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Tracing the steel supply chain of the shipbuilding industry

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INTRODUCTION

In 2023, the United Nations' International Maritime Organization agreed on a goal of achieving net-zero greenhouse gas (GHG) emissions from international shipping by around 2050. While the well-to-tank and tank-to-wake emissions from producing and using marine fuels are included, the goal does not cover the embodied emissions associated with the upstream process of shipbuilding. To date, there are no global policies that address or limit the GHG intensity of shipbuilding.

Shipbuilding requires a substantial amount of steel. It is typically 75%–85% of a ship's weight (Sustainable Shipping Initiative, 2023). The deadweight tonnage of the global ship fleet has grown over 200% since the 1980s (United Nations Conference on Trade and Development, 2023b), and further global fleet growth will increase both the demand for steel for shipbuilding and the GHG emissions associated with meeting that demand. Decarbonizing the full life cycle of a ship also requires decarbonizing the steel industry.

Three countries—China, South Korea, and Japan—dominate the shipbuilding market. In 2022, by gross tonnage (GT), China built 46.6% of ships, South Korea built 29.2%, and Japan built 17.2% (United Nations Conference on Trade and Development, 2023a). Because these ships are sold and used for transport worldwide, actions taken by these three countries can address embodied emissions in steelmaking for the shipping industry globally.

To signal commitment to using low-carbon or "green" steel, some shipping companies have joined initiatives such as SteelZero. However, there is currently no universally accepted definition of green steel. The World Economic Forum (2022) defines it as steel manufactured without the use of fossil fuels. Meanwhile, according to SteelZero, green steel is certified as meeting the highest levels of environmental, social, and governance performance, which goes beyond addressing GHG emissions

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION alone (Climate Group, 2022). SteelZero members have committed to using 50% "low-carbon steel" by 2030 and 100% by 2050. Maersk, the world's second-largest shipping company, aims to procure, specify, or stock 50% "low-emission steel" by 2030 and set a clear pathway to using 100% net-zero GHG steel by 2040 (Climate Group, 2024). Although these companies have set goals, little progress has been made to date in terms of supportive policy, steel industry commitment, and agreed-upon decarbonization pathways.

Steel is typically produced via the blast furnace-basic oxygen furnace (BF-BOF) process using coal and iron ore, or via the electric arc furnace (EAF) process using electricity and scrap or direct-reduced iron (DRI). In the BF-BOF process, coke (coal) reacts with sinter/pellets (agglomerated iron ore) in the blast furnace to form molten iron, which decarburizes in the BOF via high-purity oxygen to produce crude steel (Koolen & Vidovic, 2022). The primary sources of GHGs in the BF-BOF process are sintering/pelletizing, coking, and molten iron production from the use of coking coal as the reductant (Fan & Friedmann, 2021; Ren et al., 2021).

The DRI-EAF process omits the highly carbon-intensive steps involved in BF-BOF. The iron ore is reduced in solid-state by reducing gases (typically natural gas), which are then reformed to a mixture of carbon monoxide and hydrogen (H_2; Fan & Friedmann, 2021). Although coking coal can also be used to produce DRI-based steel, the overall carbon-intensity of steelmaking via the coal-based DRI-EAF process has been shown to be even higher than that of BF-BOF (Abdul Quader et al., 2016; Ellis & Bao, 2020). While around 80% of current global DRI steelmaking uses natural gas, it is also possible to use low-carbon hydrogen as the reducing gas, and that would considerably lower the carbon footprint of the steelmaking process (Koolen & Vidovic, 2022). The global share of EAF use in steel production is currently 29%, and it is 11% in China, 32% in South Korea, and 25% in Japan (World Steel Association, 2022).

Shifting from BF-BOF to EAF is generally considered to be the first step to fully decarbonizing steelmaking because EAF usually has much lower GHG emissions than BF-BOF (Kubokawa & Huleatt, 2023). Improving the energy efficiency of the BF-BOF process remains the major source of carbon-intensity improvement for many steel producers. Other transformative approaches for steel industry decarbonization include green hydrogen DRI and zero-carbon electricity substitution (Fan & Friedmann, 2021). These technologies are readily available for steel producers to consider incorporating into their operations.

In this study, we aim to first understand the steel supply chain of the shipping industry by identifying where ships are built and determining the respective steel suppliers. We then quantify how much steel was used to build these ships, and the GHG emissions associated with producing the required steel. In addition to the global analysis, we provide a U.S. case study to illustrate how our methodology could be used for a country-level analysis to help individual countries that want to address GHG emissions in their shipbuilding supply chain.

The rest of this paper is structured as follows. We first introduce the sources and methods used in our analysis and explain how we established the links along the supply chain from ship buyers to ship builders to steel suppliers. We next explain how we estimated the embedded GHG emissions from steel production. The results are presented with a discussion of potential technologies and practices to reduce GHG emissions from steelmaking. We conclude with key findings.

DATA

Three broad categories of data are used in this work: ship information, including ship characteristics, shipbuilders, and ship buyers; information about steel suppliers for shipbuilding; and information about the GHG intensity of steelmaking for individual steel suppliers. Each is discussed below.

SHIP INFORMATION

The ship information like deadweight tonnage (DWT), light displacement tonnage (LDT), build years, and more are from S&P Global's dataset and the World Fleet Register dataset (Clarksons Research, 2023). The ship information is publicly available with specific identification codes like International Maritime Organization (IMO) numbers or maritime mobile service identity codes. The datasets just provide a more efficient way to find the information for further analysis.

STEEL SUPPLIER INFORMATION

China, South Korea, and Japan are not only the biggest shipbuilding countries, but are also the largest steel-producing countries and are home to numerous steel suppliers. However, only some of these suppliers provided steel to the shipbuilding industry. To identify these steel suppliers and their market shares for shipbuilding steel, we retrieved information from various sources (Table 1).

Table 1

Details of steel suppliers for shipbuilding and their market share in China, South Korea, and Japan in 2021 and 2022

Country	Steel supplier	Steel for shipbuilding (tonnes)	Market share by tonne	Source
China	Rizhao Steel	1,880,000	21%	China Association of the National Shipbuilding Industry (2021)
	Valin Group	1,520,000	17%	Valin Steel (2022)
	Ansteel Group	1,180,000	13%	China Association of the National Shipbuilding Industry (2021)
	Nanjing Steel	1,154,800	13%	Nanjing Iron & Steel CO., Ltd. (2022)
	Shagang Group	850,000	10%	China Association of the National Shipbuilding Industry (2021)
	Xinyu Steel	740,000	8%	
	Shandong Steel Group	330,000	4%	
	Shougang Group	270,000	3%	
	China Baowu Group	230,000	3%	
	HBIS Group	50,000	1%	
	Other steel suppliers in China	167,445	2%	
	Imports from South Korea	—	3%	Harvard Growth Lab (2024)
	Imports from Japan	—	1%	
	Imports from all others	—	1%	
South Korea[a]	POSCO	—	54%	Dongkuk Steel (2023); Hyundai Steel (2023); POSCO Holdings, (2023); Yoo (2023)
	Hyundai Steel	—	24%	
	Dongkuk Steel	—	7%	
	Imports from Japan	—	9%	Harvard Growth Lab (2024)
	Imports from China	—	5%	
	Imports from all others	—	1%	
Japan	JFE	1,305,920	42%	JFE Holdings, Inc. (2022; 2023)
	Nippon	1,031,240	33%	Nippon Steel Corporation, (2022a; 2022c)
	Kobe	475,200	15%	(Kobe Steel, Ltd. (2022a; 2022b)
	Imports from South Korea	—	6%	Harvard Growth Lab (2024)
	Imports from China	—	3%	
	Imports from all others	—	0.1%	

Note: Because the amount of imported steel used for shipbuilding by exporting country was not available, we used the import market share of flat-rolled iron (width > 600 mm, hot-rolled, not clad, with HS code 7208).

[a] We identified the steel suppliers for shipbuilding in South Korea, but the amount of steel used for shipbuilding industry was not available. Therefore, we used these suppliers' market shares by tonnes in steel plate production in 2021.

