.

Figure 88: GHG emissions of combustion engine vehicle by productive phase and materials

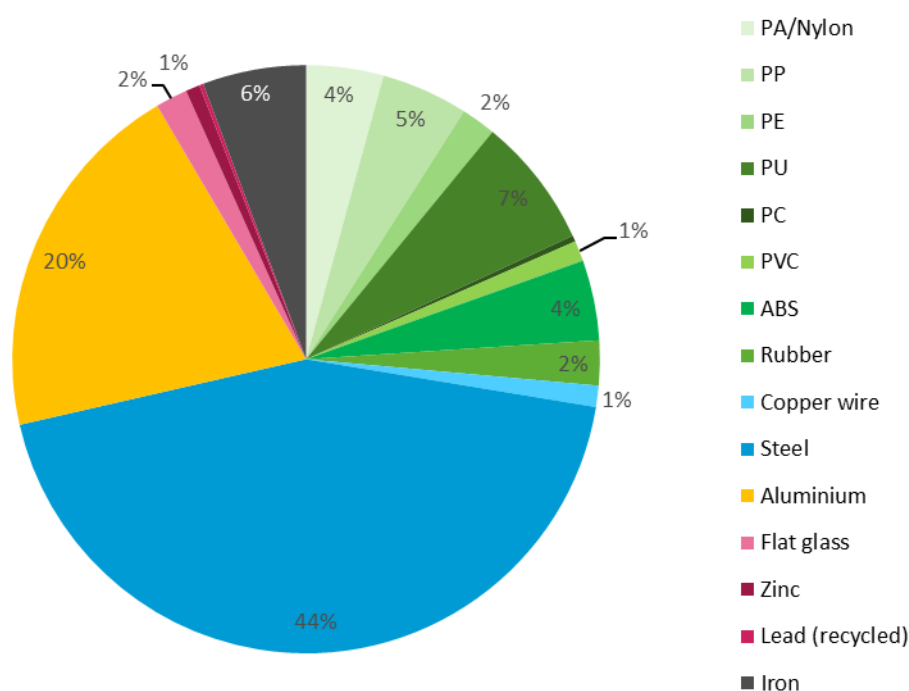


Source: own calculation

Observing the GHG emissions from the supplied parts, it becomes clear that the final assembly in the car only accounts for a small proportion. The final assembly of all parts and components to the body emits additional 42 kg CO₂eq. The production of the metals, which are used in engine, gearbox, seats etc. are responsible for 1,197 kg CO₂eq. The production of the plastic products contributes 790 kg CO₂eq. The production of glass is less relevant for the total GHG emissions, only 52 kg CO₂eq are emitted. This analysis includes all materials and components of the investigation, not only chapter 2.

Figure 89 shows the resulting GHG emissions for material and part production by material. Hence, the GHG emissions from the manufacturing of the body and the final assembly of the car are not included. When comparing the GHG emissions to the mass balance (see Figure 86), plastic products have a significantly higher share in GHG emissions. Overall, they reach a share of 30%. On the other hand, the share of aluminium and steel products in GHG missions is slightly lower than the share in mass balance.

Figure 89: GHG emissions by material for combustion engine vehicle



Source: own calculations based on chapter 2, Argonne National Library (2020), Sato & Nakata (2020), Van der Welden et al. (2012)

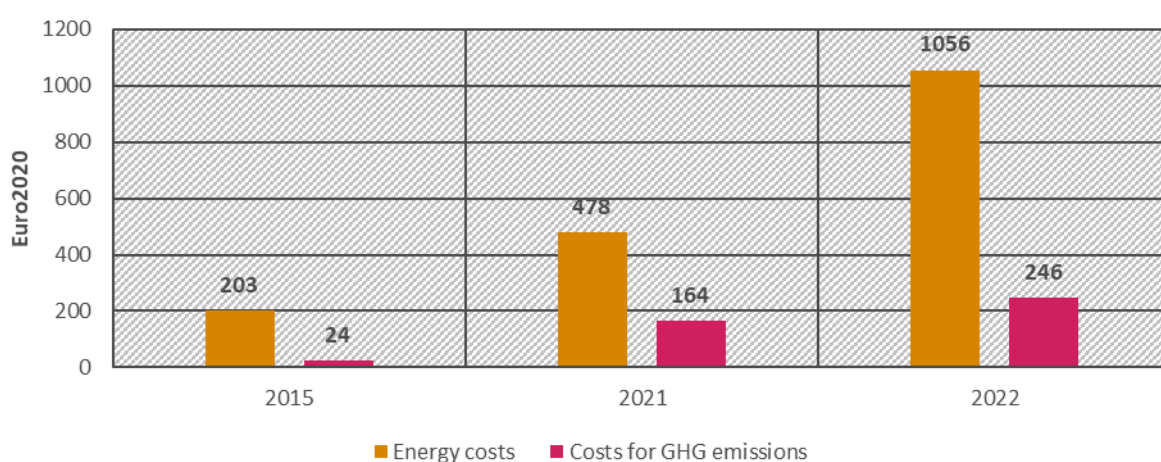
3.2.3.3 Assessment of the CO₂ cost shares

In the two following chapters, several costs for the production of the materials and components used in the combustion engine vehicle are presented, broken down by production stage. The costs for energy and GHG emissions are calculated for all materials used in the car. The enhanced cost structure of costs for material, labour, energy and GHG emissions is only done for the products from chapter 2 in chapter 3.2.3.3.2. These materials account for 50% of the energy demand and 57% of the GHG emissions, which means that there is a systematic underestimation of the costs taking into account of a passenger vehicle.

3.2.3.3.1 Costs for energy and GHG emissions

The calculation is based on the mass balance, energy demand and GHG emissions shown in Table 87. In the calculation, the framework data from chapter 3.2.1 is applied. Table 90 shows the allocation of energy costs and costs for GHG emission for material production and part production. Figure 90 shows the costs for energy and GHG emissions for the years 2015, 2021 and 2022. Throughout the year, the energy costs are significantly higher than the costs for GHG emissions. Nevertheless, the relative distribution differs. In 2015 (EUA 7.7 €/t CO₂eq), costs for GHG emissions amount to 24 € and have an average share of 11% of the costs for energy and GHG emissions. In 2021 (EUA 53.2 €/t CO₂eq), an average of 26% (164 €) is reached. Due to the higher energy costs in 2022 (EUA 80 €/t CO₂eq), the costs for GHG emissions amount to 246 €, with an average share of 19% of the costs for energy and GHG emissions.

Figure 90: Costs for energy and GHG emissions for 2015, 2021 and 2022



Source: own calculation

Assuming a price for the vehicle of about 20,000 €⁸⁵, in 2015 energy costs have a share of about 1% in 2021 of 2.4% and in 2022 of 5.3%. For the GHG emissions, in 2015 results a share of 0.12%, in 2021 of 0.8% and in 2022 of 1.2%.

⁸⁵ Price for Golf VII, see <https://www.autobild.de/artikel/vw-golf-vii-preise-3573363.html>

Table 90: Allocation of energy costs and costs for GHG emission in the production of a combustion engine vehicle for material and part production

Nr.	Material	Weight [kg]	2015				2021				2022			
			Energy		GHG emissions		Energy		GHG emissions		Energy		GHG emissions	
			Materials	Parts	Materials	Parts	Materials	Parts	Materials	Parts	Materials	Parts	Materials	Parts
1	PA/Nylon	18	0.17	9.78	0.02	0.96	0.47	29.35	0.10	6.65	1.10	69.90	0.16	9.99
2	PP	78	18.73	1.98	0.90	0.20	23.79	5.97	6.24	1.36	37.45	14.24	9.38	2.04
3	PE	25	5.95	1.49	0.29	0.15	7.64	4.50	2.01	1.02	12.12	10.73	3.02	1.53
4	PU	43	23.23	0.00	1.64	0.00	49.43	0.00	11.38	0.00	105.94	0.00	17.10	0.00
5	PC	3	0.88	0.08	0.07	0.01	2.22	0.24	0.48	0.05	5.06	0.57	0.72	0.08
6	PVC	13	3.13	0.22	0.24	0.02	7.66	0.67	1.64	0.15	17.32	1.60	2.46	0.23
7	ABS	37	11.59	0.95	0.92	0.09	28.33	2.86	6.35	0.65	63.95	6.81	9.55	0.97
8	Rubber	23	8.84	1.19	0.47	0.10	13.34	3.13	3.24	0.68	24.05	7.23	4.86	1.03
9	Copper wire	16	2.47	0.48	0.23	0.04	6.06	1.05	1.60	0.25	13.60	2.28	2.41	0.38
	Steel													
10	Hot rolled coils (preassembly)	317	18.91	0.00	6.33	0.00	43.45	0.00	43.87	0.00	92.44	0.00	65.92	0.00
11	Hot rolled coils	95	5.66	1.98	1.90	0.41	13.00	5.00	13.18	2.87	27.67	11.03	19.80	4.32
12	Hot rolled bars machining	150	3.97	0.80	0.47	0.08	11.52	2.40	3.28	0.55	27.09	5.73	4.94	0.82
13	Hot rolled bars forging	25	0.66	2.65	0.08	0.77	1.92	5.72	0.55	5.36	4.52	11.52	0.82	8.06
	Aluminium													

Nr.	Material	Weight [kg]	2015				2021				2022			
			Energy		GHG emissions		Energy		GHG emissions		Energy		GHG emissions	
			Materials	Parts	Materials	Parts	Materials	Parts	Materials	Parts	Materials	Parts	Materials	Parts
14	Stamping (preassembly)	64	0.98	0.00	0.09	0.00	2.67	0.00	0.60	0.00	6.22	0.00	0.90	0.00
15	Casting	163	13.56	0.00	1.14	0.00	35.62	0.00	7.87	0.00	82.06	0.00	11.83	0.00
16	Extrusions	49	1.37	0.00	0.10	0.00	3.22	0.00	0.69	0.00	7.17	0.00	1.04	0.00
17	Flat glass	34	0.53	3.70	0.11	0.29	0.90	9.32	0.79	2.01	1.62	21.25	1.18	3.02
18	Zinc	13	1.84	0.00	0.18	0.00	5.49	0.00	1.24	0.00	13.05	0.00	1.87	0.00
19	Lead (recycled)	13	0.38	0.26	0.03	0.02	0.91	0.70	0.19	0.15	2.05	1.61	0.29	0.23
	Iron													
20	Forging	13	0.23	2.68	0.01	0.20	0.27	6.46	0.07	1.37	0.40	14.54	0.11	2.06
21	Casting	50	0.90	2.93	0.04	0.92	1.07	6.01	0.29	6.41	1.58	11.72	0.43	9.63

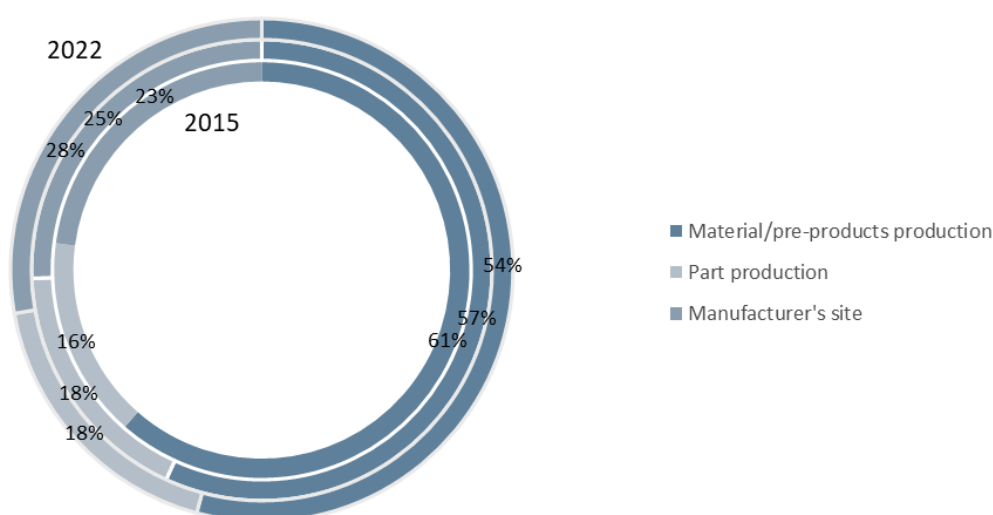
In addition to that, Table 91 shows the energy costs and costs for GHG emissions only for the processes at the manufacturer's site. As already shown in Figure 89, varnishing is responsible for most of the energy consumption and therefore also for energy costs and costs for GHG emissions.

Table 91: Allocation of energy costs and costs for GHG emission in the production of a combustion engine vehicle for production process

Stage of production process	Energy cost [Euro]			Costs for GHG emissions [Euro]		
	2015	2021	2022	2015	2021	2022
Assembly	4	11	25	0,33	2,29	3,44
Body stamping	5	15	35	0,45	3,15	4,73
Varnishing	28	80	188	2,44	16,89	25,38
Body construction	11	30	70	0,91	6,30	9,46

Furthermore, Figure 91 shows that the costs mostly account for the production of material. It is to see, that the relative distribution of costs along the value chain varies depending on the level of costs for energy and EUA. The higher the costs, the higher the importance of the (fossil) energy use in the production of materials. This is because production at manufacturer's site depends mainly on natural gas and electricity, and these prices have risen more sharply than oil and coal.

Figure 91: Share of costs for material and part production for combustion engine vehicle



Source: own calculation

3.2.3.3.2 Costs shares of relevant materials

Table 92 shows the cost structure of the products from chapter 2 for the production of the materials used in the combustion engine vehicle for 2015, 2021 and 2022. The table contains the total

production cost for the production of materials of the combustion engine including the costs for material, energy, labour and GHG emissions.

