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Ship recycling—estimating future stocks and readiness for green steel transformation

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Abstract

This article addresses ship recycling. Often criticized for dire health and safety conditions at breaking destinations in the Global South, our article considers ship recycling as a potential future source for secondary steel in green transformations. It represents an analysis of forthcoming changes in the regulatory framework, an initial assessment of steel stocks based on publicly available data, and a local case study. Here, the article assesses the capability of Bremen, a city in Northern Germany, to gain a relevant future market share. Our results indicate (a) the regulatory framework is dynamic due to the entry into force of the Hong Kong Convention in 2025 und the current revision of the EU Ship Recycling Regulation; (b) the future market is significant, roughly equivalent to the entire current US car fleet in terms of steel stocks; (c) the ability to act locally depends on a variety of critical factors, including political will, entrepreneurial capital, and space requirements. The article concludes with an outlook on the importance of such a development for the transition towards 'net zero steel' and provides a perspective on future research needs.

1. Introduction

With the increasing imperative to mitigate climate change and achieve global sustainability, the steel industry and the international shipping sector stand at the forefront of societal and environmental challenges. This article explores the potential of ship recycling as multi-faceted solution addressing challenges in both sectors simultaneously. Through secondary steel production, the steel industry can pave the way towards net-zero carbon emission. Simultaneously, promoting sustainable and safe end-of-life practices for the global shipping fleet can significantly reduce its societal and environmental footprint. Upheld at the highest international standards, ship recycling thus will trigger resource efficiency towards carbon neutrality.

Steel is the most widely used material in the world—however, steelmaking is currently one of the biggest emitters of CO_2 estimated to contribute 5%–8% to global emissions (IEA 2020). Technologies to decarbonize the sector do exist: (1) by using hydrogen in the production process and (2) by switching to secondary scrap-based steel production with 80%–90% lower emissions compared to the traditional steel route. The question arises as to where future scrap steel could come from. The International Energy Agency (IEA) forecasts an increasing amount of scrap steel over the next decades, with a remaining gap that will need to be addressed. Thus, taking a closer look at relevant market segments for future scrap is pivotal in the race to 'SteelZero'.

At the same time, prevailing waste management practices in the international shipping sector are deeply concerning. At the end of their life, most vessels end up on beaches in the Global South (e.g. India, Bangladesh and Pakistan), where they are grounded in shallow waters (known as 'beaching') and prepared for scrapping under adverse health and safety conditions. The 'Hong Kong International Convention for the safe and environmentally sound recycling of ships' has been signed in the year 2009 to end such unsustainable practices. Effects so far have been fairly limited due to a lack of political will in key countries combined with poor business behavior. The question is: what is the scope for change when the

Hong Kong Convention will come into force in 2025 and industry takes sustainability pledges seriously? Accordingly, analyzing the international regulatory framework and incentives for actors in ship recycling becomes relevant.

Against this background, this article addresses the following research questions: (1) What are the incentives, drivers, and barriers for relevant actors to establish a sound market for ship recycling? (2) What is the estimated steel stock that could be recovered from the international shipping fleet over the next years?

To assess incentives for changing current practices, this article undertakes a policy analysis of the main regulations governing the end-of-life practices in international shipping. Given the existing regulatory distortions have failed so far in providing incentives for proper ship recycling, an analysis of this sector is relevant and timely in seeking to establish more sustainable pathways in industrial resource efficiency. To add further evidence, we estimate the number of European vessels reflagged for scrapping in recent years and the share of European vessels that is actually recycled in Europe. To address the second question, this article provides a first estimate of steel stocks derived from ship recycling based on new data analytics. So far, research on this topic has been limited and focused on scrap availability from vehicles, buildings, and other infrastructures. Thus, this article enters a novel area by highlighting the contributions of ship recycling to steel stocks.

Identifying promising niches and forerunners will be key in transitioning (Bleischwitz *et al* 2011) from current systemic failures towards sustainable ship recycling with proper steel recovery. Our article assesses the capabilities in Bremen, a city in Northern Germany with a large port, shipbuilding industry with wharfs, and local steel production. Finally, this article concludes on the evidence for emerging markets in ship recycling as a potential driver for green steel and identifies research priorities.

