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Review

European Post-Consumer Steel Scrap in 2050: A Review of Estimates and Modeling Assumptions

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Abstract: This review studies the availability of post-consumer steel scrap in Europe until 2050. We introduce the indicator potentially available domestic post-consumer scrap (PADPS), which measures the amount of (steel) scrap from obsolete products available for recycling prior to trade in scrap. We analyze material flow studies from the academic literature and international organizations to quantify this indicator. The studies suggest a rising trend of post-consumer scrap amounts until a saturation level is reached and the expected yearly steel product obsolescence of the system stabilizes. Between 2010 and 2050, PADPS is expected to rise by approximately 1.6% per year. We identify in-use steel stocks, recycling rates, and product lifetimes as the three commonly gauged factors determining PADPS. While recycling rates and product lifetimes range comparatively close in the studies, the estimation of in-use stocks displays much greater variation and introduces an element of uncertainty in the estimation of post-consumer scrap amounts that can be expected in the coming decades.

Keywords: steel scrap; steel recycling; post-consumer scrap; steel stocks; Europe; 2050; literature review

1. Introduction

Steel production is responsible for approximately 7% of global greenhouse gas emissions [1] and is one of the notoriously hard-to-abate industries. Making steel from scrap rather than from primary raw materials—i.e., iron ore and coking coal—reduces its carbon footprint substantially: each recycled ton of steel scrap saves approximately 1.6 tons of CO_2 equivalents [2,3]. To illustrate the magnitude of these emission cuts: in 2018, steel production from scrap in the EU amounted to 94 million tons of steel (Mt), reducing CO_2 emissions by 157 Mt—the equivalent of the combined automobile traffic of France, Belgium, and Great Britain in the same year [4].

In addition to these climate benefits, using scrap in steelmaking keeps materials in circulation in times of globally still-growing steel stocks and, therefore, increasing steel demand [5]—every unit of scrap input relieves Earth of additional resource use and mining activities. Unlike other low-carbon or carbon-neutral steel production processes, such as hydrogen-based steelmaking, which are not established on an industrial scale yet (e.g., [1,6]), steel recycling relies on a well-established value chain, is a low-cost approach to decarbonizing steel production [7], and does not require the building of specialized infrastructure from scratch. Therefore, demand for steel scrap is likely to increase substantially with more ambitious climate policies coming into action. In the EU-27, steel production via the electric arc furnace, a production route based almost exclusively on scrap steel input, is currently at 45% [8] and is expected to grow further.

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However, supplying sufficient quantities and qualities of steel scrap is not possible without increased efforts. Contaminants such as copper limit the range of products ma-nufacturable from scrap and, if they accumulate over time, turn a fraction of scrap unusable [9]. Large-scale steel-containing structures such as storehouses or railways may be abandoned without being demolished, which keeps the materials from being circled back into use. These efforts should be part of a broader transformation towards a circular economy. The circular economy is not limited to recycling but also encompasses a reduction of material inputs and the reuse and remanufacturing of products. The efforts to increase steel recycling both qualitatively and quantitatively are likely to also impact the supply chains of scrap.

The availability of scrap in the future is, therefore, an important variable for developing efficient pathways [10] towards climate-neutral steel production and a circular economy. After all, steel production is one of the core energy-intensive industries that need to be transformed substantially in order to fulfill the European Commission's vision of climate neutrality by 2050, as outlined in the Green Deal. Pursuing these ambitious climate policy goals and lacking domestic primary raw material reserves as well as suffering from scarcities of green hydrogen to produce carbon-neutral primary steel, the European Union is particularly dependent on a reliable understanding of scrap availability.

A common way of gauging this scrap availability is studies employing material flow analyses (MFAs) to study the stocks and flows of steel, either globally [11–14] or in individual regions and countries (ref. [15] for the US; ref. [16] for Japan; ref. [17] for Sweden). Some of these studies investigate the availability of scrap explicitly [18,19], while others estimate scrap availability as an input variable to derive, for example, the energy demand of the steel sector [20]. A comparative overview of the studies honing in on developments in Europe in the coming decades, investigating their results as well as their underlying assumptions, is lacking in the literature.

In this study, we close this gap by analyzing the literature on post-consumer scrap availability in Europe for a time horizon up until 2050. We make five main contributions. First, we identify the trend and bandwidth of post-consumer scrap available in Europe that is anticipated by existing studies. Second, we uncover the main assumptions underlying the studies and sketch how they relate to the resulting numbers. Third, we contrast the expected post-consumer scrap values in the literature with our own estimation of the current apparent domestic scrap supply. Fourth, we show whether the issue of tramp elements can be addressed qualitatively and quantitatively. Fourth, we provide an overview of likely developments in steel scrap availability to decision makers, supporting a successful decarbonization of Europe's steel industry.

The study proceeds as follows. We start with an overview of the common flows of steel scrap and the situation in Europe in Section 2, where we additionally include our own estimation of the current levels of domestic scrap supply for illustrative purposes. Section 3 provides an overview of the studies compared and key assumptions in modeling future scrap amounts. In Section 4, results are provided, with subsections detailing the scrap numbers and their variations as well as commonly and less commonly considered influencing factors. Section 5 discusses the validity, variance, and political as well as economic implications of our results.

2. Background on Steel and Steel Scrap

2.1. Steel, Steel Scrap, and Steel Scrap Consumption

Steel, according to the ISO, is a "material with iron as the predominant element, having a carbon content generally less than 2.0% and containing other elements" [21]. Steel's properties can be modified by alloying elements other than iron and carbon [22].

Stainless steel, for instance, obtains its exceptional resistance to corrosion by adding at least 10.5% of chromium and limiting its carbon content to 1.5% [23].

Steel can be produced either from iron ore, the primary raw material, or from steel scrap, the secondary raw material. Primary steel is mainly produced via the blast furnace–basic oxygen furnace (BF-BOF) route. Oxygen-containing iron ores are reduced in a blast furnace using coke as the reduction agent. The resulting pig iron is then processed further in the basic oxygen furnace to produce crude steel. Up to 25% of scrap are added during this step for temperature control and to reduce carbon emissions. Secondary steel is produced in electric arc furnaces (EAF), which remelt scrap using electricity to produce new steel.

Steel scrap can be divided into three main types depending on where it accrues in the life cycle. Scrap from steelmaking itself is denoted internal or home scrap. It is recycled within the mill or foundry instead of being sold. Scrap from manufacturing steel products is termed new scrap (also prompt scrap, production and forming scrap, fabrication scrap, or pre-consumer scrap). Its composition is known to the manufacturer, it contains only few impurities, and backward logistics to the steel works is comparatively simple. New scrap is commonly bought and collected by recycling businesses, and it is recycled almost entirely. Finally, scrap at the end of a steel product's lifetime is termed old scrap, end-of-life scrap, or post-consumer scrap. Generally, it is more heterogeneous in its composition and contains more unwanted impurities, such as copper. By definition, post-consumer scrap only becomes available for recycling after product obsolescence, i.e., with a considerable time lag after steel production. This time lag is particularly pronounced for steel used in long-lived applications, such as transport equipment, industrial machinery, or infrastructure, and it contributes to a loss of information about material composition.

The use of scrap in steel production varies by country and depends on many factors, e.g., scrap supply (within the country and on the global market), quality requirements of the final product, and existing EAF infrastructure. Figure 1 displays the relationship between total steel production and scrap use in steel production for China, Turkey, the EU, and the US based on data from the Bureau of International Recycling (BIR) [24]. Turkey is by far the world's biggest steel scrap importer and has the highest rate of scrap use in steelmaking, with up to 90% scrap input. China's scrap use, on the other hand, has slowly increased from 14% in 2010 to 21% in 2022. The EU, for comparison, displays scrap use rates between 54% and 59% in the period represented, thus basing more than half of its steel production on raw materials from recycling.