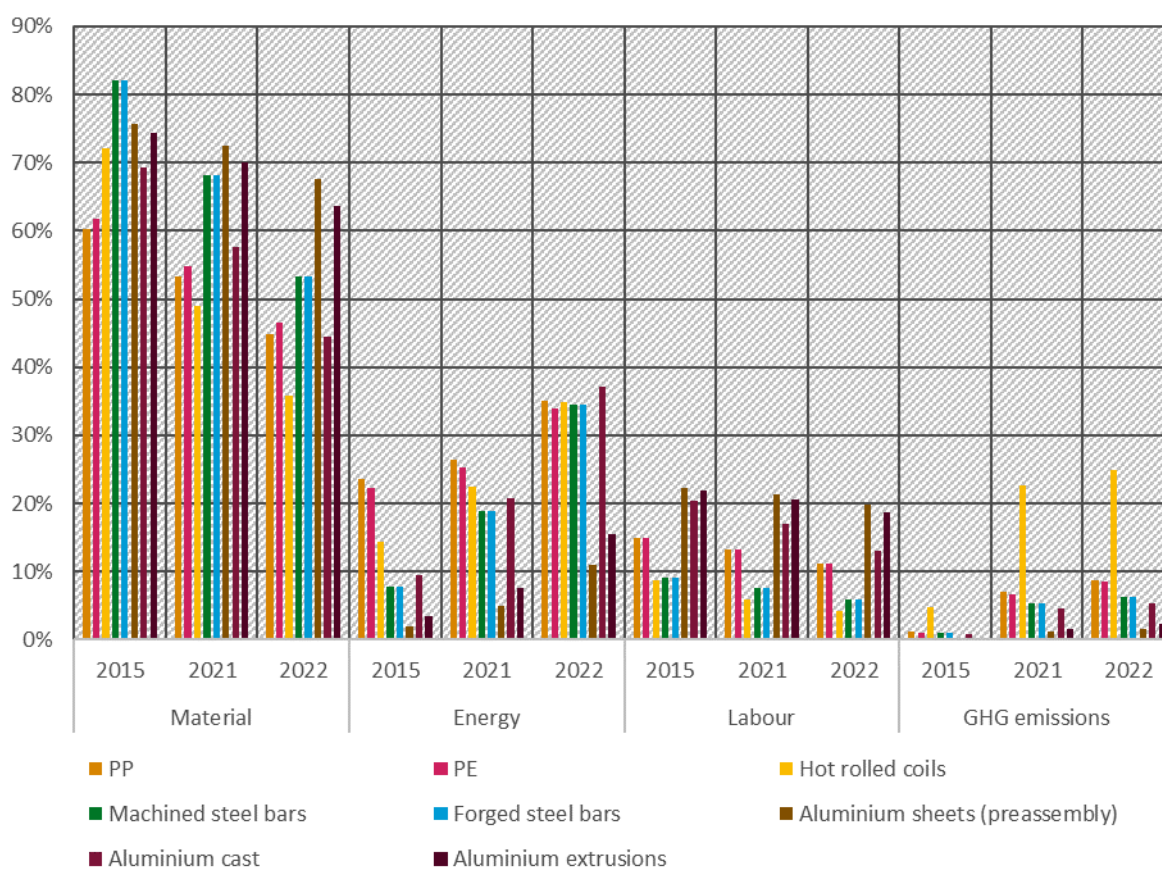
Table 92: Cost structure for the products from chapter 2 used in the combustion engine vehicle

Nr.	Products	2015	2021	2022
2	PP	79.4	89.8	106.6
3	PE	26.8	30.2	35.7
10	Hot rolled coils (preassembly)	131.7	193.8	264.8
11	Hot rolled coils	39.4	58.1	79.3
12	Hot rolled bars machining	50.9	61.2	78.4
13	Hot rolled bars forging	8.5	10.2	13.1
14	Aluminium sheets (preassembly)	50.9	53.2	57.0
15	Aluminium cast	142.2	171.0	221.4
16	Aluminium extrusions	39.7	42.2	46.5

Furthermore, Figure 92 shows the cost shares of the different costs and year for the products from chapter 2. Due to the low price for an emission allowance in 2015, the GHG emissions have the lowest share of the relevant costs for the stage of material production. Due to the higher costs for energy and EUA, the shares of the different costs differ in 2021 and 2022. With rising costs, the share for materials and labour decrease, whereas the shares for energy and GHG emissions rise. It is to say, that the share for materials sees a stronger decline than the share for labour. Due to the process emissions in the steel production, the share of costs for GHG emissions of hot rolled coils are slightly higher. Materials and energy have the highest share in the cost of the products. For plastic products, the cost of materials is about the same as the cost of energy. For the steel products, the material costs are significantly higher than the energy costs.

In 2015 (EUA 7.7 €/t CO₂eq), costs for GHG emissions from chapter 2 products amount to 11.3 €, with an average share of 1.7% of the relevant costs (energy, GHG emissions, labour and material). In 2021 (EUA 53.2 €/t CO₂eq), an average of 8.6% (78.3 €) is reached. In 2022 (EUA 80 €/t CO₂eq), the costs for GHG emissions amount to 117.6 €, with an average share of 10% of costs for energy, GHG emissions, labour and material.

Figure 92: Cost shares for the products from chapter 2 used in the combustion engine vehicle



Source: own calculation

3.2.4 Assessment of the CO₂ cost share flows in the production of battery electric vehicles

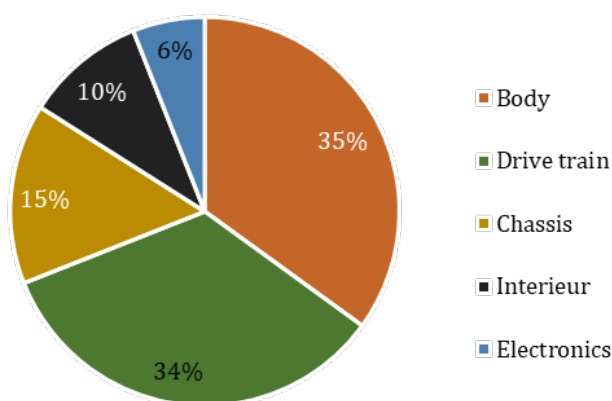
3.2.4.1 Mass and material balance of battery electric vehicle

For the battery electric vehicle (BEV), it is assumed that all parts including chassis, interior, low-voltage electricity are constructed of the same materials and by the same processes with equal energy consumption as the conventional internal combustion engine vehicle (ICEV). Only the drive train, including the electric engine and the battery, are considered to be different. Furthermore, it is assumed that the production and assembly is comparable to the combustion engine vehicle.

The mass balance of the BEV is based on the same weight per component groups as the ICEV except for the drive train. Figure 93 shows the weight distribution of the component groups. Due to data availability, some of the categories encompass slightly different components than in the ICEV case, but the differences are all within the 1% range regarding their shares of weight on the vehicle.⁸⁶ The overall weight of the BEV is 1,398 kg due to the higher weight of the drive train of 477 kg. In reality, however, BEVs are most often built with a lighter body than most ICEV.

⁸⁶ Heating and control elements are included in the Electronics category and high voltage electronics are included in the Drive train category, so the Electronics only include low voltage (LV) components. As cooling liquid is included in the cooling system, fuel and engine oil is obsolete and gear oil has a negligible weight, the category Fluids has been left out.

Figure 93: Weight distribution of BEV by component groups

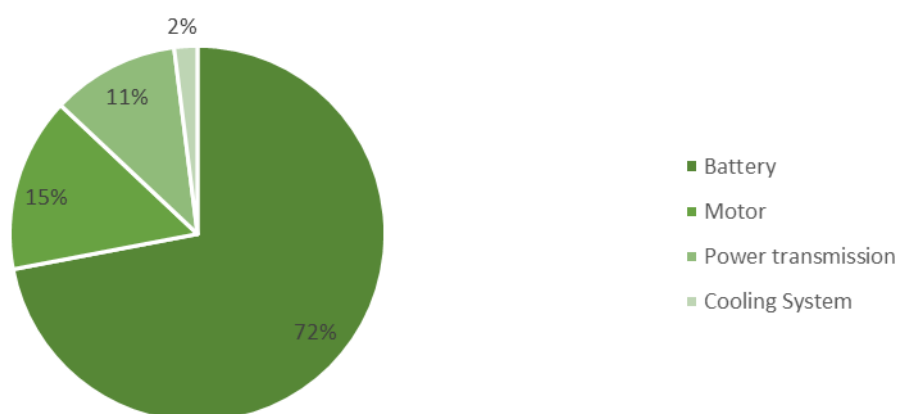


Source: own compilation based on Notter et al. (2010)

As the main difference between ICEV and BEV is the composition of the drive train, this section will be explained in more detail in the following.

As shown in Figure 94, almost three quarters of the weight of the drive train of the BEV can be assigned to the battery (approx. 232 kg/ 27 kW according to Notter et al. (2010)). Motor and power transmission technology have a similar mass and the weight of the cooling system is almost negligible. It is easily seen that the drive train of the BEV consists of much fewer components than that of the ICE.

Figure 94: Weight distribution of the Drive Train of BEV



Source: own compilation based on Notter et al. 2010

Table 93 shows in some more detail how the weight of the drive train is distributed amongst components and materials. The engine weights less than half the engine of the ICEV but it also consists to a large part of steel and to a lesser extend of aluminium and copper. The power transmission system, which includes other ancillary parts such as gearbox, controller, charger, and cables, consists mostly of aluminium, steel and electronics and cables, consists mostly of aluminium, steel and electronics.

3.2.4.2 Energy demand and GHG emissions for the production of battery electric vehicle

Table 94 gives an overview of the energy used in the production of the electric vehicle. The relevant manufacturing process is named. Due to the cut-off criterion of 1%, not all materials are considered. Apart from that, fuels are excluded, because they are allocated to the use phase of a passenger car. The calculation of the energy demand and GHG emissions is therefore based on a total weight of 1,273 kg.

The table contains the weight, the total and specific energy demand by material production and manufacturing process, and the total and specific GHG emissions for each material.

The emissions associated with material processing are calculated building upon the material and energy flow. The model includes indirect emissions generated by electricity use in the production process, direct process related emissions and direct energy related emissions caused by fuel consumption.

The analysis from Notter et al. 2010 is based on a typical battery, using datasets from Ecoinvent. The final assembly takes place in Europe, but Lithium is imported from Chile and several other components from Japan and China (Notter et al., 2010). For the purpose of this study, it is assumed that the production of the battery takes place in Europe.

Table 93: Mass balance of the drivetrain of the battery electric vehicle [in kg]

Component			Weight	Aluminium	Steel	Copper	Graphite	LiMnO	Polyethylene Sulfide	Polyethylene	Ethylene carbonate	Others
Propulsion energy converter			48.30	12.70	24.49	9.07			1.00			1.04
Power transmission			35.42	18.45	9.37				0.94			6.67
Cooling system			6.44	0.72	1.07				1.43	0.72		2.50
High voltage electronics			52.80									52.80
Energy storage	Wiring board		0.75									0.75
	Steel box		32.09	32.09								
	Cables (3-phase and data)		11.64									11.64
	Single Cell	Anode	70.91			36.50	34.41					
		Cathode	57.82	22.37				35.45				
		Separator	9.50							3.33		6.16
		Aluminium Tab	2.92	2.92								
		Electrolyt Solvent	28.29								28.29	
		Electrolyt Salt	3.36									3.36
		Package	12.96							12.96		
		Atmospheric nitrogen	1.77									1.77

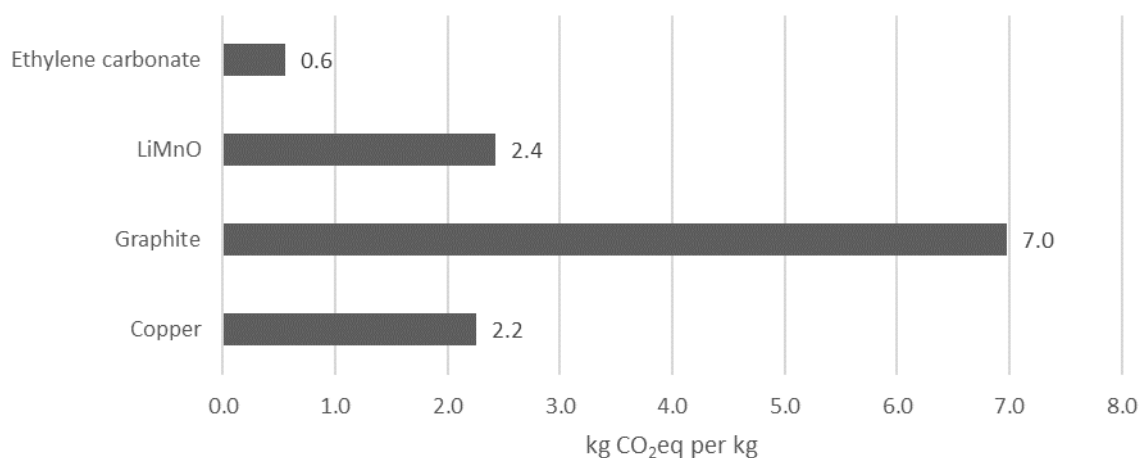
Table 94: Energy demand and GHG emissions of products by energy source and production process for the battery electric vehicle

Nr.	Material/ Product	Weight [kg]	Energy demand [MJ]			GHG emissions [kg CO ₂ eq]			Part production process
			Total	Material production	Part production	Total	Material production	Part production	
1	PA/Nylon	18	1,190	23	1,167	127	2	125	Textile production
2	PP	76	1,718	1,491	227	139	114	25	Injection molding
3	PE	20	527	385	142	46	30	15	Injection molding
4	PU	43	2,754	2,754		214	214	0	
5	PC	3	149	140	9	10	9	1	Injection molding
6	PVC	13	538	511	26	34	31	3	Extrusion
7	ABS	37	2,049	1,937	112	131	119	12	Injection molding
8	Rubber	23	1,106	929	177	74	61	13	Injection molding
9	Copper wire	16	418	370	48	35	30	5	Wiring
	Steel	528				1,157			
10	Hot rolled coils (preassembly)	317	6,634	6,634		824	824	0	
11	Hot rolled coils	54	1,442	1,131	311	171	140	30	Stamping
12	Hot rolled bars machining	135	615	530	85	65	55	9	Machining
13	Hot rolled bars forging	22	1,027	88	939	98	9	89	Casting+Forging
	Aluminium	303				238			
14	Stamping (preassembly)	64	132	132		108	108	0	
15	Casting	184	2,146	2,146		443	443	0	Casting

Nr.	Material/ Product	Weight [kg]	Energy demand [MJ]			GHG emissions [kg CO ₂ eq]			Part production process
			Total	Material production	Part production	Total	Material production	Part production	
16	Extrusions	55	114	114		112	112	0	Extrusion
17	Flat glass	32	705	144	561	50	13	36	
18	Zinc	16	270	270		28	28	0	
19	Copper	46	1,458	1,458		102	102		
20	Graphite	34	2,890	2,890		240	240		
21	Lithium manganese oxide (LiMnO)	35	1,312	1,312		86	86		
22	Ethylene carbonate	28	255	255		16	16		

For the battery electric vehicle, the same emission factors as for the combustion engine vehicle apply (see Figure 86). Figure 95 shows the additional emissions factors for the battery related components. Graphite has the highest specific emissions due to the process of graphitization, which requires temperatures of about 3,000°C (Marsh & Rodríguez-Reinoso, 2006).