2. Literature survey—severe knowledge gaps

Up to now, literature on ship recycling with a perspective on steel recovery is rare to find. Hsuan and Parisi (2020) map the supply chain of ship recycling and underline regulatory efforts. Solakivi *et al* (2021) discuss the European ship recycling regulation. Ocampo and Pereira (2019) undertake stakeholder analysis for Brazil. Recent foresight is done by Mohiuddin *et al* (2023) who evaluate emerging ship recycling options for Bangladesh. Overall, the topic has been dealt with by international organizations (UNCTAD 2020) and industry associations (BIMCO 2023); useful analysis comes from the stakeholder alliance 'Sustainable Shipping Initiative' (SSI 2021, 2023). Over years, a main concern has been hazardous waste and work conditions. The NGO 'Shipbreaking Platform' runs a good database and provides evidence-oriented reports. Held *et al* (2021) discuss changes in estimated CO_2 emissions related to scrapping from outdated vessels. Jain *et al* (2017) offer insights on the material composition in end-of-life ships. Rahman *et al* (2016) and Steuer *et al* (2021) examine the material mix in ship recycling. The key academic source on steel stock states uncertainties in data related to ships (Pauliuk *et al* 2013: 30). IEA (2020) provides a future steel roadmap, however without explicitly addressing ship recycling. (Bleischwitz *et al* 2018) discuss a future saturation in global steel demand. Nechifor *et al* (2020) assess macro-economic outcomes from a shift towards secondary steel in China. Recent literature discusses intensively the development of net zero steel and future scrap availability worldwide, however without estimating potential supply from ship recycling (Xylia *et al* 2018, Nechifor *et al* 2020, Bataille *et al* 2021, Wang *et al* 2021, Lopez *et al* 2022, Watari *et al* 2023). Our article concludes on severe gaps on steel recovery from end-of-life ships in existing knowledge and methods, which will be addressed below.

3. The international regulatory framework: changing conditions expected

The rising demand for scrap and the transition to green steel with higher shares of secondary steel production are creating a favorable environment for ship recycling. However, significant barriers exist on the ground, which manifest themselves in questionable safety and environmental standards in the industry. In countries like India, Bangladesh, Pakistan, ship 'recycling' has become synonymous with human hardship in working conditions as well as with the occurrence of local ecological disasters due to hazardous substances contaminating the coastal and marine environment. The NGO 'Shipbreaking Platform' and investigative journalism highlight numerous cases, countries and trends that underscore the need for improved and responsible ship recycling practices.

The 'Hong Kong International Convention for the safe and environmentally sound recycling of ships' has been developed and signed in 2009 to address regulatory shortcomings in the sector. It includes measures to minimize risks to human health, safety and to the environment. A significant milestone was reached in 2023, when Bangladesh, one of the world's largest ship recycling countries by capacity, and Liberia, one of the largest flag states by tonnage, both signed the convention, meeting the conditions for its entry into force. As a result, the Hong Kong Convention is set to come into effect in June 2025.

In parallel, the EU has established a ship recycling directive in 2013 to prevent, reduce, minimize and eliminate accidents, injuries and other adverse

