

# 1                   **Circular Economy, Proximity, and Shipbreaking:** 2                   **A Material Flow and Environmental Impact Analysis**

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## 15 16                   **Abstract**

17                   Circular economy focuses on the extension of material and resource circularity within  
18 the economic system in order to minimize the extraction of natural resources. Attaining such  
19 circularity requires the integration of adverse impacts on the place in which the process takes  
20 place, as not all recycling activities occur within the same perimeter. The shipbreaking  
21 phenomenon epitomizes the circularity of metal that helps reaching the circular economy targets  
22 but is often carried out far from the origin of the commodity, raising issues regarding proximate  
23 recycling. This study illustrates this aspect by analyzing the global ship flow pattern, domestic  
24 metabolism, and global environmental savings. Our results suggest that size of the ships rather  
25 than flagging pattern determines the recycling destination, as smaller ships are recycled in  
26 standard destinations despite being popularly flagged while large ships are recycled in  
27 substandard destinations despite being owned by standard recycling nations such as Turkey.  
28 We also see that shipbreaking avoids (70-90%) environmental impacts at the cost of (1-5%)

29 disposal impacts and (5-20%) domestic processing impacts. Evaluating proximate recycling  
30 against distant recycling shows that former perform worse by far (95 against 184) than distant  
31 recycling. We suggest that pursuing distant recycling rather than proximate recycling is globally  
32 imperative and thus, a beyond-border extended producer responsibility can be initiated to  
33 minimize beyond border adverse impacts of distant recycling.

34

35 **Key words: Shipbreaking, Circular Economy, Proximity, Material flow analysis,**  
36 **Resource recovery and recycling**

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## 40 INTRODUCTION

### 41 Circular economy, recycling and proximity

42 Three prior fields (ecological economics, environmental economics, and industrial  
43 ecology) contribute to the birth of Circular Economy (CE) (Ghisellini et al. 2016). Ghisellini et  
44 al. (2016) analyzed the theoretical and conceptual similarities and differences among  
45 neoclassical economics, steady state (also, degrowth) and circular economy. They also  
46 highlight that CE successfully combines several theoretical fields to develop an alternative  
47 growth model envisioned in decoupling. For example, from the systems theory, CE takes  
48 holism, system thinking, organizational learning and human resources development; from  
49 industrial ecology, CE draws from the understanding of material and energy flows between  
50 industry and environment; from ecological economics, CE acknowledges entropic limits,  
51 indefinite metal recyclability and restoring ecological provision/services to the economic  
52 systems (Daly 1977). The components of all those approaches constitute the theoretical  
53 foundation of CE that holds promise for decoupling of economic growth and environmental  
54 externalities.

55 Until recently, circularity is predominantly backed by the recycling principle, which is  
56 ranked as 8<sup>th</sup> of the 10 value retention options of CE strategy, with reuse, resale,  
57 remanufacturing and refurbishing ranked high up the order (Reike et al. 2018). In EU and other  
58 developed countries, CE and the associated 3R principles are widely applied to waste  
59 management areas, with an overarching target of achieving synergistic effects in economic  
60 growth and landfill prevention. To realize this, reuse is particularly crucial as increasing reuse  
61 will preserve structural integrity, avoiding the environmental impacts of mining virgin materials  
62 and manufacturing processes (Rahman et al. 2019). Extended Producers Responsibility (EPR)  
63 is enacted in developed countries in order to promote recycling and circularity through a  
64 monetary incentive approach. The expected repercussion of this approach is to motivate

65 manufacturers to transform product design, enable ownership access, favor radical resource  
66 productivity and rebuilding natural capital (Rahman et al. 2019). Thus, CE involves the  
67 reemergence of 3R principles with added focus on (1) appropriate design, (2) reclassification  
68 of materials and (3) upgradability (Ellen MacArthur Foundation 2017). Gregson et al. (2015)  
69 presents a critique of CE by (1) criticizing its over-reliance on global recycling networks with  
70 little or no regard of their implications due to distancing (lack of proximity principles) and (2)  
71 ignoring the type (e.g. dirty) and ethicality (illegal trade) of the accompanied activities. They  
72 suggested adopting a moral CE that embarks on ecological modernization, environmental  
73 justice, and resource insecurity. Although potentially applicable at three levels: micro, meso  
74 and macro (e.g. decoupling in EU), CE is limited mainly in national-level and in particular  
75 sector, without concerning beyond border material flow between developed to developing  
76 countries (Nordbrand 2009). For example, Cusack (1989) pointed out that in every five minutes,  
77 a toxic shipment finds ways from developed countries to the developing countries, mostly due  
78 to reasons of avoiding high disposal costs and, instead, earning handsome profit by transporting  
79 them to the developing countries. Several studies highlighted the need to understand social,  
80 economic and environmental drivers and challenges to mitigate the hazardous waste dumping  
81 (Sonak et al. 2008, Frey 2013, Sthiannopkao and Wong 2013). While CE encourages the  
82 adoption of higher value retention options, the incentives that underlie the trans-shipment of  
83 hazardous waste towards distant ‘sacrifice zone’ are largely understudied. Thus, there is a  
84 missing link between CE and recycling, in which the place where recycling occurs becomes  
85 crucial. In reality, EPR was established to promote close looping within a geographic boundary,  
86 but that is limited only to certain material categories and the rest is processed beyond, with  
87 ‘welcome in my backyard’ as a potential driver (Sonak et al. 2008, Sthiannopkao and Wong  
88 2013).

89           The Proximity principle is defined as the disposal of waste to its origin and has been  
90 successfully applied in different countries as a core driver of solid waste management (Okuda  
91 and Thomson 2007). Although involving higher costs, Japan adopted policies, devised task  
92 distributions (state and local level) and regionalized the treatment through sharing of  
93 management facilities in every locality (sometimes with sharing approach in greater regional  
94 facilities). On the other hand, the EU seems to be ignore proximity principal through, for  
95 example, the Waste Framework Directive that tends to shift incineration markets from the  
96 national level to EU level, permitting the waste flow towards a low economy region that is  
97 already overburdened with waste management issues (Sora 2013). Predominantly, waste  
98 distancing occurs due to three factors: first, waste sink capacity limitation; second, economic  
99 globalization and, finally, economic inequality (Clapp 2002). This study illustrates the  
100 implications of distancing waste by analyzing the End-of-Life (EOL) ships flow that  
101 demonstrates a ‘distant’ circularity (also global environmental sustainability) with potential  
102 damage to local human and ecological health, necessitating the recognition of proximity  
103 principles.

104

### 105 **Shipbreaking**

106           The shipbreaking industry becomes an important phenomenon for the shipping industry  
107 when ship-owners started to experience the reduced revenue at the EOL of a ship (Knapp et al.  
108 2008). Ship-owners, mostly from the developed countries, recycle their ships in South Asian  
109 shipbreaking nations, benefitting local economy by generating employment and supplying  
110 scrap resources for the construction industry (Gregson et al. 2010, Rahman and Mayer 2015).  
111 The shipbreaking industry is not, however, without localized adverse environmental and social  
112 impacts emanating from the hazardous waste content of the EOL ships. This industry pollutes

113 coastal ecosystems and exposes workers to occupational hazards leading to injuries and deaths  
114 (Abdullah et al. 2013, Cairns 2014).

115 It is generally believed that ships are dismantled in substandard contexts due to change  
116 of flag from owner nations to a nation that requires low compliance cost during their  
117 commercial life (Alcaidea et al. 2016). It seems as if the cure of the problem is in stricter control  
118 and better identification of a reflagging pattern, notwithstanding the other important socio-  
119 economic considerations, such as steel demand, capacity limitation, and competitive price gain  
120 that all require more investigation. A critical investigation of the EOL ship flow may, thus, bear  
121 important implications for resource consumption and recovery pathways for the recycling  
122 industry.