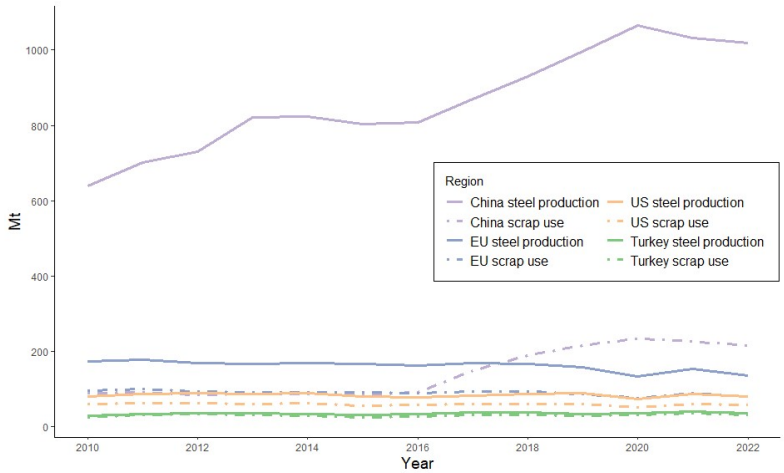


Figure 1. Overall steel production and scrap use in steel production of selected countries, 2010–2021. Data obtained from World Steel Recycling in Figures by the BIR. The BIR's scrap consumption data include home and prompt scrap as well as post-consumer scrap [25]. Before 2021, EU numbers represent 28 member states; in 2021 and 2022, UK has been excluded from the data.

2.2. Apparent Domestic Scrap Consumption

No data on the actual domestic scrap supply, which is the amount of steel scrap procured for recycling in a year disregarding trade, exists. But it is possible to estimate the apparent domestic scrap supply ($ADSS_r$) of a country r as the sum of its scrap consumption and its net export of scrap according to Equation (1). We estimate the $ADSS_r$ to illustrate the current supply of steel scrap as a basis for interpreting the evolution of the steel scrap supply in Europe and for comparing different regions of the world.

Index t represents the year and r the country. $CONS_{r,t}$ in Equation (1) represents the scrap consumption in country r and year t. $EXP_{r,t}$ and $IMP_{r,t}$ denote the total exports from r and the total imports to r, respectively. The four variables in Equation (1) comprise home, new, and post-consumer scrap because neither the scrap consumption nor the scrap trade data differentiate between scrap categories. Thus, we aggregate them when estimating the $ADSS_r$.

$$ADSS_{r,t} = CONS_{r,t} + EXP_{r,t} - IMP_{r,t} \quad (1)$$

Imports and exports of scrap are taken from the UN Comtrade database [26]. The Harmonized System (HS) code for steel scrap is 7204. Import data have been used to calculate both exports and imports of scrap. In cases where import data have been missing, we relied on export data. Data on scrap consumption are published by the Bureau of International Recycling in its World Steel Recycling in Figures series. These data are generally limited to seven key countries and regions (China, EU, USA, Japan, Turkey, Russia, and Republic of Korea). Data for Canada are available between 2017 and 2019. The EU is broken down into 22 individual steel-producing countries. European data are missing between 2018 and 2020. Thus, in 2022, we have data on scrap consumption of 27 nations, with a total consumption of 470 Mt. According to WorldSteel data, steel was produced in 96 countries in 2022. Therefore, we need to predict the steel scrap consumption in 69 nations. The largest steel producers for which scrap consumption must be estimated are India, Brazil, and Iran.

To quantify scrap consumption in countries without observable data, we estimate the recycled content per ton of crude steel production in the blast furnace (BOF) route and the electric arc furnace (EAF) route. We assume that the recycled content (the amount of scrap used per ton of crude steel) in each route, respectively, is approximately the same across all countries. This assumption appears reasonable because the recycled content is largely determined by technological factors.

Furthermore, we quantify the influence of direct reduced iron (DRI) consumption on scrap consumption. In 2022, 125.1 Mt of DRI were produced globally. India (42.3 Mt), Iran (32.9 Mt), and Russia (7.7 Mt) were the largest producers [27]. DRI is melted in electric arc furnaces to produce steel. Therefore, ignoring the role of DRI leads to an overestimation of scrap consumption by EAFs.

$$CONS_{r,t} = \beta_{BOF}\, BOF_{r,t} + \beta_{EAF}\, EAF_{r,t} + \beta_{DRI}\, DRI_{r,t} + \varepsilon_{r,t} \quad (2)$$

First, we estimate the scrap consumption in countries with observable data using a pooled ordinary least squares (OLS) approach, as shown in Equation (2). $BOF_{r,t}$ is the amount of steel produced in the BOF route in country r and year t and $EAF_{r,t}$ the amount produced in the EAF route. $DRI_{r,t}$ records the direct reduced iron consumption. DRI consumption is computed by subtracting net exports of DRI from domestic production. β_{BOF}, β_{EAF}, and β_{DRI} are the corresponding coefficients. β_{BOF} and β_{EAF} quantify the recycled content, i.e., how many tons of scrap are consumed per ton of steel production. β_{DRI} measures how many tons of scrap are replaced by one ton of DRI input. $\varepsilon_{r,t}$ represents an error term. We allow the error term to be heteroscedastic. We show robust standard

errors clustered by country. We do not estimate an intercept because scrap consumption is tied technologically to steel production. In other words, there is no scrap consumption independent of steel production.

Equation (2) is estimated econometrically based on observations for countries that provide scrap consumption data. Equation (1) is an identity. We plug the estimated scrap consumption or, if available, observed scrap consumption into Equation (1) to calculate the corresponding $ADSS_{r,t}$.

We use steel consumption data from the BIR [28] as well as from earlier versions of the World Steel Recycling in Figures series. These scrap consumption data encompass all scrap used by steel producers (home, new, and post-consumer scrap). Annual steel production by country, year, and production route, as well as DRI production per country and year, have been provided to us by WorldSteel. We restrict our sample to the years 2013 to 2022, assuming technological improvements in steel production make earlier years less representative of today's steel scrap consumption.

Table 1 displays the regression results for four specifications. Columns I and II include observations from China, and columns III and IV exclude the People's Republic. Columns I and III exclude the intercept, as shown in Equation (2). Columns II and IV constitute sensitivity checks: we include an intercept denoted β_0 to inspect whether it has an influence on the estimated coefficients. In all four specifications, the coefficients for BOF and EAF are highly statistically significant. The coefficients on DRI are not statically significant when using robust clustered standard errors, plausibly because relatively few countries in our sample employ DRI to produce steel. All specifications exhibit high R^2.

Table 1. Recycled content by production route (pooled OLS).

	I **Including China, No Intercept** ***CONS*$_{r,t}$**	**II** **Including China, Intercept** ***CONS*$_{r,t}$**	**III** **Excluding China, No Intercept** ***CONS*$_{r,t}$**	**IV** **Excluding China, Intercept** ***CONS*$_{r,t}$**
β_0		−558.1231 (1302.5915)		595.7667 *** (132.0532)
β_{BOF}	0.0780 *** (0.0129)	0.0769 *** (0.0153)	0.1322 *** (0.0194)	0.1252 *** (0.0168)
β_{EAF}	1.2298 *** (0.1398)	1.2486 *** (0.1816)	1.0455 *** (0.0448)	1.0312 *** (0.0403)
β_{DRI}	−1.2151 (0.8458)	−1.2231 (0.8690)	−0.4402 (0.3653)	−0.4170 (0.3423)
Observations	205	205	195	195
R^2	0.9665	0.9665	0.9951	0.9952
Adj. R^2	0.9661	0.9660	0.9951	0.9951
F-Statistic	2484.5290 *** (df = 3; 202)	1932.4170 *** (df = 3; 201)	18,180.1000 *** (df = 3; 192)	13,041.1200 *** (df = 3; 191)

*** $p < 0.01$. Note: Robust standard errors in parentheses.

In the models including China (columns I and II in Table 1), the estimated coefficients of the BOF route (β_{BOF}) equal 0.0780 and 0.0769, respectively. This corresponds to a recycled content of approximately 77 to 78 kg of scrap per ton of steel in the blast furnace route. Approximately 1.23 to 1.25 tons of scrap are used per ton of crude steel produced in the EAF route according to the specifications that include China in the sample. β_{EAF} represents a mix between low alloy steels, for which yield losses in the EAF imply higher recycled content, and high alloy steels, for which alloying elements replace the scrap input.

