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Notes

Abstract

Steel is of extraordinary importance for the European economy as well as society, but is responsible for enormous energy consumption and greenhouse gas emissions. Therefore, steel flows are an obvious subject for the European climate protection. The quantification of steel stocks and flows is useful to be included in discussions regarding Circular Economy, energy system transformation and resource efficiency. Therefore, we developed a retrospective and dynamic material flow model covering the entire European steel and iron cycle from 2002 to 2019. Based on data by Worldsteel and assumptions mainly adopted by Cullen et al. (2012), the value and production chain of steel and iron products is covered by the model. It appears that the European steel and iron use reached a saturation from 2007 on, where the stock of steel in anthropogenic use phase reached around 5,600 Mt. In 2019, around 140 Mt of steel left the use phase, of which circa 6 Mt dissipated or are abandoned in place. Out of the remaining scrap, 110 Mt were collected as secondary raw materials for recycling. Recycling of steel in Europe reached a peak of approx. 140 Mt in 2007, from where on recycling declined equally to overall steel production leading to an almost constant recycling input rate of 57 %. The decline of steel recycling did not significantly affect the collection of steel scrap, but led to an increase of iron and steel scrap export. In 2019, 110 Mt of steel and iron were recycled in Europe, 65 % via EAF, 25 % via BOF and the remaining via ironmaking. Post-consumer waste is by mass more important than new scraps from production and manufacturing as evident in an old scrap ratio of 73 %. Further research could examine the effect of steel scrap prices on their use, further trace these export flows or analyse the potentials of secondary steel production for industry decarbonisation.

1 Introduction

Steel is a material of extraordinary importance for the European economy and society. Whether in infrastructure, buildings, machinery or vehicles, the range of products in which steel is used is broader than for any other metallic material (EUROFER 2021). Because of its scale, steel production causes enormous energy consumption and greenhouse gas emissions. The environmental burden for steel production depends on different factors, such as the location of the ore deposits, quality of the raw materials (both ores and scrap), technology used in mining and metallurgy. However, generally speaking, recycling of steel requires less energy than its production from primary sources (mining) (IEA 2020). Therefore, the share of secondary steel production in total steel supply has a major impact on the total energy required to produce the necessary crude steel. Additionally, more circularity in the anthropogenic steel cycle helps limit mineral depletion and the environmental issues associated with mining (Broadbent 2016).

Since the steel cycle is not only large in tonnages but also complex in its behaviour, a systemic and quantitative understanding of the European steel cycle is essential for well-founded discussions on energy demand and emissions for steel production and material efficiency in the EU. To achieve this, we developed a quantification by material flow analysis (MFA) as described by Brunner et al. (2017). This work is based on preliminary work published by Herbst (2017), Le Den et al. (2020) and enhanced in the projects *UBA ETS Produkte (FKZ 3718 42 004 0)* and *newTRENDs (GA No. 89331)*. Moreover, it led to the master thesis by Wittig (2021), focusing on recycling processes, and to the conference contribution by Lotz et al. (2021).

To the best of our knowledge there are five MFA models of the European steel cycle published (Dworak et al. 2021; Fellner et al. 2018; Flint et al. 2020; Panasiyk et al. 2016; Passarini et al. 2018). The MFA described herein adds to these previous models in particular the closed mass balance in combination with a dynamic modelling approach. In particular, recycling rates are a result of the model, not an assumption as described by Glöser et al. (2013). The combination of modelling the scrap availability with the actual recycling quantities allows evaluation of the effectiveness and potentials for improvement in the management of steel scrap.

This new model of the European steel cycle can contribute to current and future discussions on decarbonisation and the Circular Economy, both in its current form and with future developments. One example is the discussion on substituting the energy- and emission-intensive blast furnace route with alternative production routes such as direct reduction or secondary production. The retrospective model provides estimates of current stocks-in-use, scrap availability and recycling rates. It can also be modified to project future developments of steel stocks and flows, thus providing quantitative basis for discussions regarding steel demand, scrap availability, down-cycling or energy demand for steel production. A second example is the extension of the single material model by further materials like alloying or coating elements, bringing a multi-material perspective into the circularity discussion.

2 Data and methods

We applied dynamic MFA with closed mass balance according to Brunner et al. (2017) to quantify steel stocks and flows in the European steel cycle. The spatial boundaries cover the current countries of the EU27 plus Great Britain.

2.1 Data input

Various data sources were utilised to implement the model. The main source are the data of the World Steel Association (WSA), published in annual yearbooks (World Steel Association 2022). According to Cullen et al. (2012), this is the source with the greatest data availability for steel. Table 1 shows the sources for the production data, while the trade data sources are presented in Table 2. The available years are also presented in the tables below. If there are several years separated by slashes, the year coverage differs for the subcategories. A detailed representation is shown in the Annex.

Historical data from the British Geological Survey (BGS) were added to include historical development (British Geological Survey 2022), as some products made from steel have a significantly longer life (cf. Table 11 in Annex). However, not all historical data can be supplemented by this. Where historical data is not available, the production of goods and trade of semi-finished and finished steel product were extrapolated into the past by linking the flows with the development of crude steel production (up to 1920) and iron ore production (1919 to 1913). The trade of steel contained in end use products (so called indirect trade) before 2002 and trade of direct reduced iron before 2004 was neglected due to data availability. Consequently, the results are given from 2002 on, as the indirect trade has a significant influence on the stock inflow, while the trade of direct reduced iron is not weighty.

Table 1: Steel production data sources. BGS: British Geological Survey; WSA: World Steel Association; CAEF: The European Foundry Association.

Production flows	Source
Iron mining	1913-1970: BGS 1971-2019: WSA
Pig iron production	1920-1967: BGS 1968-2019: WSA
Direct reduction	1977-2019: WSA
BOF, EAF and other steel production	1981-2019: WSA
Steel castings	1920-1971/83: BGS 1972/84-2019: WSA
Semi-finished and finished steel products	1972/81/84/2004-2019: WSA
Cast iron production	1946-2017: Dworak et al. (2021) 2018-2019: CAEF

Table 2: Steel foreign trade data sources. BGS: British Geological Survey; WSA: World Steel Association.