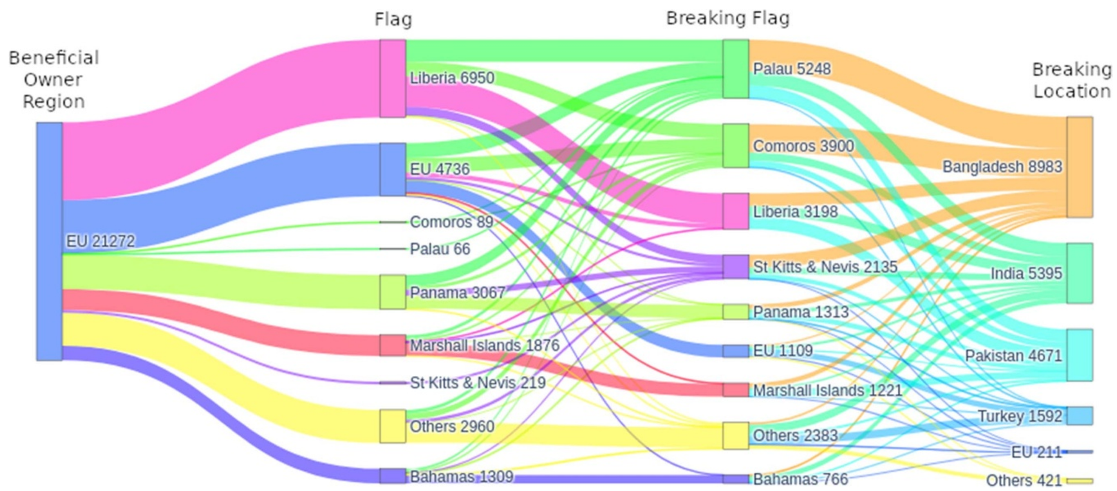

Figure 1. Flags and breaking locations of scrapped vessels with beneficial owners from countries in the European Union for the years 2017–2022. The data is based on EOLSHIPS; limitations regarding traceability, unknown owners and unknown flags are acknowledged. In case a vessel does not change its flag for breaking, its 'Flag' and 'Breaking Flag' countries match. Numbers indicate the GT sum of all vessels in thousands; colors indicate the destination with respect to the next level. The visualization follows the approach of Wan *et al* (2021).

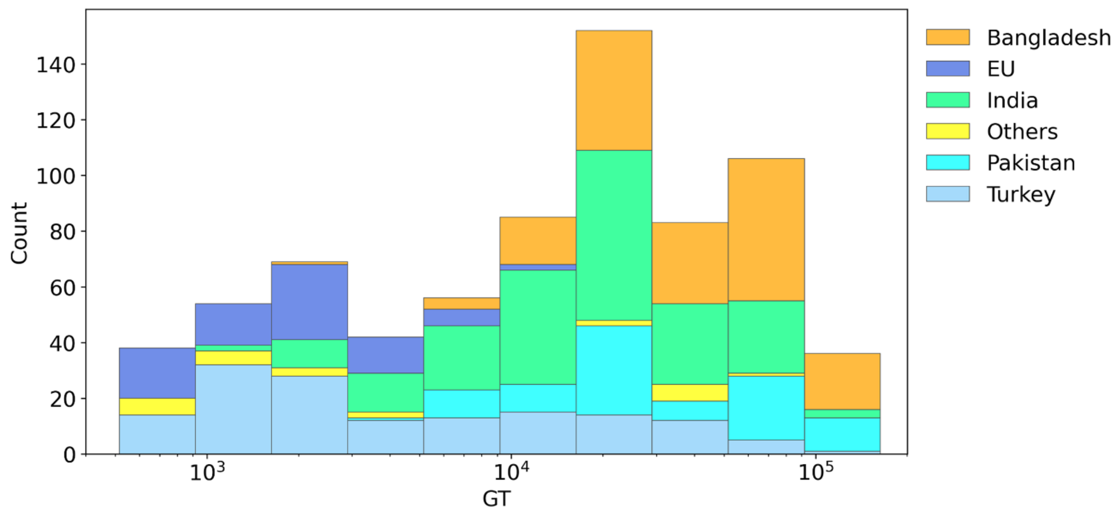

Figure 2. Numbers of scrapped ships from 2017 to 2022 in relation to their size in GT and their breaking location (colors). The data is based on EOLSHIPS (see below and in SI). Note the logarithmic scale of the *x*-axis.

effects on human health and the environment from ship recycling. While primarily targeting European vessel owners and recycling facilities in the EU, facilities in third countries can voluntarily comply with regulatory standards and become listed in the 'EU list of approved recycling facilities'. The latest EU report from 2022 lists 53 applications from outside the EU have been submitted, with 11 successful applications, particularly from Turkey (8). It has been noted, however, that the capacity in the EU is neither viable under current market conditions nor adequate to meet future demand (Solakivi *et al* 2021).

Our research provides evidence for the end-of-life destinations for European vessels (figure 1, the data base EOLSHIPS is described below and in SI). Surprisingly, only 1% of the vessels owned by EU shipping companies are actually being recycled in the EU. Instead, a common practice has emerged, involving reflagging of vessels to countries such as Palau, Comoros or Liberia, with final scraping destinations in Bangladesh, India, Pakistan and—to a lesser degree—Turkey.

The poor performance of European ship recyclers can be attributed to three factors: (i) lower costs in competing destinations, (ii) general market distortions and lack of political will, and (iii) a limited capacity favoring the recycling of small to medium sized ships (figure 2).

