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European post-consumer steel scrap in 2050: A review of estimates and modeling assumptions

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Abstract

This paper 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 when the expected yearly steel product obsolescence of the system stabilizes. Between 2010 and 2050, PADPS is expected to rise annually 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 estimating the 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

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Zusammenfassung

Dieser Artikel untersucht die Verfügbarkeit von Stahlschrott in Europa bis zum Jahr 2050. Dazu wird der Indikator PADPS (*potentially available domestic post-consumer scrap*, potenziell verfügbare inländische Altschrottmenge) eingeführt. Dieser gibt den Anfall von Stahlschrott nach Beendigung des Produktlebenszyklus aber vor internationalem Handel mit Schrotten an. Zu diesem Zweck werden Materialflussanalysen aus Wissenschaft und Industrie analysiert. Die Studien deuten auf einen Trend wachsender Altschrottmengen hin, der sich erst beim Erreichen eines Sättigungslevels auf einem gleichbleibenden Niveau jährlich anfallender Schrottmengen stabilisiert. Zwischen 2010 und 2050 wird ein Anstieg von PADPS von ungefähr 1,6% pro Jahr erwartet. In der Ökonomie befindliche Stahlmengen (*Steel Stocks*), Recyclingraten und Produktlebenszeiten kristallisieren sich als die Faktoren heraus, die bei der Schätzung von PADPS in Studien am häufigsten bestimmt werden. Recyclingraten und Produktlebenszeiten weisen in den Studien vergleichbare Werte auf. Die Abschätzung der *Steel Stocks* ist mit größeren Schwankungen behaftet und trägt zu größeren Unsicherheiten bei der Modellierung zukünftig verfügbarer Schrottmengen bei.

Schlüsselwörter: Stahlschrott; Stahlrecycling; Altschrott; Steel Stocks; Europa; 2050; systematische Literaturanalyse

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Abbreviations

PADPS	potentially available domestic post-consumer scrap
MFA	material flow analysis
BF-BOF	Blast Furnace – Basic Oxygen Furnace
EAF	Electric Arc Furnace
EOL-RR	end-of-life recycling/recovery rate

1 Introduction

Steel production is responsible for approximately 7% of global greenhouse gas emissions (International Energy Association, 2020) and 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 (Broadbent, 2016; World Steel Association, 2021). 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 (Pauliuk et al., 2013a) – 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 steel making, which are not established on an industrial scale yet (e.g. International Energy Association, 2020; Fan and Friedmann, 2021), steel recycling relies on a well-established value chain, is a low-cost approach to decarbonizing steel production (Richardson-Barlow et al., 2022) 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 policy coming into action.

However, supplying sufficient quantities and qualities of steel scrap is not possible without increased efforts. Contaminants such as copper limit the range of products manufacturable from scrap and, if they accumulate over time, turn a fraction of scrap unusable (Daehn et al., 2017). 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. The availability of scrap in the future is, therefore, an important variable for developing efficient pathways (e.g. Eurofer, 2019) towards climate-neutral steel production and a circular economy. Pursuing ambitious climate policy goals and lacking domestic primary raw material reserves, the European Union is particularly dependent on a reliable understanding of scrap availability.

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 domestic steel scrap supply per capita is currently higher than in many other world regions (compare Fig. 1). The question remains whether scrap supply can keep up with increasing demand.

A number of studies employ material flow analyses (MFAs) to study the stocks and flows of steel globally (Oda et al., 2013; Pauliuk et al., 2013b; Yellishetty et al., 2010; Wang et al., 2021) or in individual regions and countries (Cooper et al., 2020 for the US; Ohno et al., 2014 for Japan; Gauffin et al., 2016 for Sweden). Some of these studies investigate the availability of scrap explicitly (Passarini et al., 2018; Morfeldt et al., 2015) while others estimate scrap availability as an input to quantify other variables such as the energy demand of the steel sector (Pardo and Moya, 2013). 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.