Trade flows	Sources and assumptions
Iron ore	1913-1970: BGS 1971-2019: WSA
Pig iron	1920-1967: BGS 1971-2019: WSA
Ingots and semis	1984-2019: WSA
Hot rolled products, tubular products	1984/86-2019: WSA Additional assumptions on distribution
End use products (indirect trade)	2002-2018: WSA Additional assumptions on distribution
Scrap	1971-2019: WSA

In addition to production and trade volumes, other exogenous parameters are needed for modeling. These are the efficiencies indicating the material losses and scrap generation of the individual process steps, the distribution of the finished steel products to the end use products, the lifetime distribution of the end use products, the end-of-life waste distribution, the factor collection rate and the waste separation efficiency (cf. Table 3). With the exception of the end use goods distribution, the parameters are assumed to be constant over time. An overview of these constant parameters is also shown in the Annex. The end-use goods distribution is varied annually in the years 1946-2019. Before 1946, the same distribution is assumed. In contrast to the statistically reported data, these parameters are based on literature source and combinations hereof. Due to the heterogeneity of the sources, the reliability of the data is comparably lower. This applies in particular to values that are not varied over time.

Table 3: Additional exogenous assumptions.

Parameter	Source
Process efficiencies	Cf. Table 8, Table 9 and Table 10 according to Cullen et al. (2012)
End use goods distribution	Dworak et al. (2021)
Lifetime distribution of products in use	Cf. Table 11 according to Wittig (2021)
End of life waste distribution	Cf. Table 12 according to Wittig (2021)
Factor collection rate	Cf. Table 13 according to Wittig (2021)
Waste separation efficiency	Cf. Table 13 according to Wittig (2021)

2.2 Model Structure

The general concept of the model is schematically shown in Figure 1. The degree of detail in the model follows from the available data and the typical production routes for steel. Table 4 lists the stocks and flows calculated by the model.

Figure 1: Scheme of the European steel cycle.

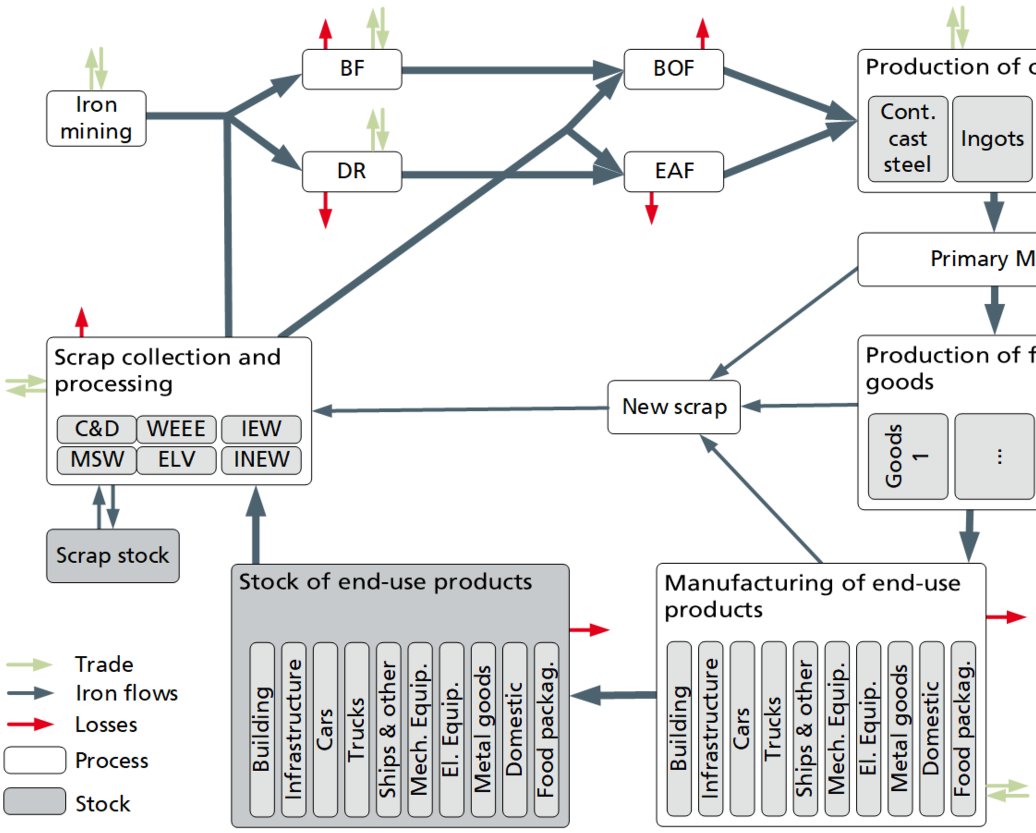


Table 4: Endogenous parameters calculated within the MFA model.

Parameter
End use goods production
New scrap generation
Stock of products in use
End of Life goods
Scrap collection, separation and processing
Recycling flows
Process losses

The steel production shown in Figure 1 is divided in five main steps (Cullen et al. 2012; IEA 2020): iron mining, iron making, steel making, production of castings and production of finished goods. The first step covers the production and trade of iron ore, which is the main inflow of the iron making process. Two processes for the production of iron (step 2) are covered by the model. The first is the production of pig iron in blast furnaces (BF), which is closely linked with the steel production in basic oxygen furnaces (BOF). The produced pig iron can be processed directly to cast iron products and processed further to steel, both covered in the model. Alternatively, direct reduced iron (DRI) can be produced via direct reduction. In the third step the iron is further processed to steel in the BOF, the open hearth furnace (OHF) or the electric arc furnace (EAF). The OHF is no longer used today, but has been relevant in the past. While steel scrap and DRI are used in all three, the BOF, the OHF and the EAF, the latter is more common. Thus, it is assumed that DRI is exclusively used in the EAF. Afterwards, the produced crude steel is cast into crude steel forms (blooms, billets and slabs) with the exception of liquid steel casting. It is assumed that this flow is used exclusively for cast steel products. Continuously cast steel is processed directly to the mentioned crude steel forms while the ingots pass through a further processing stage, the primary mill. In contrast to the other processes, material losses of the primary mill are not calculated using an efficiency. Instead, it is calculated by subtracting the inflow of the production of finished goods from the outflow of the steel casting. The last step is the production of finished goods from the crude steel forms. This is done directly for sections, bars, plates and coils. Further processing steps (welding, rolling or coating) are necessary for other products, which are not considered individually here. However, the respective efficiencies are taken into account. The finished goods are then processed further to end-use goods according to the end-use good distribution provided by Dworak et al. (2021).