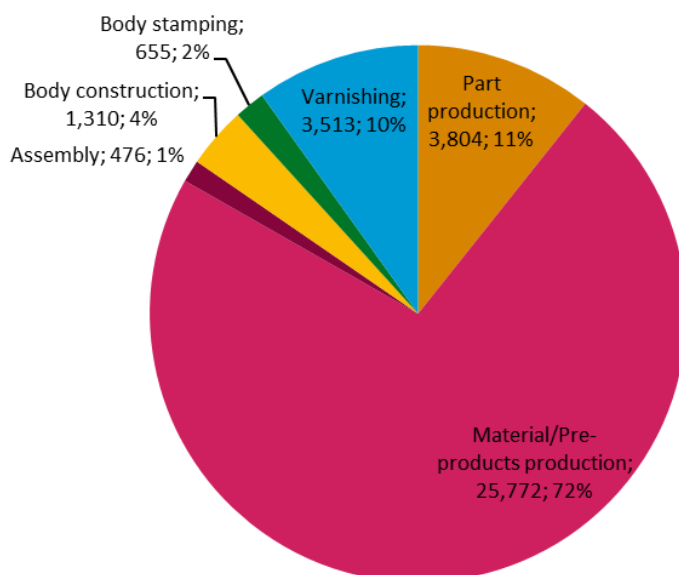
Figure 95: Additional emission factors by material for the battery electric vehicle



Source: own calculation

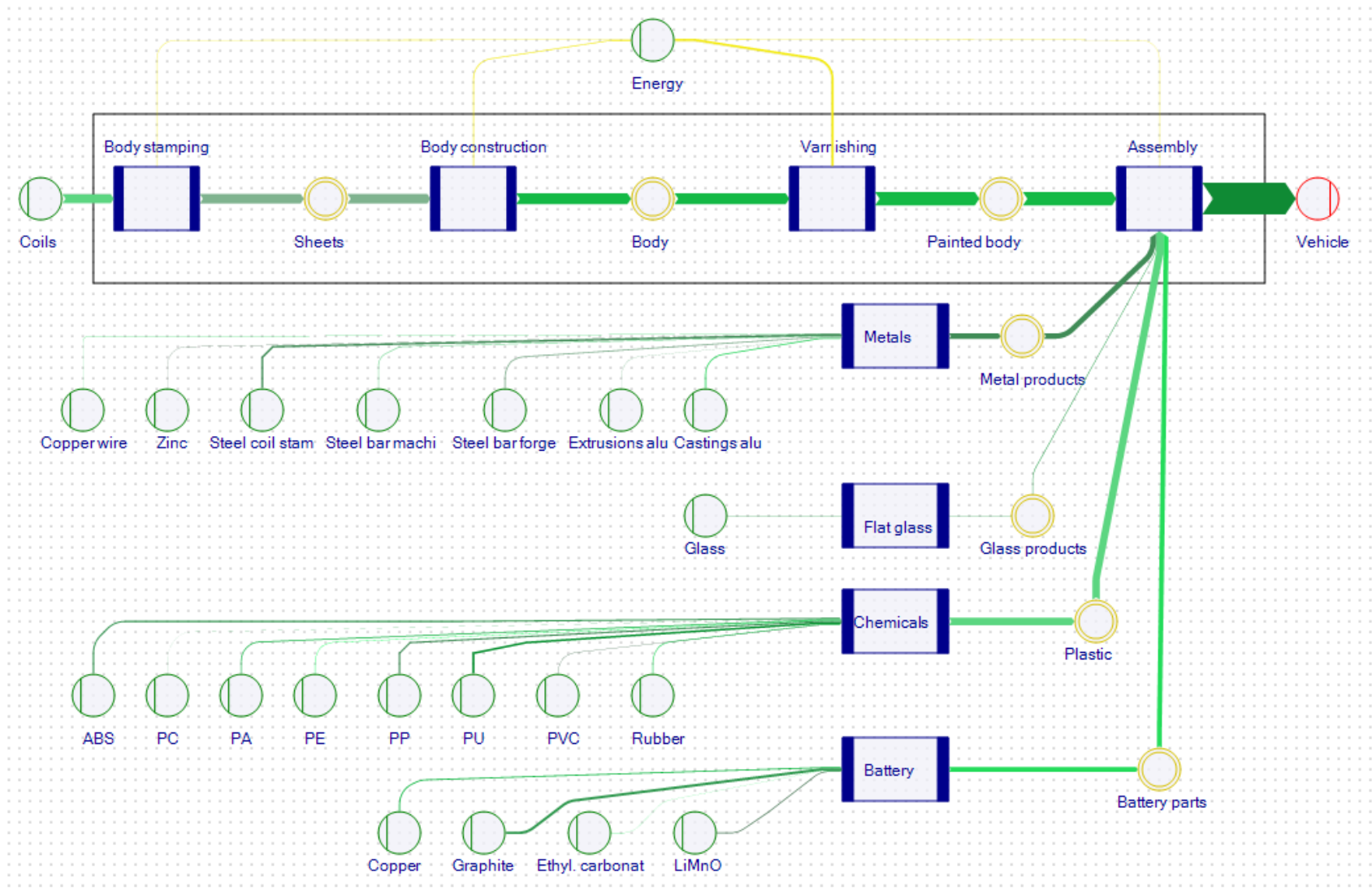
The total energy demand, for material and part production and vehicle assembly amounts to 35,530 MJ, so more than the ICEV. Per kg of vehicle produced, this corresponds to 27.9 MJ, which is more than the specific energy consumption of the ICEV. The relative consumption of each of the process steps is very similar for each vehicle. In both cases, most of the energy demand (more than three quarters) is used for material production.

Figure 96: Energy demand in vehicle production by productive phase for the battery electric vehicle



Source: own calculation

Figure 97: GHG emissions of the battery electric vehicle by productive phase and materials



Source: own calculation

Figure 97 shows the simplified production process and the GHG emissions resulting from the productive phases of the BEV. In total, 3,700 kg CO₂eq are emitted for the production of an electric passenger car with a weight of 1,273 kg.

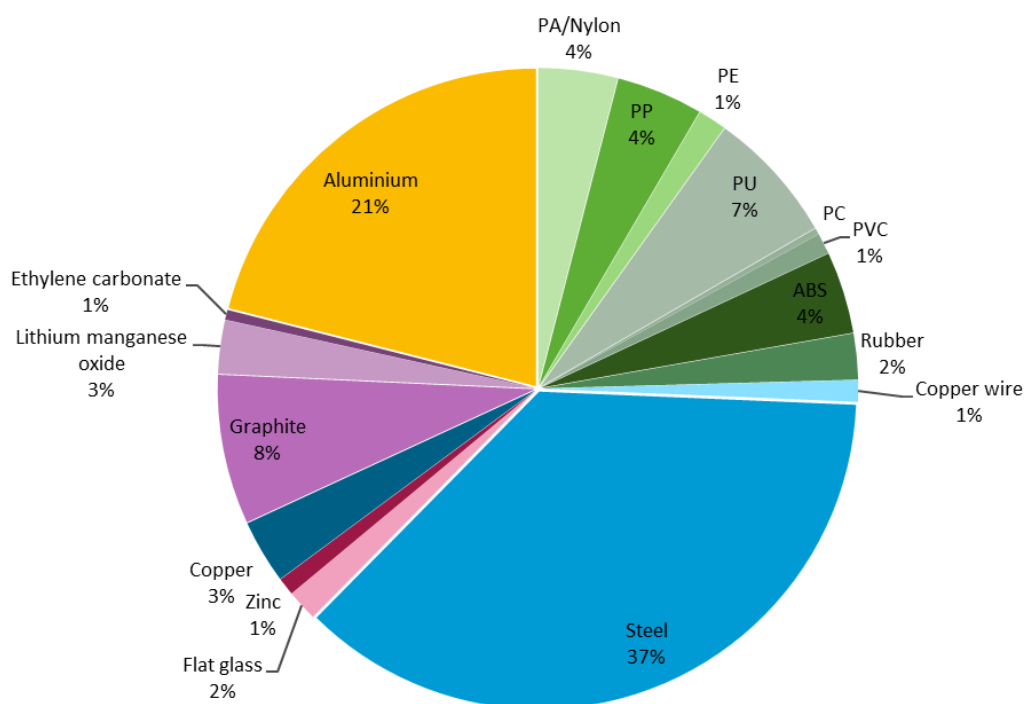
The diagram shows that the manufacturing of the body and especially the application of the paint has a relevant share of the GHG emissions. As the battery electric vehicle is slightly heavier than the combustion engine vehicle, more energy is used in the production process. Therefore, the GHG emissions for body stamping, body construction and varnishing amount to 1,440 kg CO₂eq. The final assembly of all parts and components to the body emit additional 43 kg CO₂eq.

In comparison to the combustion engine vehicle less steel is used in the battery electric vehicle. Because of that, the production of the metals, which are used in engine, gearbox, seats etc., are responsible for 951 kg CO₂eq. The production of the plastic products contributes 774 kg CO₂eq. The production of glass is less relevant for the total GHG emissions, only 50 kg CO₂eq are emitted. Therefore, the production of the battery is adding another 444 kg CO₂eq to the total GHG emissions of the BEV.

The emissions per kg of the battery electric vehicle are higher than those of the combustion engine vehicle (2.9 kg CO₂eq /kg as compared to 2.83 kg CO₂eq /kg of the ICE).

Figure 98 shows the resulting GHG emissions by material. In this figure, the GHG emissions from the manufacturing of the body and the final assembly of the car are not included. The overall picture is again similar to the ICE. Nevertheless, in comparison the BEV has lower emissions in the steel category because fewer parts are produced by the energy intense hot rolled coil process. Moreover, in the electric vehicle no iron is used in the gearbox and engine as well as an alternator is not needed because of the battery in the ICE. On the other hand, more aluminium parts are used due to the lower weight of the metal. The share of aluminium in total GHG emissions is therefore higher than for the ICE. Furthermore, the production of the battery is very energy intense.

Figure 98: GHG emissions by material for the battery electric vehicle



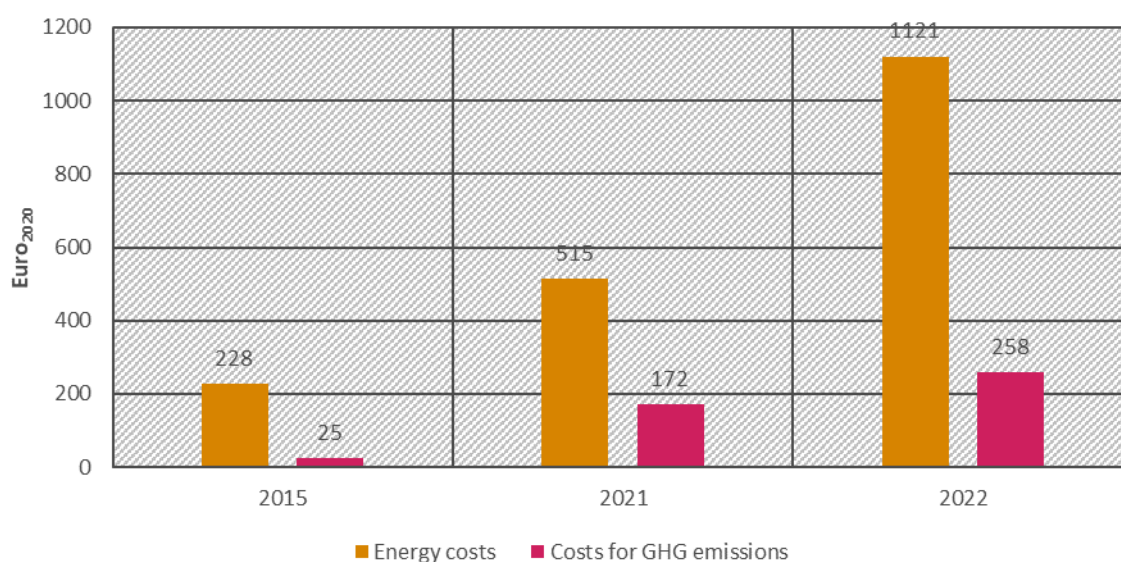
Source: own calculation

3.2.4.3 Assessment of CO₂ cost shares

In this section, the costs for the production of the materials and components used in the electric vehicle are presented, broken down by production stage. As for the ICEV, the costs for energy and GHG emissions are calculated for all materials used in the car. The enhanced cost structure of costs for material, labour, energy and GHG emissions is only done for the products from chapter 2. The calculation is based on the mass balance, energy demand and GHG emissions shown in Table 94. In the calculation, the framework data from chapter 3.2.1 is applied.

Figure 99 shows the costs for energy and GHG emissions for the years 2015, 2021 and 2022. The overall cost of producing a BEV is higher than that of an ICEV because the energy required to produce the battery components and the electric motor is higher than that required to produce the combustion engine. In 2015, the costs for energy amount to 228 €, the costs for EUA to 25 €. In 2022, energy costs amount to 1,121 € and GHG emission costs to 258 €. In 2015, costs for emissions have a share of 10% of the costs for energy and GHG emissions. This share increases to 25% in 2021. In 2022, costs for EUA have a share of 19%. Table 95 shows the allocation of energy costs and costs for GHG emission for material production and part production for the BEV. Table 95 shows the allocation of energy costs and costs for GHG emission for material and part production for the BEV.