GREENHOUSE GAS INTENSITY OF STEEL SUPPLIERS

Steel for shipbuilding is typically of high-quality, and some of it possesses high tensile and yield strength. Because of a lack of detailed data on the steel used to build each ship, we used the steel company-level average GHG intensity. We identified several studies that provided estimates of the GHG intensity of steelmaking, but they either used different data sources or estimated their results using different scopes of emissions, which made the results incommensurable. Few studies reported results at the steel-company level. A recent study by Xu et al. (2023) provided steel company-level CO_2 emission estimates, but the researchers only had access to detailed data from steel suppliers in China. Therefore, for South Korea and Japan, we retrieved inputs from individual steel suppliers that voluntarily disclose that information to the public (Dongkuk Steel, 2021; Hyundai Steel, 2022; JFE Holdings, Inc., 2020; Kobe Steel, Ltd., 2020; Nippon Steel Corporation, 2022b; POSCO, n.d.; Statista, 2024; World Steel Association, 2020). The data used included scope 1 and scope 2 emissions.[1] For imported steel, we used the country-level average CO_2 emission intensity as a proxy (Hasanbeigi, 2022).

There are several steps involved in the steelmaking process that contribute GHG emissions that are not accounted for in scope 1 and scope 2 CO_2 emissions. These include non-CO_2 GHG emissions from fuel consumption during the BF-BOF process, emissions from upstream mining activities for steelmaking, methane emissions from natural gas DRI production, and material losses during processes like hot rolling to convert crude steel into products for shipbuilding. For these emissions, we used inputs from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, which incorporates not only CO_2 but also methane and nitrous oxide emissions (Wang et al., 2022).[2] The inputs are industry-average numbers not tailored to specific countries and they were then integrated into the CO_2 emission intensity of scope 1 and scope 2 to develop a GHG emissions intensity for steelmaking. The details of the data used to get the final GHG emissions intensity are in Table A2 in the Appendix.

SHARE OF EAF STEEL

The shares of steel produced by the EAF process per steel supplier were collected for illustrative purposes. Detailed data sources and results are in Table A3 of the Appendix.

METHODS

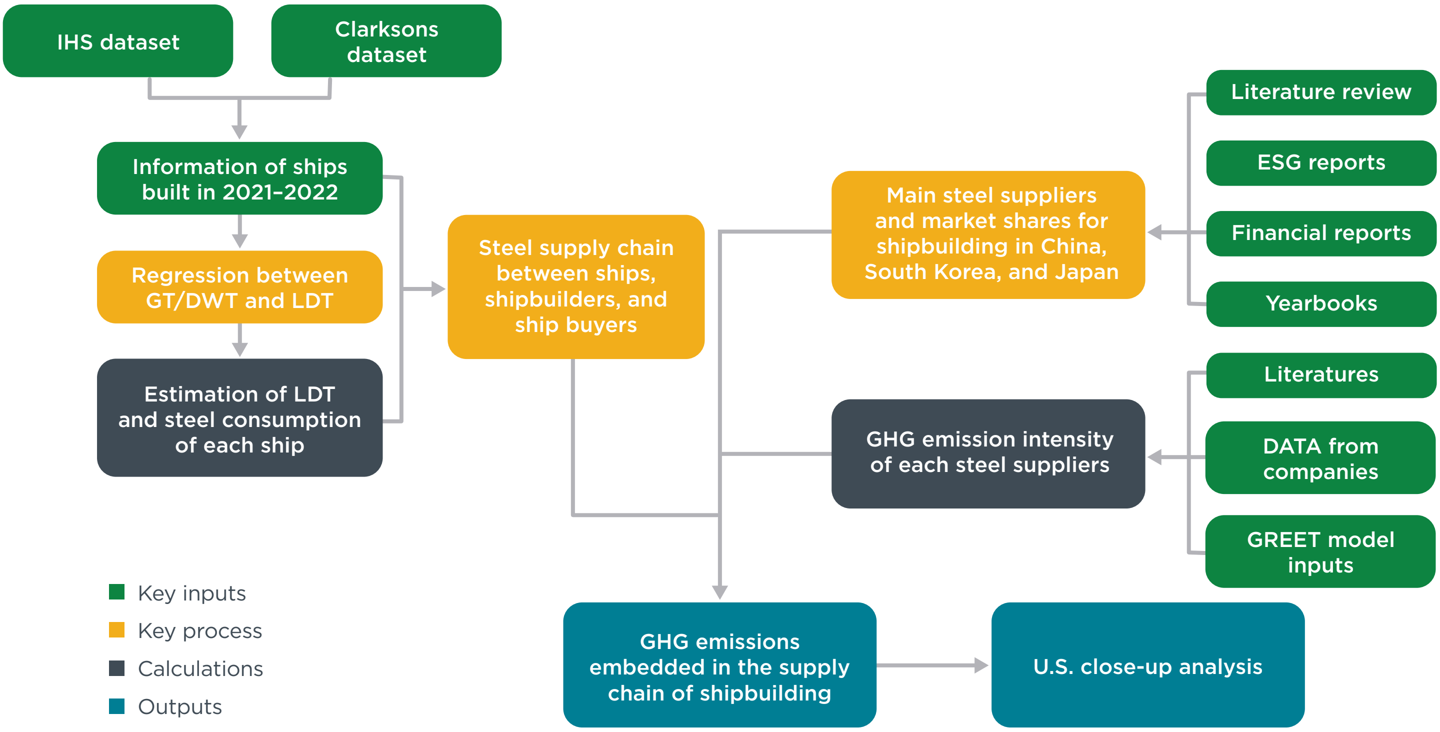
The overall methodology of this study is illustrated in Figure 1.[3] The analysis period is 2021 and 2022 combined.

1 Scope 1 emissions include the direct, energy-related emissions from to the use of fuels for coking, pelletizing, sintering, iron making, steelmaking, and aftertreatment of crude steel like hot rolling. Scope 2 emissions include indirect emissions from the electricity used across all steps of the value chain of the steel industry.

2 The non-CO_2 emissions intensity of CH_4 and N_2O were converted to CO_2 equivalents (CO_2e) using the latest GWP100 values from the IPCC (Smith et al., 2021).

3 The datasets from S&P Global and Clarksons are commercially available.

Figure 1
Study methodology



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We estimated steel demand for each ship based on its light displacement tonnage (LDT), which represents the weight of a ship without any load on board and is used to calculate steel value at scrapping (Gard, 2012). We found high correlation between GT/DWT and LDT, as shown in Figure 2.[4] We estimated the LDT of each ship using the statistical relationship between GT/DWT and LDT for each ship type, based on over 70,000 ships in the S&P Global dataset (detailed regression results are in Table A1 of the Appendix). As the industry estimates that steel accounts for 75%–85% of a ship's weight (Sustainable Shipping Initiative, 2023), we used the mid value (80%) to convert LDT to the steel demand of a ship. We identified a total of 5,907 ships built in 2021 and 2022 combined.

4 GT is a measure of a ship's overall internal volume and is determined by dividing the contents (in cubic feet) of the ship's enclosed spaces by 100. DWT is a measure of how much weight a ship can carry, including the weight of cargo, fuel, fresh water, ballast water, provisions, passengers, and crew.

Figure 2

Statistical relationship between deadweight/gross tonnage and light displacement tonnage for all ship types in 2021 and 2022

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To estimate GHG emissions, we combined the GHG intensity values with the steel demand values as seen in (1). Because one-to-one mapping of steel suppliers and shipbuilders is not available, we assumed that steel suppliers would supply steel to all shipbuilders in the same country, apportioned based on the supplier's domestic market shares (Table 1). Additionally, as the one-to-one mapping of each ship and its buyer can be identified using the S&P Global dataset and Clarksons World Fleet Register, the GHG emissions associated with steelmaking for building ships can be aggregated to the ship buyer level.

$$GHG\ emissions_{i,j} = \sum steel\ consumption_i \times market\ share_{j,k} \times CI_{j,k} \quad (1)$$

Where:

$GHG\ emissions_{i,j}$:	GHG emissions from steel for building ship *i* in country *j*, in tonnes
$steel\ consumption_i$:	steel consumption of ship *i*, in tonnes
$market\ share_{j,k}$:	market share of steel supplier *k* in country *j*, in percentage
$CI_{j,k}$:	GHG emissions intensity of steel from steel supplier *k* in country *j*, in tonne CO_2e/tonne steel

For the U.S. analysis, we identified ships that transported products to the United States in 2021 and 2022 using our Systematic Assessment of Vessel Emissions (SAVE) model (Olmer et al., 2017), and further filtered these ships to identify those built in 2021 and 2022. The same methodology described above was also used for the U.S. analysis.