123 Demand for secondary steel – a product of shipbreaking activity - is expected to increase  
124 in developing countries. The steel production process is responsible for 25% of industrial  
125 carbon emissions worldwide (Pauliuk et al. 2013). The steel industry, therefore, focuses more  
126 on reusing and recycling of scrap steel, and it is forecasted that secondary steel production will  
127 exceed primary production after 2060 (Pauliuk et al. 2013). Tracing EOL vehicles, Nakamura  
128 et al.(2014) found that around 80% of the recovered steel is used in the construction industry,  
129 which is the burgeoning sector of the developing economy. Per capita, in-use stock estimates  
130 showed that steel demand may continue to rise unless it reaches the saturation level of  $13 \pm 2$   
131 tons per capita(Pauliuk et al. 2013). The demand for steel poses challenges to carbon mitigation  
132 targets unless more effective strategies for steel reuse are adopted (Cullen et al. 2012). Global  
133 shipbreaking is thus an important supplier of scraps as Cullen et al. (2012) showed that in-use  
134 steel stocks of ships were about 3% (31 million tons) of the total steel inputs in 2008. In 2016,  
135 about 7.2 million tons of EOL ships were scrapped.

136 No existing study has applied MFA to the shipbreaking system on a global scale. This  
137 study is designed to explore the relationship among the ship-owning countries (countries that

138 own the ships during their commercial life) to the Destination countries (Countries that recycle  
139 ships: mostly Bangladesh, India, Pakistan, China, and Turkey) via flag state in relation to EOL  
140 shipbreaking.

141

## 142 **MATERIALS AND METHODS**

143 Several studies have highlighted the need to apply material flow analysis (MFA) to  
144 better understand shipbreaking phenomenon that may allow further analysis (Jain et al. 2016,  
145 Sujauddin et al. 2017). Hendriks et al. (2000) mentioned three objectives of MFA application:  
146 1) identify material flows and stocks, 2) evaluate the flow results and finally 3) transform flows  
147 in order to achieve certain social and environmental goals. They also commented that MFA is  
148 ‘excellent’ as far as the first objective is concerned and provides an analytical base for the latter  
149 two objectives. Data acquisition is difficult for MFA, and has to be sourced from market  
150 research, expert judgment, best scenarios and interviews and ‘hands-on’ knowledge. In order  
151 for MFA to communicate at a policy-making level, researchers with multidisciplinary expertise  
152 that cuts across social science, policy science and engineering are suggested (Hendriks et al.  
153 2000). In this study, we have applied Sankey MFA software tool that serves three broad  
154 purposes: 1) it helps to compare the scale of resource flows; 2) it can explain overall resource  
155 flow networks and their interconnectedness, and finally 3) it can help define important  
156 conditions that improve resource constraints and efficiency.

157

### 158 **Data**

159 From NGO shipbreaking platform, Number of LDT dismantled by ship type (General  
160 Cargo, Bulk Carrier and Oil Tanker) and by country (Bangladesh, India, Pakistan, China,  
161 Turkey and others) were estimated in excel worksheet (NGO Shipbreaking Platform 2017).  
162 Secondly, type and quantity of material recovered are identified in percentage by ship type from

163 Adak (2013) and Anderson et al. (2001). The material recovery types include ferrous scrap,  
164 remelting scrap, cast iron, nonferrous scrap, machinery, electrical and electronic compounds,  
165 minerals, plastics, liquids, chemicals and gases, joinery and miscellaneous. The percentage is  
166 then multiplied with the quantity each country represents by the ship type. This gives us the  
167 amount of metal/material recovered in each material category in tons ( $R_k$ ), which is then  
168 multiplied by the environmental impacts per kg ( $I_k$ ), taken from ecoinvent database version 3.1  
169 using TRACI method (e.g., data of 1 kg steel metal, steel, low-alloyed, at plant  
170 metals/extraction in the ecoinvent database). This gives the total avoided impact of the primary  
171 metal/material production ( $I$ ). Impacts of Ferrous and remelting scrap category is calculated  
172 based on steel production impact item in ecoinvent; impacts of Cast iron are calculated by the  
173 cast iron production impact item (Equ. 1). Environmental impacts of non-ferrous scrap are  
174 estimated by the impact of copper (14%) , zinc (43%) and bronze (43%) which were calculated  
175 by the non-ferrous recovery data. For example, Table S1 shows the conversion of 1 kg cast iron  
176 to its corresponding impacts. We exclude the other material category (Machinery, Electrical  
177 and electronic compounds, Minerals, Plastics, liquids, Chemicals and Gases, Joinery and  
178 Miscellaneous) from impact calculation due to the lack of appropriate conversion factor. The  
179 avoided environmental impact represents 81% of the total material recovered in the  
180 shipbreaking process.

181

182 *Avoided environmental impacts ( $I$ ) = Material recovery ( $R_k$ ) X Environmental impacts/per kg*  
183 *of materials ( $I_k$ ) .....( $I$ ); k represents each metal recovered.*

184

185 For domestic scrap processing, estimates from Sujauddin et al.(2017) and Rahman et al. (2016)  
186 were used. Sujauddin et al.(2017) were used for estimating the amount of steel that underwent  
187 domestic processing, which is then multiplied by the impact estimated in Rahman et al. (2016)



188 per ton. To get the total domestic processing impact (D), 70% of the total scrap recovered were  
189 considered that undergone energy intensive processes (Sujauddin et al. 2017). The energy  
190 consumption for the domestic processing varies by the processing method and primary energy  
191 used. The data for the standard destinations are not available.

192 For waste disposal impact (L), we have categorized waste disposal method as landfill,  
193 incineration and bilge oil incineration and their corresponding proportion, estimated by  
194 Hiremath et al. (2015). The proportion of waste landfilled, incinerated and bilge oil processed  
195 was estimated as 74%, 7% and 19% respectively. To estimate impacts of waste disposal,  
196 hazardous waste landfill, hazardous waste incineration and bilge oil incineration were chosen  
197 from ecoinvent database at global scale. TRACI impact estimation method was used. It is  
198 noteworthy that IMPACT 2002+ were used to estimate domestic processing impacts in Rahman  
199 et al. (2016), of which four impact categories were converted to compare with avoided  
200 environmental impacts and waste disposal impacts in equ. (2).

201 *Net avoided impact = Avoided environmental impact (I)- Domestic processing impact (D)-*  
202 *Waste disposal impact (L) .....2)*

### 203 **Categorization of vessels**

204 We have categorized ship-owning nations, flagging nations and recycling nations in  
205 order to understand the underlying factors behind the flows (Table S2). Ship-owning countries  
206 are classified in six categories based on the primary function of those nations regarding the  
207 shipping industry: 1) Recycling beneficiary owners (BO) are defined as the owning nations  
208 such as India, Pakistan, Bangladesh, China, and Turkey that mostly dismantle ships. 2) Popular  
209 flag BO represents nations that are familiar as popular flagging nations, such as Liberia, Panama  
210 and others. 3) Developing country BO represents nations that have GDP per capita lower than  
211 8,000 USD per year in 2016. 4) Developed country with facility represents nations that have  
212 GDP per capita above 8,000 USD per year in 2016 and possess a ship demolition facility.

213 European countries (For example, UK, France, Netherlands etc.) fall into this category. 5)  
214 Countries that have high GDP per capita but have no ship demolition facility are included in  
215 the Developed country without facility category. Finally, 6) Unknown BO represents ships that  
216 could not be identified with any owner nations.