Figure 99: Costs for energy and GHG emissions of BEV for 2015, 2021 and 2022



Source: own calculation

Assuming a price for the vehicle of about € 32,000⁸⁷, in 2015 energy costs have a share of 0.7% in 2021 of 1.6% and in 2022 of 3.5%. For the GHG emissions, in 2015 results a share of 0.07%, in 2021 of 0.53% and in 2022 of 0.8%.

⁸⁷ Price for E-Golf 2014, see <https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/vw/golf/vii-facelift/266575/>

Table 95: Allocation of energy costs and costs for GHG emission in the production of a battery electric vehicle by production phase

Nr.	Material	Weight [kg]	2015				2021				2022			
			Energy		GHG emissions		Energy		GHG emissions		Energy		GHG emissions	
			Material	Parts	Material	Parts	Material	Parts	Material	Parts	Material	Parts	Material	Parts
1	PA/Nylon	18	0.17	9.78	0.02	0.96	0.47	29.35	0.10	6.65	1.10	69.90	0.16	9.99
2	PP	76	18.21	1.92	0.88	0.19	23.13	5.81	6.07	1.32	36.41	13.84	9.12	1.98
3	PE	20	4.80	1.20	0.23	0.12	6.15	3.63	1.62	0.82	9.76	8.65	2.43	1.24
4	PU	43	23.23	0.00	1.64	0.00	49.43	0.00	11.38	0.00	105.94	0.00	17.10	0.00
5	PC	3	0.88	0.08	0.07	0.01	2.22	0.24	0.48	0.05	5.06	0.57	0.72	0.08
6	PVC	13	3.13	0.22	0.24	0.02	7.66	0.67	1.64	0.15	17.32	1.60	2.46	0.23
7	ABS	37	11.59	0.95	0.92	0.09	28.33	2.86	6.35	0.65	63.95	6.81	9.54	0.97
8	Rubber	23	8.84	1.19	0.47	0.10	13.34	3.13	3.24	0.68	24.05	7.23	4.86	1.03
9	Copper wire	16	2.47	0.48	0.23	0.04	6.06	1.05	1.60	0.25	13.60	2.28	2.40	0.38
	Steel	528							0.00		0.00	0.00	0.00	0.00
10	Hot rolled coils (preassembly)	317	18.91	0.00	6.33	0.00	43.45	0.00	43.86	0.00	92.44	0.00	65.90	0.00
11	Hot rolled coils	54	3.22	1.13	1.08	0.23	7.41	2.85	7.48	1.61	15.76	6.28	11.23	2.42
12	Hot rolled bars machining	135	3.57	0.72	0.43	0.07	10.38	2.17	2.95	0.49	24.41	5.17	4.43	0.74
13	Hot rolled bars forging	22	0.60	2.39	0.07	0.68	1.73	5.15	0.49	4.72	4.07	10.38	0.74	7.10
	Aluminium	303	0.00	0.00					0.00		0.00	0.00	0.00	0.00

Nr.	Material	Weight [kg]	2015				2021				2022			
			Energy		GHG emissions		Energy		GHG emissions		Energy		GHG emissions	
			Material	Parts	Material	Parts	Material	Parts	Material	Parts	Material	Parts	Material	Parts
14	Stamping (preassembly)	64	0.98	0.00	0.09	0.00	2.67	0.00	0.60	0.00	6.22	0.00	0.90	0.00
15	Casting	184	15.28	0.00	1.28	0.00	40.14	0.00	8.87	0.00	92.47	0.00	13.33	0.00
16	Extrusions	55	1.55	0.00	0.11	0.00	3.63	0.00	0.78	0.00	8.08	0.00	1.18	0.00
17	Flat glass	32	0.41	3.56	0.10	0.28	0.76	8.96	0.71	1.93	1.42	20.43	1.07	2.90
18	Zinc	16	2.24	0.00	0.22	0.00	6.68	0.00	1.51	0.00	15.88	0.00	2.27	0.00
19	Copper	46	7.99	0.00	0.79	0.00	16.37	0.00	5.45	0.00	34.30	0.00	8.20	0.00
20	Graphite	34	19.88	0.00	1.84	0.00	27.66	0.00	12.77	0.00	45.86	0.00	19.19	0.00
21	LiMnO	35	8.54	0.00	0.66	0.00	16.58	0.00	4.57	0.00	34.15	0.00	6.87	0.00
22	Ethylene carbonate	28	2.12	0.00	0.12	0.00	3.62	0.00	0.84	0.00	7.02	0.00	1.26	0.00

In addition to that, Table 96 shows the energy costs and costs for GHG emissions for the production process for the electric vehicle. The relative shares are similar to the combustion engine vehicle, but the absolute costs are slightly higher due to the higher weight of the electric vehicle.

Table 96: Allocation of energy costs and costs for GHG emission in the production of a battery electric vehicle for production process

Stage of production process	Energy cost [Euro]			Costs for GHG emissions [Euro]		
	2015	2021	2022	2015	2021	2022
Assembly	4	10	25	0.34	2.34	3.52
Body stamping	5	14	34	0.5	3.22	4.84
Varnishing	27	77	182	2.5	17.29	25.98
Body construction	10	29	68	0.9	6.45	9.69

Due to the battery in the electric car, the share of materials in the costs for energy and GHG emissions is even higher than for the combustion vehicle. In 2015 only 10% of the costs account for the part production, in 2021 and 2022 this value increases to 13%. The cost at the manufacturer's site of the BEV account for 20% of the costs for energy and GHG emissions in 2015. This share increases to 23% in 2021 and 26% in 2022. In return decreases the share of costs for the production of materials from 70% in 2015 to 64% in 2021 and 61% in 2022.

As the cost structure of the materials of chapter 3.2.4 is similar to the combustion engine vehicle in chapter 3.2.3, in this section it will not be analysed separately.

3.3 Balancing the CO₂ cost share flows in the production of plastic products

In this chapter, the CO₂ cost share flows in the production of two plastic products, a plastic bag, and a plastic bowl, are analysed. For the purpose of this case study, a production of 1000 plastic bags und 1000 plastic bowls is assumed. The chosen plastic bag is made of low-density polyethylene (LDPE) with an average weight of 25 g and a volume of 22,4 litre (Bisinella et al., 2018) . The plastic bowl is made of polypropylene and has a weight of 420 g (Manufactum, 2021).

3.3.1 Methodology and assumptions

For the assessment of the CO₂-cost share flows, the following steps are carried out:

1. Evaluation of the production process(es)
2. Development of mass and material balance
3. Calculation of the total energy demand and GHG emissions
4. Analysis of CO₂ and material cost shares

Assumptions

It is assumed that the production of materials and final products takes places in Europe. Table 97 gives an overview of the materials used in plastic bags. Apart from low-density polyethylene, dyes and solvent are used for printing the pattern of the plastic bag. In comparison to the amount of polyethylene (PE), the amount of the chemicals used is neglectable. Therefore, only polyethylene is considered in the analysis.

Table 97: Materials used in plastic bags

Material	kg per plastic bag
Polyethylene	0.025
Toluene	0.00068991
Ethanol	0.00229614
Ethyl acetate	0.00048605

Source: Bisinella et al. (2018)

Furthermore, no net-losses in production processes for plastic bags and bowls are assumed, which is reasonable, as both PE and PP are thermoplastics, and all production residues can be fed back in the production process.

3.3.2 Material and energy balance

As input material for the production of plastic bags, polyethylene (PE) from chapter 2 is used. PE is produced mainly from naphtha in a steam cracker, and then polymerised. To produce plastic bags, PE pellets are melted down, and then extruded using natural gas and electricity (Bisinella et al., 2018).

As no losses are assumed for the production of plastic bags, 0.025 kg PE per plastic bag is used. For a production of 1.000 plastic bags, 25 kg polyethylene is used. For the production of 1 kg ethylene, 1 kg of naphtha is necessary. In addition, 16.5 MJ of naphtha are used for energy purposes. Table 98 shows the energy balance for the production of 1,000 plastic bags.

Table 98: Energy balance for production of 1000 plastic bags

	Naphtha [MJ]	Electricity [MJ]	Natural gas [MJ]
Steam cracker	396		
Polymerisation		64.8	
Extruder		23.95	36.48

As input material for the production of 420 kg of plastic bowls, polypropylene (PP) from chapter 2 is used. PP is produced through to the same production route as PE: naphtha is used as steam cracker feedstock, and the steam cracker produces a portfolio of olefins, with ethylene and propylene being the dominant species. Subsequently, propylene is polymerised to win PP. To produce a plastic bowl out of PP pellets, it is extruded and injection moulded (Gallego-Schmid et al., 2019).

Table 99 shows the energy balance for the production of 1000 plastic bowls. Dependent from the facilities and the energy efficiency, the energy demand for extrusion and injection moulding differs enormously. The energy demand for extrusion varies between 1.8 and 6.1 MJ per kg. The energy demand for injection moulding can vary between 2,1 and 9.76 MJ per kg (Weiß, 2016; Ecoinvent, 2021). The GREET database indicates 3 MJ of electricity per kg for injection moulding (Argonne National Laboratory, 2020).

For injection moulding, it is assumed that a fully electric machine with an energy consumption of 3.2 MJ per kg is used (Weiß, 2016). For extrusion, data from EcoInvent is used.

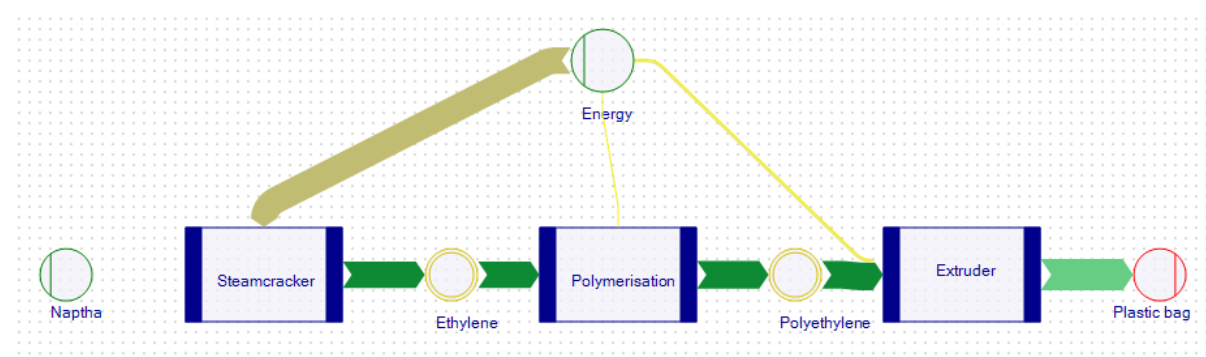
Table 99: Energy balance for production of 1000 plastic bowls

	Naphtha [MJ]	Electricity [MJ]	Natural gas [MJ]
Steamcracker	6,930		
Polymerisation		840	504
Extruder		998	340
Injection moulding		1,361	

3.3.3 Energy demand and GHG emissions

Figure 100 shows the production process of plastic bags and the resulting GHG emissions from the production of 1,000 plastic bags. GHG emissions come exclusively from the energy required for production. The yellow arrows represent the GHG emissions from energy consumption during production. The green arrows add up the GHG emissions over the entire production process. For the production of 1,000 plastic bags, 45 kg CO₂eq are emitted. Most greenhouse gas emissions (29 kg CO₂eq) result from the use of naphtha in the production of ethylene. About 7 kg CO₂eq result from using naphtha as feedstock in the steam cracker.

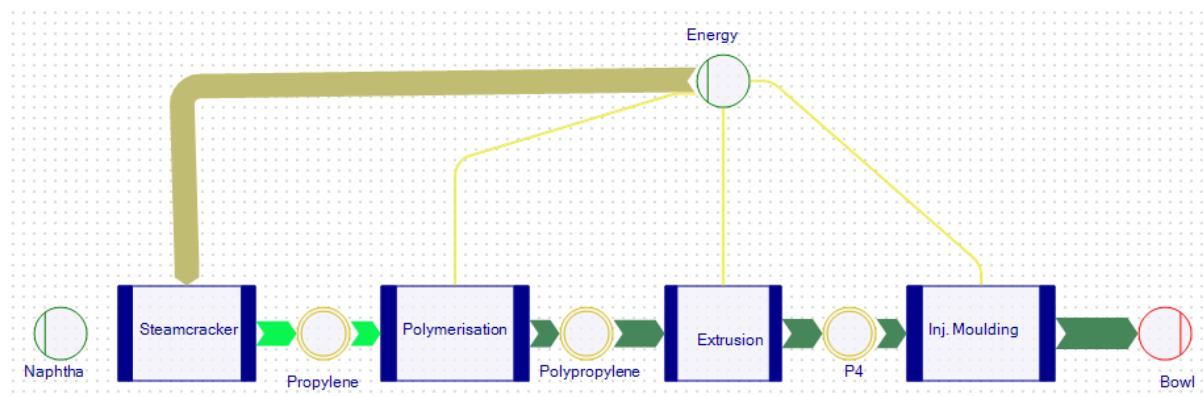
Figure 100: GHG emissions from the production of 1,000 plastic bags



Source: own depiction

Figure 101 shows the production process of plastic bowls and the resulting GHG emissions from the production of 1,000 plastic bowls with a weight of 420 kg. In total, for the production of 1,000 plastic bowls, 1,027 kg of CO₂eq are emitted. As with the production of plastic bags, most of the GHG emissions result from the use of naphtha (513 kg CO₂eq) in the production of propylene. About 349 kg CO₂eq result from the use of electricity in the production process. Using naphtha as feedstock in the steam cracker is responsible for 118 kg CO₂eq, the rest is accounted by natural gas used in the polymerisation and injection moulding.

Figure 101: GHG emissions from the production of 1,000 plastic bowls



Source: own depiction

When comparing the specific energy demand for both products, it results that for the production of plastic bags 20.7 MJ per kg and for the production of plastic bowls 24.4 MJ per kg are necessary. This is due to the design of the production process, as the production of plastic bowls is more complex and energy intensive than the production of plastic bags.