If China is excluded from the sample (columns III and IV in Table 1), the estimated β_{BOF} increases to 0.1322 and 0.1252, respectively. The corresponding values for the EAF route drop to 1.0455 and 1.0312, respectively.

Data on scrap consumption split between the BOF and EAF routes are available for Germany between 2016 and 2019 [29], allowing us to conduct a plausibility check. The average recycled content in these years was 0.177 t of scrap for the BOF route and 1.034 t of scrap for the EAF route. These closely resemble our estimates excluding China. The higher recycled content in Germany's BOF route could be explained by environmental regulations, including CO_2 prices set by the EU Emissions trading system. The observed recycled content cautions against the results including China (columns I and II): β_{BOF} in this specification is implausibly low. A β_{EAF} of 1.23 to 1.25 suggests yield losses of about one quarter, which seems unreasonable as well.

Accounting for 54.0% of the global crude steel production, China is the world's largest steel producer [27]. Steelmakers in China consumed 215.3 Mt of scrap in 2022, making it the largest scrap consumer as well [28]. China thus has a sizeable impact on our estimates. But recycled content in China is substantially lower than in other major steelmaking nations, even though scrap consumption has increased in the last ten years [28]. This pattern can be explained by supply-side constraints: The amount of scrap available in the People's Republic is insufficient to achieve the same recycled content as in other regions. We conclude that China constitutes an outlier with respect to its scrap consumption [30] and that the estimates excluding Chinese observations are more representative of recycled content in other nations.

Comparing the estimates with (columns II and IV) and without an intercept (columns I and III) shows that the estimated coefficients β_{BOF}, β_{EAF}, and β_{DRI} are robust with regard to the intercept's inclusion. As argued above, an intercept would imply scrap consumption independent of steel production. Therefore, we select the specification excluding China and without an intercept (column III) as our preferred specification among the four pooled OLS estimates.

In this specification, the coefficient $\beta_{DRI} = -0.4402$ implies that the consumption of one ton of direct-reduced iron reduces the estimated scrap consumption by approximately 440 kg. It appears plausible that one ton of DRI replaces less than one ton of scrap because DRI is first and foremost used as a raw material for primary steel production, not secondary steel production from scrap.

We conducted extensive statistical tests and sensitivity checks to explore the properties of our data. Appendix A displays the details. The statistical tests favor a fixed effects model over pooled and random effects models. Unfortunately, the resulting parameter estimates imply implausibly recycled contents in both the EAF and the BOF routes. The variation in steel production and scrap consumption in our sample is likely to be insufficient to distinguish between their relationship and truly country-specific determinants of scrap consumption, such as efficiency differences between steel-producing nations. Therefore, we rely on the pooled model.

We use the coefficients of our preferred specification to estimate scrap consumption (Equation (2)) and employ the resulting numbers to quantify the $ADSS_{r,t}$ (Equation (1)). Our results suggest a global apparent domestic scrap supply of 679.6 Mt in 2022. The largest steel scrap suppliers in 2022 were China (ADSS of 215.0 Mt), the USA (63.3 Mt), and India (53.0 Mt). The EU27 exhibited an ADSS of 92.0 Mt in 2022. Figure 2 illustrates the ADSS per capita based on our estimation.

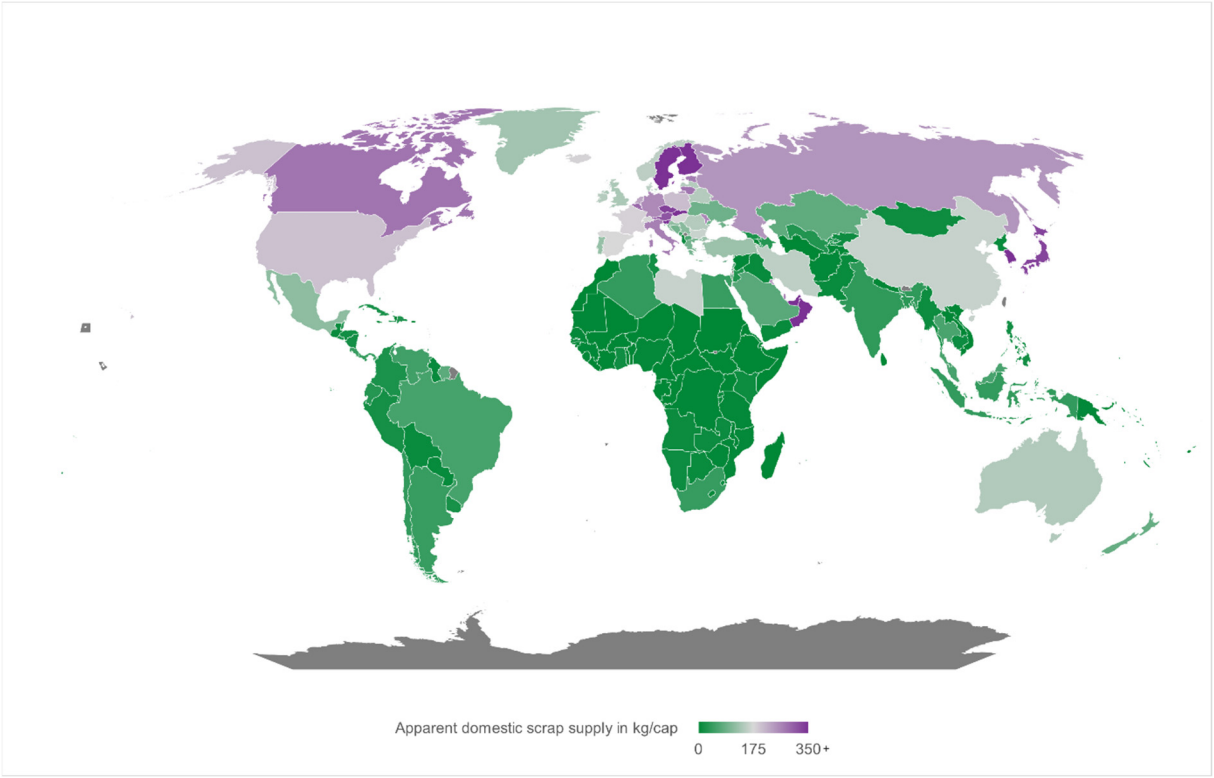


Figure 2. Estimated apparent domestic scrap supply per capita in 2021. Apparent domestic scrap supply includes home and prompt scrap figures in addition to post-consumer scrap; total scrap accumulation thus hinges on existing steel stocks as well as current steel production. Apparent domestic scrap supply is capped at 350 kg/cap to ease interpretation.

Post-consumer scrap originates from products currently in use—buildings, bridges, ships, batteries, household appliances, and many more—once they reach obsolescence. It is already the dominating form of steel scrap and it is entirely dependent on the steel use of the past. Given that most European countries amassed large in-use steel stocks (i.e., the amount of steel currently in its use phase) in the last decades, the apparent domestic steel scrap supply per capita is currently higher than in many other world regions (compare Figure 2). The question remains whether the scrap supply can keep up with increasing demand.

When considering the totality of steel scrap in industrialized countries, it is expected that the share of new scrap will decrease while the share of post-consumer scrap will increase in the coming decades. On the one hand, this is due to (expected) technical improvements in manufacturing, which lead to a more efficient use of materials [31] and, consequently, smaller new scrap yields. On the other hand, steel stocks globally are still growing, even in industrialized countries, which entails an increasing post-consumer scrap output until a stock saturation level has been reached.

Plausibly, the availability of post-consumer steel scrap will grow primarily in industrializing nations and only moderately in industrialized ones. Steel is used in long-lived applications. Therefore, the dynamic increase in steel use in nations such as China will be reflected in scrap availability with substantial time lags. In industrialized countries, steel stocks converge to saturation over time, leading to a stagnating steel demand and a plateauing scrap output at an elevated level. The list of major scrap exporting countries in 2022 (including Japan, the US, the EU-27, Great Britain, and Canada) reflects this pattern [28].