217 Flag countries are categorized into three groups: 1) BO flag countries are those ships  
218 flagged by the owning nations. 2) Popular flag countries are top thirty countries that flagged  
219 most of the ships and 3) Non-popular flag countries are those nations that are not popular flag  
220 bearing countries. Owner nations usually reflag their ships to avoid high environmental  
221 compliance costs. Demolition destinations have three categories: substandard destinations  
222 (India, Bangladesh, and Pakistan), standard destinations (China and Turkey) and European  
223 destinations.

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## 225 **Data Quality and Issues (Robustness of the estimate)**

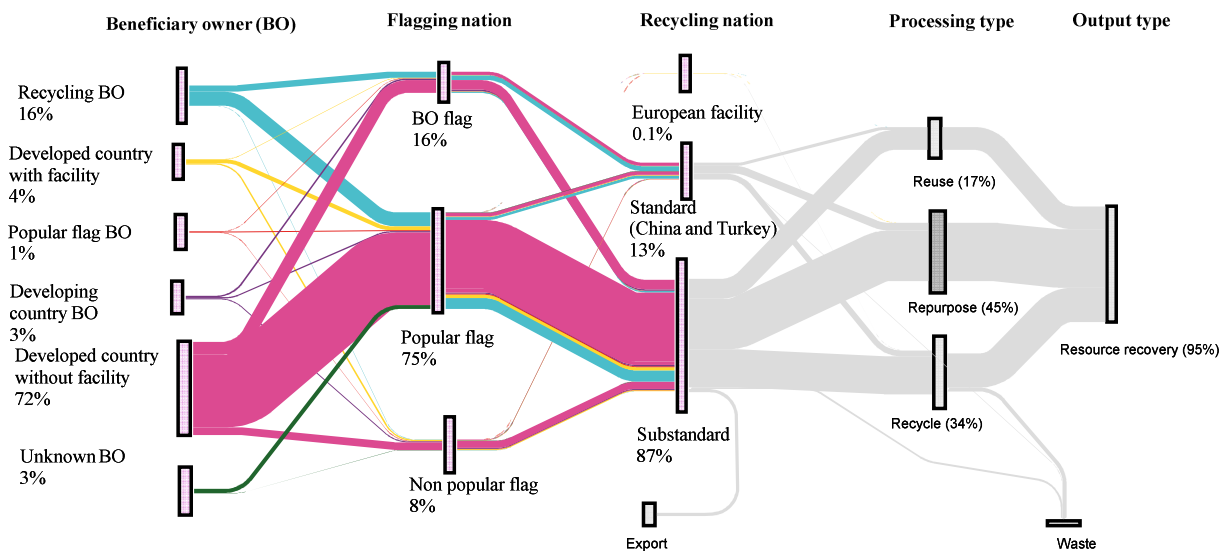
226 Estimates of demolition waste present considerable uncertainty. To the best of the  
227 authors' knowledge, no existing study takes into account the waste content variation by ship  
228 types, age and cultural contexts in which dismantling is performed. In particular, Turkey waste  
229 data is suspicious, showing lower waste content than the major shipbreaking nations. We apply  
230 Nesar et al. (2008) to expert estimate for Turkey and China. In addition, there is an absence of  
231 data for domestic scrap processing in other countries, except for Bangladesh. For Bangladesh,  
232 Sujauddin et al. (2017) conducted a material flow analysis of domestic scrap processing and  
233 distribution, which is assumed to be representative of the other ship recycling nations. Similarly,  
234 recovered scrap type also varies by composition and types. We have surveyed the existing  
235 literature and found considerable differences among estimates. Although a level of uncertainties  
236 exists in our data, largely due to the informal nature of the documentation, we believe that more  
237 comprehensive data would not radically alter the scrap distribution and waste discharge pattern.

238 In addition, this level of data reliability is consistent with the aim of the study (overall  
 239 understanding of ship flow, overall environmental impacts, and resources consumption).

240

241 **RESULTS AND DISCUSSION**

242 In 2016, 862 ships were demolished worldwide, with a total weight of 7.2 million Light  
 243 Displacement Tonnage (LDT) (Figure S1). Out of this 7.2 million LDT, 76% by weight is  
 244 owned by developed countries (GDP 8000 USD or higher), 16% is owned by the recycling  
 245 nations, such as China, India and Turkey, 3% by the developing countries (GDP lower than  
 246 8,000 USD), 1% by popular flag nations, leaving 3% that was not identified by the owning  
 247 nations. 75% of the ships, by weight, carried flags of popular flag countries and 16% were  
 248 operated with the flags of owning countries (BO flag). Only 8% carried flags of non-popular  
 249 countries. At their EOL, approximately 87% of the ships are taken to substandard facilities  
 250 namely in Bangladesh, India and Pakistan and 13% are taken to the standard facilities namely  
 251 in China and Turkey, while the remaining 0.1 % are recycled in EU facilities (Figure 1).



252

253 Figure 1. Global material flow of EOL ships processing in 2016 in LDT.

254 After dismantling the EOL ships, substandard facilities reused 17% of the total scraps  
 255 that are certified (American Society for Testing Material grade) steel, mainly in the form of

256 machinery and rolled 45% in induction furnaces to produce high quality, certified bar and other  
257 steel products. The lower quality scrap (34%) is melted and rerolled to make uncertified rebar.  
258 About 95% of the total scrap is recovered for domestic use with about 2% waste, which varies  
259 depending on where the ships are dismantled. These high recovery percentages, with more reuse  
260 and repurpose mix and less recycling makes the processing stage important for global  
261 sustainability.

262 Individually, ships destined for substandard destinations (India, Bangladesh, and  
263 Pakistan) represent similar flow patterns as before, with the majority share (70% of the  
264 beneficiary owner countries) belonging to the developed country (Figure 2). It can be seen that  
265 India is the leading recycling nation by the number of ships, while Bangladesh tops the scale if  
266 the LDT is considered (2.5 million LDT compared to 2.1 million LDT in India) (Figure S2).  
267 Overall, Pakistan is positioned third by the number of ships and by LDT.