Given the long-standing practices, institutional path dependencies surrounding reflagging and beaching, and the lack of capacities in Europe it is difficult to anticipate major changes towards more sustainable patterns in the near-term future. However, the following factors create a momentum for disruptive change in the industry and relevant countries:

1) The Hong Kong Convention will enter into force within the next two years and gives strong incentives to monitor compliance and track activities. The EU Ship Recycling Regulation currently undergoes a public consultation with an expected review in 2024/25, likely proposing enhanced standards and tighter monitoring, which will create a level playing field for relevant actors and incentivize compliance with sustainable ship recycling practices. It needs to be pointed out that neither of the two regulations specifically targets steel recovery.
2) Climate policy will provide stronger incentives for the adoption of green steel practices. This could involve the inclusion of both steel and shipping into emissions trading and carbon markets as well as by potentially applying a carbon border adjustment mechanism to penalize unfair international competition.
3) Relevant industry actors such as ArcelorMittal have made pledges towards net zero carbon goals. Recently, the large shipping company Møller–Mærsk has joined the 'SteelZero' alliance, and international finance is extending their 'Poseidon Principles' towards 'Sustainable Steel Principles'.

Europe has high ambitions both in terms of climate policies as well as for securing the supply of raw materials. A political shift is thus at the horizon to combine those efforts within an alliance of clean steel producers, like-minded countries and ship recycling facilities.

4. Methods: challenges and approaches to address steel recovery from ships

Until now, there has been no estimate of steel stocks in the international shipping industry. Contemporary steel stock analyses have been based on material flows analysis using monetary international input–output Tables with extended physical data on materials typically applied to housing and mobility (e.g. Pauliuk *et al* 2013, 2017, IRP 2020). While this approach is well-established and robust, it has limitations in addressing commodities such as international trade of used passenger vehicles as well as the shipping sector. Resulting data constraints are then propagated to scenarios such as the IEA steel technology roadmap (IEA 2020), which is considered state-of-the-art on the steel transition pathway. Another reason for data limitations is the age of the current shipping fleet, with most vessels produced decades ago (UNCTAD 2020); if analyses use only recent production figures to estimate steel stocks in the sector, the results are inevitably lower than a long-term analysis of actual stocks would suggest. Accordingly, this article intends to raise awareness on the interface of shipping, data, and scenarios to spur better research.

Our article uses data from the NGO shipbreaking platform and the United Nations Conference on Trade and Development (UNCTAD) to address this research gap. According to Jain *et al* (2017), steel constitutes the largest proportion of a vessel's Light Displacement Tonnage (LDT)[1], typically accounting for 75%–85% of the total. To be on the conservative side, we chose the lower limit and thus estimate a vessel's steel mass by multiplying its LDT by a factor of 0.75. Although we are aware of material mixes in the recycling process (see SI) we assume those numbers as proxy for steel recycling. In the following, we refer to our data set about scrapped vessels from 2017 to 2022 as 'EOLSHIPS' (see SI). To investigate recent ship scraping patterns and relate them to those modelled by Held *et al* (2021), we additionally use data from UNCTAD on the numbers of ships in the world fleet in 2019 per ship type.

5. Results: more secondary steel to come

The results of our analysis suggest a significant upward shift in ships nearing the end of their operational lifetime, consequently leading to an increase in demand for ship recycling capacity in the foreseeable future (figure 3). Two trends are relevant for shaping this dynamic: firstly, high freight rates and relatively low scrap prices during the years of the pandemic 2020–2022 have made the continued operation of even older (and typically smaller) fleet segments more economical (figure 4); secondly, significantly more ships will reach the end of their lifetime compared to previous years.

Historically, about 50% of the deadweight capacity of bulk carriers, tankers, and container ships was recycled when the ships reached 25 years of age, increasing to around 90% by the time they reached 30–35 years. Over the next decade, ships built in the 2000s will be the main contributor to ship recycling. Compared to the 1990s, more than twice as much deadweight capacity was built in the 2000s, contributing to the expected increase in in recycling volumes in the future (see figure 3). Furthermore, the deadweight

[1] Light Displacement Tonnage (LDT) is defined as the weight of the ship with all its permanent equipment, excluding the weight of cargo, fuel, water, ballast, stores, passengers, crew, but usually including the weight of permanent ballast and water used to operate steam machinery. The difference between the loaded displacement and the light displacement is the weight that the ship can actually carry and is known as the Deadweight Tonnage (DWT, DT). Gross tonnage (GT, G.T. or gt) is a nonlinear measure of a ship's overall internal volume.