RESULTS AND DISCUSSION

STEEL SUPPLY CHAIN FOR SHIPS

In total, we estimate that 33.23 million tonnes of steel was consumed for shipbuilding globally in 2021 and 2022 combined. Of this, China, South Korea, and Japan together consumed 29.30 million tonnes and China, the largest steel-producing country in the world, consumed the most. The steel consumption from the three countries in 2021 and 2022 is shown in Table 2, where our estimates are also compared with other publicly available statistics.

Table 2
Validation of estimated steel consumption (million tonnes) for shipbuilding from public statistics in 2021 and 2022

	2021		2022	
	Other published statistics	ICCT estimates	Other published statistics	ICCT estimates
China	7.55	7.62	—	7.24
South Korea	4.55	4.88	—	4.01
Japan	3.08	2.93	2.80	2.62

Note: The statistical information was from China shipbuilding industry Yearbook (2022) for China, SteelDaily (2022) for South Korea, and Nippon Steel Corporation (2023) for Japan.

The supply chain from steel producers to shipbuilders is mapped in Figure 3.[5] All three countries mainly sourced shipbuilding steel domestically. In China, bulk carriers consumed around 40% of the total shipbuilding steel, followed by container ships and oil tankers (19% and 15%, respectively). In South Korea, 34% of shipbuilding steel was used to make oil tankers (34%), followed by liquefied gas tankers (30%) and container ships

5 The figure was created using the ship information, steel supplier information, and methods of estimating steel consumption mentioned above.

(21%). Japan's pattern was similar pattern to that of China, as almost half of the steel was used for building bulk carriers, with another 33% for oil tankers and container ships.

We observe substantial concentration among shipbuilders. Globally, we identified approximately 500 shipbuilding companies. China State Shipbuilding Corporation (CSSC), the largest shipbuilding company in China in 2019, accounted for 17% of the global steel consumption for shipbuilding. HD Hyundai from South Korea was second largest and had a 15% share. The remaining eight of the top 10 shipbuilding companies in terms of steel use consumed another 34%, with the remaining 490 companies using 34%.

Figure 3

Steel supply chain for ships from shipbuilders to steel producers in 2021 and 2022