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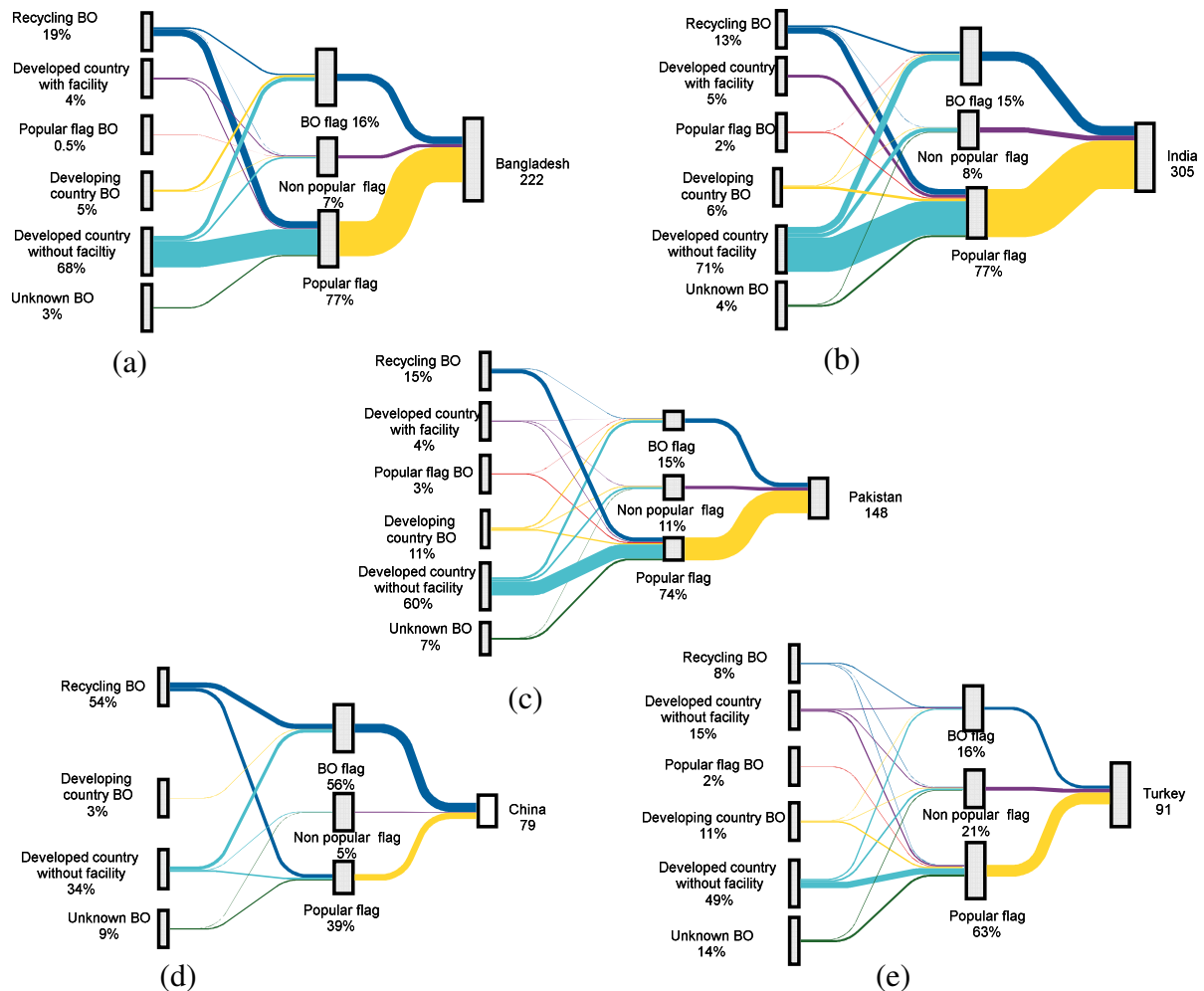


Figure 2. Source distribution of ship flow by number to five major shipbreaking nations in 2016 (Percentage calculated based on number of ships).

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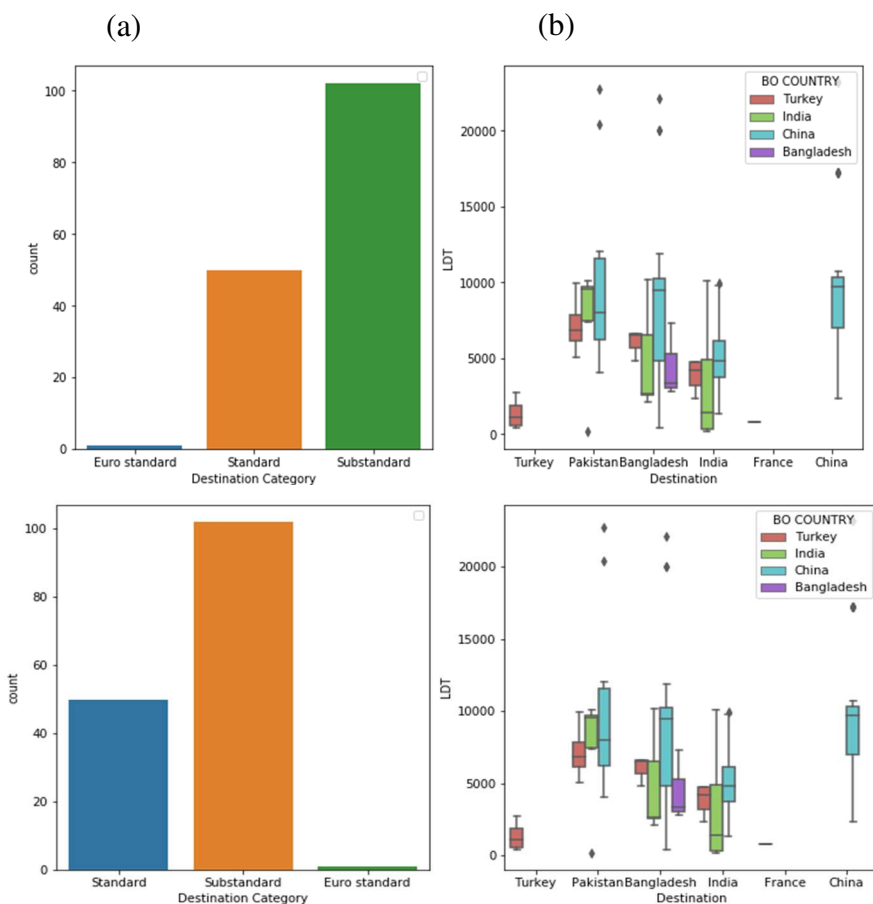
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China exhibits a different flow pattern (Figure 2, d). Out of 105 ships owned by China, 75 ships used popular flags and 29 used the Chinese flag, only one used a non-popular flag. China dismantled 43 Chinese ships (54%), which used 29 Chinese flag and 14 popular flag. The average LDT of Chinese ships is 10,000 LDT, almost equal to other popularly flagged ships that are dismantled back in China. This has two important implications: (1) China has the capacity to dismantle bigger ships as substandard facilities do and second, even after being popularly flagged, Chinese ships return home for recycling. Out of the remaining 62 Chinese ships, 32 were recycled in Bangladesh, 20 in India and 10 in Pakistan. These remaining ships generally are equal or lower in LDT compared with those dismantled in China, leading to an

282 interesting question: why China, despite her capacity to handle bigger ships, dismantled in  
 283 substandard countries (Figure S4). Maybe, China is unable to handle that many ships in one  
 284 year, in other words, Chinese capacity may be limited by the year capacity, or may be Chinese  
 285 companies lost out in price negotiation offered by the companies of the substandard yards.  
 286 Another possible factor is the distance of the given ships from the facilities when the recycling  
 287 decision is made.

288 Like China, out of 20 Turkish ships, 12 are popularly flagged and 6 are BO flagged.  
 289 Turkey dismantles 7 in its own yard, while sending 3 to Bangladesh, 5 to India, and 4 to Pakistan.  
 290 Out of 25 ships, India dismantles 12, while 8 are sent to Pakistan and 5 to Bangladesh. Turkish  
 291 yards are seriously limited to dismantling only smaller vessels in their own territory, while  
 292 sending larger vessels to Pakistan, Bangladesh and India. The reason India sent ships to  
 293 Bangladesh and Pakistan remains unknown at the moment (Figure 3).