Gauging the potential of steel scrap over the next decades will be of crucial importance for the efficient recovery of a globally sought-after and traded material. While efficient wide-reach may exist on the scale of single products, retrieving steel from long-lived

applications, such as buildings and infrastructure, as well as preventing the material from being downcycled (for a differentiated view on the various dimensions of downcycling that need to be considered, see [32]) is still a Herculean task which requires political support measures as well as business efforts. Currently, there is a tendency for post-consumer scrap from any sector to overwhelmingly end up in buildings after remelting; the established "car to rebar" pipeline needs to transform into a closed material loop.

In the following section, we describe our choice of studies for the comparison of potentially available post-consumer scrap in the future and the assumptions feeding into the respective models.

3. Data and Methodology

In this study, we quantify the development and the potential bandwidth of PADPS (potentially available domestic post-consumer scrap) in Europe. We conduct a semi-structured literature review. Due to the small number of studies analyzing the future scrap supply in Europe, we do not conduct a full systematic review of the literature but compile all studies providing data which we can analyze and compare.

We collected and contrasted the results and assumptions of previous studies, focusing on plausible influencing factors and expected post-consumer scrap ranges. To this end, we conducted a wide-reaching search for academic papers as well as industry reports with a focus on post-consumer steel scrap, supplemented by citation tracking within the found publications to stake out the relevant scope of literature. During this process, material flow analyses (MFA) emerged as the main methodological framework for the desired contents. This semi-structured literature search was complemented by the discussion of preliminary results with industry stakeholders and iteratively followed pointers for further publications and reports. The collected papers and reports were then read and filtered for eligibility according to the following criteria:

(i) The publication or dataset is not older than 15 years;
(ii) Potential post-consumer scrap supply is predicted until at least 2050 and
(iii) Specifically for Europe (i.e., the EU member states) or a relevant fraction thereof;
(iv) Raw data regarding the scrap supply development were made accessible, either as Supporting Information or after a request to the respective authors.

Following these selection criteria, altogether four academic studies as well as one study by an international organization were the foundation of our comparison [33–37]. An overview of the studies, their temporal and thematic scope, as well as their respective demarcation of Europe, is given in Table 2 below. Milford et al. [35] include two diverging scrap series depending on scenario developments, yielding altogether six time series of scrap development until 2050 across all studies. Dworak et al. [33] provide multiple variants of scrap availability. We opted for their PoCSg (post-consumer scrap generated) series, which accounts for the export of end-of-life products that have not been scrapped yet, especially relevant for obsolete automobiles.

As can be gathered from the description of the studies in Table 2, future scrap supply was in some cases the main object of investigation, including downcycling issues and the complications of closing material loops. In other cases, its availability and use were addressed as one of many possible levers to reduce the overall CO_2 emissions of the steel sector.

The temporal and areal scope also varied considerably between studies. We were mainly interested in predictions until the year 2050 as a common target year for political advancements such as the European Green Deal [38]. The models in Milford et al. [35] and Xylia et al. [37] consider developments beyond the year 2050. The delimitation of Europe commonly included the current 27 members of the European Union, Great Britain (as a

former EU member and important economic player), and selected EFTA states. A notable exception is Hatayama et al. [34], whose global study modeled scrap amounts for only a handful of countries which represent steel-intensive nations of each major world region.

Table 2. Overview of compared studies, the time period and scope covered by them as well as their thematic focus.

Study	Period	Scope	Thematic Focus
Dworak et al. (2022) [33]	1911–2050	EU-27 [i] and Great Britain	Increasing rates of post-consumer scrap compared to new scrap; accumulating tramp elements and quality deterioration
Hatayama et al. (2010) [34]	1980–2050	Belgium, Luxembourg, Germany, Greece, Norway, Spain, Turkey, Great Britain	Future steel use as a function of existing stocks and economic growth; stock growth in a global perspective
Milford et al. (2013) [35]	2009–2100	Western Europe, precise scope unclear [ii]	CO_2 abatement potential of the steel sector, including energy and emission efficiency as well as material efficiency
WSA/WorldSteel (2023) [36]	2020–2050	EU-27 and Great Britain	Industry statistics
Xylia et al. (2018) [37]	1970–2100	EU-27 and Great Britain, Iceland, Norway, Switzerland	Increasing importance of the secondary steel production route; regional scrap availability and scrap trade

[i] EU-27 in this overview table refers to the member states as of 2024: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden. [ii] Defined in the original dataset as "Western Europe (all European countries which have not been part of the former Soviet Union, not Turkey and Cyprus)".

Naturally, the studies vary in their precise approach, but they do have in common that the future scrap amounts they are depicting are derived from steel within the system—that is, they generally depict the potential amount of steel scrap available if, at the end of the use phase, 100% of steel-containing products were collected for recycling at the end of the use phase and no trade happened. Material flow analysis approaches were predominantly used in the studies. While the intricacies of MFA methodology cannot be presented in an exhaustive manner here, generally, they are based on the definition of a system and its (spatial and temporal) boundaries [39] as well as the flows to and from the system and the stocks of a material accumulating within it. The principle of mass conservation needs to be adhered to [40].

Both conditions outlined above, i.e., 100% recollection rate and no scrap trade, are not meant to be realistic but serve to represent a potential maximum of secondary material which can be recovered within a given system. To differentiate this theoretical maximum of domestic post-consumer scrap from similar concepts (which may include international scrap trade or recognize the actual amounts that are collected), we term it potentially available domestic post-consumer scrap, hereafter abbreviated to PADPS. Certain key assumptions are essential for estimating PADPS and were consequently an integral consideration in most of the studies. These key assumptions and their delineation are described below.

Steel stock development and stock saturation levels. Steel stocks are the quantities of steel that currently exist within a given system. Sometimes, in-use stocks (steel in products that are currently used) and obsolete stocks (steel in products that are not in use anymore but have not been collected for recycling yet) are gauged separately. Many studies assume a saturation level beyond which existing steel stocks need to be replaced at the end of their

use phase but cease to grow further. To account for varying population densities between regions as well as future population development, this value is often expressed as steel stock in tons per capita (t/cap).

For industrialized nations, this saturation level is estimated to be between 10 and 16 t/cap [12,15,41]. It is assumed that industrializing nations will expand their steel stocks until a comparable saturation level is reached, thus steadily increasing the global per-capita steel stocks (currently at around 4 t/cap as estimated in [41]). Two main conclusions can be drawn from this assumption; first, future potential domestic scrap availability depends on the speed of convergence to the saturation level; second, only mature steel stocks will generate enough scrap to renew existing amounts and fulfill the steel demand [42] under optimal conditions. For still-growing stocks, a fully circular economy without additional material inputs is not feasible. On the global level, steel must be produced from primary raw materials to fulfill demand at least until the end of this century [5].

Product lifetimes. When estimating the amount of post-consumer scrap that becomes available for recollecting, it is necessary to assign lifetimes to steel-containing products, given that the steel stocks of today will become the future end-of-life scrap. As a compromise between data manageability and reflecting the vastly differing lifetimes between finished steel products, most studies provide lifetimes for four broader end-use categories, albeit of varied composition: construction (including buildings as well as civil engineering infrastructure), transport (e.g., cars, trucks, trains—ships are not included in all cases), machinery, and metal products (often including packaging). The average product lifetimes are generally either assumed to remain stable or increase over time for certain regions but never decrease. It is often not stated explicitly whether these lifetime assumptions include a time lag reflecting a possible period of obsolescence, i.e., between a product falling out of use and being collected for recycling. Depending on the concrete product, e.g., obsolete railways, which can lie dormant for many years before demolition, this time lag may be of a non-negligible order.