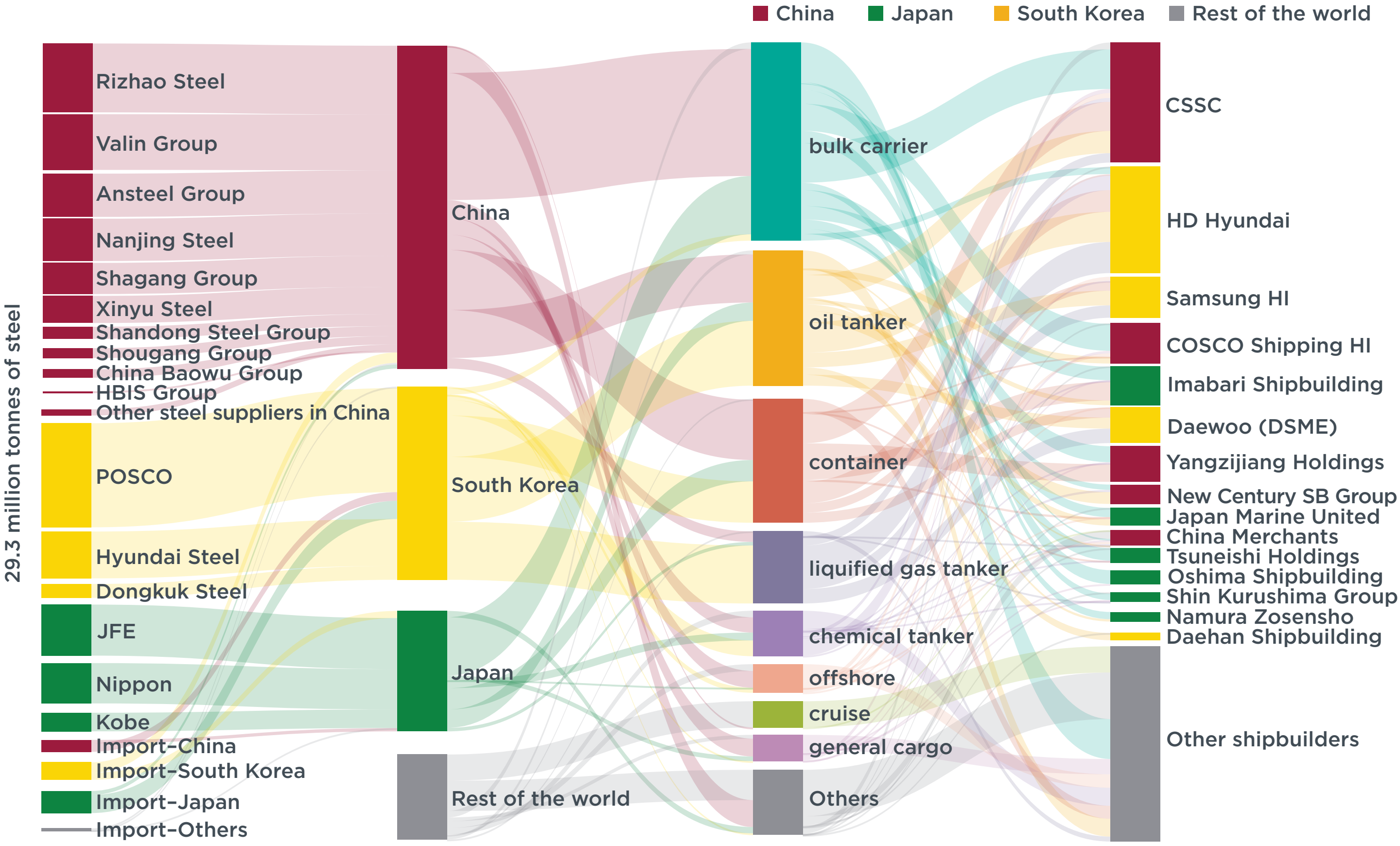

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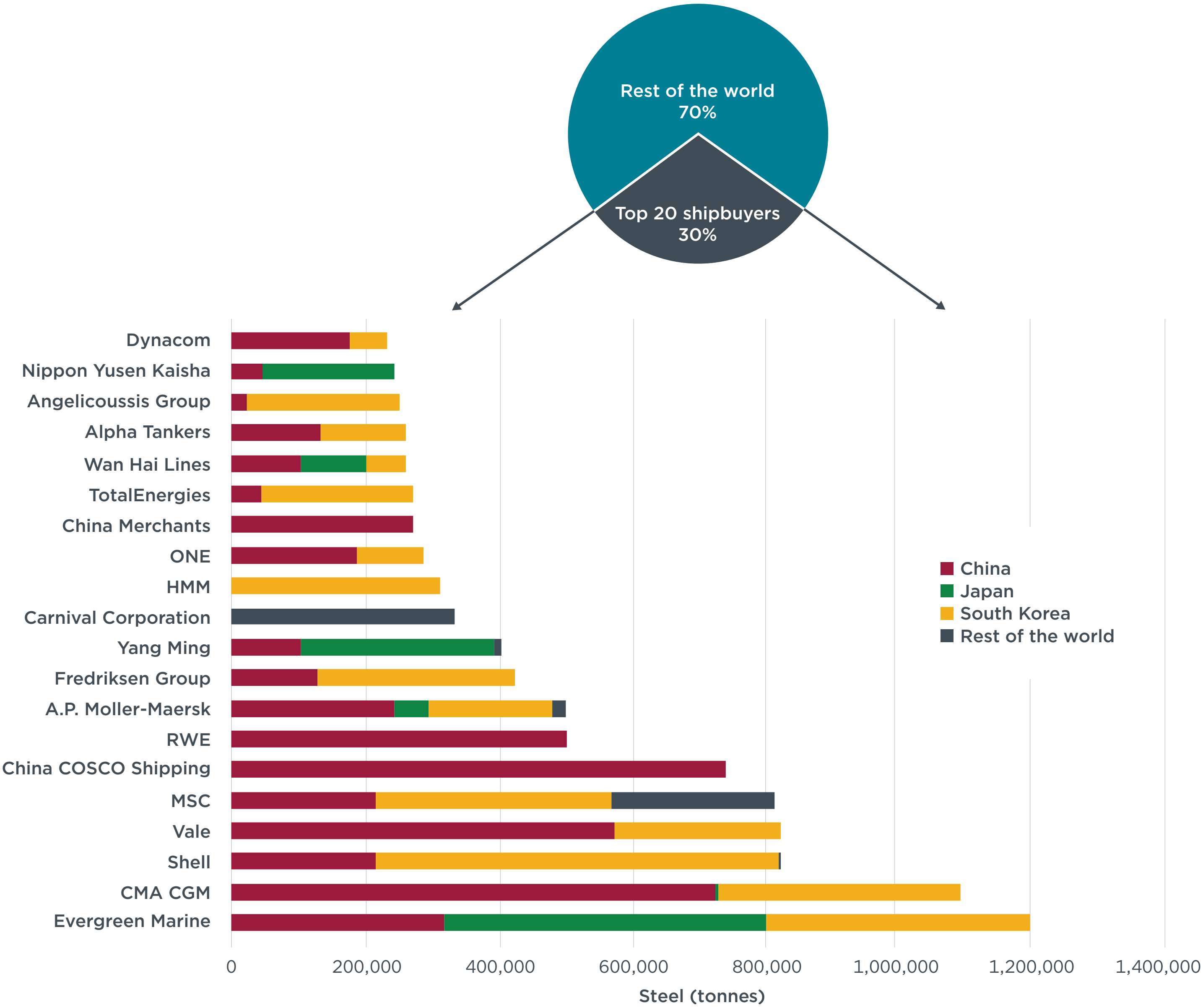
Figure 4 shows the top 20 ship buyers in terms of steel consumption.[6] Compared with the shipbuilders, the purchasers were more diverse. The top 20 ship buyers only accounted for 30% of the total steel used for shipbuilding worldwide. Within the top 20, ship buyers in China and South Korea showed preference for contracting with local shipbuilders. For example, China COSCO shipping and South Korea's Hyundai Merchant Marine (HMM) both purchased all of their ships from domestic builders. Meanwhile, ship buyers from Europe showed preference for purchasing ships from China and South Korea. For example, CMA CGM mainly ordered its ships from China, and A.P. Moller-Maersk purchased ships primarily from China and South Korea.

6 To more accurately represent those who initiate the order of newbuild ships, rather than those who legally own the ships, we identified ship buyers using the ship operator data instead of ship beneficial owner data from the S&P Global and Clarksons data. The figure was generated using the ship information and steel consumption estimates mentioned above.

Figure 4

Top 20 ship buyers in terms of steel consumption in 2021 and 2022



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EMBODIED GHG EMISSIONS IN STEELMAKING FOR SHIPBUILDING

Figure 5 shows the estimates of overall market share and average GHG emissions intensity based on mass of steel produced for the main suppliers of steel for shipbuilding in China, South Korea, and Japan.[7] The market-share-weighted average of the respective companies' average GHG emission intensities are used to estimate the GHG intensities of steel used for shipbuilding, and these are 2.2 tonnes CO_2e/tonne of steel in China, 2.0 tonnes CO_2e/tonne of steel in South Korea, and 2.4 tonnes CO_2e/tonne of steel in Japan. Overall, GHG intensities of most steel suppliers fall within the range of 2.0–2.3 tonnes CO_2e/tonne of steel.

7 The results in this figure include GHGs from scope 1, scope 2, methane slip, upstream coal mining, and material losses during processes; it is based on the data sources mentioned above and might not exactly match the estimates in other reports.

Figure 5

Estimates of market share and GHG intensities of steel suppliers for shipbuilding in China, South Korea, and Japan in 2021 and 2022

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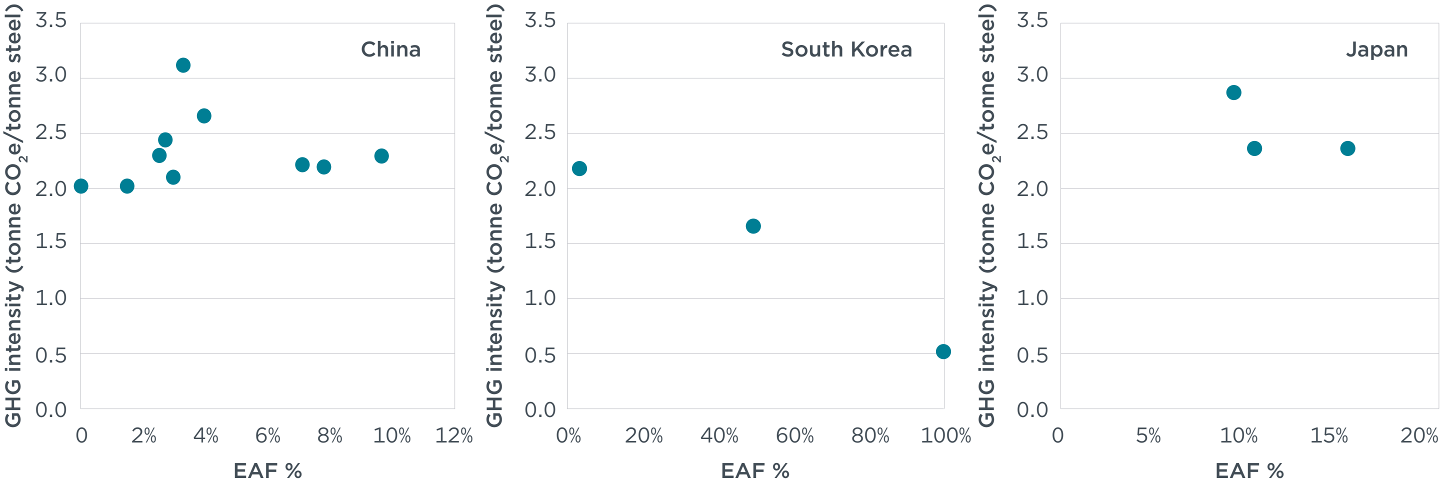
Figure 6 shows the shares of steel produced via the EAF process (including all feedstocks, like DRI or scrap), and the corresponding GHG intensity of the steel suppliers included in Figure 5. In South Korea, the GHG intensity of the steel suppliers correlates well with EAF the shares. However, for China, a higher EAF share does not generally correlate with a lower GHG intensity; this is due to the use of pig iron as the main EAF feedstock and because electricity with a relatively higher GHG intensity (557 gCO_2e/kWh) was used in China compared with 462 gCO_2e/kWh for Japan and 411 gCO_2e/kWh for South Korea (Carbon Footprint, 2023). As a result, the average GHG intensity of EAF steel in China was about 1.4 tonnes CO_2/tonne of steel (Hasanbeigi, 2022). This is not a significant improvement compared with steel produced via BF-BOF, which could have a GHG intensity of 1.5 tonnes CO_2/tonne of steel by improving energy efficiency, shutting down old plants, which are inefficient, and increasing capacity. In the short term, a supplier with a lower EAF share that increases energy efficiency could demonstrate lower GHG intensity than one with a higher EAF share. In addition to further improvements in energy efficiency and expanding the EAF share of steelmaking, the use of low-carbon electricity generation and replacing pig iron with DRI or scrap steel will be a crucial near-term step for further decarbonization of steel in China.