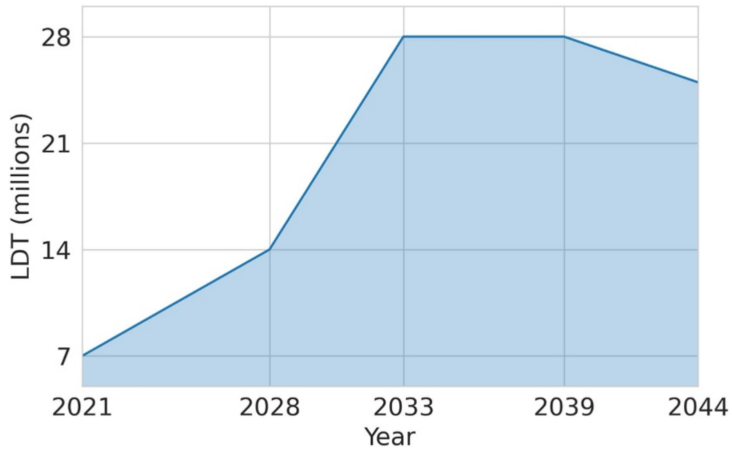

Figure 3. Projected need for ship recycling capacity between 2021 and 2044. Own development based on SSI (2021). Adapted with permission from Sustainable Shipping Initiative (2021).

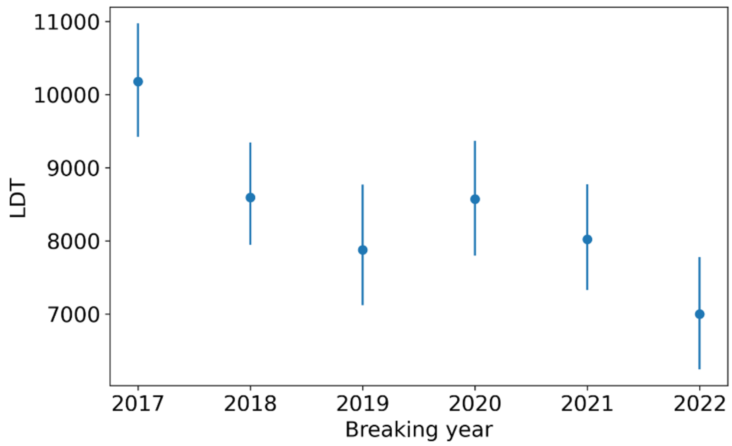

Figure 4. Mean LDT of scrapped vessels from 2017 to 2022 based on our EOLSHIPS calculation. Markers denote the mean LDT of all vessels scrapped in a specific year; bars indicate the 95% confidence interval.

capacity built during the 2010s increased by an additional 65%, indicating the potential for even higher levels of ship recycling ten to twenty years from now.

Our analysis relates to observations presented in the grey consultancy literature. BIMCO (2023) estimates a doubling in demand for annual ship recycling capacity until the year 2033 compared with the previous ten years, while consultancy 2BHonest projects even larger increases (figure 3). Following a period of considerable growth, a high and comparatively stable annual supply of about 28 million LDT is expected from ship recycling.

Based on our analysis of all vessels scrapped between 2017 and 2022 ('EOLSHIPS', see table 1, SI), the average vessel amounted to 8525 LDT, equivalent to a steel mass of approx. 6400 t. Combining this average with the BIMCO estimate of 15 000 ships that will undergo recycling during the next 10 years, we project a total of roughly 96 Mt of steel that can be recovered from ship recycling activities until 2032. Comparing this projection to the amount of scrap steel made available through ship recycling in past years (estimated at 2.3–6.4 Mt per year), our analysis indicates a doubling or even tripling in the amount of scrap steel that can be expected from future ship recycling. Moreover, anticipating larger ships coming to an end of their lifetime in the future, this figure of 96 Mt of steel can be expected to increase even further. To put it into an illustrative perspective, the future availability of scrap steel from the shipping industry appears to be approximately equivalent to the steel stock in the entire contemporary US car fleet[2].