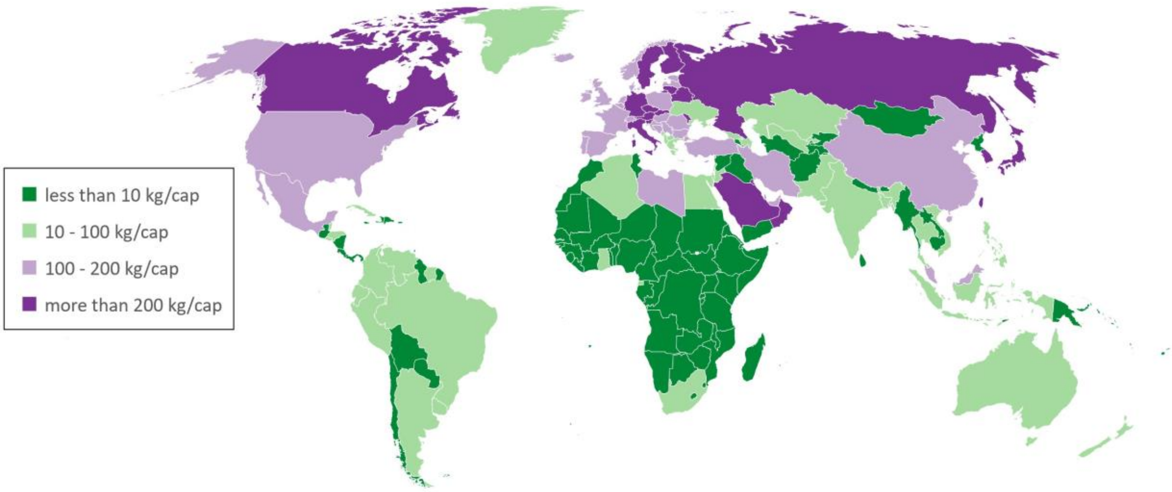

Figure 1 Estimated apparent domestic scrap supply per capita in 2022.
Apparent domestic scrap supply includes home and prompt scrap figures in addition to postconsumer scrap; total scrap accumulation thus hinges on existing steel stocks as well as current steel production. Own calculations based on BIR figures; methodological background of estimation to be found in Appendix A.

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 three main contributions. First, we identify the trend and bandwidth of scrap available in Europe supported by existing studies. Second, we uncover main assumptions underlying the studies and sketch how they relate to the resulting numbers. Third, we show whether the issue of tramp elements can be addressed qualitatively and quantitatively.

The study proceeds as follows. We start with an overview of the common flows of steel scrap and the current situation in Europe in Section 2. 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 variation as well as commonly and less commonly considered influencing factors. Section 5 discusses the validity, variance, and political implications of our results.

2 Steel and steel scrap

Steel is a “material with iron as the predominant element, having a carbon content generally less than 2.0% and containing other elements” (ISO, 1982). Steel’s properties can be modified by alloying elements other than iron and carbon (e.g. Verhoeven, 2007). Stainless steel, for instance, obtains its exceptional resistance to corrosion from adding at least 10.5% of chromium and limiting its carbon content to 1.5% (ISO, 2014).

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 steel making itself is denoted internal or home scrap. It is recycled immediately within the mill or foundry and is usually not available on the market. 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 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 2 displays the relation of 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). Turkey is by far the world’s biggest steel scrap importer (Bureau of International Recycling, 2022) and has the highest rate of scrap use in steel making of these countries with up to 90% scrap input. China’s scrap use on the other hand has been slowly increasing 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.