Figure 6

EAF share and estimated average GHG intensity of steel suppliers for shipbuilding in China, South Korea, and Japan in 2021 and 2022



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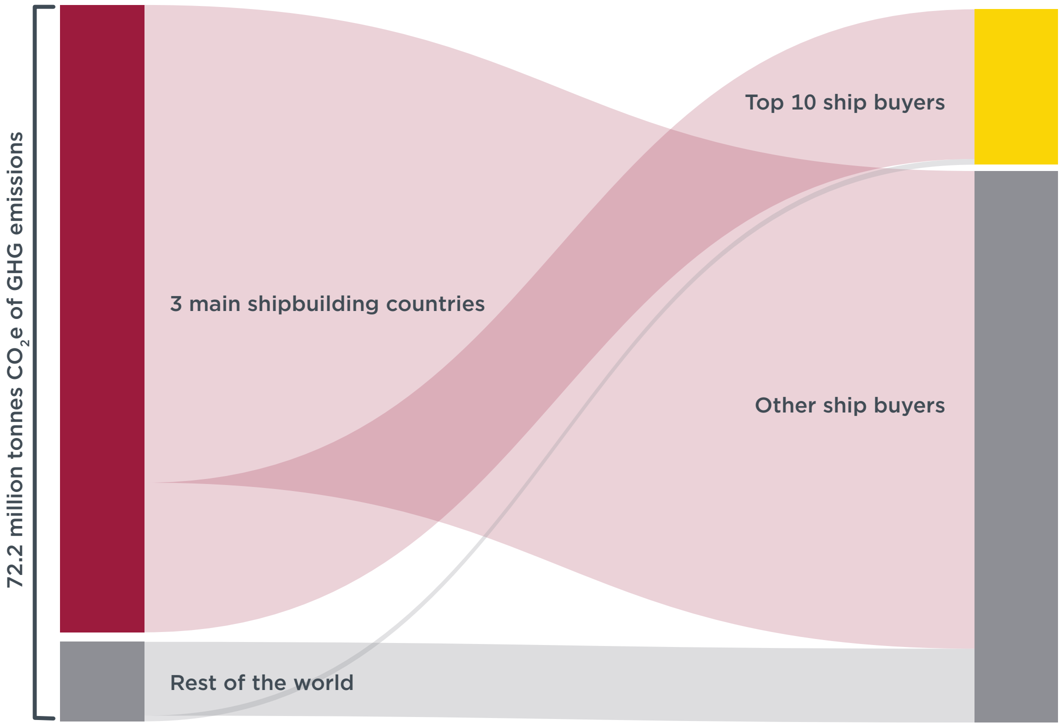
As shown in Figure 7, the total embodied GHG emissions in steelmaking for shipbuilding were estimated to be 72.2 million tonnes CO_2e globally in 2021 and 2022, and most of these were from the three main shipbuilding countries (63.5 million tonnes). As the global GHG emissions of shipping activities estimated by our SAVE model were 894 million tonnes in 2021 and 901 million tonnes in 2022, including embodied steelmaking emissions would add around 4.0% to the total. The top 10 purchasers of ships collectively accounted for 22.0% of the total embodied GHG emissions for steel used in shipbuilding.

Figure 7

Total estimated GHG emissions embedded in steel for shipbuilding in 2021 and 2022



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Recall that these results are based on assumptions that the steel was supplied by the identified steel producers in the respective shipbuilding country, apportioned by market share, and that the steel reflects the steel company average GHG emissions intensity. The results for GHG intensities and emissions are average-level values reflecting steelmaking technologies and location. Considering the steel from each identified supplier was based on the real-world market share for the shipbuilding steel market, the estimation of total GHG emissions was relatively less sensitive to the assumptions. Nevertheless, estimations of GHG intensity and GHG emissions from specific shipbuilders or ship buyers will be more sensitive to the assumptions. We expect there would be cases where the shipbuilders or ship buyers obtain more steel from smaller or larger steel suppliers with a larger or smaller market share, or steel suppliers provide steel with GHG intensities that diverge from their average level.

To incorporate these uncertainties, we took five major ship buyers as cases and calculated best-case and worst-case sensitivities. For the best-case sensitivity analysis, we selected steel suppliers with the lowest average GHG emissions intensity in each country, and the converse for the worst-case sensitivity analysis. For South Korea, Hyundai Steel was used for the best-case analysis instead of Dongkuk Steel, a scrap-based EAF steel supplier, due to concerns in the shipbuilding industry regarding the use of scrap-based steel (Sustainable Shipping Initiative, 2023). However, the share of scrap-based steel used for shipbuilding could be increased once the quality of it can be improved and guaranteed. Note that these sensitivities assume that the GHG emissions of the steel supplied to a shipbuilding company correspond to the average GHG emissions of the respective steel company.

Table 3 shows the weighted-average GHG emissions for the cases, with the average GHG emission intensities and the sensitivities mentioned above. Overall, the weighted-average GHG emission intensities of the five major ship buyers show slight variations between 2.02 and 2.13 tonnes of CO_2e/tonne of steel, as the ships purchased were primarily built by the three main countries with similar average emissions intensity. As shown by the sensitivity estimates, the GHG emissions intensity would deviate from the average depending on whether the steel for a ship buyers' fleet is proportional to the steel suppliers' market shares or by those with highest/lowest emission intensity. The emission intensities would be reduced by 10.1%, on average, under the best case and increase by 24.6%, on average, under the worst case.

Table 3
Case analysis of major ship buyers in 2021 to 2022 with sensitivity results

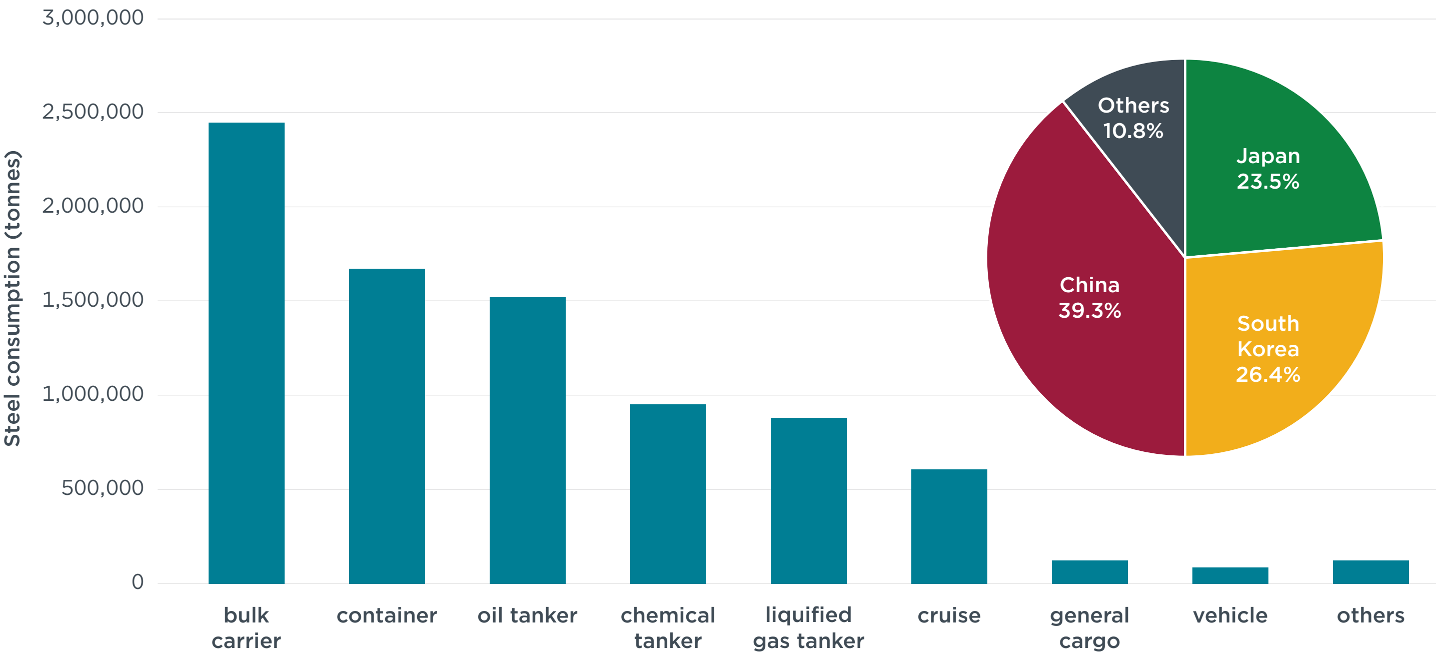
Ship buyer	Overall GHG emissions (million tonnes)	GHG intensity (tonne of CO_2e/tonne of steel)		
		Weighted average	Best case sensitivity	Worst case sensitivity
CMA CGM	2.3	2.12	1.90	2.80
Vale	1.8	2.13	1.91	2.82
Shell	1.7	2.02	1.76	2.43
MSC	1.7	2.10	1.92	2.44
A.P. Moller-Maersk	1.1	2.13	1.93	2.70