End-of-life recycling rate (EOL-RR) or recovery rate. The end-of-life recycling rate signifies how much of the obsolete material is recovered from obsolete stocks (and is not to be confused with recycling input rates, which quantify the share of scrap in steel production). Obsolete steel stocks will never entirely equal the amount of scrap available for recycling due to in-use dissipation, material dilution, techno-economic restraints in recovering material, iron lost to slag in remelting, and similar thermodynamic constraints [43,44]. Yet, even though EOL-RRs can never reach complete material recovery, they can still be vastly improved through better material sorting and material recollection, reductions in landfilling, or information storage about the materials used in buildings [45,46]. These improvements are a prerequisite to establishing closed material loops and a cornerstone of the EU's Circular Economy Action Plan [47]. Consequently, in some studies, the EOL-RR of different end-use sectors was predicted to increase until 2050. In contrast, an already established recycling rate of 100% is commonly set for home and fabrication scrap, e.g., in [37,48].

4. Results

This section is divided into three parts, presenting (i) the time series of potentially available domestic post-consumer scrap, (ii) common assumptions in scrap modeling, as laid out in Section 3, and (iii) an outlook on the transferability of the results to the stainless steel sector.

4.1. Potentially Available Domestic Post-Consumer Scrap

Figure 3 displays the annual amount of post-consumer scrap available for recollection in megatons (Mt) between 1990 and 2050, according to the studies in our sample. We focus on 2050 as the target year for a number of EU directives and include 1990 as a starting point to facilitate a comparison with the recent past. The dashed line represents an alternative scenario in Milford et al. [35]. WorldSteel provided us with values for selected years which are represented as black dots.

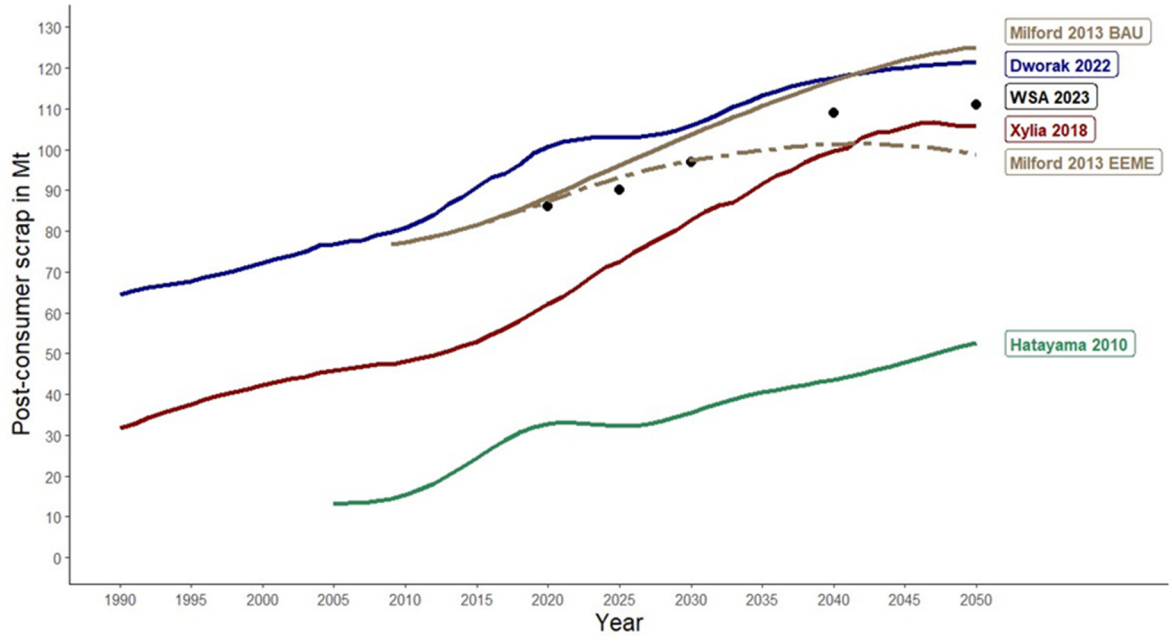


Figure 3. Time series of steel scrap availability in the different studies [33–37].

Within this time frame, the plot lines show a generally linear increase in PADPS up until a certain amount is reached, after which the annual steel falling out of use levels off. Naturally, the predicted amounts vary between studies. However, aside from the general pattern of a mostly linear increase followed by a plateau, a certain bandwidth can be gathered from the data. For 2030, PADPS in Europe is expected to be between 80 and 105 million tonnes; for 2050, it is expected to rise to 100 to 125 million tonnes of post-consumer scrap per year. Between 2010 and 2050, the average growth rate of PADPS across all series (except WSA/WorldSteel, for which no yearly values are given) is 1.6% per year. The lowest growth rate at 0.6% can be found in Milford et al.'s EEME scenario, which is plausible given that this scenario describes an earlier saturation at a lower level and even displays a decreasing PADPS towards the end of the highlighted period. In comparison, the average yearly growth rate is twice as high for the BAU scenario from the same study.

An apparent outlier in Figure 3 is Hatayama et al. [34]. However, their below-average values can be explained by their limitation to three sectors and eight countries representing Europe in a global model. Extrapolated to the whole of the EU and all sectors, their results are comparable to the values modeled in other studies, yielding approximately 93 Mt of European post-consumer scrap in 2030 and 137 Mt in 2050. Details of our extrapolation approach can be found in Appendix B.

Figure 3 reveals that most studies calculate PADPS in the same order of magnitude for the early 2020s as our estimated apparent domestic scrap supply (ADSS) of 92.0 Mt in 2022, further validating the MFA results. Recall, however, that these numbers are not directly comparable: ADSS also includes home and prompt scrap in addition to post-consumer scrap but is limited to the scrap that is actually traded and used. PADPS, on the other hand,

is by definition post-consumer scrap only but defines a theoretically available maximum of available obsolete steel in the system.

Two studies estimate the availability of post-consumer scrap until 2100 [35,37]. These studies indicate that the potentially available domestic post-consumer scrap is likely to plateau around 2050 in Europe. This phenomenon can be explained by stock saturation. When steel stocks in Europe reach their saturation levels and other factors (e.g., end-of-life recycling rates) converge to their maximum, PADPS ultimately also reaches a plateau with a time lag.

One study considers two scenarios to highlight how changes in material use affect post-consumer scrap output. These scenarios imply visible differences in the potentially available domestic post-consumer scrap in the near future. Milford et al. [35] differentiate between the post-consumer scrap amounts in a "business as usual" (BAU) and an "energy efficiency and material efficiency fully applied by 2100" (EEME) scenario. The EEME scenario combines many factors of both higher material efficiency (e.g., fabrication yield improvements, lifetime extensions, "less metal, same service" strategies) and higher energy efficiency (e.g., heightened shares of top gas recycling and direct reduction, as well as continued decarbonization of electricity generation). With these assumptions, the difference between the two scenarios is highest towards the end of the examined period; compared to the BAU scenario, the plateau phase of EEME sets in earlier and at a lower level of post-consumer scrap output per year.

Milford et al.'s [35] scenarios highlight that the potentially available domestic post-consumer scrap is not predicted based on physical laws alone but that it also depends on behavioral factors. Furthermore, contrasting the two scenarios reveals something about the time lags between behavioral changes and their impact on scrap availability. Changing demand for steel affects PADPS in ten to fifteen years at the earliest, adding to the plausibility of the bandwidth shown in Figure 3.

A final consideration is the quality of PADPS, which directly affects how much of the potential material will be remelted and actually used for new steel production. Steel contamination through insufficient recycling and hard-to-segregate alloys is a growing concern and was discussed qualitatively in most publications we found on the topic of post-consumer scrap. Among the scrap series depicted in Figure 3, only the one by Dworak et al. [33] established further subcategories of post-consumer scrap based on the included content of selected elements (quality classes Q1–Q4 with an expected content of Cu, Sn, Cr, Ni, and Mo) and attempted a quantification of PADPS quality based on the sector of origin. According to their material pinch analysis, low-purity scrap—for which there is only very limited demand—could rise to about 43 Mt/year or roughly a third of all available post-consumer scrap by 2050 if no further changes are implemented.