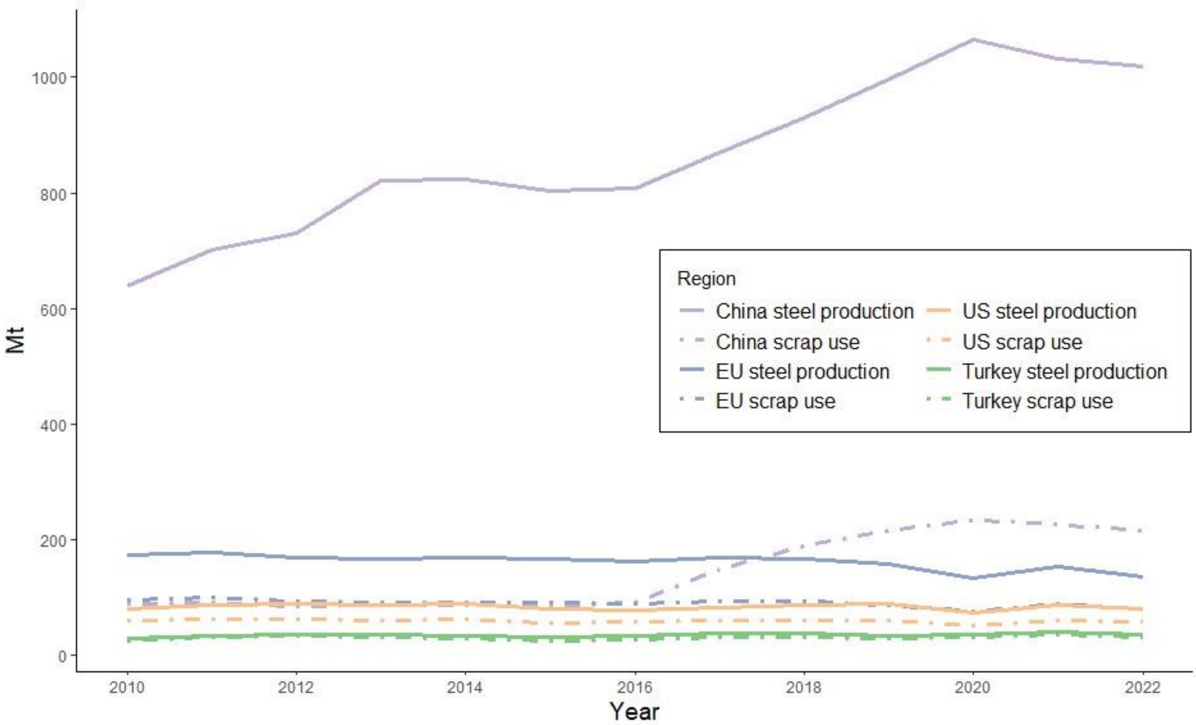

Figure 2 Overall steel production and scrap use in steel production of selected countries, 2010 – 2021.

Data obtained from *World Steel Recycling in Figures* by the Bureau of International Recycling. The BIR's scrap consumption data includes home and prompt scrap as well as postconsumer scrap (Willeke, 2023). Before 2021, EU numbers refer to 28 member states; in 2021 and 2022, to 27 member states due to Great Britain leaving the European Union.

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 (Bataille et al., 2021) 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, Canada) reflects this pattern (Bureau of International Recycling, 2023).

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

3 Data and Methodology

In this study, we collect and contrast the results and assumptions of previously conducted studies, focusing on plausible influencing factors and expected post-consumer scrap ranges. The choice for inclusion was made based on 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 was made accessible, either as Supporting Information or after a request to the respective authors.

Following from these selection criteria, altogether four academic studies as well as one study by an international organization are the foundation of our comparison: Milford et al. (2013), Dworak et al. (2022), Xylia et al. (2018), Hatayama et al. (2010), and World Steel Association (2023a). An overview of the studies, their temporal and thematic scope as well as their respective demarcation of Europe is given in Table 1 below. Milford et al. (2013) include two diverging scrap series depending on scenario developments, yielding altogether 6 time series of scrap development until 2050 across all studies. Dworak et al. (2022) provide multiple variants of scrap availability. We opted for their PoCSg (postconsumer scrap generated) series, which accounts for the export of end-of-life products that have not been scrapped yet, especially obsolete cars.

As can be gathered from the description of the studies in Tab.1, 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 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 (European Commission, 2019). The models in Milford et al. (2013) and Xylia et al. (2018) 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. (2010), whose global study modeled scrap amounts for only a handful of countries which represent steel-intensive nations of each major world region.