ANALYSIS FOR THE UNITED STATES

For the U.S. analysis, we identified 677 ships that were built in 2021 or 2022 and anchored or berthed in a U.S. port in 2022. These ships accounted for 27% of total newbuild ships delivered in these years in terms of GT, and 25.5% of total steel consumption. Figure 8 shows the steel consumption for these ships by ship type and shipbuilding country. Bulk carriers, container ships, and oil tankers were the main ship types built, and accounted for 67% of the steel consumption.

Figure 8

Share of steel consumption and shipbuilding country by ship type in the United States in 2021 and 2022



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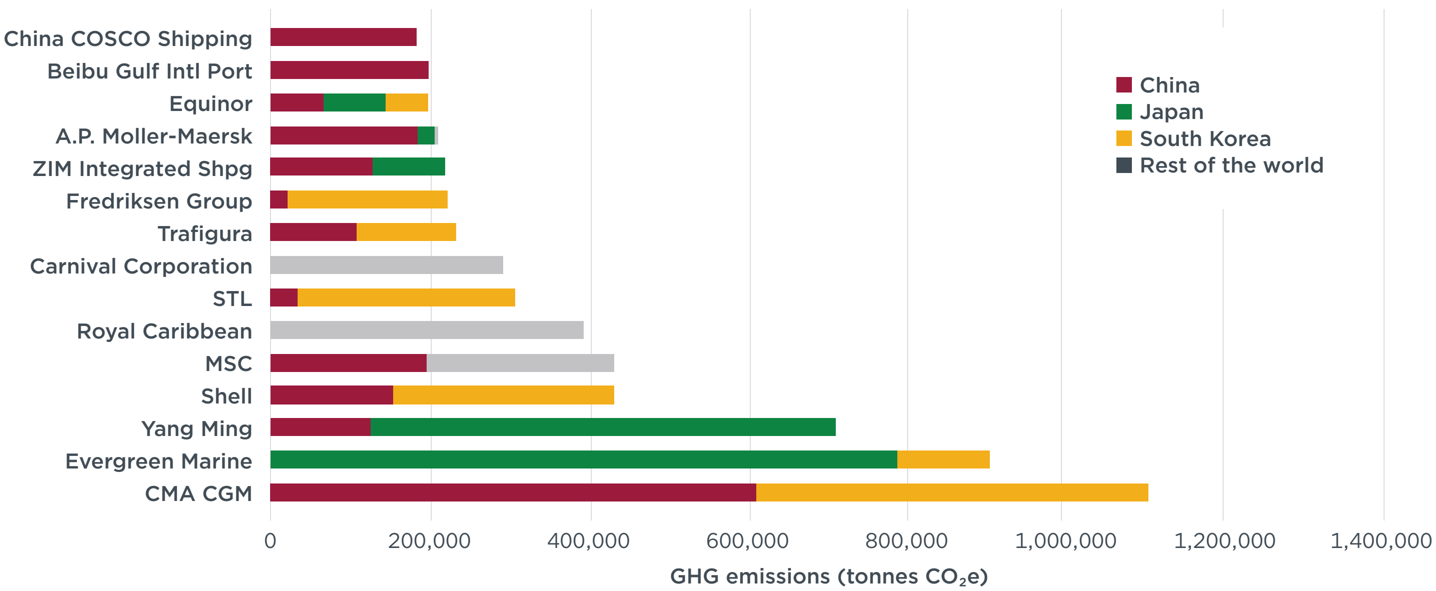
The steelmaking from building these ships led to 18.5 million tonnes CO_2e of GHG emissions, with 16.5 million tonnes coming from steel suppliers in China, South Korea, and Japan combined. As shown in Figure 9, the top 15 ship buyers accounted for 34% of the 18.5 million tonnes of CO_2e emissions. While China contributed the most with 40%, Japan followed closely with a share of 31% of these GHG emissions. Compared with the global analysis, the top ship buyers in the United States differ with the addition of two major cruise line companies (Royal Caribbean, ranked 6th, and Carnival Corporation, ranked 8th). However, these ships were built outside of the major shipbuilding countries, mainly by countries in Europe, including Italy, France, and Finland.

Figure 9

Embodied GHG emissions from steelmaking for the top 15 U.S. ship buyers in 2021 and 2022



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OPTIONS TO REDUCE THE GHG INTENSITY OF STEELMAKING

To reduce GHG emissions in the steelmaking process, several technologies have been developed or explored by the industry, including optimization of the BF-BOF process and the transition toward the EAF process. Top gas recycling (TGR), utilization of biomass, and smelting reduction (HIsarna) can help reduce emissions from the BF-BOF process, and using scrap or DRI as feedstock for the EAF process can lead to further GHG reductions. Details of each technology are in the Appendix.

We estimated the decarbonization potential of steelmaking via different pathways in China, South Korea, and Japan using the findings of this analysis and an extensive literature review, shown in Table 4. In 2021, the share of steel produced by the BF-BOF process was 89% in China, 68% in South Korea, and 75% in Japan (World Steel Association, 2022). We assumed the source of DRI for the EAF process was imported from India (coal-based) and Iran (gas-based), the two largest DRI producers in the world (Fan & Friedmann, 2021; Nduagu et al., 2022; Rahmani & Sani, 2020). For steelmaking via hydrogen-based DRI, the final carbon intensity values varied depending on the hydrogen production pathway (Hornby & Brooks, 2021; Rechberger et al., 2020). The feedstock for black and blue hydrogen was assumed to be coal, mainly due to the lack of available natural gas reserves and the dependence on coal and oil for energy production in China, South Korea, and Japan (International Energy Agency, 2024). Green hydrogen refers to hydrogen produced by the electrolysis of water using renewable electricity. The emissions reduction potential of using biomass, TGR, and HIsarna in the BF-BOF process were estimated based on literature (Fan & Friedmann, 2021; Guevara Opinska et al., 2021; Keys et al., 2021). In addition to the decarbonization pathways listed above, carbon capture and storage (CCS) technology could also be utilized to help reduce the carbon intensity of steelmaking (De Ras et al., 2019). However, drawbacks associated with the use of CCS in steelmaking include high costs and an inability to achieve high CO_2 capture efficiency due to the structure of steel plants and the variability of emission sources (Abdul Quader et al., 2016; World Steel Association, 2023; Zhou, 2020). Because these drawbacks could not be quantified and could outweigh any of the attained benefits, the use of CCS was not considered as an alternative for reducing carbon intensity of steelmaking production in this study.

Table 4
CO_2 intensity reduction potential via different steelmaking production routes compared with a 2018 baseline

Production route	China	South Korea	Japan
Baseline – CO_2 intensity (t-CO_2/t-steel)[a]			
Steelmaking – 2018	1.94	1.78	1.93
EAF steelmaking			
DRI (coal, India)	2.39 (-23%)	2.28 (-28%)	2.36 (-17%)
DRI (gas, Iran)	1.52 (22%)	1.41 (21%)	1.39 (28%)
DRI (black H_2 from coal)	1.75 (10%)	1.64 (8%)	1.62 (16%)
DRI (blue H_2 from coal)	0.85 (56%)	0.74 (59%)	0.72 (63%)
DRI (green H_2)	0.78 (60%)	0.67 (62%)	0.65 (66%)
Recycled scrap	0.77 (61%)	0.66 (63%)	0.64 (67%)
BF-BOF steelmaking			
Biomass	1.32 (32%)	1.25 (30%)	1.35 (30%)
TGR	1.52 (21%)	1.41 (20%)	1.54 (21%)
HIsarna	1.62 (16%)	1.50 (16%)	1.63 (16%)

[a] Includes CO_2 intensity for casting and rolling crude steel
Note: Sources for the 2018 baseline CO_2 intensities are Koolen and Vidovic (2022), Ren et al. (2021), and World Steel Association (2019).