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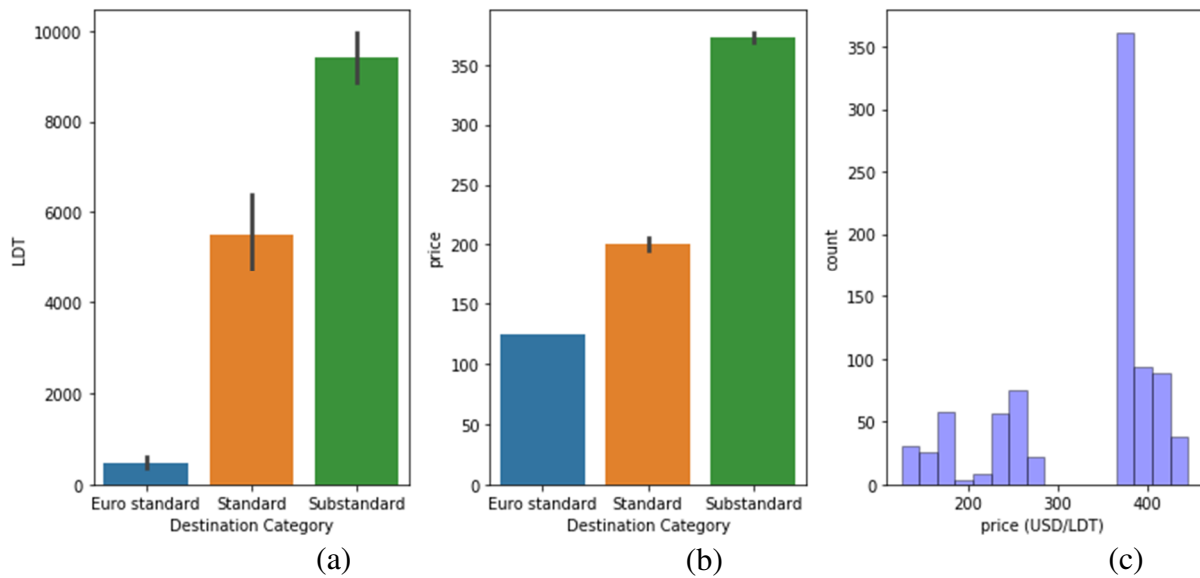
297 Figure 3. Analysis of Chinese, Turkish and Indian ship recycling. (a) shows the number of  
298 ships from these three countries and their destination categories; (b) shows destination  
299 nations; Bottom error bar represents minimum to first quartile of data, the rectangular box  
300 represents data from first quartile to third quartile with a line indicating median data point.  
301 The upper error bar represents the fourth quartile of the data. Outlier represents the data points  
302 that lie beyond the upper error bar.

303  
304 Popular flag bearing ships account for about 500 ships that went to substandard  
305 destinations, while less than a hundred ships go to standard destinations (Figure S6). The  
306 average LDT of ships that go to substandard destinations ranges from over 5000 to 15,000 LDT,  
307 whereas those destined for standard destinations weigh less than 7000 LDT. Similarly, non-  
308 popular flag bearing ships are separated in terms of their size. Out of 60 non-popular flagged  
309 ships, about 10, which are smaller, are sent to the standard destinations. This suggests that  
310 flagging a ship appears to play a role in an efficient selection procedure, depending largely on  
311 the size of ships (Figure S7 and Figure S8).

312 However, the BO flag shows a different pattern in that almost identical numbers and  
313 size of ships are sent to both substandard and standard facilities, largely due to the influence of  
314 Chinese ships that are dismantled in China as BO flag (Figure S4). Apart from China, other BO  
315 flag countries concord with same size based segregation (Figure S5). Thus, this study highlights  
316 the need to investigate the pattern and functions of popular flagging nations critically: recycling  
317 BO and BO flags may complicate the claim that flagging loopholes cause EOL ships to  
318 substandard yards.

319 The capacity limitation might have been reinforced by the price offered by the  
320 substandard destinations. Bangladesh, India and Pakistan offer high prices per LDT, ranging  
321 from 380-420 USD/LDT, compared with about 200 USD /LDT in China and Turkey and about  
322 130 USD/LDT in European destinations (Figure 4; b, c). This means that the ship-owners have  
323 monetary incentives to send to substandard destinations, which influence the direction of  
324 material flows. The four scenarios resulting from the combination of the size and price offered  
325 are as follows: bigger AND high priced offered ships end up in South Asian destinations;

326 smaller AND high price offered ships are unlikely; bigger AND low price offered end up in  
 327 China, and smaller AND low price offered ships have more likely to be dismantled in Turkey.



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330 Figure 4. Price differences based on destinations

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333 Major BO countries have inconsistent pattern in term of destination selection. Greece  
 334 has almost equal distribution among Bangladesh, India and Pakistan, whereas Germany sends  
 335 most of the ships to Bangladesh and India, far fewer to Pakistan. Singapore and Taiwan  
 336 distribute almost equally, however, Hong Kong is found to have a high preference for  
 337 Bangladesh (8%), compared to about 1% for both India and Pakistan (Figure S3 and Table S6).  
 338 Further study can explore if the selling process involves embedded relationships among cash  
 339 buyers of a particular nation. Detailed investigation of Greece as a major BO country supports  
 340 the claim that although popularly flagged, ships find destinations based on size (Table S4).

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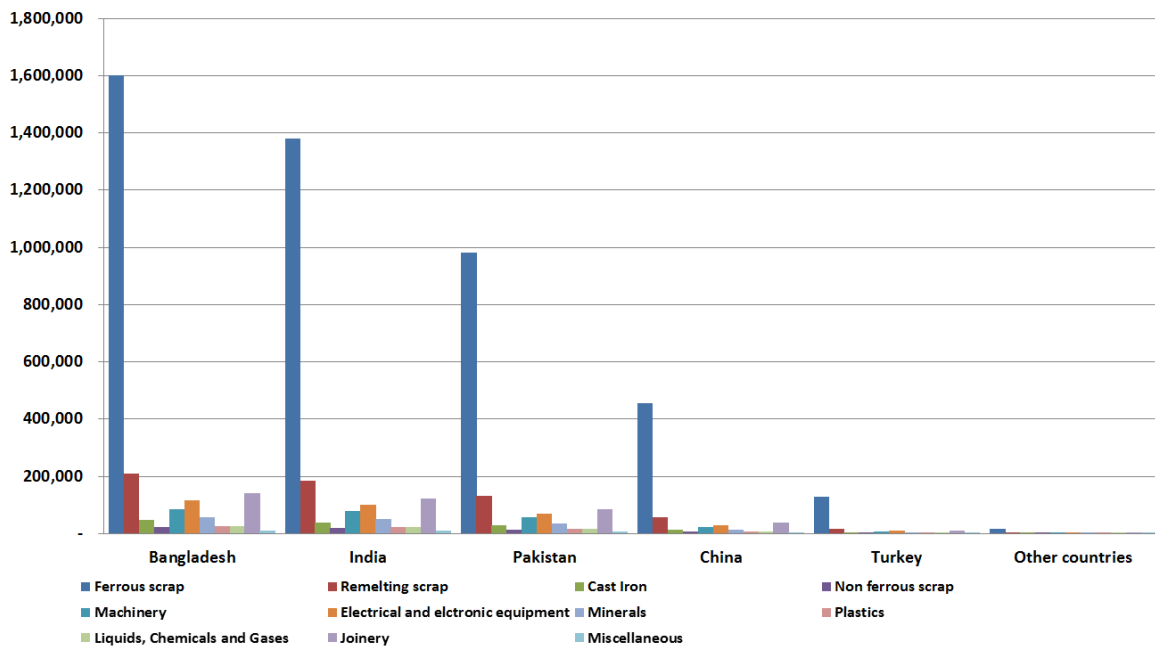
### 341 Domestic scrap generation and global level environmental savings

342 Figure 5 provides the amount of ferrous scrap and other types of non-ferrous scrap, with  
 343 machinery and furniture, recovered in shipbreaking countries. A total of 7.2 million ton was



344 dismantled in 2016 worldwide. About 79% (5.3 million ton) of ferrous scrap is recovered with  
 345 about 35% (1.8 million ton) of it recovered in Bangladesh. India, Pakistan, China, Turkey and  
 346 other countries recovered 30%, 22%, 10%, 3% and 0.01% respectively. Corresponding  
 347 environmental savings were also estimated in table S9. South Asian nations are observed to  
 348 contribute to avoid more than 90% environmental savings. Compared to the domestic  
 349 processing impacts and waste disposal impacts, avoided environmental savings are much larger,  
 350 with about 80% in all impact categories (Figure 6).