Study	Period	Scope	Thematic Focus
Dworak et al. (2022)	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)	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)	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 (2023)	2020-2050	EU-27 and Great Britain	industry statistics
Xylia et al. (2018)	1970-2100	EU-27 and Great Britain, Iceland, Norway, Switzerland	increasing importance of the secondary steel production route; regional scrap availability and scrap trade

Table 1 Overview of compared studies, the time period and scope covered by them as well as their thematic focus.

[i] EU-27 in this overview table refers to the member states as of 2023: 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 approaches, but they do have in common that the future scrap amounts which 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. Both conditions 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 consequently were an integral consideration in most or all 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 which currently exist within a given system. Sometimes, in-use stocks (steel in products which are currently used) and obsolete stocks (steel in products which are not in use any more but have not been collected for recycling yet) are considered 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 (Watari et al. 2020; Pauliuk et al. 2013b; Cooper et al. 2020). It is assumed that developing 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 by Watari et al. 2020). 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 (Müller et al., 2011) 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 the century (Pauliuk et al., 2013a).

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 4 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 quantifies the share of scrap in steel production). Obsolete steel stocks will never be entirely equal to 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 (Gonzalez Hernandez et al., 2018; Reuter et al., 2019).

However, while EOL-RRs can only ever approach 100%, they can still be improved through better material sorting and material recollection, reduction of landfilling, or information storage about the materials used in buildings (Nakamura et al., 2014; Charpentier Poncelet et al., 2022). These improvements are a prerequisite to establishing closed material loops and a cornerstone of the EU's Circular Economy Action Plan (European Commission, 2020). 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. Watari and Yokoi 2021; Xylia et al. 2018).

4 Results

This section is divided in 3 parts presenting (i) the time series of potentially available domestic post-consumer scrap, (ii) common assumptions featuring into 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. (2013). The World Steel Association provided us with values for selected years which are represented as black dots.

Within this time frame, the plot lines show a generally linear increase of PADPS up until a certain amount is reached after which the steel falling out of use annually 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, for which no yearly values are given) is 1.6% per year. The smallest growth rate at 0.6% can be found in Milford et al. (2013)'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.