3.3.4 Assessment of the CO₂ cost shares

In this chapter, the cost structure for the production of plastic products (plastic bag and plastic bowl) will be analysed in order to assess the CO₂ cost shares of the products. For the calculation, the framework data from chapter 3.2.1 is used. It is to note, that the energy demand for the production of naphtha as feedstock is not included in this analysis due to lack of data (see chapter 2.6 Refineries).

Figure 102 shows the cost structure for the production of 1,000 plastic bowls with a weight of 420 kg for 2015, 2021 and 2022. In 2015, the costs for energy, GHG emissions, material and labour amount to 444 €. With 58%, material has the highest share of the considered costs, followed by costs for energy and labour with a share of 20%. The cost for GHG emissions amount to only 1% of the total cost. In 2021, the costs for energy, GHG emissions, material and labour increase to 602 €. The share of material and labour decrease, whereas the shares of energy and GHG emissions increase. In 2022, the costs amount to 1055 €. The costs for material have a share of 24%, the share of labour has decreased to a share of 9%. Due to the high energy costs, the share of energy amounts to 61%. The costs for GHG emissions have a share of 6% of the costs.

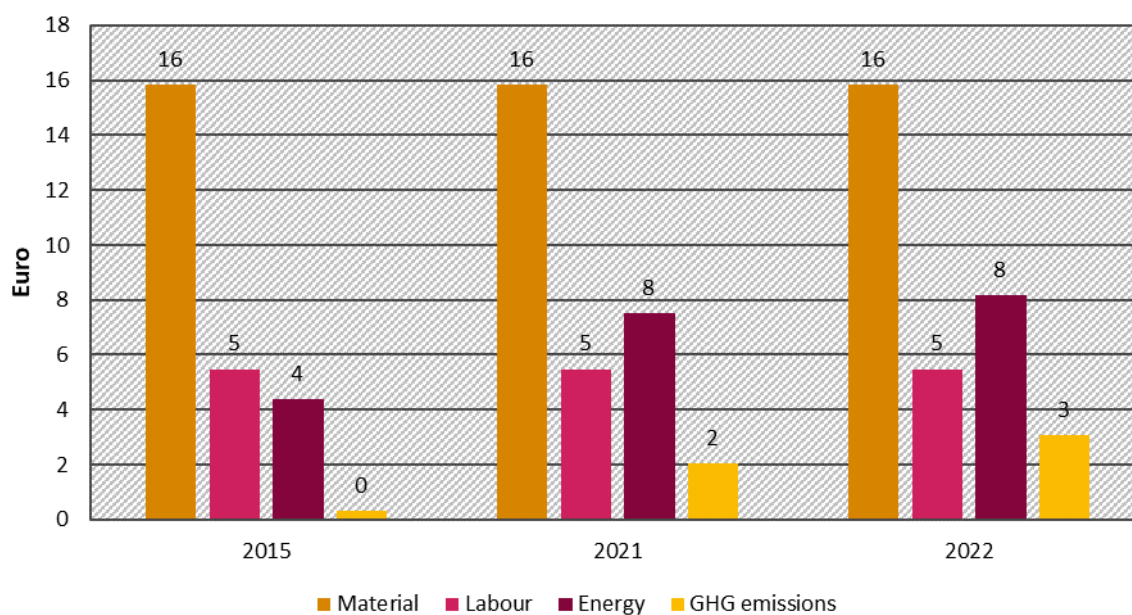
Figure 102: Cost structure for the production of 1,000 plastic bowls out of propylene



Source: own calculation

Figure 103 shows the cost structure for the production of 1,000 plastic bags with a weight of 24 kg for 2015, 2021 and 2022. In 2015, the costs for energy, GHG emissions, material and labour amount to 26 €. The relative distribution of the costs is similar to the plastic bowl. With increase in energy prices, the importance of material costs decreases. Nevertheless, the material costs remain the main cost driver of plastic bags.

Figure 103: Cost structure for the production of 1,000 plastic bags out of ethylene



Source: own calculation

3.4 Limitations and discussion

The calculation of energy use and greenhouse gas emissions in the production of an internal combustion car and an electric car is based on a generic car. However, due to the bottom-up analysis based on the components in the car, a very detailed consideration of the materials used has been carried out. The final material balance is also comparable with other studies (see (Danilecki et al., 2017; Göbbels et al., 2011; Sato & Nakata, 2020; Schweimer & Levin, 2000)).

With a specific energy consumption of 26.2 MJ per kg passenger car, a significantly lower value results in comparison with Sato & Nakata, 2020 (42 MJ per kg). However, this is due to the fact that no raw material extraction is considered in the case study.

Nevertheless, it must be pointed out that the generic car is a simplification. For example, the analysis did not take into account the energy required to assemble components. In addition, screws and other joining techniques were disregarded.

The calculation of energy consumption in the production line can be assumed to be an overestimate, as the total energy consumption of the plant in Wolfsburg was divided by the number of cars produced.

Overall, it must be noted that statements on the electric car are only possible to a limited extent, as only the drive train has been changed in comparison to the combustion engine car. The electric car therefore does not correspond to a realistic model. In addition, the energy input in the production of the electric car is not realistic. Due to the higher total weight, more energy is required for the production of the electric car compared to the combustion engine. However, it should be noted that in reality the production process of an electric car is very different.

As well as the passenger cars, the plastic products are a simplified representation. For both products, it is assumed that they only consist of one material, which has the largest share of the mass. Materials with a share of less than 5% are not taken into account. In addition, a loss-free production process is assumed.

Furthermore, only energy-related emissions are considered due to data availability. The naphtha used as a raw material in production is therefore not taken into account.

3.5 Summary and Conclusions

In this case study, the energy flows and the resulting greenhouse gas emissions in the production of passenger cars and plastic products are calculated in order to determine the cost shares along the value chain. Throughout the calculations it becomes clear which production processes and which materials have the largest share in energy consumption. However, due to the different procedure for determining the mass balances on which the calculation is based, the results of passenger cars and plastic products are not comparable.

For passenger cars, a very detailed bottom-up analysis is carried out based on the components installed in the car. On the basis of the mass balance, the material balance for a generic passenger car is drawn up. In the calculations, the generic car is adapted to the requirements of a combustion engine and a battery electric vehicle.

In the case of passenger cars, it can be seen that the production of materials accounts for the largest share of energy consumption. The production of the components as well as the assembly have a comparable energy input.

In total, 3,522 kg CO₂eq are emitted for the production of a passenger car with a combustion engine with a weight of 1,242 kg. The manufacturing of the body and especially the application of

the paint has a relevant share of the GHG emissions. Body stamping, body construction and varnishing are responsible for 1,422 kg CO₂eq. However, the coils used in the stamping of the body already amount to 932 kg CO₂eq. The energy used in the production process itself has a minor responsibility regarding GHG emissions. The final assembly of all parts and components to the body emits additional 42 kg CO₂eq. The production of the metals, which are used in engine, gearbox, seats etc. are responsible for 1,215 kg CO₂eq. The production of the plastic products contributes 790 kg CO₂eq. The production of glass is less relevant for the total GHG emissions, only 52 kg CO₂eq are emitted.

The calculation of the energy demand and GHG emissions of the battery electric vehicle is based on a total weight of 1,273 kg. The total energy demand, for material, part production and vehicle assembly amounts to 35,402 MJ, so more than the ICEV. Per kg of vehicle produced, however, this corresponds to 27.81 MJ, which is more than the specific energy consumption of the BEV.

In total, 3,700 kg CO₂eq are emitted for the production. As the electric vehicle is slightly heavier than the combustion engine vehicle, more energy is used in the production process. Therefore, the GHG emissions for body stamping, body construction and varnishing amount to 1,440 kg CO₂eq. The final assembly of all parts and components to the body emit additional 43 kg CO₂eq. In comparison to the combustion engine vehicle less steel is used in the electric vehicle. Because of that, the production of the metals, which are used in engine, gearbox, seats etc., are responsible for 951 kg CO₂eq. The production of the plastic products contributes 774 kg CO₂eq. The production of glass is less relevant for the total GHG emissions, only 50 kg CO₂eq are emitted. Therefore, the production of the battery is adding another 444 kg CO₂eq to the total GHG emissions of the electric vehicle.

For the assessment of the CO₂ cost shares, several costs for the production of the materials and components used in both vehicles are presented. The costs for energy and GHG emissions are calculated for all materials used in the vehicle. The enhanced cost structure of costs for material, labour, energy and GHG emissions is only done for the products from chapter 2 (thus, flat glass, zinc, lead, iron, copper and some chemicals are excluded). With regard to the relative distribution of costs for energy and GHG emissions along the value chain, there is to say, that the costs mostly account for the production of materials. Nevertheless, the shares are depending on the level of costs for energy and EUA. The higher the costs, the higher the importance of the (fossil) energy use in the production of materials. This is because production at manufacturer's site depends mainly on natural gas and electricity, and these prices have risen more sharply than oil and coal.

When looking only at the products from chapter 2 and thus also the costs for labour and material, a different result emerges. Due to the low price for an emission allowance in 2015, the GHG emissions have the lowest share of the cost for the production of materials. Due to the higher costs for energy and EUA, the shares of the different costs differ in 2021 and 2022. With rising costs, the share for materials and labour decrease, whereas the shares for energy and GHG emissions rise. In 2015 (EUA 7.7 €/t CO₂eq), costs for GHG emissions from chapter 2 products amount to 11.3 €, with an average share of 1.7% of the relevant costs (energy, GHG emissions, labour and material). In 2021 (EUA 53.2 €/t CO₂eq), an average of 8.6% (78.3 €) is reached. In 2022 (EUA 80 €/t CO₂eq), the costs for GHG emissions amount to 117.6 €, with an average share of 10% of costs for energy, GHG emissions, labour and material.

The material balances of the plastic products are based on comparable literature. In the case study, the value chain of plastic bags and plastic bowls are analysed.

GHG emissions resulting from the production of plastic bags come exclusively from the energy required for production. For the production of 1,000 plastic bags, 45 kg CO₂eq are emitted. Most

greenhouse gas emissions (29 kg CO₂eq) result from the use of naphtha in the production of ethylene. About 7 kg CO₂eq result from using naphtha as feedstock in the stream cracker. For the production of 1,000 plastic bowls, 1,027 kg of CO₂eq are emitted. As with the production of plastic bags, most of the GHG emissions result from the use of naphtha (513 kg CO₂eq) in the production of propylene. About 349 kg CO₂eq result from the use of electricity in the production process. Using naphtha as feedstock in the steam cracker is responsible for 118 kg CO₂eq, the rest is accounted by natural gas used in the polymerisation and injection moulding. When comparing the specific energy demand for both products, it results that for the production of plastic bags 20.7 MJ per kg and for the production of plastic bowls 24.4 MJ per kg are necessary.

In 2015, the analysed for the plastic bowls amount to € 444. With 58%, material has the highest share of the total cost, followed by costs for energy and labour with a share of 20%. The cost for GHG emissions amount to only 1% of the total cost. In 2021, the relevant costs increase to € 602. The share of material and labour decrease, whereas the shares of energy and GHG emissions increase. In 2022, the costs amount to € 1,055. The costs for material have a share of 24%, the share of labour has decreased to a share of 9%. Due to the high energy costs, the share of energy amounts to 61%. The costs for GHG emissions have a share of 6% of the analysed costs.

In 2015, the costs for energy, GHG emissions, labour and material for plastic bags amount to € 26. The relative distribution of the costs is similar to the plastic bowl. With increase in energy prices, the importance of material costs decreases. Nevertheless, the material costs remain the main cost driver of plastic bags.

4 Conclusion and outlook

The aim of this study was to establish a solid information and data basis for enabling insights on the potential scope of demand-side options to reduce CO₂ emissions. A variety of different factors needed to be considered to analyse the most important products in the industrial EU ETS sectors, such as material flows, associated energy demand, resulting GHG emissions and economic indicators.

For iron and steel, the developed model of the material flows, final energy demand and CO₂ emissions enables the identification of relevant processes and products. In combination with additional sources on the economic indicators, in particular costs, this results in an appropriate data basis for the estimation of CO₂ cost shares (of total production cost). However, a challenge arises from different product definitions in the statistics. Furthermore, the availability of data is partly limited to global or average sources. The data situation can be improved through more detailed statistical recordings of individual products and processes as well as their end-uses. Additionally, the static model can be dynamised based on the available data to determine recycling indicators, the future scrap availability and potentials of the secondary production route.

It was possible to develop a consistent model for the cement value chain that enables in combination with cost data from literature the estimation of CO₂ cost shares (of total production costs). Meanwhile, a challenge arose from the allocation of delivery and cement types. Also, data on energy demand, GHG emissions and prices are not available from statistics but had to be calculated. Statistical data on energy demand and emissions as well as market data are necessary to improve the data situation. The cement model can be improved by explicitly including the end uses, such as buildings.

For aluminium, the model and data situation is similar to steel. Accordingly, an aluminium model was developed, which underlined the vital role of the secondary production route for the future efficiency of the aluminium industry. While sufficient data is available on production processes, varying product definitions and average values were challenging. For this reason, expert interviews were conducted to fill data gaps related to the end-uses. The data situation can be improved through more detailed statistical recordings of individual products and processes as well as their end-uses. Model improvements should focus on recommendations for improving recycling practices and analysing alloying elements.

For refineries, it was not possible to develop a naphtha model similar to the other materials. In contrast, different refinery types were analysed and compared with statistical data. The results show considerable differences with regard to GHG emissions and energy demand that can be assigned to the respective naphtha production and in particular, to differences in hydrogen demand. In particular, the analysis was challenging due to the high complexity of the plants and the products. Consequently, hardly any statistical data could be used, and experts had to be consulted. Naphtha can be further processed to the downstream products PE and PP.

For the basic chemicals, it was possible to develop two material flow and CO₂ emission models for PE and PP. In combination with data on cost, these allow the estimation of CO₂ cost shares (of total production). The data availability for PE and PP was better compared to the other basic chemicals. A dynamisation of these models would enable analyses of the end-of-life of plastic products and decarbonisation options for the feed. This is relevant as the feedstock, so far naphtha, for the production of these materials consists of fossil carbon, which is released at the end of life.