In the model, the end-use production plus the net foreign trade equals the stock inflow of products in use. The products remain in the use phase for a certain characteristic lifetime. A lifetime distribution described by an average lifetime and a standard deviation (cf. Table 11) determines the probability of a certain product at a certain age to reach their end of life (EoL). The EoL products equal the outflow of the in-use stock. Products reaching the EoL are potential sources for recycling and therefore secondary raw materials.

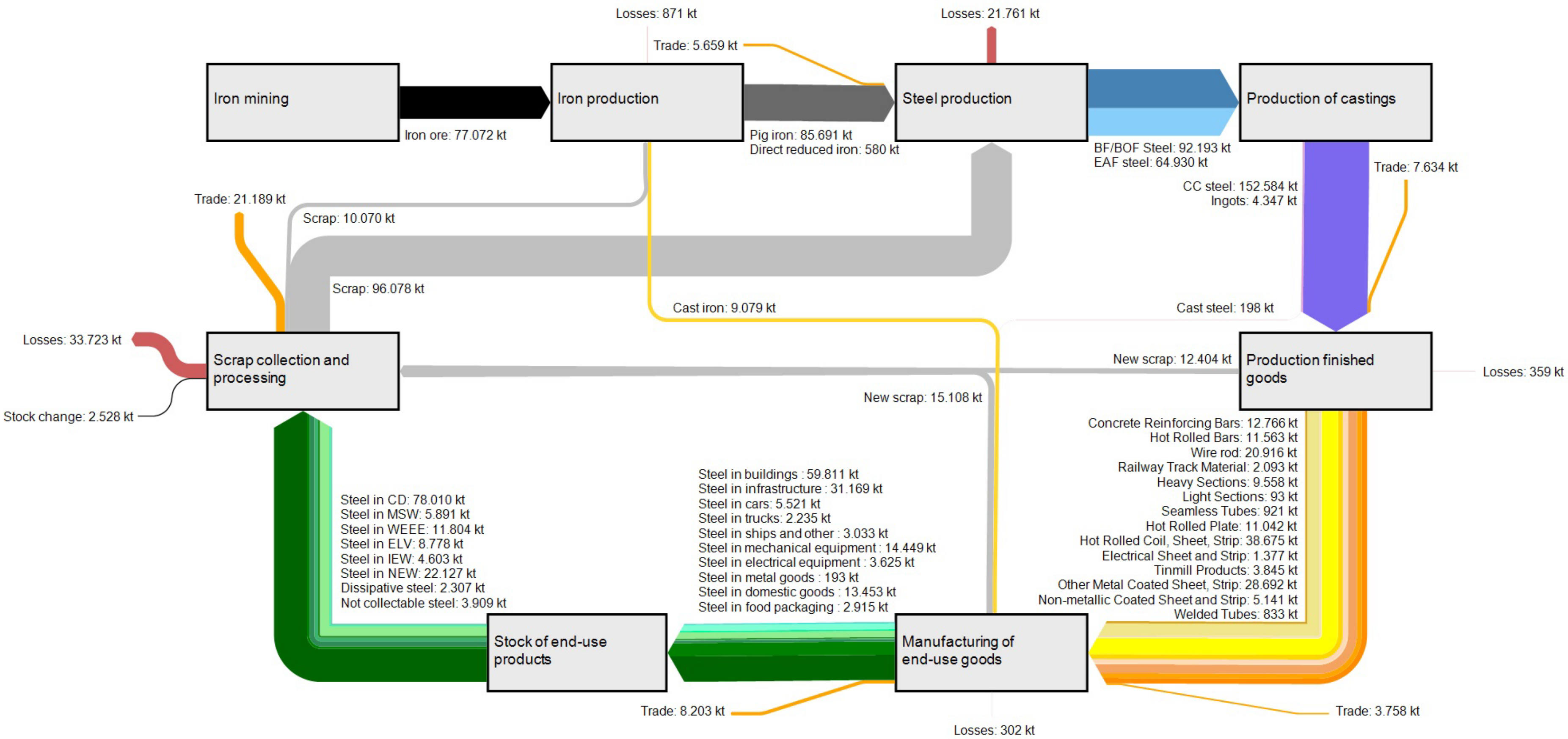
Steel recycling occurs at two stages of the material cycle: (1) In ironmaking via blast furnace or direct reduction and (2) in steelmaking via BOF or EAF and formerly additionally via OHF. Both recycling flows are calculated by mass balance as illustrated in Figure 1. The input for ironmaking consists of primary and secondary material, while the output of ironmaking is available as pig iron and direct reduction production data (cf. Table 1). The primary iron for ironmaking is calculated by the consumption of iron ore and two additional assumptions: (1) 98 % of the iron ore is used for iron making, while the rest is used for chemical and cement industry (Wittig 2021) and (2) the iron ore has an average iron content of 62 % (IEA 2020; World Steel Association 2021). The difference of needed iron input for ironmaking and primary iron input has to come from secondary sources. The calculation of the recycling pathway entering steelmaking follows analogically. Scrap input to BOF is calculated by subtracting the pig iron production from BOF steel production, while the scrap input to EAF is calculated by subtracting the direct reduced iron production from EAF production.

The feedstock of scrap for recycling can be differentiated into new scrap from production of finished steel goods, new scrap from manufacturing of end-use goods and old scrap from products leaving the use phase after their useful lifetime. The new scrap flows are calculated from production data (cf. Table 1) and production efficiencies taken from (Cullen et al. 2012) for steel and estimated to be 99.5 % for cast iron, where most of the material is recycled internally. The remaining required raw material to meet the secondary iron demand has to come from EoL scrap. Consequently, the collection of EoL scrap is the step for closing the mass balance of the iron and steel cycle, as methodologically described by Glöser et al. (2013). The total amount of arising EoL scrap results from the stock outflow of products reaching the end of their useful lifetime. The subsequent waste processing depends on the waste category. Common waste categories found in literature (e.g. Soulier (2018)) are Construction and Demolition waste (C&D), Municipal Solid Waste (MSW), Waste Electric and Electronic Equipment (WEEE), End-of-Life Vehicles (ELV), Industrial Electrical Waste (IEW) and Industrial Non-Electrical Waste (INEW). The end use of a steel product determines its probability to enter a certain waste flow. Table 12 in the Annex provides the distribution of the end uses to the waste flows. The subsequent scrap processing is dependent on the scrap waste category. Sorting and separation processes aim to generate secondary raw materials which are usable for iron- or steelmaking. The corresponding efficiencies are provided in Table 13. Wittig (2021) describes these processes and how they are implemented in the model in detail. The recycling indicators were calculated as defined by Tercero Espinoza et al. (2018).