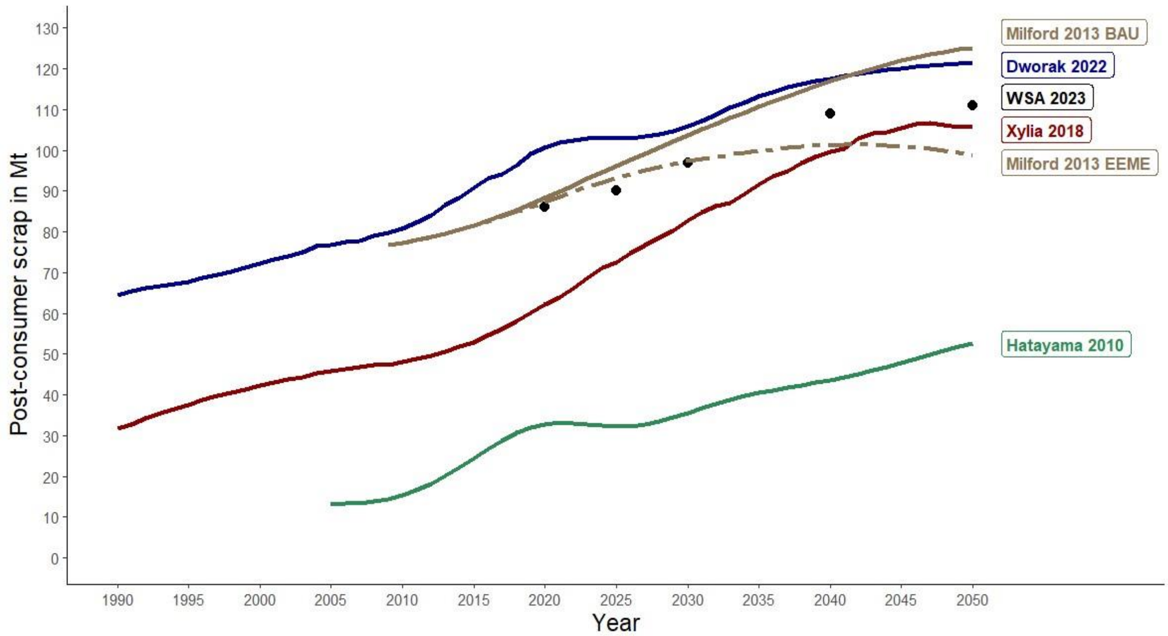

Figure 3 Time series of steel scrap availability in the different studies.
Studies named by first author only, with the exception of WSA (World Steel Association) data. BAU: Business As Usual scenario, EEME: Energy & Material Efficiency scenario.

An apparent outlier in Fig. 3 is Hatayama et al. (2010). However, their below-average values can be explained by their limitation to 3 sectors and 8 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.

Two studies estimate the availability of post-consumer scrap until 2100 (Milford et al., 2013; Xylia et al., 2018). 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. (2013) 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 a 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. (2013)'s scenarios highlight that the potentially available domestic postconsumer 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 Fig. 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 Fig. 3, only the one by Dworak et al. (2022) 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 to a third of all available post-consumer scrap by 2050 if no further improvements are made.

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 which is actually collected – are not a primary consideration in determining the scrap which 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 which 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 2 below. While the origin of these assumptions was not studied systemically, some cross-citation of values between studies became noticeable.

Product lifetimes. The four categories of steel products laid out in Table 2 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.

	Product lifetimes (years)				**Recycling rates (%)**				**Steel stocks (t/cap)**	
Study	**con**	**tra**	**mac**	**pro**	**con**	**tra**	**mac**	**pro**	**2010**	**2050**
Dworak et al. (2022)	65	15[i]	15 - 17.5	14	82 - 87	82 - 98	87 - 91	58 - 71	9.5	10.5
Hatayama et al. (2010)	60	13	15	-	not considered				4[ii]	9[ii]
Milford et al. (2013)[iii]	75	20	30	15	85 - 90	85 - 95[iv]	90 - 95	50 - 75	saturation at 12.8 in 2030	
World Steel Association (2023)[v]	35 - 80	8 - 18	10 - 25	4 - 12	80% across sectors				22.8 in 2021	
Xylia et al. (2018)	75[vi]	20	30	15	60% to 85%, aggregated across sectors				saturation at 12	

Table 2 Comparison of relevant assumptions for modeling post-consumer scrap supply in Europe across the studies.

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 is Milford et al. (2013), the corresponding modeling assumptions are found in Pauliuk et al. (2013a).

[iv] automotive only

[v] values obtained in personal communication

[vi] product lifetime values adapted from Pauliuk et al. (2013a)

While the different lifetime values in Table 2 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, Pauliuk et al. (2013a) show that out of 4 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 2 demonstrates. In the two studies which 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 have 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 Dworak et al., 2022; World Steel Association, 2023a) – it is simply not a factor which can be observed without hurdles.

On the other hand, differences in the approach to model 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, 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.

The factors laid out in Table 2 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 as 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. (2022) 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. (2018) 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. (2013) have significant potential to influence the future availability of scrap; for example, product life extensions lead to a 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 Fig. 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 (Maga et al., 2022). 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 (Mitchell and Pickens, 2022). Third, stainless steel production and recycling take place in separate value chains. The flows of stainless steel and scrap need to be considered separately because of its content of alloying materials and different sectoral shares compared to carbon steel. Unfortunately, most material flow analyses of stainless steel are only backward-looking (Reck and Rotter, 2012; Reck et al., 2010). The current study by Karlsruhe Institute of Technology (2023) only quantifies historic scrap inputs as well. Other recent studies focus on the individual metals nickel and chrome rather than stainless steel as the composite material (Su et al., 2023; Gao et al., 2022a,b; Zeng et al., 2018; Eckelman et al., 2012). 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 postconsumer scrap in the coming decades. In 2030, between 80 and 105 Mt of post-consumer scrap are 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 in the next ten years.