In summary, it became clear that the statistical collection of data can be improved for some of the materials. This is especially true for end-use and market data. For steel, aluminium and basic

chemicals the development of dynamic material flow models is crucial to analyse the end-of-life and recycling options. In addition, basic chemicals play a special role, as decarbonisation of the raw material, so far naphtha, is necessary in the future. The research interests for cement are different. Here, the trade-off between cement quality, e.g. specific strength, and embedded emissions is in the foreground. Based on such analyses, it would be possible to derive policy recommendations for relevant industrial processes and products, e.g. regarding the exposure to CO₂ costs.

Following the calculation of CO₂ cost shares of the basic materials, an analysis of CO₂ cost shares along the value chain was carried out within this study. In two case studies the energy flows and resulting emissions in the production of passenger cars and plastic products are calculated in order to determine the cost shares along the value chain. However, due to the different procedure for determining the mass balance, the results of passenger cars and plastic products are not comparable. In brief, a detailed bottom-up analysis of the production and material balance was developed for passenger cars. On the one hand, this can be the baseline for further analyses of changing production processes and material compositions. On the other, this enables the analysis of the price pass-through of CO₂ costs.

In summary, the developed data basis and analyses enable the development of further (dynamic) material flow models for relevant industrial processes and products. Besides the exposure to CO₂ prices analysed within this study, further decarbonization options including recycling strategies can be assessed. Henceforth, this is the baseline for ambitious GHG mitigation pathways by integrating material production and their connection to the energy system and emissions. This gains momentum in the European political debate driven by concerns over sustainability and supply risks for future technologies. It becomes clear that synergies exist between the decarbonization, the circular economy and industrial agendas.

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A Data sources on the trade relevance, an example for the iron and steel industry

For the assessment of physical and monetary indicators for the trade relevance of the iron and steel industry several data sources are available. In addition to the commodity statistics of the UN and the EU, the publications of industry associations on the international and the EU level are particularly relevant. Consequently, the data availability, the usability of the data sources as well as differences and similarities between the data sets are summarised in the following sections. The aim of this comparison is the selection of appropriate data sources for the assessment in section 2.3.4.1.

A.1 Summary of the considered data sources

For the assessment of the trade relevance of the iron and steel industry on EU and national level the commodity statistics of the UN, *Comtrade*, the EU, *Prodcom*, as well as the publications of the international industry association, World Steel Association (WSA), and on the EU level, Eurofer, are evaluated. An overview of the metadata, the data availability and the data source usability is given in the following sections as a baseline for the subsequent comparison.

A.1.1 Metadata

The metadata of the considered data sources are summarised in Table 100 on the basis of the following characteristics: Type, Publisher, Products, Classification, Indicators, Region, Period. Only the variable relevant to the comparison are taken into account.

Table 100: Metadata of the considered data sources for the iron and steel industry

	Comtrade	Prodcom	Steel Statistical Yearbook 2020	Steel in Figures 2020
Type	Commodity statistic	Commodity statistic	Annual report	Annual report
Publisher	UN	Eurostat/ EU	WSA	Eurofer
Products	Total iron and steel industry, wire rod	Total iron and steel industry, wire rod	Semi-finished and finished products	Finished products
Classification	SITC	NACE	WSA	Eurofer
Indicators	Export quantity, import quantity, export value, import value	Export quantity, import quantity, export value, import value	Export quantity, import quantity	Export quantity, import quantity
Region*	EU, Germany	EU, Germany	Germany	EU
Period	2000-2019	2008-2019	2009-2018	2010-2019
Source	UN (n.d.)	Eurostat (2020b)	WSA (2020)	Eurofer (2020a)

*the considered regions are described further in section A.2

Both of the considered commodity statistics are distinguishing product groups according to the international classification systems (SITC and NACE). A direct correspondence table for these

systems is not available but can be derived from another classification system; ISIC. An overview of this process is given in Table 101.

Table 101: Correspondence of the classification systems for the iron and steel industry

SITC, Rev. 3/4 ⁸⁸	ISIC, Rev. 3.1 ⁸⁹	ISIC, Rev. 4 ⁹⁰	NACE, Rev. 2 ⁹¹
67	271	241	24.1
			24.2
			24.3
		2431	24.51
			24.52

Source: UNSD n.d.

A.1.2 Data availability

Comtrade provides physical and monetary trade data on the EU level from the year 2000 and on the national level from the year 1991 until 2019 (SITC, Rev. 3) (UN, n.d.).

Prodcom provides physical and monetary trade data on the EU level and the national level from the year 2008 until 2019 (NACE, Rev. 2) (Eurostat 2020b).

The *Steel Statistical Yearbook 2020* provides physical data on the national level from the year 2009 until 2018. Earlier data are available publications dating back to 1978 (WSA, 2020).

Steel in Figures 2020 provides physical data on the EU level from the year 2010 until 2019. Earlier data are available in other publications as well as in the interactive tool for statistics (Eurofer 2020a; Eurofer 2020b).

The *Steel Statistical Yearbook 2020* and *Steel in Figures 2020* also provide data on the EU respectively the national level. These data will not be considered in the comparison. The reason is described further in section A.2 (Eurofer 2020a; WSA 2020).

A.1.3 Database usability

Comtrade enables the export of data as CSV-file for five years at the same time. Both total values and product group specific values can be called up easily (UN n.d.).

Prodcom enables the export of data as a CSV-file for all available years at the same time. The exported data table can be customised. The export of product group specific data is easy to implement. However, the access to total values is limited because every product group is selected individually and thus the maximum number of variables for the export is exceeded. Consequently,

⁸⁸ <https://unstats.un.org/unsd/trade/sitcrev4.htm>

⁸⁹ <https://unstats.un.org/unsd/statcom/doc02/isic.pdf>

⁹⁰ https://unstats.un.org/unsd/classifications/Econ/tables/ISIC/ISIC31_ISIC4/ISIC31_ISIC4.txt

⁹¹ https://unstats.un.org/unsd/classifications/Econ/tables/ISIC/ISIC4_NACE2/ISIC4_NACE2.txt

total values for the industry have to be accessed via other sources (e.g. Eurostat Data Browser) (Eurostat 2020b).

The *Steel Statistical Yearbook 2020* has a PDF-format and has to be converted manually for the comparison with the other data sources. Furthermore, the concise version of the publications for the years 2019 and 2020 do not include all product groups as in older versions (WSA 2020).

Although *Steel in Figures 2020* has a PDF-format the interactive tool for statistics on the webpage of Eurofer enables the data export as a CSV-file for each product group individually (Eurofer 2020a).

As sector specific reports The *Steel Statistical Yearbook 2020* and *Steel in Figures 2020* do not include total values for the industry (Eurofer 2020a; WSA 2020).

A.2 Comparison of the data for the iron and steel industry

For the comparison of the trade data of the iron and steel industry the data sources described in the preceding sections are used. Initially, the monetary values provided by *Comtrade* and *Prodcom* for the years 2008 until 2019 are assessed for the whole iron and steel industry and for a product group; wire rod. The values provided by *Prodcom* in € is converted to \$ using the average exchange rate published by Eurostat. Subsequently, the physical values for the whole iron and steel industry in the years 2010 until 2019 respectively 2009 until 2018 for the commodity statistics and the industry association reports are reflected upon. Additionally, the evaluation of the product group wire rod can be assessed from the Eurofer publication.

For the purpose of the comparison, the delimitation of the data coverage is necessary since it is not identical for all data sources - especially concerning the consideration of the intra-EU-trade. Consequently, the commodity statistics can be compared with the Eurofer publication on the EU level and with the WSA publication on the national level. Furthermore, the varying product coverage of the sources must be taken into account. In *Comtrade* and *Prodcom* all products of the iron and steel industry are mapped, in the *Steel Statistical Yearbook 2020* exclusively semi-finished and finished products and in *Steel in Figures 2020* exclusively finished products (see Table 102).

Table 102: Considered trade flows for the iron and steel industry

	Comtrade	Prodcom	Steel Statistical Yearbook 2020	Steel in Figures 2020
EU level	Extra-EU-trade	Extra-EU-trade	Intra- and Extra-EU-trade	Extra-EU-trade
Germany	Intra- and Extra-EU-trade	Intra- and Extra-EU-trade	Intra- and Extra-EU-trade	Extra-EU-trade

A.2.1 Data for the iron and steel industry on EU level

As shown in Figure 104 and Figure 105, the monetary import and export values of iron and steel products provided by *Comtrade* and *Prodcom* are almost identical. Minor deviations (< 1.5%) can be explained by the conversion using the average exchange rate.

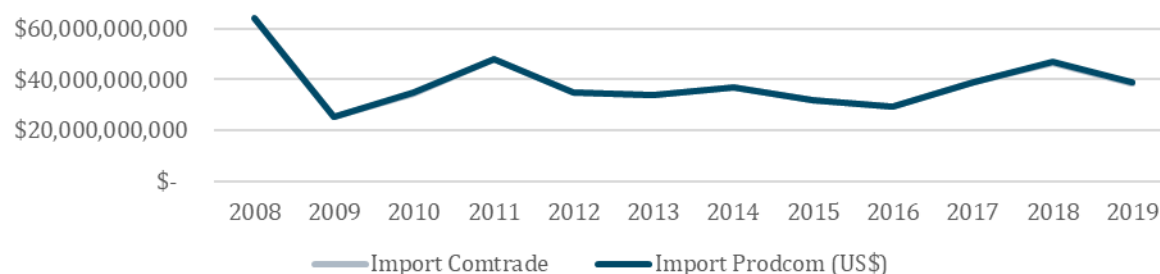
In contrast, the monetary import and export values of wire rod are deviating up to 4% until 2016 and from 2017, the databases do not match at all (see Figure 106 and Figure 107). The initial deviation can be explained by varying product group definitions but for the general deviation from 2017, no explanation can be derived from the databases.

Figure 104: Export of iron and steel products, EU27+UK 2008 to 2019



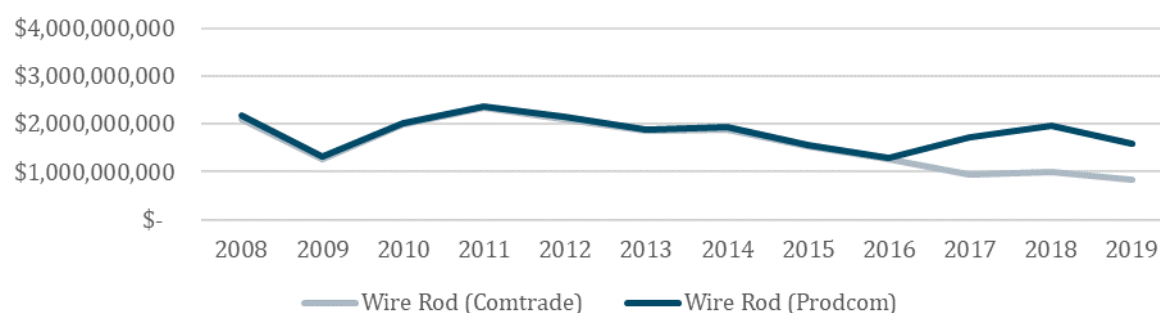
Source: UN (n.d.); Eurostat (2020b)

Figure 105: Import of iron and steel products, EU27+UK 2008 to 2019



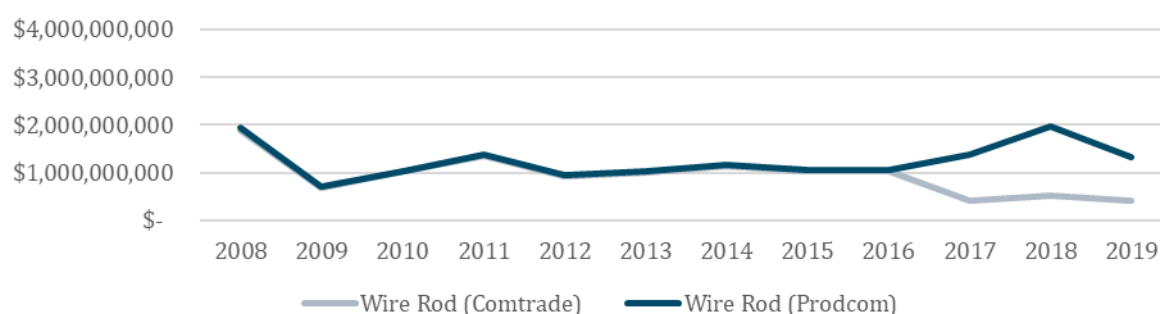
Source: UN (n.d.); Eurostat (2020b)

Figure 106: Export of wire rod, EU27+UK 2008 to 2019



Source: UN (n.d.); Eurostat (2020b)

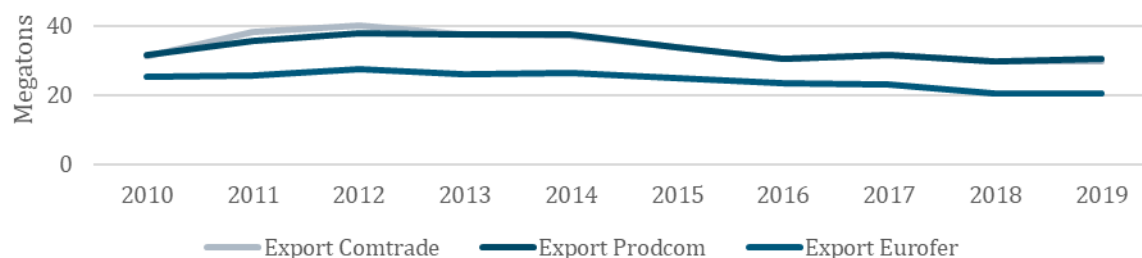
Figure 107: Import of wire rod, EU27+UK 2008 to 2019



Source: UN (n.d.); Eurostat (2020b)

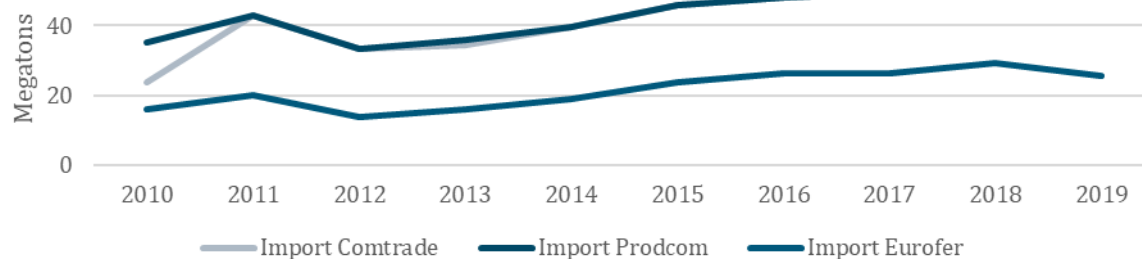
On an EU level, the data can be additionally compared with the physical values for all iron and steel products and for wire rod provided by Eurofer as shown in Figure 108 to Figure 111. The values provided by Eurofer are below the commodity statistics because only finished products are included. Overall, it is apparent that the databases match for iron and steel products. For wire rod, again a strong deviation from 2017 until 2019 can be assessed. However, the trends displayed by *Prodcom* and *Steel in Figures 2020* match. For this reason, it is assumed that the *Comtrade* data set is incorrect after 2016.