3 Results

Figure 2 shows the flows of steel in the EU27+GB in 2019. The depiction shows the material and trade flows as well as the losses of the considered processes. The outflows of iron mining and iron production are stated as quantity of the respective products, iron ore and iron. The other flows refer to the quantity of steel within the flow. The trade flows depicted show the trade balance of the flow. Trade inflows indicate net imports of the products while trade outflows are net exports. Process losses are estimated for each of the five steps of steel production described above. As the efficiencies are assumed to be constant over time, these results are not further described. Instead, the following sub-sections focus upon the modelling results for the use phase, scrap collection and recycling. Since the indirect steel trade data is only available from 2002 on (cf. Table 2), the European steel flows hereinafter are shown for 2002 to 2019.

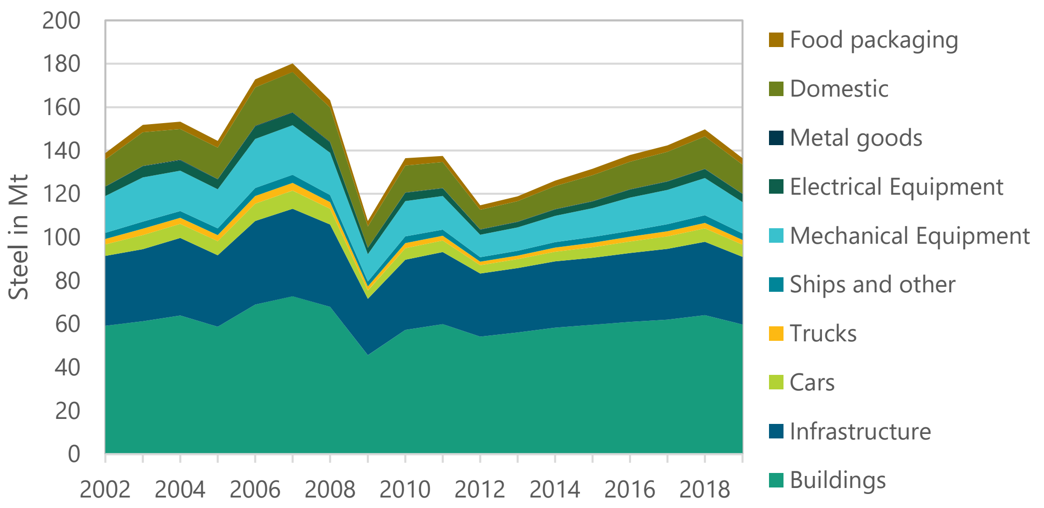
Figure 2: Steel flows in the EU27+GB in 2019.



3.1 Use phase

The inflow of finished goods into the stock of products in use equals the production of steel containing products within the EU[1] minus the net export of finished products to non-EU countries. The inflow to the stock shown in Figure 3 reaches a peak of 180 Mt in 2007. The financial crisis in 2009 lead to a significant decline in European steel demand, leading to a reduction of the stock inflow of around 70 Mt within two years. The steel addition to the stock recovered in 2010-2011, but did not reach the level of 2006-2008 until 2019, where the stock inflow accounted for less than 140 Mt.

Figure 3: Stock inflow of finished goods in use for the EU27+GB.



The stock of steel in use is mainly driven by the long-living application of steel in buildings and infrastructure, which accounted for approx. 83 % of the steel in use in 2019. Further important product groups are mechanical equipment and domestic goods. Even though the overall trend remains the same, the shares of the end use sectors varies according to the end-use distribution. The European stock of goods in use reached around 5,600 Mt in 2007, from where on a saturation level set in.

[1] We use "EU" or "Europe" to describe the geographical scope of the model for the sake of simplicity. However, the model covers the EU27 + Great Britain, cf. Section 2.

Figure 4: Stock of finished goods in use.

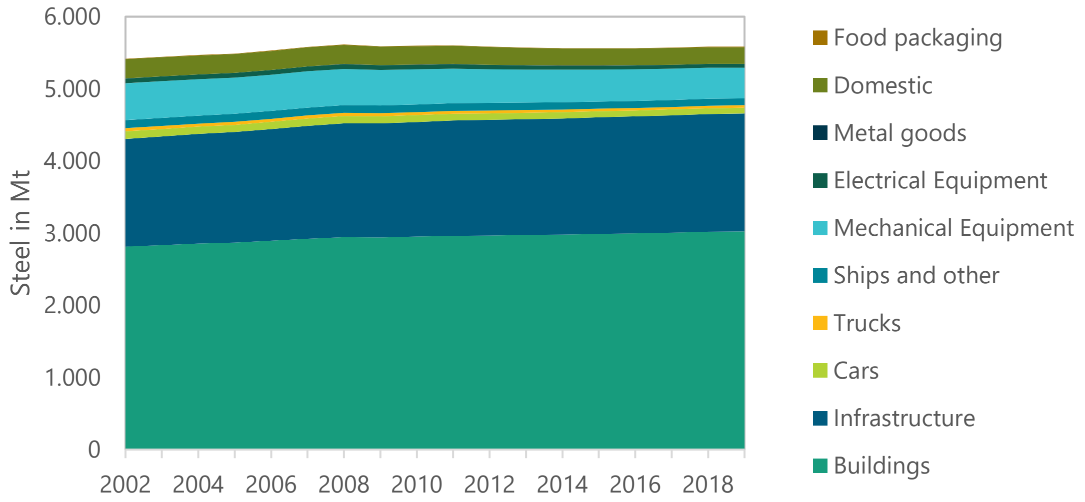
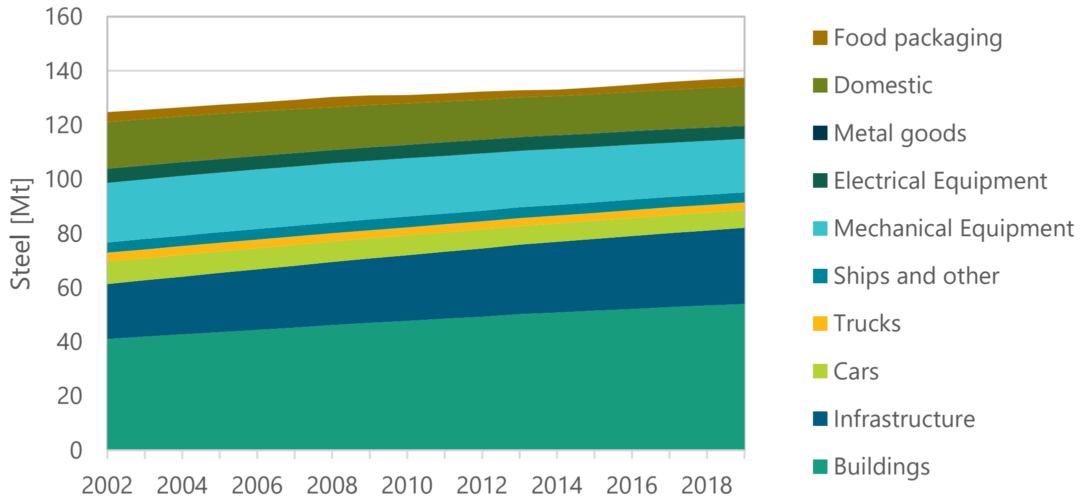