6. Capabilities at the regional level: the case of Bremen

Bremen is a comparatively small federal state located in North-West Germany. It consists of the City of Bremen and its seaport exclave Bremerhaven,

[2] 2020 roughly 105 M cars with an assumed average steel share of 1 t per vehicle; source: Forbes data.

located some 60 km downstream the river Weser with access to the North Sea. Bremen has a strong industrial tradition, including expertise in ship building, steel production, automotive manufacturing. Notably, Bremen features large port facilities and has recently started efforts to establish an 'energy port'. While ship recycling activities have not been actively pursued in the area on a larger scale, various actors along the ship recycling value chain are already present in the area. Moreover, the interest to further develop ship recycling has been expressed on various political levels.

Our estimation on future supply of roughly 100 Mt of secondary steel from ship recycling worldwide over the next ten years as stated above can be compared with current demand from the local steel factor, which is according to interviews we conducted around 600 000–700 000 t of scrap steel per year. With the anticipated shift towards hydrogen and increased use of secondary steel in a new electric arc furnace (EAF) production process over the next years as part of climate commitments, local demand for secondary steel is expected to rise to approximately 1.7 Mt per year. Two strategic options arise from our analysis: in a global sourcing perspective, future local steel demand can be met via supply of 10% from global ship recycling market expected for 2033; alternatively and taking into account potential local capabilities of about 20 ships per year, local ship recycling could supply about 15% of local steel demand. The latter can be considered a base load in resource security. For sure, combinations of local and international supply can be chosen too, and other European ship recycling facilities may well become part of it.

Semi-structured interviews conducted with relevant stakeholders have confirmed significant interests in ship recycling and a strong willingness to develop capabilities in this field. Its strategic geographical location and existing industrial competencies could help establishing Bremen among the largest European hubs for ship recycling with steel recovery and climate-friendly steel production. Preliminary evidence suggests the possibility to dismantle large ships of the 'Panamax' category at three specific locations suitable to handle vessel dimensions and shipping sluice capabilities. Based on our EOLSHIPS data for the past 5 years, it appears that a ship recycling facility in Bremen could be capable of managing over 90% of all ships under the beneficial ownership of Germany and the EU.

Moving forward, five factors appear crucial for successful development of ship recycling in the region:

1) political will across local interests as well as leveraging early investments to initiate ship recycling activities
2) availability of dock capacity, considering a potential fit to an 'energy port' perspective, competing interests as well as potential citizen's concerns
3) establishing and upscaling of local dismantling capacity along with an innovation cluster in alignment with waste management legal requirements and logistics
4) need for external ambassadorship towards international shipping companies and better European regulations on accountability to minimize or end 'reflagging'
5) implementation of a business plan to upscale early niches with medium-sized domestic and coastal ships towards larger vessels and addressing place-based innovation opportunities.

7. Discussion: disruptive regulatory and market changes ahead

Given all hardship around ship recycling a proper regulatory framework matters. Our analysis reveals a window of opportunities for change, as the Hongkong Convention will enter into force in 2025 and the EU ship recycling is currently under revision. Industrial capabilities and pioneering activities could establish the state of Bremen, Germany, as a large European maritime cluster on the topic in alignment with a transition towards net zero steel. However, regulatory uncertainties about future accountability of shipping, application of environmental legislation, and the need to streamline local planning in port development with docks and shipping industry will require political will, deliberations, and a multi-stakeholder alliance. Over the next years, we expect an international race towards advancing standards and innovating ship recycling. Pakistan, India, and Bangladesh are likely to maintain their strong position in the market, with regional competition, and spurred by foreign investments. On the other hand, a revised European ship recycling directive could establish a 'golden standard' for premium clean supply, especially if European ship owners are incentivized to follow. The recent establishment of a 'Zero Emissions Maritime Buyers Alliance' (ZEMBA) could point in such direction.

Steel scrap from ship dismantling and recycling can be regarded as a potentially significant source of secondary steel in the future. An upscaling from today's levels to 96 Mt steel from ship dismantling over the next ten years, followed by 20–25 Mt p.a thereafter will contribute substantially to the currently estimated 445 Mt of global end-of-life scrap steel per year, estimated in the IEA Steel Technology Roadmap (2020:63). According to our conservative estimates (see SI), one may anticipate a higher figure closer to 150 Mt of secondary steel coming from dismantled vessels over the next ten years. Though scrap steel from ships appears unlikely to become a game changer in global markets, it can be characterized as a solid and relevant source for future efforts to enhance collection rates and increase scrap availability.