Figure 108: Export of iron and steel products, EU27+UK 2010 to 2019



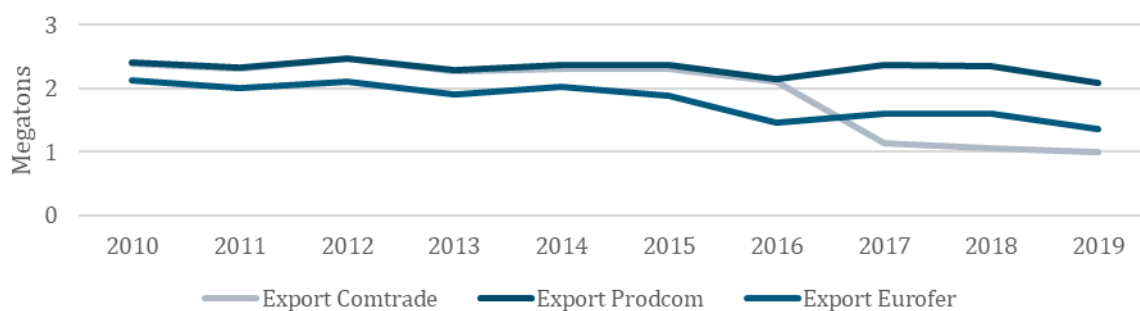
Source: UN (n.d.); Eurostat (2020b); Eurofer (2020b)

Figure 109: Import of iron and steel products, EU27+UK 2010 to 2019



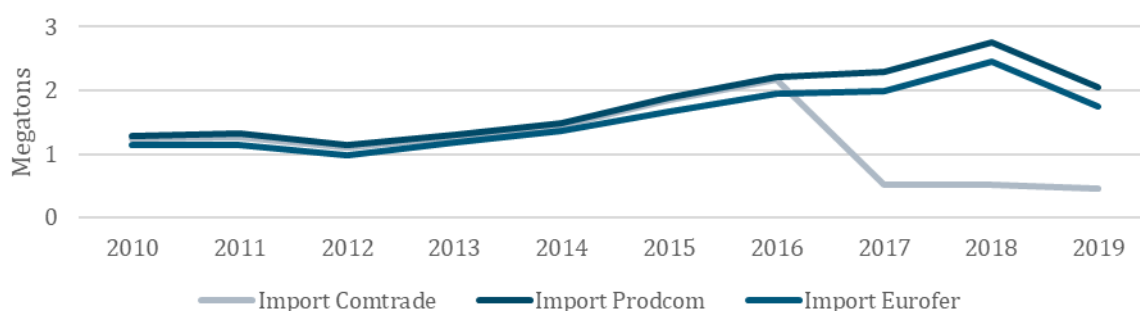
Source: UN (n.d.); Eurostat (2020b); Eurofer (2020b)

Figure 110: Export of wire rod, EU27+UK 2010 to 2019



Source: UN (n.d.); Eurostat (2020b); Eurofer (2020b)

Figure 111: Import of wire rod, EU27+UK 2010 to 2019



Source: UN (n.d.); Eurostat (2020b); Eurofer (2020b)

A.2.2 Data for the iron and steel industry on a national level

As shown in Figure 112 and Figure 113 the monetary import and export values of iron and steel products provided by *Comtrade* and *Prodcom* are similar to the EU level assessment almost identical. Minor deviations (< 1%) can also be explained by the conversion using the average exchange rate.

Again, the monetary import and export values of wire rod are deviating up to 6.6% until 2016 and from 2017, the databases do not match at all (Figure 114 and Figure 115). The initial deviation can be explained by varying product group definitions but for the general deviation from 2017, no explanation can be derived from the databases.

Figure 112: Export of iron and steel products, Germany 2008 to 2019



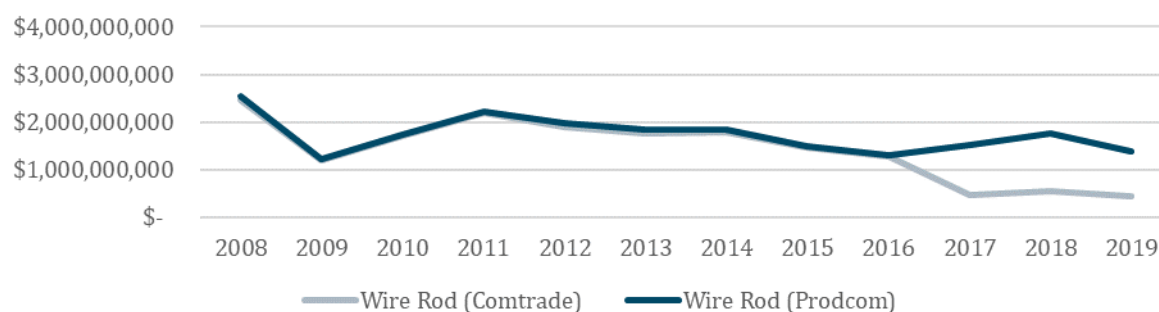
Source: UN (n.d.); Eurostat (2020b)

Figure 113: Import of iron and steel products, Germany 2008 to 2019



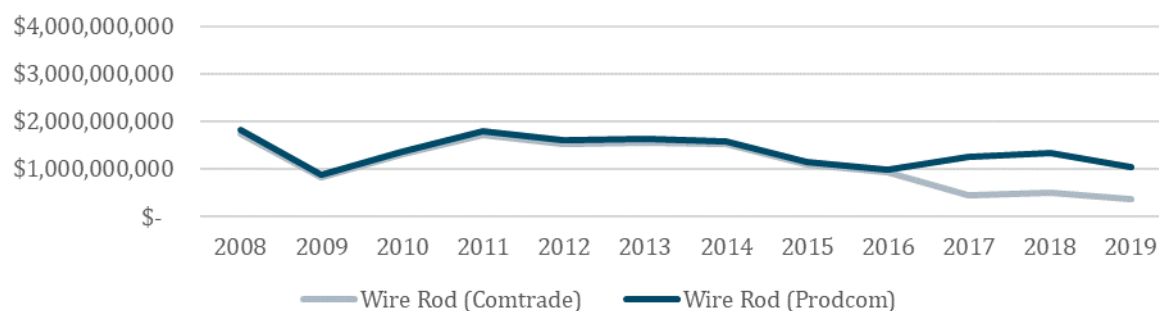
Source: UN (n.d.); Eurostat (2020b)

Figure 114: Export of wire rod, Germany 2008 to 2019



Source: UN (n.d.); Eurostat (2020b)

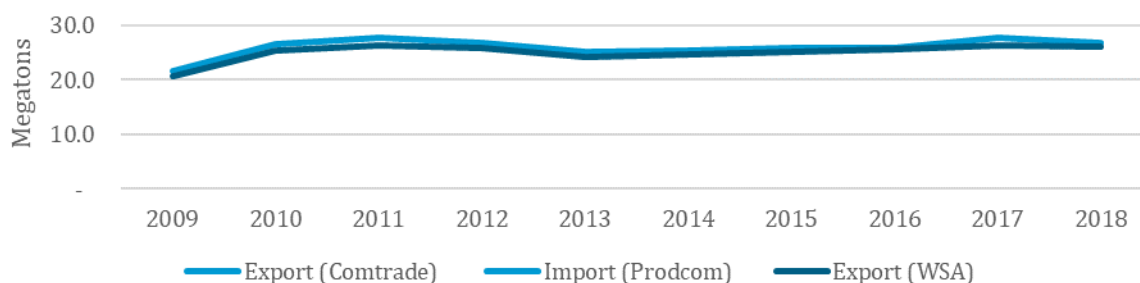
Figure 115: Import of wire rod, Germany 2008 to 2019



Source: UN (n.d.); Eurostat (2020b)

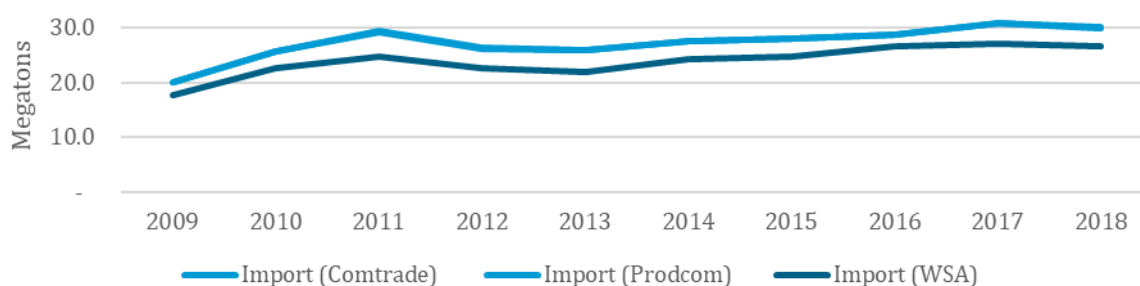
On a national level, the data can be additionally compared with the physical values for all iron and steel products provided by the WSA as shown in Figure 116 and Figure 117. It is apparent that the data sources match approximately even though the deviation is greater for the assessed import values. This is caused by the varying trade relevance of individual products.

Figure 116: Export of iron and steel products, Germany 2008 to 2019



Source: UN (n.d.); Eurostat (2020b)

Figure 117: Import of iron and steel products, Germany 2008 to 2019



Source: UN (n.d.); Eurostat (2020b)

A.2.3 Conclusion

Based on the described characteristics for the assessment of the trade relevance of steel and iron products the data sources *Prodcom* and the publications of Eurofer are selected. *Prodcom* is used for the product specific assessment due to the product data availability and the inclusion of monetary flows. Eurofer is used for the industry assessment due to the higher product aggregation and the exclusion of intra-EU-trade.

Even though *Comtrade* provides in general the same data sets as *Prodcom*, the captured inaccuracy on product level lead to the exclusion of the database. The data from the WSA, which are used for the material flow modelling, is not used for the assessment of the economic indicators because of the described consideration of intra-EU-trade on the EU level. Furthermore, the product specific assessment is not possible for trade flows.

B Data sources on market prices of the cement industry

Table 103: Overview of considered price lists for the price assessment of cement, precast concrete and transport concrete

	Supplier	Year	Product
Cement	Cemex	2020	CEMI, CEMII, CEMIII
	Dyckerhoff	2020	CEMI, CEMII
Precast concrete	Innbau	2020	Double wall, solid wall, element ceiling
	Innbau	2021	Double wall, solid wall, element ceiling
Transport concrete	Cemex München	2020	XC1/XC2 C20/25 F3 32 Mittel
	Cemex München	2021	XC1/XC2 C20/25 F3 32 Mittel
	Cemex Nord	2020	XC1/XC2 C20/25 F3 32 Mittel
	Cemex Nord	2021	XC1/XC2 C20/25 F3 32 Mittel
	Cemex Nordbayern	2021	XC1/XC2 C20/25 F3 32 Mittel
	Cemex Ostbayern	2020	XC1/XC2 C20/25 F3 32 Mittel
	Cemex Ostbayern	2021	XC1/XC2 C20/25 F3 32 Mittel
	Dyckerhoff Elbe-Spree	2021	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Hamburg	2020	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Mobile Anlagen	2019	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Odenwald	2021	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Rheinland-Pfalz	2020	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Rhein-Main-Taunus	2021	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Rhein-Ruhr	2020	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Saar-Mosel	2021	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Schmalkalden	2021	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Thüringen	2021	XC3 C20/25 F3 32 Mittel
	Dyckerhoff Weser Ems	2021	XC2 C20/25 F3 32 Mittel
	HeidelbergCement Bayerwald	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Deggendorf	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Donau-Iller	2020	XC3 C20/25 F3 32 Mittel
	HeidelbergCement Donau-Naab	2021	XC1/XC2 C20/25 F3 32 Mittel

	Supplier	Year	Product
	HeidelbergCement Grenzland	2021	XC3 C20/25 F3 32 Mittel
	HeidelbergCement Inntal	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Kurpfalz	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Lohr-Beton	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Main-Tauber	2019	XC1/XC2 C20/25 F3 22 Mittel
	HeidelbergCement Mittelfranken	2021	XC1/XC2 C20/25 F3 22 Mittel
	HeidelbergCement München	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Naabbeton	2021	XC1/XC2 C20/25 F3 22 Mittel
	HeidelbergCement Niederbayern	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Nord-Ost	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Nord-West	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Oberschwaben	2021	XC3 C20/25 F3 32 Mittel
	HeidelbergCement Oder-Spree	2018	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Paderborner TB	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Pinzl	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Stuttgart	2021	XC3 C20/25 F3 22 Mittel
	HeidelbergCement Süd-West	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Unterfranken	2021	XC1/XC2 C20/25 F3 32 Mittel
	HeidelbergCement Werner	2021	XC1/XC2 C20/25 F3 32 Mittel
	Holcim Fulda-Würzburg	2021	XC1/XC2 C20/25 F3 22 Mittel
	Holcim Rhein-Main/Lahn-Sieg	2021	XC1/XC2 C20/25 F3 22 Mittel
	Holcim Saar-Mosel	2021	XC1/XC2 C20/25 F3 22 Mittel
	Holcim Stuttgart	2021	XC3 C20/25 F3 22 Mittel
	Holcim Südbaden	2021	XC3 C20/25 F3 32 Mittel
	Holcim West	2021	XC1/XC2 C20/25 F3 32 Mittel
	Opterra	2021	XC3 C20/25 F3 32 Mittel
	Schwenk Abel	2020	XC1/XC2 C20/25 F3 16 Mittel
	Schwenk Abel	2021	XC1/XC2 C20/25 F3 16 Mittel
	Schwenk Alb-Donau	2020	XC1/XC2 C20/25 F3 32 Mittel