For the EAF process, DRI imported from India would increase CO_2 intensity levels in China, South Korea, and Japan because coal is the feedstock. Although DRI imported from Iran would provide some reductions of CO_2, it could potentially lead to an increase in upstream methane (CH_4) emissions because natural gas is used as a reductant (Souza et al., 2023). Overall, scrap-based steelmaking is estimated to offer the highest CO_2 reduction potential for both EAF production and all potential steelmaking pathways. However, a key barrier in the shift to scrap-based EAF production is the limited supply of scrap steel, as the scrap availability of 667 million tonnes in 2021 falls short of global steel demand, which is approximately 1,800 million tonnes (Lee et al., 2024; World Steel Association, 2022).

Mission Possible Partnership (2022) projected that, even with increased scrap steel availability, up to 60% of steel demand will still be provided by BF-BOF by 2050 unless there are major material breakthroughs and advances toward circular economy. Challenges associated with controlling impurities when producing steel via recycled scrap may also limit its utilization for shipbuilding, as there is uncertainty regarding the technical requirements and quality of steel which can qualify as high grade (Sustainable Shipping Initiative, 2023). Further, steelmaking via the DRI-EAF process using green hydrogen can offer CO_2 reductions that are almost equivalent to that of recycled scrap without presenting any quality concerns (Sustainable Shipping Initiative, 2023). However, steelmaking via this pathway relies on high-quality iron ore that is not readily available and the production scale of green hydrogen is quite limited, with only 0.1% of global hydrogen produced using the renewable electricity-water electrolysis process (International Energy Agency, 2022; Sustainable Shipping Initiative, 2023).

China, South Korea, and Japan have already taken actions to reduce GHG emissions from steelmaking, both at the national and steel-company levels. Table 5 summarizes their announced decarbonization targets and actions or roadmaps. At the national level, South Korea and Japan have set more ambitious targets than China, but at the company level, the ambitions are similar. The recognized technology pathways to implement those targets are also similar, namely adopting H_2-DRI, carbon recycle in BF and deploying carbon capture utilization and storage (CCUS). However, there are financial and technological limitations regarding the use of CCUS for steelmaking, and these could impede the steelmaking decarbonization roadmap within the respective countries (Nicholas & Basirat, 2024; Zhou, 2020).

Table 5

Targets, actions, and roadmaps for steelmaking decarbonization in China, South Korea, and Japan

Country	Scale	Target	Actions/roadmaps	Source
China	National	• Peak national GHG emissions by 2030 and achieve carbon neutrality by 2060 • Energy consumption reduction of over 2% for steelmaking by 2025	• Increase EAF steel production share to over 15% by 2025 and over 20% by 2030 (from 10% in 2021) • Increase steel scrap supply from 260 million tonnes/year in 2020 to 320 million tonnes/year by 2025	National Development and Reform Commission (2021); The Ministry of Industry and Information Technology of China (2022)
	China Baowu Group	• Reduce CO_2 intensity of steelmaking by 30% compared with 2020 levels • Achieve carbon neutrality by 2050	• Use hydrogen DRI technology • Use hydrogen-rich carbon cycle blast furnace technology • Use CCUS	Carbonbase (2021)
South Korea	National	• GHG reduction of 11.4% from 2018 levels for industry sector (including steel industry) by 2030 • Achieve carbon neutrality by 2050	• Invest ₩26.9 billion from 2023–2025 for development of hydrogen DRI technology • Produce 1 million tonnes of steel annually using hydrogen DRI by 2030 • Replace 11 blast furnaces with 14 hydrogen DRI reactors by 2050	Oh (2023); The Government of the Republic of Korea, (2020); Yep and Lee (2023)
	POSCO	• 20% GHG reduction by 2030 and a 50% by 2040 compared with 2017–2019 baseline • Net-zero GHG emissions by 2050	• Improve energy efficiency and increase use of low-carbon raw material alternatives • Use of natural gas and hydrogen DRI, and increase use of EAF and CCUS • Use of green hydrogen DRI and EAF using renewable energy	POSCO (2021)
Japan	National	• 46% GHG reduction by 2030 compared with 2013 level • Net-zero GHG emissions by 2050	• Implement the COURSE50 and SuperCOURSE50 projects to reduce CO_2 emissions from blast furnaces using hydrogen injection technology • Use of carbon recycling in blast furnaces, hydrogen DRI, larger EAFs, and CCUS	Government of Japan (2022); The Japan Iron and Steel Federation (n.d.)
	Nippon Steel	• 30% reduction of CO_2 emissions compared with 2013 level • Achieve carbon neutrality by 2050	Similar to national roadmap	Nippon Steel Corporation (2021)

FIRST STEPS TO REDUCE THE GHG INTENSITY OF STEEL USED IN SHIPBUILDING

As the actions the major shipbuilding countries plan to undertake to decarbonize their steel industries are similar, and because of the steelmaking capacity limitations for these countries, switching supply chain partners may not be an option for ship buyers to meaningfully reduce their carbon footprint. Instead, ship buyers can consider the following:

» *Improve traceability of steel in the shipbuilding value chain*: This analysis provided information on methods to trace the steel used for shipbuilding and how it can help assess the embedded GHG emissions of the ships. Ship buyers potentially have access to more accurate information on the steel used for ship production. To improve the traceability of steel used in their ships, ship buyers could: (1) request that shipbuilders disclose the steel source or suppliers used in building their ships; (2) identify the main steel suppliers for their ships; (3) calculate the embedded

GHG emissions of their ships and figure out the decarbonization potential; and (4) find key steel suppliers and shipbuilders that can assist in decarbonization efforts.

- *Enhance cross-industry collaboration:* Closer collaboration between ship buyers, shipbuilders, and steel suppliers could benefit everyone in the steel supply chain. For ship buyers, closer collaboration can help achieve their decarbonization targets. For shipbuilders who can prove lower embodied GHG emissions, their ships may be favored by buyers looking to decarbonize. For steel suppliers, the demand for more low-emission steel could spur them to develop decarbonization technologies and production lines for those technologies. There have been successful cases of such collaboration in the automotive sector. For example, BMW Group and HBIS Group signed a memorandum of understanding to create a green and low-carbon steel supply chain for automotive steel (BMW-Brilliance, 2022). To enhance cross-industry collaboration, ship buyers could share decarbonization goals and request steel decarbonization from shipbuilders and steel suppliers. In addition, including decarbonization requirements in shipbuilding and steel supply contracts would help ensure buyers meet decarbonization goals while guaranteeing the demand for low-carbon steel from suppliers.

CONCLUSIONS

This analysis estimated that about 33.2 million tonnes of steel was used to construct the over 5,000 ships built in 2021 and 2022, and 88.3% of it was used in China, Japan, and South Korea. We traced and identified the steel supply chain in the shipbuilding industry, assessed the embedded GHG emissions, and summarized potential technologies and practices to reduce these emissions. Some key takeaways are presented below.

The 10 ship buyers in 2021 and 2022 accounted for 22% of the total embodied GHG emissions in steelmaking for shipbuilding. The overall GHG intensities of the ship buyers' fleets vary between 2.0 and 2.4 tonnes of CO_2e per tonne of steel used in each ship. Our analysis shows that steel could be produced at a GHG intensity lower than 1 tonne of CO_2e per tonne of steel, and that shows considerable decarbonization potential.