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352

353 Figure 5. Scrap generation of shipbreaking industry in 2016 by country data taken from NGO

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Shipbreaking platform (Unit: Metric tons) <sup>19</sup>

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357 **Waste estimation and localized environmental impact**

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The quantity of waste from shipbreaking process is not easy to estimate. The waste  
 359 content varies significantly with the type of ships, the age, the country in which the ships are  
 360 recycled. For example, 95% of glass wool is reused in Bangladesh. Asbestos and asbestos-

361 containing material content differs substantially depending the type of ships: Merchant ship or  
362 Navy ship. Table 2, below, shows that in India, the waste content percentage varies from  
363 2.13% to 7.90% for refrigerator ships, while it is far below that in Bangladesh, only 0.99%,  
364 compensated for mostly by glass wool reuse. Turkey's data is, however, suspicious, with only  
365 0.56% waste content. Instead, we relied on Nesar et al. (2008) study that estimated waste  
366 percentage at 10% in Turkey. European Commission (EC) data is more reliable, as this data is  
367 collected from a US company directory (European commission, 2009). This shows that the  
368 waste content percentage is 1.86 % to 3.96 %. World bank report estimates detailed hazardous  
369 material from a merchant and navy vessel and reported waste percentage about 21% and 42%,  
370 much higher than the other estimates (Table S10).

371 Table 1. Waste estimation in metric tons from different published sources in different countries and in different ships

	Hiremath et al. (2015)				Sofies (2016)			NGO Shipbreaking Platform (2017)	European Commission (2009)	
	India				Bangladesh			Turkey	U.S.	
Items (Metric tons)	General Cargo, Bulk Carrier and Container ships	Oil and Chemical Tanker	Refrigerator Ship	Passenger ship	General Cargo	Bulk Carrier	Tanker		Merchant ship	Navy Ship
Asbestos + asbestos-containing materials	11.00	11.00	1.35	0.70	11.50	11.50	12.50	5.23	7.00	771.00
Glass wool	132.00	100.00	390.00	250.00	7.00	7.00	6.00	n/a	n/a	n/a
Other landfill waste	27.00	8.50	7.00	21.50	29.55	29.55	10.00	n/a	n/a	n/a
Incineration waste	27.00	24.00	27.50	10.00	28.52	28.52	29.00	n/a	n/a	n/a
Bilge water	21.00	37.50	87.50	16.50	22.50	22.50	43.50	0.55	n/a	n/a
PCB	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0001	122.00
Heavy metals	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.26	0.22
Oil	n/a	n/a	n/a	n/a	n/a	n/a	n/a	27.02	315.00	35.00
Oil sludge	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	375.00	312.00
Tri butyl tin	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.20	1.00
Mercury	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0002	2.00
Ozone Depleting substances	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.72	0.90	0.75
Waste Cable	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.56	n/a	n/a
Total (Metric tons)	218.00	181.00	513.35	298.70	99.07	99.07	101.00	45.08	699.36	1,243.97
Ship weight	9,500	8,500	6,500	11,500	10,000	10,000	10,000	8,000	37,500	31,400
Percentage w/w	2.29%	2.13%	7.90%	2.60%	0.99%	0.99%	1.01%	0.56%	1.86%	3.96%

372

373 Given the best available estimates from different studies mentioned in table 1 and table  
374 S10, we have estimated total waste generation in 2016. In this study, the percentage of waste  
375 generation is estimated as follows: Bangladesh (1.01%), India and Pakistan (2.29%), Turkey  
376 and other EU countries (10%) (European Commission 2009, Hiremath et al. 2015, Sofies 2016,  
377 NGO Shipbreaking Platform 2017). This aggregate waste is appalling for developing countries,  
378 in the sense that these countries are not known to have a waste management system in their  
379 facilities. Bangladesh generates about 23 thousand tons while Pakistan generates 33 thousand  
380 tons. India generates about 46 thousand tons (Table 2). Transforming waste to energy may be  
381 an option to manage this waste for these substandard recycling countries, which economically  
382 and environmentally feasible. In Indian context, waste is treated by landfilling, incinerating and  
383 disposal of bilge oil, with about 74% waste landfilled, 7 % incinerated and 14% bilge oil treated  
384 (Deshpande et al. 2013, Hiremath et al. 2015). Using TRACI, environmental impacts are  
385 estimated in nine categories from eco-invent database. Hazardous waste landfill, hazardous  
386 waste incineration and bilge oil incineration were chosen as the dominant disposal methods for  
387 global scale.

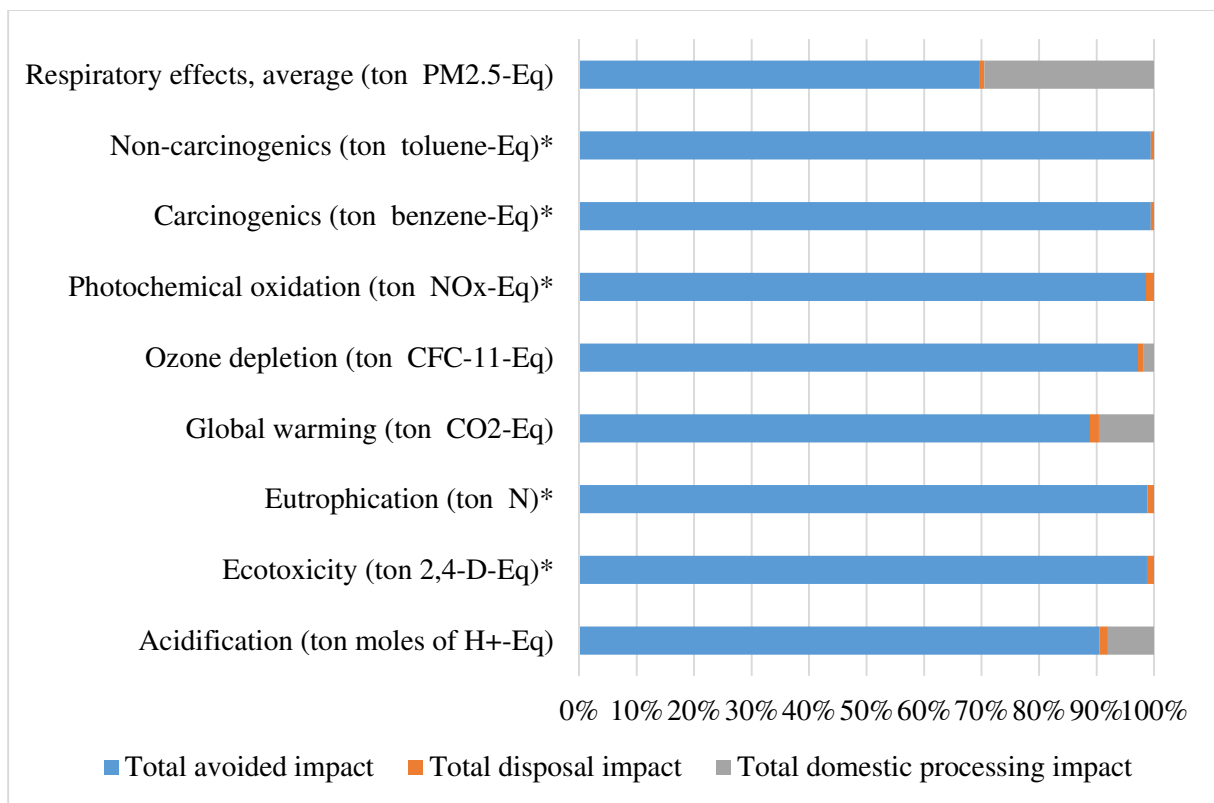
388 Table 2. Waste generation in LDT in 2016