4.2. Commonly Included Determinants of Scrap Availability

The typically considered determinants for which concrete values need to be assumed in order to determine future potential post-consumer scrap amounts were outlined in Section 3. They encompass the steel presently in the system (steel stocks) as well as a likely period of it leaving the system (end-use sector shares and corresponding product lifetimes). End-of-life recycling or recovery rates (EOL-RR)—the fraction of now-obsolete scrap that is actually collected—are not a primary consideration in determining the scrap that is theoretically available (i.e., PADPS). However, given that EOL-RR assumptions feature prominently in the respective studies and are relevant for estimating the amounts that are truly recoverable, they were included here. The assumptions for lifetimes by sector, recycling rates, and stock development in the respective studies can be found in

Table 3 below. While the origin of these assumptions was not studied systemically, some cross-citation of values between studies became noticeable.

Table 3. Comparison of relevant assumptions for modeling post-consumer scrap supply in Europe across the studies.

	Product Lifetimes (Years)				Recycling Rates (%)				Steel Stocks (t/cap)	
Study	**Con**	**Tra**	**Mac**	**Pro**	**Con**	**Tra**	**Mac**	**Pro**	**2010**	**2050**
Dworak et al. (2022) [33]	65	15 [i]	15–17.5	14	82–87	82–98	87–91	58–71	9.5	10.5
Hatayama et al. (2010) [34]	60	13	15	-	not considered				4 [ii]	9 [ii]
Milford et al. (2013) [iii] [35]	75	20	30	15	85–90	85–95 [iv]	90–95	50–75	saturation at 12.8 in 2030	
WSA/WorldSteel (2023) [v] [36]	35–80	8–18	10–25	4–12	80% across sectors				22.8 in 2021	
Xylia et al. (2018) [37]	75 [vi]	20	30	15	60% to 85%, aggregated across sectors				saturation at 12	

Con = construction, Tra = transport equipment, Mac = industrial machinery and industrial goods, Pro = finished metal products. Where two values are given for the end-of-life recycling rate, the higher end represents an assumed future development. [i] Lifetime assumption for cars & trucks only; "other transport": average lifetime of 55 years. [ii] Own calculation based on the in-use stock levels provided by the study authors as well as past and predicted population numbers by the UN. [iii] While the suggested citation for the scrap dataset by the original authors is [35], the corresponding modeling assumptions can be found in [5]. [iv] automotive only. [v] values obtained in personal communication. [vi] product lifetime values adapted from [5].

Product lifetimes. The four categories of steel products laid out in Table 3 are the smallest common denominator of product classes across the studies; in some cases, we merged sub-classes. While the details of how these categories are delimited vary (see Section 3 for details) and are often not precisely documented, the order of magnitude still remains close in comparison. Some studies work with the average lifetime of a product category, while others make use of distributions. Note that steel stocks are not spread evenly across these sectors; regional differences notwithstanding, construction and civil engineering, which are by far the most long-lived applications, generally account for the majority of steel present in the system.

While the different lifetime values in Table 3 are comparable estimates, it would be beneficial to pin down the lifetime distributions more reliably in future studies. In the global sensitivity analysis of their model, ref. [5] shows that out of four different parameters (product lifetimes, stock saturation level, stock saturation year, and population development), a steel product lifetime increase or decrease by 30% has the most sizable impact on global scrap availability until the end of the century. This indicates that significant effects on scrap availability may be hinging on this factor.

Recycling rates. Although a precise amount of past and future steel stocks is not available, recycling rates are generally estimated to be in the ballpark of 80%, with a tendency to increase in the coming years, as Table 3 demonstrates. In the two studies that considered a sector split for recycling rates, it is notable how metal products display comparatively small recovered amounts after the end of the use phase.

Steel stocks. Steel stocks are the factor with the most obvious differences between studies. On the one hand, current steel stocks are not directly observable; instead, they need to be inferred from data such as iron and steel trade, total railway length and other infrastructure measures, or degree of urbanization. This data uncertainty explains why steel stocks across the studies vary so considerably and in parts by over 100%, even for past years (compare [33,36])—it is simply not a factor that can be observed without hurdles.

On the other hand, differences in the approach to modeling future steel stocks exacerbate comparability issues: some studies model stock development across time based on current growth rates or estimate a number for certain years while some consider a saturation level at which the in-use stocks cease to grow further. The per-capita values by themselves introduce a non-negligible degree of uncertainty, as future population development is likewise modeled using a number of assumptions.

Other factors. The factors laid out in Table 3 represent the ones most commonly considered across the studies as well as the most crucial ones for estimating future scrap amounts, thus lending themselves to comparison. Nevertheless, other relevant properties are sometimes considered. Although they cannot be compared systematically due to their infrequent appearance, some will be briefly listed here to provide an idea of further possible influences on potentially available scrap.

While trade of scrap is not a consideration for assessing PADPS, the data by Dworak et al. [33] account for the export of end-of-life products from the transport sector. This export of not-quite-yet-scrap is of a non-negligible order (set to 30% for cars and even 70% for trucks in the study) and reduces the amount of post-use steel in the system. Xylia et al. [37] employ past values of apparent steel use, an indicator accounting for steel production and net import/exports of a country, to gauge the steel presently in the system. Finally, a number of material efficiency strategies, as laid out in Milford et al. [35], have significant potential to influence the future availability of scrap; for example, product lifetime extensions lead to later obsolescence, while "less metal, same service" strategies (e.g., through lightweighting objectives in product design) inspire a lower level of in-use stocks. The whole array of considered efficiency measures realized to the full possible extent leads to the EEME scenario in Figure 3.

4.3. Special Case: Stainless Steel

Stainless steel accounts for approximately 3% of global steel production. Nevertheless, the PADPS of stainless steel scrap is of interest in and of itself for three reasons. First, recycling one ton of (nickel-containing austenitic) stainless steel saves substantially more greenhouse gas emissions than recycling carbon steel scrap, approximately 6.7 t of CO_2 per ton of scrap [49]. These larger reductions can be ascribed to avoiding the carbon-intensive refining of chrome and nickel. Second, recycling stainless steel scrap mitigates the demand for primary nickel, which is expected to rise in the coming decades because of its use in batteries [50]. Third, stainless steel production and recycling take place in separate value chains. The flows of stainless steel and stainless scrap need to be considered separately because of their content of alloying materials and different sectoral shares compared to carbon steel. Unfortunately, most material flow analyses of stainless steel are only backward-looking [51,52]. A current study by KIT [53] only quantifies historic scrap inputs as well. Other recent studies focus on the individual metals nickel and chrome rather than stainless steel as the overarching composite material [54–58]. Therefore, no quantitative predictions about future stainless steel scrap availability can be made at the moment.

5. Discussion

This study seeks to quantify the amounts of potentially available domestic post-consumer steel scrap (PADPS) which are available for recycling in Europe until 2050. To this end, we analyze modeling studies with material flow analysis as their core method. We derive the general trends and bandwidth of PADPS as well as key assumptions of the studies in our sample.

Our results indicate a moderate increase in potentially available domestic post-consumer scrap in the coming decades. In 2030, between 80 and 105 Mt of post-consumer

scrap should be theoretically available for recycling. In 2050, this amount is expected to rise to 100 to 125 Mt. That corresponds to an average annual growth rate of PADPS of approximately 1.6%. The bandwidth of PADPS shrinks until 2050, indicating that the studies' results converge rather than diverge in the future. The amount is likely to plateau after 2050. Due to long steel product lifetimes, even recent changes in consumption and production behavior would be unlikely to have major impacts on PADPS within ten years' time.

In 2022, the EU's steel producers consumed 79.4 Mt of scrap, corresponding to a recycled content of 58% in that year (compare Figure 1). These include home, manufacturing, and post-consumer scrap. This amount of scrap consumption falls within the range predicted by the studies, which estimate PADPS to be between 66 and 102 Mt in the same year. Scrap use in steel production and PADPS cannot be compared at face value, however, because (i) scrap use in steel production includes fabrication and home scrap, (ii) scrap use in steel production is a reported variable, while PADPS is estimated based on plausible assumptions, and (iii) trade flows (i.e., steel scrap imports to and exports out of the EU) are not considered in the modeling of PADPS. However, the juxtaposition of these factors reveals that the results of the studies in our sample yield plausible amounts of post-consumer scrap availability.