Figure 5 shows the outflow of steel from the use phase, including products that reached the end of life as well as dissipated material. The stock outflow increased around 10 % between 2002 and 2019. It appears that a saturation level of the stock outflow will be reached at around 140 Mt per year due to the stagnation of the stock in use.

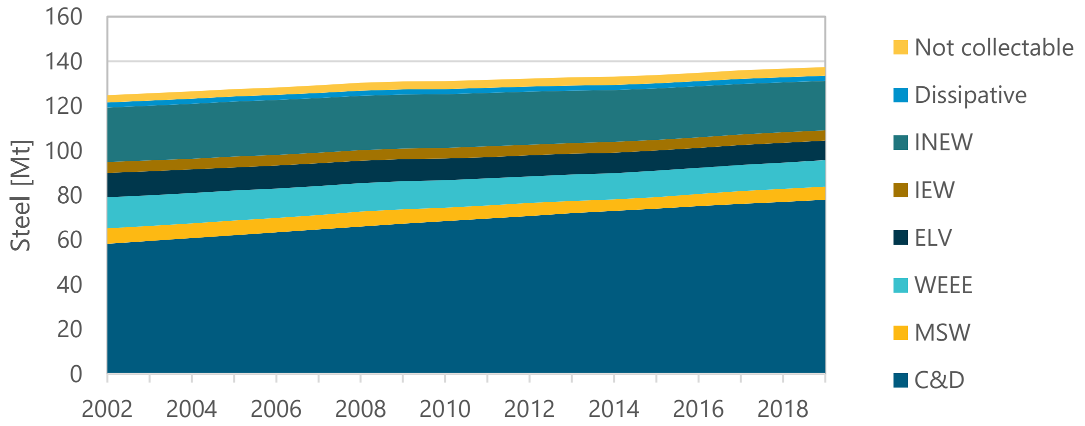
Figure 5: Outflow of end products from the stock in use.



3.2 EoL scrap processing

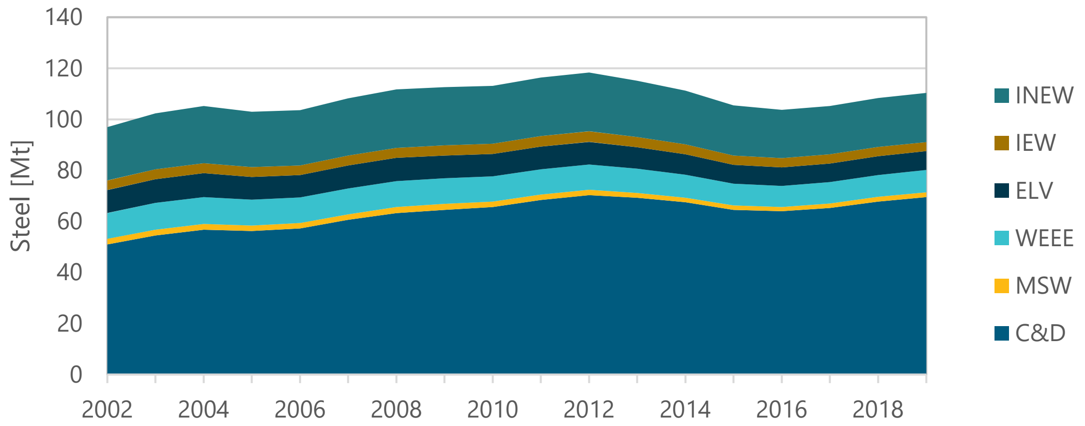
The processing of EoL scrap consists of collection and separation processes, aimed at receiving scrap flows which are usable as secondary raw material in iron- or steelmaking. The stock outflow for each product category shown in Figure 5 is distributed to the waste categories shown in Figure 6. A relatively constant share of about 4 % of the total stock outflow are products being abandoned in place or that enter the environment due to corrosion or abrasion. These flows, labelled *not collectable* and *dissipative* in Figure 6, are lost to the anthropogenic steel cycle. The remaining scrap flows account for approx. 130 Mt in 2019 and are potentially available for recycling. Consequently, these scrap flows equal the theoretical old scrap recycling potential. Within the evaluated period of time, the proportion of construction and demolition waste increased from 47 % (58 Mt) to 57 % (78 Mt), while the other waste categories decreased not only in percentage but also in quantity.

Figure 6: Generated EoL waste flows in the EU.