	Total tonnage	Percentage	Waste
Bangladesh	2,342,407,581	1	23,424.08
India	2,029,849,034	2.29	46,483.54
Pakistan	1,442,060,537	2.29	33,023.19
China	6,576,636,088	5	32,883.18
Turkey	1,869,795,622	10	18,697.96
Other countries	2,325,439,186	10	2,325.44
Total	6,682,214,715	-	156,837.38

389  
390 According to equation. (2), disposal impact and domestic processing impact were  
391 estimated in addition to total avoided impact. For domestic processing impacts, Rahman et al.  
392 (2016) estimated specific stage wise energy use and accompanying environmental impact using

393 life cycle assessments, dividing the process into seven stages: transportation of EOL ships; ship  
 394 cutting while beached; section dragging in the yard; yard cutting; transportation to domestic  
 395 rerolling mills, and rerolling process. The results were aggregated on a global scale based on  
 396 70% (3.7 million tons) of the scrap generated that undergoes induction processing for secondary  
 397 steel production, leaving 30% (1.6 million tons) that require no/little energy input. The  
 398 domestic impacts were then compared with waste disposal impacts and avoided environmental  
 399 impacts in figure (6). In figure (6), it shows that disposal impacts are lower than domestic  
 400 processing environmental impacts. Disposal impacts occupy about less than 5% in all  
 401 categories, whereas domestic processing represents about 5-20%. Avoided impacts represent  
 402 about 70% to 90%.

403



404  
 405 Figure 6: Environmental impact comparison of shipbreaking scrap processing in tons. Only four  
 406 of the impact categories: Acidification, Global warming, Ozone depletion and Respirator

407 effects were transformed to the similar unit. Domestic processing impacts of the other  
408 categories (given in \*) are not considered in this figure.

409

#### 410 **Implications of EOL ship material flow**

411 Global EOL shipbreaking material flow provides three insights about the drivers of the  
412 activities, with implications for circularity and distant recycling: (1) capacity limitation of the  
413 developed countries, (2) market dynamics influencing direction of material flow, and (3) global  
414 environmental savings and localized waste burden.

415 It is quite obvious that dismantling destination is chosen based on the size. For example, figure  
416 4(a) shows that ships less than 1000 LDT are dismantled in EU facilities, whereas those less  
417 than 6000 LDT are dismantled in standard facility. And ships that are above 9000 LDT  
418 dismantled in substandard destinations. Close analysis of top shipowner's destination selections  
419 reveals similar insight. Greece owned 113 ships in 2016. 27 ships of average 14000 LDT, 43  
420 ships of average 7600 LDT and 34 ships of average 10000 LDT are dismantled in Bangladesh,  
421 India and Pakistan respectively. In contrast, 9 ships of average 1300 LDT are dismantled in  
422 Turkey (Table S4).

423 The same size-based destination selection persists for the ships that are flagged by popular  
424 flagging countries (Figure S6). Total 602 ships are popularly flagged, in that 511 ships of  
425 average 9800 LDT are dismantled in substandard destinations. Whereas, 83 ships of average  
426 5200 LDT are dismantled in standard destinations. Thus, disregarding who owns and who flags,  
427 ships are predominantly segregated based on the size. Why are ships reflagged? This is probably  
428 due to the fact that this will help avoid high compliance cost of the owners of the developed  
429 countries.

430 Size-base hypothesis becomes shaky when we closely look at the dismantling pattern of  
431 recycling BO countries that have the capacity of dismantling larger ships. For example, China

432 owned 105 ships, out of which 43 ships of average 9900 LDT are dismantled in China. In  
433 contrast, 62 ships are dismantled in substandard destinations: 32 ships of average 8400 LDT,  
434 21 of average 5600 LDT, 10 of average 10000 LDT are dismantled in Bangladesh, India and  
435 Pakistan respectively. That means that smaller ships are sent to other substandard destinations,  
436 quite contrary to size based segregation hypothesis. Likewise, out of 25 Indian ships, 12 ships  
437 of average 2800 LDT are dismantled in India. Whereas 5 ships of average 4800 LDT, 8 ships  
438 of average 8000 LDT are dismantled in Bangladesh and Pakistan respectively (Figure 3).  
439 Average size of ships dismantled in India is 7100 LDT. NGOs generally prescribe that the  
440 capacity building of developed countries and correction of flagging loopholes can change the  
441 ship flow pattern.<sup>17</sup> This claim is somewhat untenable unless the reasons behind anomalous  
442 dismantling pattern among the large capacity nations are identified (Table S5).

443         Socio-economic features such as owner financial incentives, national dependency,  
444 employment potentials, second hand consumerism, and market demand for scraps, play crucial  
445 role in selecting destinations (Gregson et al. 2010, Frey 2013, Rahman and Mayer 2015,  
446 Devault et al. 2017). Crucially, owners consider EOL ships sale as an opportunity to capital  
447 recovery, arising from the high selling prices offered by substandard nations, which differ by a  
448 margin of about 200 USD per LDT. That means that owners worldwide are rewarded about 1.2  
449 billion dollars for substandard selections as opposed to incur financial burden for standard  
450 destination selection. In addition, shipbreaking represents a WIMBY phenomenon for  
451 substandard nations: in that more than 100,000 employment is generated in the recycling  
452 nations, and 50-70%, 1-2%, 15% and 11% of the national steel demand for Bangladesh, India,  
453 Pakistan and Turkey respectively is met by the shipbreaking scrap (Crang et al. 2013)(S7).  
454 Furthermore, an embedded recycling business is emerged to constitute the back end of the  
455 resource value chain (Crang et al. 2013, Gregson and Crang 2015).The domestic metabolism

456 of the EOL ship signals high efficiency with increasing shares of reuse than recycling (Gregson  
457 et al. 2010, Rahman and Mayer 2015).

458 Besides these socio-economic factors, the fact that steel consumption continues to  
459 increase in substandard destinations makes the EOL dismantling a long-term phenomenon in  
460 substandard destinations until the saturated level of in-stock steel is achieved (Lyons et al. 2009).  
461 It is well known that substandard destinations have a high demand for scrap metal for their  
462 burgeoning construction industries. India, Bangladesh, and Pakistan do not export any, but  
463 import 6,710, 946 and 2,119 million tons of scrap steel annually, respectively. The scrap  
464 demand factor may play a role for Turkey and China as well. Turkey and China import more  
465 scrap than they export. Turkey exports 145 million tons and imports 16,251 million tons. China  
466 exports none but imports 2,328 million tons. This demand for scrap may be a reason that these  
467 countries still insist on recycling EOL ships, and creates a basis for the type of circularity  
468 adopted. Certain EU countries import scrap from other countries (for example, Greece, export  
469 24 but imports 438; The Netherlands exports 55 but imports 1641), indicating that a demand-  
470 based proximity condition exists in some EU countries, which can be explored for further  
471 market opportunities (Table S3).