It is to be expected that no two models will make the same predictions for the future, yet the results show a considerable variation in scrap amounts even for the past. A small amount of variation may be attributable to the different areal scopes of Europe applied in the studies (see Table 2). Most of the divergence of past scrap amounts, however, is due to in-use stocks not being readily available and observable data. Steel in-use stocks are rather estimated by means of proxy values such as the past apparent steel use of a country and trade flows of iron ore, steel intermediates, and scrap; this is complemented by reasonable assumptions about material losses, product obsolescence, unrecorded trade, or landfilling.

A multitude of assumptions and modeling decisions underlie the studies that we analyzed. We investigated how key assumptions, such as the product lifetimes, affected the results. However, model complexity and the number of assumptions made it impossible to reveal the precise influence of the chosen parameters. What future steel scrap amounts can be expected if, ceteris paribus, the average assumed lifetime for buildings is extended by 10 years or if a steel stock saturation level in Europe is not reached before 2070? Some sensitivity analyses in the studies provided glimpses into alternative future scenarios. Yet, in order to answer this kind of question in a more comprehensive manner, a comparison of the models themselves would be necessary, akin to the work of the Stanford Energy Modeling Forum (e.g., [59] for carbon pricing modeling). Due to the rising complexity of models, this takes a dedicated effort paired with programming expertise and standardization guidelines (for an overview of possible pathways and obstacles, see [60]). This endeavor would not only contribute to a better understanding of the models but also illustrate side effects within a circular economy. For example, a longer lifetime for buildings would reduce demand for construction materials but also lower PADPS in the future.

Further modeling exercises have been conducted by international organizations and consulting firms. Unfortunately, we could not include their insights in our study because detailed results and assumptions are unavailable due to confidentiality reasons. Fostering cooperation between academic research groups as well as those in international organizations and consulting firms could generate synergies when mapping the future of the circular use of steel.

An increasing amount of post-consumer scrap, combined with stagnant or falling amounts of home and prompt scrap, implies changes in the composition of raw materials from recycling. Scrap increasingly stems from discarded products rather than production processes. This trend will exacerbate the challenges posed by contaminants such as cop-

per [9]. The scenario outlined by Dworak et al. [33], i.e., an abundance of low-purity scrap if no countermeasures are taken, thus seems realistic. Therefore, more effort will be necessary to separate and process post-consumer scrap in order to avoid downcycling and, ultimately, losing precious material. Downcycling issues are a prevalent concern, although they are usually only discussed qualitatively; it is difficult to estimate the amounts of post-consumer scrap that are likely to be contaminated by which material and to which degree. A focus on research and development funding in adjacent fields—such as resource efficiency, material sorting and purifying technology, backward logistics of steel products to the manufacturer, alloyed steel reuse, building information modeling, and material-preserving demolition—from both industry and policymakers will be necessary to tackle this large-scale issue from different angles.

As stated before, Europe is lacking in primary steelmaking resources while being a main player in steel production and steel use. Therefore, it is possible that the EU will become a net scrap importer, and protectionist measures will be discussed to keep a tight hold on scrap as a secondary resource. It is imperative to recognize steel scrap, as well as the contained alloying elements, as finite resources and to strive for circularity.

Steel scrap is likely to become an increasingly important raw material for Europe's steel industry. It reduces greenhouse gas emissions compared to the blast furnace-basic oxygen furnace route, and it reduces electricity consumption compared to hydrogen-based primary steel production. Providing high-purity steel scrap, which can be used to produce steel for demanding applications (e.g., the automotive sector), is associated with higher processing costs. Our results highlight this challenge: they show a trend towards a greater accumulation of post-consumer scrap. The steel recycling industry and the steel industry should jointly create a market for high-purity scrap on which a premium for high-quality scrap is paid to justify the additional costs of providing this quality.

Policy makers should incentivize setting up this market, which rewards more sophisticated processing of steel scrap. For instance, programs that promote green steel production could be extended to include scrap processing projects to reduce costs for the first adopters of these processes and to ease their introduction to the market.

Circularity in the bigger picture, however, starts way before scrap collected for recycling is being processed to achieve the demanded qualities. It rather relies on strategic thinking along the whole product lifecycle. This includes multiple stages and participants in order to achieve long-term sustainable supply chain management as well as a rethinking of scrap as a commodity [61].

Some studies (e.g., [62,63]) make the case for thinking in supply networks rather than supply chains due to their increasing complexity and interconnectedness. Analyzing the (positive as well as negative) interactions in such a network, as well as the required conditions for efficient backward logistics [63], will provide insights into a more sustainable scrap steel management that delivers the needed qualities where they are required while minimizing material losses and thus closing the material cycle.

In the future, the uncertainty regarding actual steel stocks may be alleviated through material or product passports [64,65], especially for large steel sinks such as buildings and infrastructure. These passports, once established, will trace, among many other factors, the amount and form of materials built into a given construction (as a simplified example for steel: carbon steel or alloyed steel, sheet steel or rebar), thus aiding the process of demolition and recycling at the end of its service life. However, the details, scope, and standardization of material passports across product groups remain issues that need to be solved. In the intervening time, the extended use of administrative records and remote sensing are promising methods to better gauge the steel currently in the system [66,67] and to verify the results of material stock modeling, at least for certain sectors. While the scope

is mostly limited to buildings and similar large-scale, above-ground objects, this is still an advancement given that the construction sector is prone to an elevated level of stock uncertainty due to the long lifetimes and variety of included steel parts.

6. Conclusions

Our review of the literature revealed the general outcome that potentially available post-consumer scrap originating from European in-use stocks will continue to grow until the middle of the century, after which it is deemed to reach a plateau. An average increase in potentially available domestic post-consumer scrap (PADPS) of 1.6% per year is expected. The estimated 100 to 125 Mt in 2050 constitute a substantial urban mine. However, it needs to be kept in mind that the amount of potentially available scrap, even if the predictions made in the studies are accurate, does not equal the amount of scrap available on the market, as recycling and recovery activities need to be taken into account. Estimated recollection and recycling levels range between 60 and 95%, depending on the respective study and sector of origin. This bandwidth shows that the amount of material which is actually collected from the respective sectors of origin remains an area of high uncertainty.

The main methodology of gauging post-consumer scrap in the reviewed papers are material flow analyses (MFA), which commonly frame PADPS as (obsolete) steel stocks. Broadly speaking, an MFA estimates the material input into a system (e.g., through steel consumption of the past) and employs product lifetimes for assessing when the steel stock will fall out of use. Both factors carry their own uncertainty, as the comparison of modeling assumptions has shown, but are the best basis for stock predictions in the absence of observable data.

In addition to the amount of PADPS, the quality of post-consumer scrap is often discussed qualitatively as an issue that contributes to a suboptimal use of currently obsolete stocks. A quantification, however, is complex as it needs to take a variety of alloying elements, impurity sources, the separate stainless steel market, and the demands of the target sector into account. This calls for further interdisciplinary research to paint a more thorough picture of the post-consumer scrap situation in Europe and worldwide.

Simultaneously, the quality of post-consumer scrap is not inherently lacking but rather depends on the effort put into sorting and processing this resource. Growing demand for high-quality and high-purity steel scrap, as opposed to primary raw material demand, would incentivize the extension of current efforts. At the same time, ensuring the quality of scrap steel cannot be the sole responsibility of recyclers at the end of a product's lifetime. Instead, its recyclability and longevity in the product cycle need to be a dedicated thought in all steps before steel ultimately becomes scrap—this includes upstream factors such as product design, consumer behavior, backward logistics, or information modeling.

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Appendix A. Estimating Domestic Scrap Supply: Further Explanations and Tests

Tables A1 and A2 show statistical tests and panel data models to further explore the statistical properties of our dataset. These estimates and tests have been conducted in a sample without China.

Table A1. Results of the statistical tests and sensitivity checks.