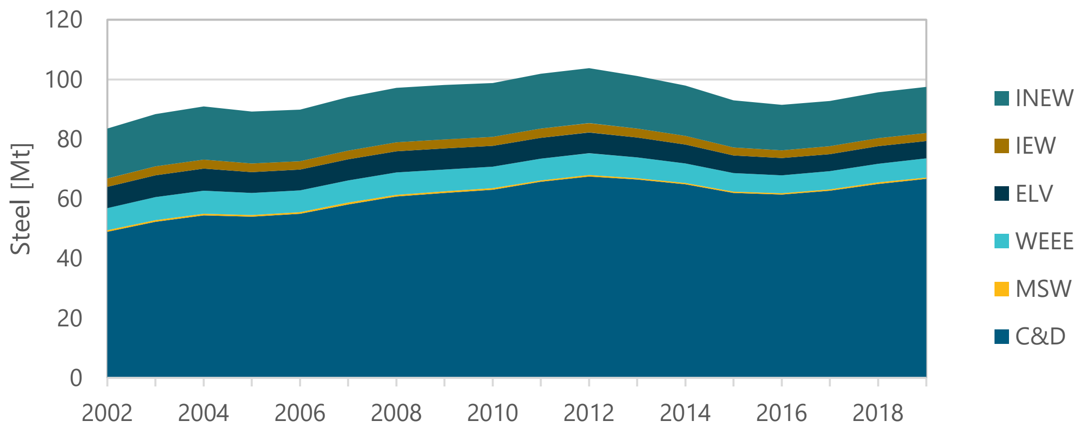
The collection of EoL scrap is calculated by mass balance as described in section 2.2 and shown in Figure 7. The collection of EoL steel scrap increased until 2012 where the flow reached around 120 Mt. Afterwards the collected EoL scrap decreased in spite of a slightly increasing EoL scrap generation, leading to a decline of the EoL collection rate (CR). According to our modelling results, the average EoL CR between 2002 and 2019 was 86 %.

Figure 7: Collection of EoL scrap in the EU, by scrap type.



The separation processes lead to additional material losses due to imperfect sorting systems and amounted to approx. 13 % of the collected scrap on average. The separated EoL scrap flows shown in Figure 8 are applicable feedstock raw materials for EAF, BOF, BF or DR. The average EoL recycling rate (2002-2019), describing the ratio between recycled EoL scrap and theoretical EoL scrap availability, was 76 %.

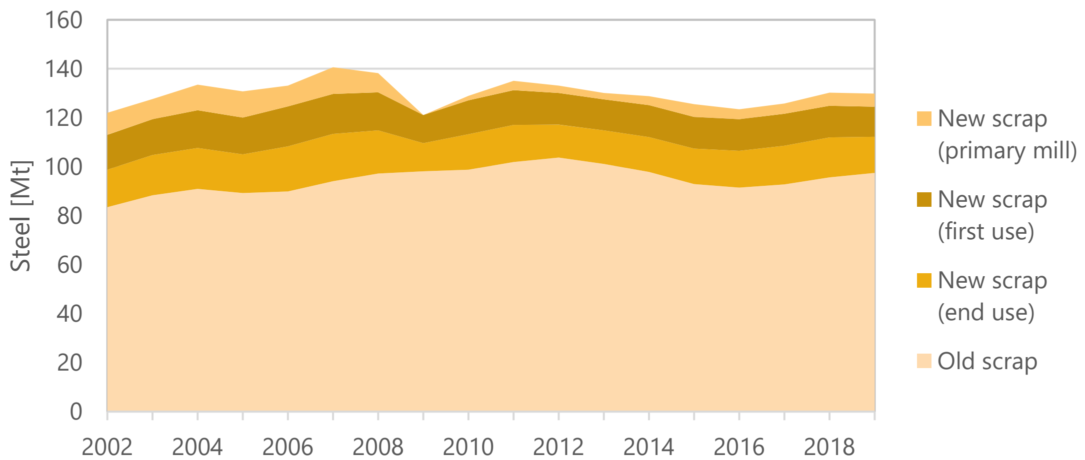
Figure 8: European EoL steel scrap separated for recycling, by scrap type.



3.3 Recycling

Secondary raw materials for recycling originate from both new and old scrap. As Figure 9 shows, the total amount of collected steel and iron scrap remained at a level of around 130 Mt per year. Old scrap is the major feedstock for iron and steel recycling. This leads to an old scrap ratio of 73 % between 2002 and 2019. End use manufacturing is the largest source for new scrap as secondary material, followed by the production of finished steel goods and scrap from primary mills (cf. Figure 9). The recycling of internal scrap, often called home scrap, is excluded from the model.

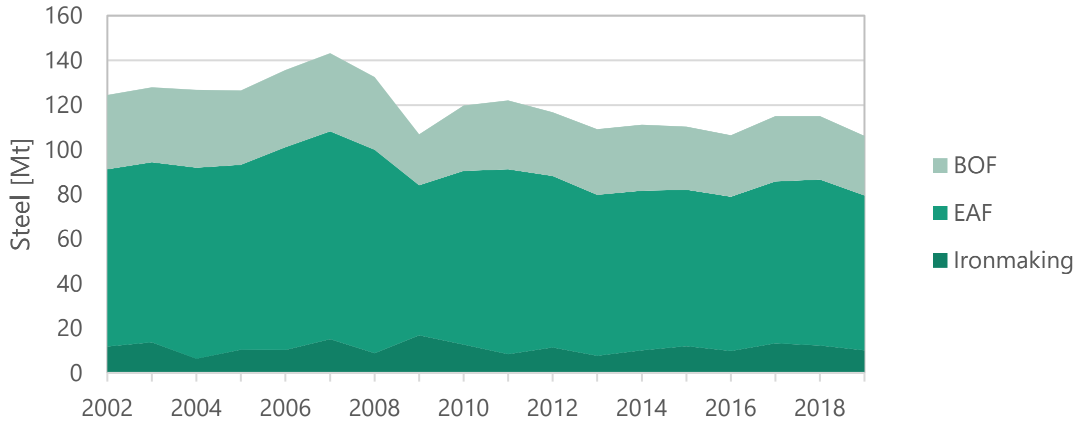
Figure 9: Steel scrap collection in the EU, by source.