Steel used for shipbuilding had analogous GHG intensities in the three main shipbuilding countries, ranging from 2.0 to 2.4 tonnes of CO_2e per tonne of steel. The GHG emissions embodied in steelmaking for shipbuilding were estimated to be 72.2 million tonnes CO_2e in 2021 and 2022 combined, equivalent to around 4.0% of the total GHG emissions from fuel combustion in global shipping.

The GHG intensities of most steel suppliers for the shipbuilding industry fall within the range of 2.0–2.3 tonnes CO_2e/tonne of steel, and BF-BOF dominates the steelmaking process. The lowest GHG intensity of the steel suppliers in our study was 0.53 tonnes of CO_2e/tonne of steel using the scrap-EAF process, but production is still limited by scrap feedstock availability. In the short term, energy-efficiency improvements could help to reduce the GHG intensity of the BF-BOF process. In the long term, increased steel production from hydrogen DRI-EAF powered by renewable energy can lead to further decarbonization.

To decarbonize the steel used by their fleets, ship buyers could consider improving the traceability of steel in the shipbuilding value chain. This can assist ship buyers in determining the embodied emissions from the steel used and the possible decarbonization potential. It can also help ship buyers to work with shipbuilders to procure low-emission steel. Enhancing cross-industry collaboration between ship buyers, shipbuilders, and steel suppliers would also contribute to decarbonization. Increased collaboration can also potentially grow the market competitiveness of shipbuilders that have lower embedded GHG emissions in the ships they build, and steel suppliers can benefit from the demand for more low-emission steel.

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APPENDIX

Table A1

Regression relationship between GT/DWT and LDT for each ship type

Ship type	R^2_DWT	Regression_DWT	R^2_GT	Regression_GT
Yacht	0.23	0.5922*DWT+646.0716	0.94	0.6368*GT+61.3168
Offshore	0.57	0.1745*DWT+4606.2125	0.77	0.3570*GT+2472.3123
Container	0.96	0.2848*DWT+2176.3808	0.97	0.2958*GT+3269.6900
Service-tug	0.61	0.6898*DWT+390.3726	0.91	0.8659*GT+134.8810
Chemical tanker	0.94	0.1954*DWT+1440.6988	0.95	0.3303*GT+1258.5698
Service-other	0.64	0.2803*DWT+1482.0135	0.85	0.4425*GT+791.2975
Fishing	0.74	0.7878*DWT+478.7081	0.91	0.6312*GT+284.7685
Ferry, pax only	0.94	2.3998*DWT+41.5112	0.91	0.6474*GT-73.1640
Oil tanker	0.97	0.1350*DWT+2803.7203	0.98	0.2684*GT+2061.5229
Liquefied gas tanker	0.97	0.3680*DWT+988.0757	0.97	0.2883*GT+2838.6379
Ro-Ro	0.82	0.5396*DWT+1399.1840	0.88	0.3264*GT+1381.5461
Ferry, Ro-Pax	0.55	1.2700*DWT+1642.1298	0.79	0.3793*GT+884.8143
Bulk carrier	0.94	0.1228*DWT+3332.7110	0.95	0.2452*GT+2459.7510
General cargo	0.63	0.2923*DWT+672.4219	0.73	0.4520*GT+360.8132
Miscellaneous-other	0.41	0.3470*DWT+2377.0453	0.82	0.4311*GT+1087.2000
Refrigerated bulk	0.80	0.5296*DWT+494.7541	0.89	0.4520*GT+360.8132
Other liquids tanker	0.96	0.3041*DWT+318.7906	0.98	0.3947*GT+381.8767
Vehicle	0.64	0.5373*DWT+4215.9335	0.76	0.2404*GT+2774.6464
Cruise	0.79	3.9006*DWT-131.1689	0.94	0.4052*GT+2186.5753

Table A2

Greenhouse gas emission intensity for steel suppliers in this study

		GHG emissions intensity (tonne CO_2e/tonne steel)					
		CO_2 emissions under scope 1 and scope 2	Non-CO_2 GHG from BF-BOF	Coke coal mining	Thermal coal mining	Non-CO_2 GHG from natural gas DRI	Iron ore mining
China	Rizhao Steel	Please contact the corresponding author of Xu et al. (2023) to request data.	0.0873	0.09	0.011	0.15	0.05
	Valin Group						
	Ansteel Group						
	Nanjing Steel						
	Shagang Group						
	Xinyu Steel						
	Shandong Steel Group						
	Shougang Group						
	China Baowu Group						
	HBIS Group						
South Korea	POSCO	1.83					
	Hyundai Steel	1.40					
	Dongkuk Steel	0.40					
Japan	Nippon	2.00					
	JFE	1.98					
	Kobe	2.46					

Table A3
Steel production share of EAF and data source

Country	Steel supplier	EAF share	Data source
China[a]	Rizhao Steel	0%	World Steel Association (2020); Metal Consulting International Limited (2019)
	Valin Group	2%	
	Ansteel Group	3%	
	Nanjing Steel	8%	
	Shagang Group	10%	
	Xinyu Steel	3%	
	Shandong Steel Group	4%	
	Shougang Group	3%	
	China Baowu Group	7%	
	HBIS Group	3%	
South Korea	POSCO	3%	POSCO (2023)
	Hyundai Steel	50%	SFOC (2021)
	Dongkuk Steel	100%	
Japan	Nippon	10%	Crocker et al. (2019)
	JFE	15%	
	Kobea	9%	World Steel Association (2020) Metal Consulting International Limited (2019)

[a] Due to lack of production detail information, the EAF share of steel suppliers were estimated by BF-BOF and EAF capacity from Metal Consulting International's database and national-level average capacity utilization of BF-BOF and EAF from World Steel Association.

OVERVIEW OF THE TECHNOLOGIES TO REDUCE GHG EMISSIONS ASSOCIATED WITH SHIPBUILDING STEEL

EAF STEELMAKING PROCESS

Scrap-EAF: In the EAF steel production process, recycled scrap is used as the main feedstock to produce crude steel (Koolen & Vidovic, 2022). Unlike the traditional BF-BOF process, scrap-EAF route does not require the production of molten iron; this avoids consumption of coal at any stage and leads to a significant drop in CO_2 emissions (An et al., 2018).

DRI-EAF: Apart from recycled scrap, EAF can also produce low-carbon steel using DRI as the main feedstock. This production route uses pelletized iron ore and low-carbon reducing gases, typically natural gas or pure hydrogen to remove the oxygen from the iron in a solid state to form DRI (Fan & Friedmann, 2021; Koolen & Vidovic, 2022). While it is possible to utilize a solid reducing agent like coal to produce DRI, this will offer considerably lower GHG reduction compared to gas/hydrogen-based DRI (Hasanbeigi, 2022). However, the carbon footprint of steel produced using hydrogen-based DRI will vary according to the source of hydrogen (Fan & Friedmann, 2021; ING Group, 2023). Importantly, gas-based DRI is likely only an interim solution, as in the long term green hydrogen-based DRI will likely allow the production of steel with net zero emission (ING Group, 2023; International Energy Agency, 2023).

OPTIMIZING BF-BOF PROCESS OF STEELMAKING

Top gas recycling (TGR): This process involves modifications to an existing BF to recycle reducing agents: CO and H_2 contained in the top gas leaving BF after CO_2 removal (Keys et al., 2021). This modification reduces the demand for coke and hence reduces energy use and carbon emissions from the coking plant (Guevara Opinska et al., 2021).

Biomass: This process uses solid biomass (biofuels) as an alternative reducing agent to that of coking coal in the BF-BOF process. Biomass is generally characterized by its high moisture and volatile contents and thus it must undergo preliminary thermal treatments before utilization (Guevara Opinska et al., 2021).

Smelting reduction (HIsarna): The smelting reduction process, commonly known as the HIsarna process, eliminates the pre-processing of iron ore into sinter and pellets and coal into coke, as required in the conventional BF-BOF system (Keys et al., 2021). In this process, iron ore is reduced directly into liquid hot metal (i.e., pig iron) in a reactor that maintains a temperature above the melting point of iron throughout, and powdered coal (as reductant) is injected at the final stage (Guevara Opinska et al., 2021; Tata Steel, 2020).

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