In 2022, the EU's steel producers consumed 79.4 Mt of scrap, corresponding to a recycled content of 58% in that year (compare Fig.2). 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 import to and export out of the EU) are not considered in the modeling of PADPS. However, the juxtaposition of these factors reveals that 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 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 1). Most of the divergence of past scrap amounts, however, is due to in-use stocks not being readily available historical data. Steel in-use stocks are rather estimated by means of proxy values such as past apparent steel use of a country; trade flows of iron ore, steel intermediates, and scrap; and reasonable assumptions about material losses, product obsolescence, unrecorded trade or landfilling.

A multitude of assumptions and modeling decisions underlie the studies which 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. Boehringer et al. (2022) 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 Pauliuk et al. (2015)). This endeavor would not only contribute to a better understanding of the models but also illustrate side-effects within a circular economy. 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 or by consulting firms. We could not include their results 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 copper (Daehn et al., 2017). Therefore, more effort will be necessary to separate and process post-consumer scrap in order to avoid down-cycling 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.

In the future, the uncertainty regarding actual steel stocks may be alleviated through material or product passports (Çetin et al., 2023; European Commission, 2022), 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 an issue to be solved. In the intervening time, the extended use of administrative records as well as remote sensing are promising methods to better estimate the steel currently in the system (Peled and Fishman, 2021; Rajaratnam et al., 2023) 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.

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Appendices

Appendix A Estimating domestic scrap supply

No data on actual domestic scrap, which is the amount of steel scrap procured for recycling in a year ignoring trade, exists. But it is possible to estimate a country's Apparent Domestic Scrap Supply ($ADSS_r$) as the sum of its scrap consumption and its net export of scrap according to equation A.1. $CONS_r$ in Equation A.1 represents scrap consumption in country r. $ADSS_r$ and $CONS_r$ comprise home, new, and old scrap respectively. EXP_r and IMP_r denote the total exports from r and the total imports to r, respectively. Neither the scrap consumption nor the scrap trade data differentiate between the scrap categories. Thus, we aggregate them when estimating domestic scrap supply.

$$ADSS_r = CONS_r + EXP_r - IMP_r \tag{A.1}$$

Imports and exports of scrap are taken from the UN Comtrade database (United Nations, 2019).[1] Data on scrap consumption is published by the Bureau of International Recycling in its *World Steel Recycling in Figures* series. This data is limited to seven key countries and regions (China, EU, USA, Japan, Turkey, Russia, South Korea). For other nations, including large steel producers such as India, no consumption data is available.

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

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[1] The Harmonized System (HS) code for steel scrap is 7204. Import data has been used to calculate both exports and imports of scrap.

Furthermore, we quantify the influence of direct reduced iron (DRI) production 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 (World Steel Association, 2023b). 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.

We estimate the scrap consumption in countries with observable data using a pooled ordinary least squares (OLS) approach as shown in Equ. A.2. Index t represents the year and r the country. $BOF_{r,t}$ is the amount of steel produced in the BOF route in country r and year t, $EAF_{r,t}$ the amount produced in the EAF route. $DIR_{r,t}$ records the direct reduced iron production in year t and country r. β_{BOF}, β_{EAF}, and β_{DRI} are the corresponding coefficients. $\varepsilon_{r,t}$ represents an independent and identically distributed error term. Note that we do not estimate an intercept because there is no scrap consumption independent of steel production.

$$CONS_{r,t} = \beta_{BOF}\, BOF_{r,t} + \beta_{EAF}\, EAF_{r,t} + \beta_{DRI}\, DIR_{r,t} + \varepsilon_{r,t} \qquad \text{(A.2)}$$

We use steel consumption data from the Bureau of International Recycling (2023) as well as from earlier versions of the *World Steel Recycling in Figures* series. This scrap consumption data encompasses all scrap used by steel producers (home, new, and old 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 the World Steel Association.[2] We restrict our sample to 2013 to 2022, assuming technological improvements in steel production make earlier years less relevant.