		F-Test		
	F-Statistic	**df1**	**df2**	***p*-Value**
Country FE	488.3 ***	37	165	$<2.2 \times 10^{-16}$
Time-FE	381.91 ***	20	182	$<2.2 \times 10^{-16}$
Two-way FE	417.42 ***	46	156	$<2.2 \times 10^{-16}$
	Breusch–Pagan Lagrange Multiplier Test			
	χ^2	**df**	***p*-value**	
Country FE	0.89995	1	0.3428	
Time-FE	0.34836	1	0.555	
Two-way FE	1.2483	2	0.5357	
	Hausman Test			
	χ^2	**df**	***p*-value**	
Country FE	23.518 ***	3	3.149×10^{-5}	
Time-FE	17.834 ***	3	0.0004759	
Two-way FE	18.065 ***	3	0.0004264	
	Levin–Lin–Chu Panel Unit Root Test			
	z	***p*-value**		
CONS	−5.1712 ***	1.163×10^{-7}		
BOF	−5.2677 ***	6.909×10^{-8}		
EAF	−4.2875 ***	9.033×10^{-6}		
DRI	−3.5911 ***	0.0001647		
	Im–Pesaran–Shin Panel Unit Root Test			
	$W\bar{t}$	***p*-value**		
CONS	−3.3672 ***	0.0003797		
BOF	−3.7985 ***	7.278×10^{-5}		
EAF	−2.5614 ***	0.005213		
DRI	−2.3726 ***	0.008832		

*** $p < 0.01$.

Table A1 displays the results of F-Tests that reject the pooled OLS model, showing that country fixed effects, time fixed effects, and two-way fixed effects are all jointly statistically significantly different from zero.

Table A2 displays the estimates for models with country fixed effects (column I), time fixed effects (column II), and two-way fixed effects (column III). In all cases, the estimated coefficients for β_{BOF} and β_{EAF} are all significant. Introducing country fixed effects (columns I and III) has a substantial influence on the coefficients. The implied recycling content of EAF steel decreases to an implausibly low value of 840–850 kg per ton. Time fixed effects (column II) yield similar parameter estimates as our preferred specification of the pooled OLS model (column III in Table 1).

The country-specific intercepts mask the relationship between steel production and scrap consumption. Plausibly, the variation of steel production and scrap consumption in our sample is insufficient to distinguish between their relationship and truly country-specific determinants of scrap consumption, such as efficiency differences between steel-producing nations. Therefore, the fixed effects models are not suitable for predicting scrap consumption of countries without observed data.

The Breusch–Pagan Lagrange Multiplier Test tests the null hypothesis that the individual-specific component of the error term is zero. As shown in Table A1, we are unable to reject this hypothesis. The Hausman tests displayed in Table A1 also reject a random effects model in favor of a fixed effects model. Nevertheless, column IV in Table A1 shows the parameter estimates for a random effects model of scrap consumption because the random effects model allows us to predict the scrap consumption for countries that are not part of the sample.

The coefficient of the BOF route (β_{BOF}) equals 0.1579, and that of the EAF route (β_{EAF}) equals 1.0171. These values resemble those of the preferred pooled OLS specification. The random effects model finds a stronger impact of DRI consumption (β_{DRI}) on scrap consumption. One ton of DRI consumption replaces approximately 605 kg of steel scrap.

We employ two tests to check for non-stationarity in our data. First, we use the Levin–Lin–Chu panel unit root test [68]. Second, we use the Im–Pesaran–Shin panel unit root test [69], which allows for heterogeneity in the panel. We must exclude the European countries when testing for non-stationarity because their time series contain gaps. We also exclude Canada because there are only three associated observations.

Table A1 shows that the null hypothesis of non-stationarity is rejected for all variables and for both statistical tests. This result indicates that random walks or trends in the variables do not pose an issue for our estimation. The results of the unit root tests should be interpreted with care for three reasons. First, it is only applied to five countries (USA, Japan, Turkey, Russia, and Republic of Korea). Second, the panel covers a relatively short time period of ten years. Third, these ten years include the COVID-19 pandemic during which steel production and, thereby, scrap consumption fell temporarily.

We estimate two more specifications of our model of scrap consumption to investigate how strategies to tackle non-stationarity would affect the estimates. Column V of Table A2 shows the result of a model with country-specific time trends that capture the (heterogeneous) development of steel production and scrap consumptions in the nations in our sample. These estimated coefficients resemble those of our preferred specifications of the pooled model.

Column VI of Table A2 displays the results of a first-differences model. The coefficients resemble those of the country and two-way fixed effects models (columns I and III). This suggests that taking first differences also masks the relationship between steel production and scrap consumption, making them unsuitable for predicting scrap consumption in those countries not part of our sample.

Table A2. Recycled content by production route (FE, RE, and FD).

	I Country-FE $CONS_{r,t}$	II Time-FE $CONS_{r,t}$	III Two-Way-FE $CONS_{r,t}$	IV RE $CONS_{r,t}$	V Time Trends $CONS_{r,t}$	VI FD $CONS_{r,}$
β_{BOF}	0.2015 * (0.0778)	0.1262 *** (0.01783)	0.1637 * (0.06947)	0.1579 *** (0.03651)	0.1217 *** (0.0056)	0.2479 *** (0.04122)
β_{EAF}	0.8506 *** (0.1372)	1.0343 *** (0.03942)	0.8378 *** (0.14137)	1.0171 *** (0.05345)	1.0654 *** (0.0103)	0.8491 *** (0.0738)
β_{DRI}	−0.5244 (0.3349)	−0.4068 (0.34846)	−0.5341 (0.34665)	−0.6045 (0.37099)	−0.5293 *** (0.1326)	0.4496 *** (0.11796)
Observations	195	195	195	195	195	168
R^2	0.7443	0.9945	0.6922	0.9624	0.9986	0.8895
Adj. R^2	0.6994	0.9942	0.6172	0.9621	0.9983	0.8882
F-Statistic	160.13 *** (df = 3; 165)	11,004.11 *** (df = 3; 182)	116.95 *** (df = 3; 156)		6103.78 *** (df = 3; 165)	441.60 *** (df = 3; 165)

* $p < 0.10$, *** $p < 0.01$. Note: Robust standard errors in parentheses.

Ultimately, we use the coefficients of the pooled OLS model without China and exclude the intercept, as shown in column III of Table 1, to predict scrap consumption in countries without observed data. It constitutes a simple and transparent model whose parameter estimates closely resemble those with country-specific time trends as well as the random effects model. The statistical tests shown in Table A1 favor fixed effects models. However, the implausible parameter estimates show that these models fail to distinguish between country-specific particularities and the technological relationship between steel production and scrap consumption.

Our estimates imply global steel scrap consumption of 679 Mt in 2022. 470 Mt thereof were consumed in the BIR's seven key countries and regions. The largest scrap consumers were China (215 Mt), India (60 Mt), and the USA (57 Mt).

Equipped with the (estimated) scrap consumption, we use Equation (1) to compute the apparent domestic scrap supply. Globally, *ADSS* and *CONS* correspond to each other because all scrap consumed must have been supplied somewhere. The countries with the largest apparent domestic scrap supply in 2022 were China (215 Mt), India (60 Mt), and the USA (59 Mt). Dividing these values by the countries' population yields apparent domestic scrap supply per capita, as displayed in Figure 1.

Appendix B. Systematizing the Scrap Amounts by Hatayama et al. [34]

In Section 4, it was mentioned that the results by Hatayama et al. [34] differ significantly due to the scope of 8 countries as well as the limitation to 3 sectors (civil engineering, buildings, vehicles) instead of the 4 most common steel product categories detailed in Table 3. As a back-of-the-envelope approach to establishing comparability with the wider areal scope of the other studies, the 2022 steel use levels from WorldSteel [36] were used to approximate the stock share of the 8 countries included in Hatayama et al. [34] in relation to the EU (plus the non-EU countries included: Norway, Turkey, UK). This approximation puts the 8 countries at roughly half the steel use of the current EU plus Norway, Turkey, and the UK. Combined with an additional factor to balance the inclusion of fewer sectors, which are roughly gauged to encompass about 70% of all material end uses of steel, this yields upscaled post-consumer scrap amounts comparable to those of the other studies: about 93 Mt in 2030 and 137 Mt in 2050. This upscaling approach is entirely our rough estimate for the sake of comparability and does not in any way reflect the premises of the original authors.

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