	Supplier	Year	Product
	Schwenk Alb-Donau	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Anhalt	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Anhalt	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk ASB	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk ASB	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Bamberg	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk BeHaGe	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Berlin-Brandenburg	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Berlin-Brandenburg	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Chemnitz	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Chemnitz	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Dresden	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Dresden	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Elbe-Harz	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Elbe-Harz	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Gelnhausen	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Heidenheim	2020	XC1/XC2 C20/25 F3 22 Mittel
	Schwenk Heidenheim	2021	XC1/XC2 C20/25 F3 22 Mittel
	Schwenk Kinzigbeton	2020	XC1/XC2 C20/25 F3 22 Mittel
	Schwenk Leuchtkirch	2020	XC3 C20/25 F3 22 Mittel
	Schwenk Leuchtkirch	2021	XC3 C20/25 F3 22 Mittel
	Schwenk Mainfranken	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Nordost	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Nordost	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Oberlausitz	2020	XC3 C20/25 F3 22 Mittel
	Schwenk Oberlausitz	2021	XC3 C20/25 F3 22 Mittel
	Schwenk Ostalb	2019	XC3 C20/25 F3 22 Mittel
	Schwenk Ostalb	2020	XC3 C20/25 F3 22 Mittel
	Schwenk Saale-Beton	2020	XC1/XC2 C20/25 F3 32 Mittel

	Supplier	Year	Product
	Schwenk Schwaben/Allgäu	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Schwaben/Allgäu	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Stuttgart	2020	XC3 C20/25 F3 22 Mittel
	Schwenk Stuttgart	2021	XC3 C20/25 F3 22 Mittel
	Schwenk Südbayern	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Südbayern	2021	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Untermain	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Vogelsberg	2020	XC1/XC2 C20/25 F3 32 Mittel
	Schwenk Vogtland	2020	XC1/XC2 C20/25 F3 32 Mittel

C Data sources on the mass and energy balance for case study

C.1 Mass balance of Polo V

Table 104: Mass balance of Polo V

Components groups	kg	Per cent	Components	Per cent	Kg
Body	478.96	34%	Structure	53%	252.03
			Fender	2%	9.90
			Front doors	10%	49.62
			Back doors	8%	49.62
			Bonnet	3%	12.94
			Hatchback	3%	14.12
			Wipers	1%	4.81
			Bumper	3%	14.42
			Mirrors	1%	2.45
			Windshield	3%	14.22
			Side-window	1%	5.79
			Rear side-window	1%	4.31
			Back window	1%	5.98
			Insulation / acoustics	3%	12.45
			Crash system	7%	31.28
			Others	1%	5.39
Drive train	308.96	22%	Engine	49%	150.08
			Engine Oil	0%	0.00
			Clutch	7%	22.85
			Gear	18%	54.75
			Gear oil	0%	0.00
			Axis	5%	16.41
			Fuel tank	3%	9.45
			Fuel system	2%	5.78
			Exhaust system	10%	29.54
			Cooling system	4%	11.55
			Ventilation	3%	8.53

Components groups	kg	Per cent	Components	Per cent	Kg
Chassis	278.89	20%	Front axle	18%	49.61
			Shock absorber	5%	13.18
			Rear axis	13%	37.10
			Wheels	30%	82.50
			Brake system	20%	56.13
			Steering system	9%	23.78
			Electronic stabilisation system	1%	3.40
Electrics	44.96	3%	Low voltage buffer batterie	31%	14.12
			low voltage cabling	27%	11.94
			Exterior lighting	17%	7.58
			Interior lighting	1%	0.35
			Low voltage - others	6%	2.53
			Heating	19%	8.45
Interieur	227.89	16%	Front seats	29%	65.38
			Backseats	17%	38.78
			Interior panelling	17%	38.95
			MQT	5%	12.01
			Dashboard	5%	11.67
			Centre console	2%	4.63
			Compartments	3%	7.55
			Infotainment	3%	6.18
			Instrumentation	2%	4.29
			Airbags front	3%	6.52
			Airbags back	3%	6.18
			Belts	5%	12.36
			Other safety systems	1%	1.72
			Pedal set	2%	4.29
			Sonstiges	3%	7.38
Fluids	64.63	4.60%			

C.2 Materials used in the generic medium car

Table 105: Material balance of generic medium car

Material	Weight [kg]
Steel	586,5
Iron	62,5
Aluminium	275,7
Plastics	217,8
Flat Glas	33,0
Rubber	23,3
Copper	16,1
Lead	13,0
Zinc	13,0
Fluids	48,49
Filling material	11,86
Water	3,46
Sulfuric acid	2,16
Antimon	0,2
LED	1,10
Epoxy resin	1,03
Fibre glass	1,12
Brass	0,79

C.3 Energy balance of combustion engine vehicle

Table 106: Energy demand by productive phase and energy source for combustion engine vehicle

Material/ Product	Weight [kg]		Energy demand by process [MJ]	Energy demand by source [MJ]						Energy demand by process [MJ]	Energy demand by source [MJ]				
				Electricity	Coal	Coke	Natural gas	Oil	Other gases		Electricity	Coal	Coke	Natural gas	Oil
PA/Nylon	18.15	1,190	23	13			10			1,167	1,124			44	
PP	77.83	1,767	1,533	156			93	1,284		233	233				
PE	25.14	654	478	68				410		176	176				
PU	43.18	2,754	2,754	907			1,209	639							
PC	3.11	149	140	22			118			9	9				
PVC	13.11	538	511	39			472			26	26				
ABS	37.25	2,049	1,937	149	74		1,713			112	112				
Rubber	23.26	1,106	929	9			460	460		177	55			122	
Copper wire	16.13	418	370	122	61		161	26		48	32	0			16
Steel	586.46														
Hot rolled coils (preassembly)	316.92	6,634	6,634	444	1,317	3,036	755	36	1,047						

Material/ Product	Weight [kg]		Energy demand by process [MJ]	Energy demand by source [MJ]						Energy demand by process [MJ]	Energy demand by source [MJ]				
		Total energy demand [MJ]	Material/Pre-product	Electricity	Coal	Coke	Natural gas	Oil	Other gases	Part production	Electricity	Coal	Coke	Natural gas	Oil
Hot rolled coils	94.85	2,531	1,985	133	394	909	226	11	313	546	115	431			
Hot rolled bars machining	149.73	684	590	407	78	78	26			94	94	0			
Hot rolled bars forging	24.96	1,140	98	68	13	13	4			1,042	34	1,008			
Aluminium	275.74														
Stamping (pre-assembly)	63.80	132	132	71			58	2							
Casting	163.03	1,904	1,904	763			1,096	46							
Extrusions	48.91	215	101	16			191	8							
Flat glass	33.70	740	157	0	142		0	15		583	96	0		488	0
Zinc	12.99	222	222	205			17								
Lead (recycled)	12.98	104	65				65			39	13			26	
Iron	62.51														
Forging	12.50	464	18	1				16		446	16			430	
Casting	50.01	1,321	71	5				66		1,250		1,250			

C.4 Energy balance of battery electric vehicle

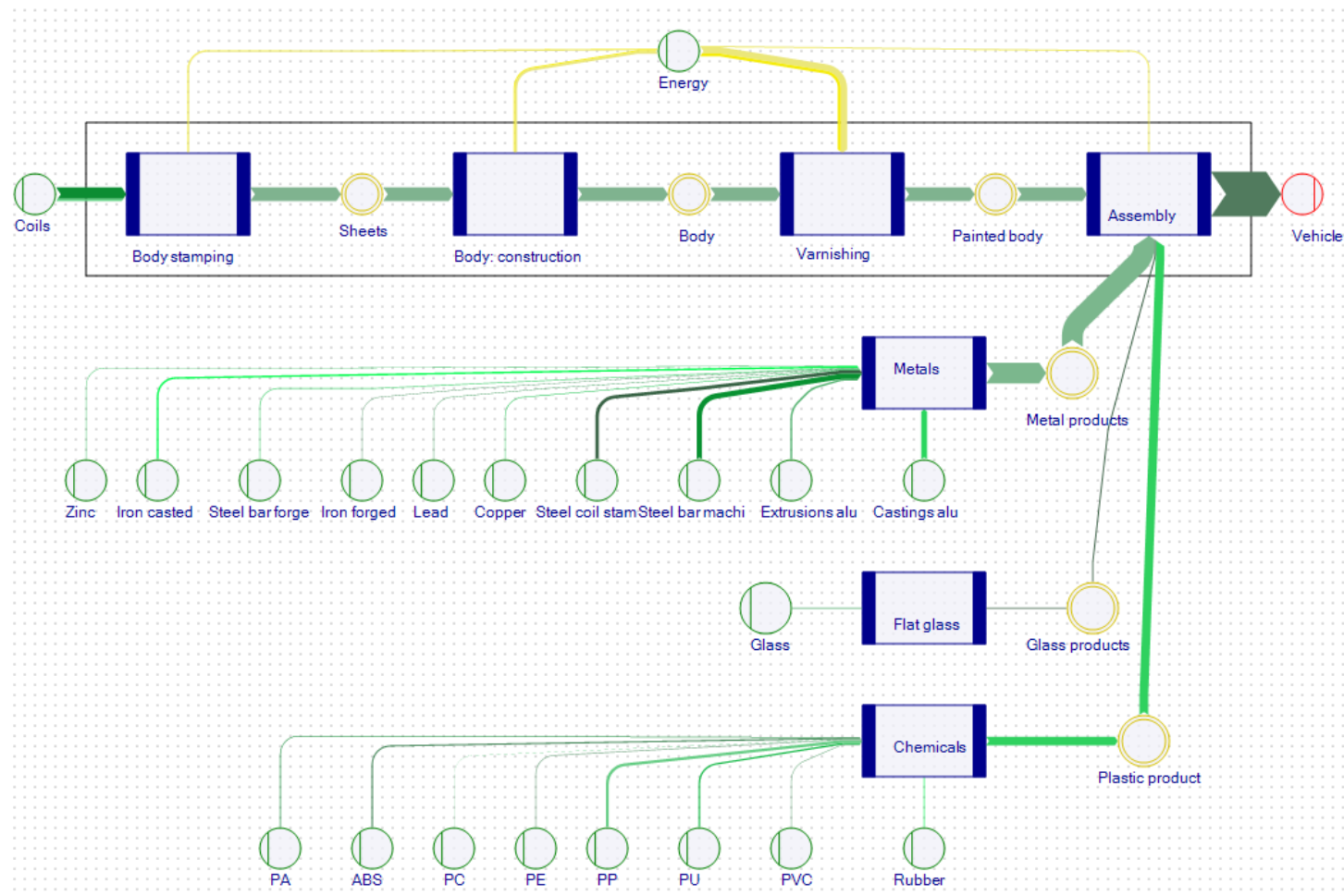
Table 107: Energy demand by productive phase and energy source for battery electric vehicle

Material/ Product	BEV Weight [kg]		Energy demand by process [MJ]	Energy demand by source [MJ]						Energy demand by process [MJ]	Energy demand by source [MJ]			
				Electricity	Coal	Coke	Natural gas	Oil	Other gases		Electricity	Coal	Natural gas	Oil
		Total energy demand [MJ]	Raw material							Part production				
PA/Nylon	18.15	1,190	23	13			10			1,167	1,124		44	
PP	75.67	1,718	1,491	151			91	1,249		227	227			
PE	20.25	527	385	55				330		142	142			
PU	43.18	2,754	2,754	907			1,209	639						
PC	3.11	149	140	22			118			9	9			
PVC	13.11	538	511	39			472			26	26			
ABS	37.25	2,049	1,937	149	74		1,713			112	112			
Rubber	23.26	1,106	929	9			460	460		177	55		122	
Copper wire	16.13	418	370	122	61		161	26		48	32	0		16
Steel	528.31	0												
Hot rolled coils (preassembly)	316.92	6,634	6,634	444	1,317	3,036	755	36	1,047					
Hot rolled coils	54.03	1,442	1,131	76	224	518	129	6	178	311	65	246		

Material/ Product	BEV Weight [kg]		Energy de- mand by process [MJ]	Energy demand by source [MJ]						Energy de- mand by pro- cess [MJ]	Energy demand by source [MJ]			
				Total energy demand [MJ]	Raw mate- rial	Electricity	Coal	Coke	Natural gas		Oil	Other gases	Part produc- tion	Electricity
Hot rolled bars machi- ning	134.89	615	530	366	70	70	24			85	85	0		
Hot rolled bars forging	22.48	1,027	88	61	12	12	4			939	31	908		
Aluminium	302.64	0	0											
Stamping (preassembly)	63.80	132	132	71			58	2						
Casting	183.73	2,146	2,146	860			1,235	51						
Extrusions	55.12	242	242	18			215	9						
Flat glass	32.40	705	144	0	137		0	7		561	92	0	469	0
Zinc	15.81	270	270	250			21							
Copper	45.57	1,458	1,458		456		866	137						
Graphite	34.41	2,890	2,890		1,445		344	1,101						
LiMnO	35.45	1,312	1,312		213		886	213						
Ethylene carbonate	28.29	255	255				170	85						

C.5 Material flow model of combustion engine vehicle

Figure 118: Material flow model of combustion engine vehicle



Source: own depiction