	I Excluding China $CONS_{r,t}$	II Including China $CONS_{r,t}$
β_{BOF}	0.1710***	0.0801***
	(0.016)	(0.016)
β_{EAF}	1.0088***	1.1952***
	(0.019)	(0.019)
β_{DRI}	−0.3632**	−0.8134**
	(0.116)	(0.116)
Observations	185	195
Adj. R^2	0.996	0.972

* p < 0.10, ** p < 0.05, *** p < 0.01

Note: Robust standard errors in parentheses

Table A.1 Recycled content by production route

[2] We thank Adam Szewczyk for providing the data to us.

Table A.1 displays the regression results for two samples. Column I excludes observations from China, column II includes the People's Republic. In our preferred model, we exclude China.

In the model excluding China (column I in table A.1), the adjusted R^2 of 0.996 shows that the pooled OLS model fits the scrap consumption in our sample well. All coefficients are highly statistically significant. The estimated coefficient of the BOF route (β_{BOF}) equals 0.1710. This corresponds to a recycled content of 17.1% in the blast furnace route. Approximately 1.01 tons of scrap are used per ton of crude steel produced in the EAF route. 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 scrap input.

Data on scrap consumption split between BOF and EAF route is available for Germany between 2016 and 2019 in Wirtschaftsvereinigung Stahl (2022), allowing us to conduct a plausibility check. The average recycled content in these years were 17.7% for the BOF route and 103.4% for the EAF route. These closely resemble our estimates (17.1% and 100.9%).

The coefficient $\beta_{DRI} = -0.3632$ implies that the production of one ton of DRI reduces scrap consumption by 363 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 substitute for primary steel production, not secondary steel production from scrap.

The estimated coefficients change substantially if observations from China are included in the sample (column II in table A.1). The coefficient of the BOF route (β_{BOF}) is more than halved to 0.0801. The amount of scrap consumed per ton of crude steel production in the EAF route increases from 1.01 to 1.20 tons. One ton of DRI production reduces scrap consumption by 813 kg. The adjusted R^2 drops slightly from 0.996 to 0.972.

Our results are highly sensitive to whether China is included or excluded in the estimation. Accounting for 54.0% of global crude steel production, China is the world's largest steel producer (World Steel Association, 2023b). Steelmakers in the People's Republic consumed 215.3 Mt of scrap in 2022, making it the largest scrap consumer as well (Bureau of International Recycling, 2023). Thus, China has a sizeable impact on our estimates. But recycled content in China is substantially lower than in other major steel making nations even though scrap consumption has increased substantially in the last ten years (Bureau of International Recycling, 2023). We conclude that China constitutes an outlier with respect to its scrap consumption (Wübbeke and Heroth, 2014) and that the estimates excluding Chinese observations are more representative of recycled content in other nations.

We use the coefficients of column I in Table A.1 to predict scrap consumption in countries without observed data. This process implies a global scrap consumption of 682 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 (62 Mt), and the USA (57 Mt).

Equipped with the (estimated) scrap consumption, we use Equ. A.1 to compute the Apparent Domestic Scrap Supply. Globally, $ADSS_r$ and $CONS_r$ 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), the USA (62 Mt), and India (53 Mt). Dividing these values by the countries' population yields Apparent Domestic Scrap Supply per capita as displayed in Fig. 3.

Appendix B Systematizing the scrap amounts by Hatayama et al. (2010)

In Section 4, it was mentioned how the results by Hatayama et al. (2010) 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 2. 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 the World Steel Association (World Steel Association, 2023a) were used to approximate the stock share of the 8 countries included in Hatayama et al. (2010) in relation to the EU (plus the non-EU countries included: Norway, Turkey, UK). This approximation puts the 8 countries at about 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 estimate for the sake of comparability and does not in any way reflect premises of the original authors.

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