The amount of iron and steel recycled in the EU reached a peak of approx. 140 Mt in 2007 and decreased from there on to less than 110 Mt in 2019, as shown in Figure 10. EAF was the preferred recycling route, accounting for circa 65 % of iron and steel recycled, while BOF accounted for around 25 % of the total. The remaining share were recycled via ironmaking in both DR and BF process. The difference between scrap collection and recycling occurs due to foreign trade of steel scrap. The decline of iron and steel recycling in the EU led to an increase of net steel scrap exports. In 2005, there was a net import of approx. 300 kt of steel scrap, while in 2019 the net export reached over 21 Mt. Therefore, the decline in iron and steel recycling did not lead to a decline of scrap collection, but to a higher export ratio. The amount of recycled steel declined because of a decreasing steel production in the EU. Between 2002 and 2019, steel production declined by around 17 %

while the amount of steel recycling declined by approx. 15 %. As both total steel production and recycling declined simultaneously, the recycling input rate fluctuated only slightly at around 57 %.

Figure 10: Iron and steel recycling in the EU, by process.



4 Discussion

4.1 Literature comparison

The studies from Dworak et al. (2021), Flint et al. (2020), Passarini et al. (2018), Fellner et al. (2018) and Panasiyk et al. (2016) are sufficiently similar in scope to allow direct comparison with the model presented here. Table 5 sums up central results of these studies compared to the results for 2017 from our work. Most of the studies use production data published by the WSA. Subsequent stocks and flows differ due to different calculation methods, assumptions or spatial and temporal boundaries. Our estimation of new scrap generation agrees with the calculations by Fellner et al. (2018), Flint et al. (2020) and Passarini et al. (2018), while Panasiyk et al. (2016) give lower and Dworak et al. (2021) higher amounts of new scrap.

The stock of finished goods fits well with the estimation by Passarini et al. (2018), while the estimation by Panasiyk et al. (2016) lies about 30 % lower. The other studies did not report stocks in use. The lower stock of finished goods reported by Panasiyk et al. (2016) may result from the difference in special scope. Panasiyk et al. (2016) quantify the stock in EU27, while our results cover the EU28, so that Croatia is included which was not a part of the EU before 2013. Additionally, the stock of steel and iron goods in use rose between 2012 (Panasiyk et al. (2016)) and the point in time we show in Table 5. Further differences may occur due to different assumptions of lifetimes.

Both the generation of EoL scrap and the total amount of recycled scrap exceeds the values published in the other discussed studies, if calculated and published. While the calculated recycling flows by Passarini et al. (2018) have the same magnitude as our results, Fellner et al. (2018) indicate significantly lower recycling flows. This comes inter alia from a different scope of recycling. We include all recycling pathways entering both steel and iron production, while Fellner et al. (2018) calculate exclusively the recycling of steel via steelmaking processes regardless of secondary material entering pig iron making or cast iron making. Nevertheless, this distinction in scope does not justify the high difference in recycling numbers.

Table 5: A comparison of modelling results with literature results.

Source	Year	Area	Production scrap [Mt]	Fabrication scrap [Mt]	Stock in use [Mt]	EoL scrap generation [Mt]	Recycling [Mt]
Own results	2017	EU 28	17.6	16.1	5,570	136	115
Dworak	2017	EU 28	15.5	26.5	-	96**	-
Fellner	unclear	EU 28	15.6*	15.6*	-	66.8*	62*
Flint	2013	EU (n.s.)	13.0	19.1	-	-	-
Panasiyk	2012	EU 27_2007	-	24.1	4,210	-	-
Passarini	2015	EU 28	13	25	5,329	108	105

*Internal scrap, calculated from per capita values with 445.53 Mio capita in EU28 in 2017
**Calculated by EoL recycling and EoL recycling rate

Nevertheless, many dynamics and trends of the steel recycling fit with the compared studies: The allocation of steel recycling via EAF and BOF is the same in the model published by Passarini et al. (2018) and in our model. Both give a share of approx. 71 % steel recycling in the EAF process route. Also the feedstock for steel recycling is confirmed with an OSC for 2017 of 70 % by Dworak et al. (2021) and around 74 % in our results for the same year.

4.2 Uncertainties

Stock and flow models comprising total material cycles base on available data and additional assumptions. As both data and literature used to derive exogenous model parameters are not complete, results are subject to uncertainty. This holds true for the historic production and trade of semi-finished and finished steel products as described in Section 2.1. These numbers were extrapolated into the past by using crude steel production (up to 1920) and iron ore production (1919 to 1913). Products from these early years leave the stock after a maximum of 100 years so that the impact of the uncertainty of historic production numbers does not significantly affect results for recent years.

The largest source of uncertainty is the lifetime of end use goods. Even though we conducted an extensive literature research (cf. Table 11 and Wittig (2021)), the actual lifetime of products is not known and affected by a wide variety of influencing factors like recent trends in consumption, economic situation and regional differences. This uncertainty exists in any similar study and is e.g. set to by ± 15 % by Rostek et al. (2022). The uncertainty of the lifetime distributions leads to sensitivities of the stock in use and the EoL scrap generation. The collection of EoL scrap and subsequent stocks and flows are not affected by the lifetime, as these flows are calculated backwards by mass balance as described in Section 2.2.

Beside these uncertainties, we needed to make simplifications regarding the trade data. Exclusively aggregated trade data are available for the finished goods and the end use goods. Consequently, we have assumed the same distribution as in the production of the goods. While for cast iron the export data are available by The European Foundry Association, import data is not explicitly published. Therefore, we neglected trade of cast iron, thereby assuming equal import and export quantities, which is not critical due to the low amounts compared to the overall flows.

5 Conclusion

Overall the aim to develop a dynamic material flow model covering the overall European steel cycle was achieved. Results cover relevant stocks and flows of steel from mining to recycling. This new model improves upon published European steel flow models by making collection and processing of post-consumer scrap endogenous as opposed to input parameters. The results indicate a saturation of steel and iron use in Europe as evident in a constant stock of steel and iron products being in the use phase. This balance of the anthropogenic stock leads to the conclusion, that most of the material entering the stock is replacement material. The collection and processing of old scrap is efficient, which leads to an EoL collection rate exceeding the rate of most other metals. Nevertheless, European steel recycling decreased strongly from 2007 until today due to a reduction of steel production. The decline in steel recycling did not significantly affect the collection of steel scrap, but led to an increase of iron and steel scrap export. It is expected that exported secondary raw materials are utilized for iron- or steelmaking in non-European countries, leading to a spatial shift rather than a decline in global steel recycling in the past two decades. Consequently, we expect the impact of decreasing steel recycling in Europe on the global circularity of steel to be minor. Further research could examine the effect of steel scrap prices on their use, further trace these export flows or analyse the potentials of secondary steel production for industry decarbonisation.