Better long-term outlooks on scrap markets are urgently needed in light of disruptive changes ahead: IEA's Stated Policies Scenario forecasting a 40% increase for global steel end-use demand in 2050 compared to 2019, mainly driven by emerging economies and demand from construction. Could such increasing demand be met by secondary sources? Total scrap availability is expected to increase considerably by about 70%, mainly driven by current stocks being released back into industrial processes. Overall, IEA estimates future scrap to account for 43%–45% to future steel production, a notable increase from the current estimated share of 33%. Other estimates suggest higher shares: according to Xylia *et al* (2018), secondary steel production will exceed the share of primary steel production globally by 2060, with annual demand for 1500 Mt and quite uneven regional availabilities. The 'NetZeroSteel' report (Bataille *et al* 2021) proposes a doubling of recycled steel in all scenarios, pointing at a feasible share of 63% for the secondary route in global steel production in 2050. In the long run, Wang *et al* (2021) and Lopez *et al* (2022) expect a share closer to 90% in 2100—quite different from contemporary markets.

Based on such tentative outlooks, scrap steel markets might be on the cusp of a radical transformation in the future. In the past, the demand for scrap has been a derived demand and prices for scrap have been a function of prices for steel (Söderholm and Ejdemo 2008). Accordingly, prices for scrap have been highly volatile and set by steel world market prices. This has been a disincentive to invest in recycling capacity, where the business model is characterized by relatively stable production costs and runs into liquidity challenges when prices decline.

In a future of rising demand for scrap and increasing capability, new business models could emerge (Franconi *et al* 2022) that will make ship recycling a supplier for a reconfigured steel supply chain. Core competitive advantages can be seen in reliability, quality assurance, and security of supply. Such profile would match with emerging demands from green steel producers and efforts towards global benchmarks for secondary steel along the entire value chain and coordinated efforts in dispersed supply and demand towards mitigation, supported by generating renewable electricity in the secondary EAF route. Finance can be expected to become a driver for such transformation; there are sustainability disclosures on material passports at e.g. London metal exchange and emerging climate standards via Sustainable STEEL Principles and Poseidon Principles, the latter now representing an estimated 50% signatory banks of the global ship finance portfolio. Within such efforts, innovation will be needed to improve the quality of steel scrap sorting and re-use and counter trends towards downcycling that have been observed in Japan (Watari *et al* 2023). At the same time, we may expect new maritime clusters for a circular economy to emerge comprising re-use of offshore energy, e-waste, and others to support industrial delivery of net zero carbon.

8. Conclusions

Our study provides a first estimate on the potential amount of steel that could be recovered from global ship recycling activities, projecting a substantial supply of 96–150 Mt over the next 10 years with a stable supply thereafter. Further research is necessary and should incorporate detailed calculations that could become part of global steel stock assessment over time.

The tide is turning on the regulatory side. For many years, the practice of 'beaching' has been an unregulated activity with devastating effects on human health and coastal environments. The entry in force of the Hong Kong Convention in 2025 is expected to bring strong incentives towards proper ship recycling. The EU ship recycling directive is also undergoing a revision with expected strengthening of standards and efforts towards steel recovery. As our analysis shows that only 1% of EU ships are currently recycled within the EU, it is reasonable to expect an increased recycling rate within the EU and globally with appropriate efforts.

Closing implementation gaps and taking pledges towards climate neutrality seriously will be key in delivering a higher amount of secondary steel from ship recycling over the next years. Establishing local capabilities to handle large ships ('Panamax' and beyond) will be essential too. A strategic approach involving technology clusters and innovation systems with collaboration among ship builders, steel producers, port authorities, logistics, and industries focused on the energy transition and circular economy is pivotal in turning the market into competitive sustainable business.

From a research perspective, more will need to be done to close data gaps and develop robust scenarios for the future of steel, supported by models on both climate and macro-economic impacts. Doing complementary research on engineering and the regulatory dimension will be useful too. After all, we hope to spark further contributions on the topic.

Data availability statement

All data that support the findings of this study are included within the article and a supplementary file.

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