Acknowledgement

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Supporting data

We provide the model output data in the form of a supporting excel file. If you are interested in this supporting data, please send your request to the email address mentioned in the imprint.

6 List of figures

7 List of tables

8 Bibliography

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A.1 Annex

Table 6: Steel production data sources. BGS: British Geological Survey; WSA: World Steel Association.

Production flows	Source
Iron mining	1913-1970: BGS 1971-2019: WSA
Pig iron production	1920-1967: BGS 1968-2019: WSA
Direct reduction	1977-2019: WSA
BOF, EAF and other steel production	1981-2019: WSA
Castings	
Castings (aggregated)	1920-1971/83: BGS
Continuous cast steel	1972-2019: WSA
Ingots	1972-2019: WSA
Liquid steel casting	1984-2019: WSA
Semi-finished and finished steel products	
Concrete reinforcing bars	1984-2019: WSA
Hot rolled bars	1984-2019: WSA
Wire rod	1984-2019: WSA
Railway track material	1984-2019: WSA
Heavy sections	1984-2019: WSA
Light sections	1984-2019: WSA
Seamless tubes	1981-2019: WSA
Hot rolled plate*	2004-2019: WSA
Hot rolled coil, sheet and strip*	2004-2019: WSA
Electrical sheet and strip	1984-2019: WSA
Tinmill products	1984-2019: WSA
Other metal coated sheet and strip	1984-2019: WSA
Non-metallic coated sheet and strip	1984-2019: WSA
Welded tubes	1981-2019:WSA

* The production quantities for Hot rolled plate and Hot rolled coil, sheet and strip are edited from the data in the yearbook of the WSA. In the yearbook these categories cover all products of first transformation that may be further worked. To avoid double counting of products of further transformation, the other flat products are subtracted from Hot rolled plate and Hot rolled coil, sheet and strip. It is assumed that Welded tubes are produced from Hot rolled plate and all other flat products are produced from Hot rolled coil, sheet and strip.

Table 7: Steel foreign trade data sources. BGS: British Geological Survey; WSA: World Steel Association.

Trade flows	Sources and assumptions
Iron ore	1913-1970: BGS 1971-2019: WSA
Pig iron	1920-1967: BGS 1971-2019: WSA
Ingots and semis	1984-2019: WSA
Hot rolled products **Tubular products**	1984-2019: WSA 1986-2019: WSA Additional assumptions on distribution
End use products (indirect trade)	2002-2018: WSA Additional assumptions on distribution
Scrap	1971-2019: WSA

Table 8: Process efficiencies of iron and steel production (Cullen et al. 2012).

Process	Efficiency
Blast furnace	0.99
Direct reduction	0.99
Basic oxygen furnace	0.871
Electric arc furnace	0.889
Other steel	0.871

Table 9: Process efficiencies of semi-finished and finished product production (Cullen et al. 2012).

Semi-finished and finished product	Efficiency
Concrete reinforcing bars	0.940
Hot rolled bars	0.940
Wire rod	0.940
Railway track material	0.900
Heavy sections	0.900
Light sections	0.900
Hot rolled plate	0.900
Hot rolled coil, sheet and strip	0.957
Electrical sheet and strip	0.910

Semi-finished and finished product	Efficiency
Tinmill products	0.851
Other metal coated sheet and strip	0.8874
Non-metallic coated sheet and strip	0.870
Seamless tubes	0.867
Welded tubes	0.883
Steel cast	0.995
Iron cast	0.995

Table 10: Process efficiencies of end use product production (Cullen et al. 2012; Dahlström et al. 2004; Hatayama et al. 2010).

End use product	Efficiency
Buildings	0.94
Infrastructure	0.95
Cars	0.8
Trucks	0.8
Ships and other transportation	0.88
Mechanical equipment	0.85
Electrical equipment	0.86
Metal goods	0.86
Domestics	0.87
Food packaging	0.82

Table 11: Useful lifetime of end use products in use (Wittig 2021).

	Lifetimes in literature [y]	Average lifetime and standard deviation [y]
Buildings	28.9 – 75	50 (23)
Infrastructure	24.5 – 75	50 (23)
Cars	8.7 – 20	15 (4)
Trucks	8.5 – 20	15 (4)
Ships and other transportation	12.1 – 60	30 (13)
Mechanical equipment	12.1 – 40	25 (10)
Electrical equipment	12.1 – 16	14 (3)
Metal goods	< 1 – 30	13 (4)

	Lifetimes in literature [y]	Average lifetime and standard deviation [y]
Domestics	7 – 30	18 (4)
Food packaging	< 1 – 2	2 (1)

Table 12: Distribution of discarded end products to waste category (Wittig 2021). C&D = Construction and Demolition; MSW = Municipal Solid Waste; WEEE = Waste Electric and Electronic Equipment; ELV = End of Life Vehicles; IEW = Industrial Electrical Waste; INEW = Industrial Non-Electrical Waste; Dis. = Dissipative; Not col. = Not collectable.

Category	C&D	MSW	WEEE	ELV	IEW	INEW	Dis.	Not col.
Buildings	0.95	0	0	0	0	0	0.01	0.04
Infrastructure	0.95	0	0	0	0	0	0.01	0.04
Cars	0	0	0	0.94	0	0	0.01	0.05
Trucks	0	0	0	0.94	0	0	0.01	0.05
Ships and other transportation	0	0	0	0	0.2	0.7	0.1	0
Mechanical equipment	0	0	0	0	0	0.99	0.01	0
Electrical equipment	0	0	0.19	0	0.8	0	0.01	0
Metal goods	0	0.2	0	0	0.2	0.5	0.1	0
Domestics	0	0.2	0.75	0	0	0	0.05	0
Food packaging	0	0.94	0	0	0	0	0.01	0.05

Table 13: Technical separation efficiency and factor collection rate (Wittig 2021).

Waste category	Technical separation efficiency [%]	Factor collection rate []
C&D	0.95	1.37
MSW	0.25	0.5
WEEE	0.73	1.14
ELV	0.79	1.3
IEW	0.75	1.2
INEW	0.80	1.34