472 Distant recycling of EOL ships exemplifies circular economy at the global level but  
473 exhibits ‘ambiguity’ at the national level. Globally shipbreaking generates environmental  
474 benefits, but it causes adverse effects locally that, arguably, offset the positive environmental  
475 load (Demaria 2010). Shipbreaking activities save environmental emissions that benefit global  
476 communities but require management of about 25 thousand tons of waste for Bangladesh and  
477 50 thousand tons for India. For example, global warming potentials were avoided by 10 million  
478 tons CO<sub>2</sub> eq. as opposed to generating 1 million tons due to domestic processing. Similar  
479 magnitude is also saved for other categories (Table S9, Figure 6). In addition, secondary

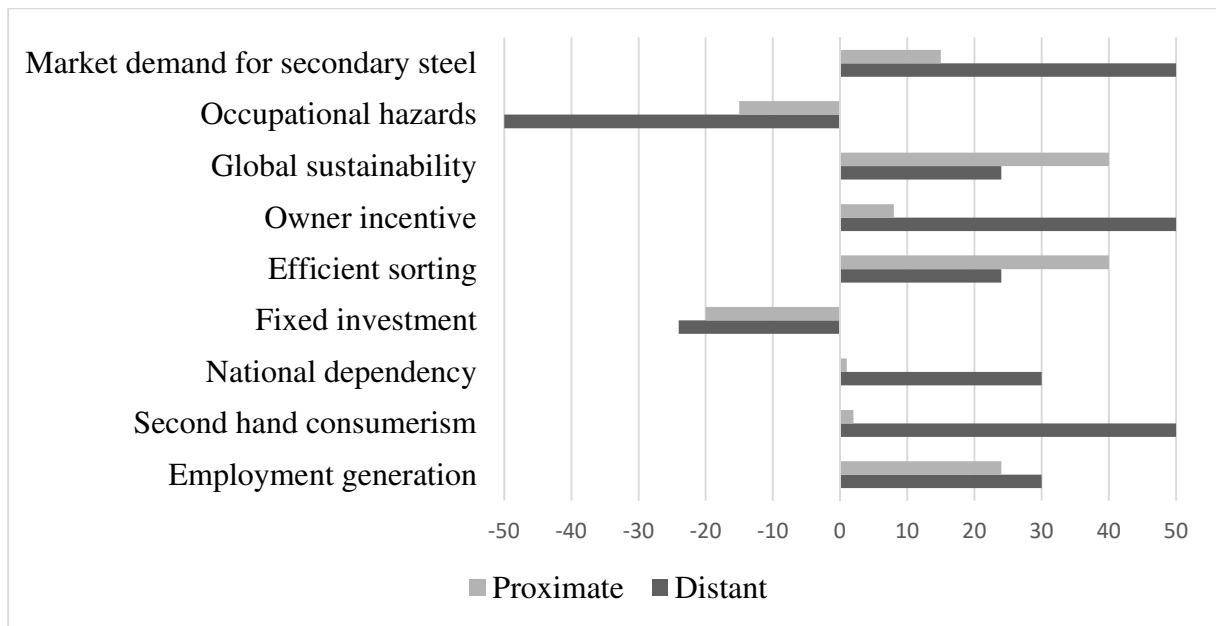


480 material consumption largely reduces the landfill cost otherwise incurred by the yard owner of  
481 the developed countries due to absence of secondary product demand.

482 In order to understand if proximate recycling is any way more sustainable than the  
483 distant recycling, nine parameters are identified and scored. A maximum value, 10 (-10, for  
484 negative parameter) is assigned for a recycling system and a relative value (minimum, 1, or -1)  
485 in relation to the maximum is judged for the other recycling system. The score is then  
486 multiplied with another score level called importance of the parameter (range 0 to 5), which  
487 gives total score of a parameter. The individual score is then added to get the total value of the  
488 two recycling systems (detailed in Table S7). This scoring is performed based on the expert  
489 judgement of a researcher in this field.

490 The figure (7) shows that all parameters favor distant recycling except efficient sorting  
491 and occupational hazards. Distant recycling performs worse in occupational hazards parameter  
492 with maximum -50 points whereas proximate recycling represents only -15 points as  
493 occupational hazards are seriously treated and almost nonexistent in developed countries.  
494 Financial motivation of the owner gets maximum points 50, which favors distant recycling as  
495 opposed to proximate recycling, which scores only 8 for mainly transportation savings. Market  
496 demand for secondary steel and second hand consumerism also attain highest 50 points for  
497 distant recycling. Proximate recycling scores very low in these parameters (15 and 2  
498 respectively). Interesting judgement came in employment generation parameter in which scores  
499 in both recycling system are quite close: distant recycling, 30 and proximate recycling, 24. This  
500 reflects that employment generation is no less important in the European nations. The global  
501 sustainability score is somewhat intuitive. Proximate recycling wins over by 16 points, mostly  
502 due to the local dismantling impacts. This score did not however consider waste landfill impacts  
503 in the proximate recycling as higher proportion of waste is expected to be generated due to  
504 absence of secondary products' demand and subsequently, be landfilled. Overall the distant

505 recycling gets 184 points and proximate recycling gets 95. While, this score is just an expert  
 506 judgement, the parameters used are quite directive in understanding the contexts of different  
 507 recycling systems. Thus, it seems that suggesting for support programs for distant recycling is  
 508 sustainable and cost effective.  
 509



510

511 Figure 7: Evaluation of proximate recycling against distant recycling

512

513 The above figure also shows that the effect of forced proximity may exacerbate the  
 514 socio-economic conditions of the existing recycling nations. For example, national dependency,  
 515 second hand consumerism and employment generation are important factors that create stability  
 516 in the society and disruption of these factors may create subsistence crisis in the region.<sup>33</sup> This  
 517 is an interesting challenge for CE to impose geographical constraints on material circularity  
 518 trend. Particular concern is highlighted in Gregson and Crang (2015). They state that waste  
 519 ‘dumping’ imagery in the south tends to prohibit flows of waste from the environmental justice  
 520 point of view, but this ignores the aspect that reuses, recycles and recommodifies the material,  
 521 that once ‘discarded’ as waste and typically destined to landfill in the ‘rich’ countries.

522 **Conclusion**

523 This study argued that decision to fix geographical traction over hazardous waste  
524 treatment is a complex phenomenon and needs to handle carefully. Proximate circularity  
525 necessitates the dismantling of EOL ships within the country of origin of the owner, which  
526 seems impossible as the study shows that developed countries with facilities have limited ability  
527 to dismantle larger ships, at least in the short term. Although European policy on ship recycling  
528 makes it mandatory for the EU owners to dismantle their ships within the EU. Alternatively, it  
529 can be considered that distant recycling is an emerging reality and that a management approach  
530 to mitigate beyond border adversaries could be adopted. Along the line of distant recycling, it  
531 is seen that EOL ship recycling saves greenhouse gas emissions, leading to global  
532 environmental benefits that need to be reflected in global environmental policy. For example,  
533 we can think of formulating beyond-border EPR (mimicking the EPR in the US and the EU  
534 level) so that the local level burden management capacity is enhanced, which fosters the  
535 attainment of the global sustainability most cost effectively. As this study demonstrated that the  
536 minimization of adverse impact through capacity enhancement program in occupational  
537 hazards and waste management is a far better approach for global sustainability and material  
538 circularity. Several articles in shipbreaking have mentioned the need to some form of financial  
539 capacity building measures, but not quite a prescriptive way. One exception is however Rahman  
540 and Mayer (2016), that mentioned about deposit refund system. Furthermore, in waste  
541 management literature, global level EPR was prescribed, in response to e-waste export to the  
542 developing countries. Therefore, further research is needed to devise ways so that a cost  
543 effective and sustainable recycling program can be initiated (Wilts et al. 2011).

544  
545 **ACKNOWLEDGMENT**

546 This paper does not receive any funding.

547

548 **SUPPORTING INFORMATION AVAILABLE**

549 Supporting information attached contains figures, tables and analysis that support the paper and  
550 will benefit the readers. It also contains methodological detail and assumptions made. This  
551 material is available free of charge at <http://pubs.acs.org>.

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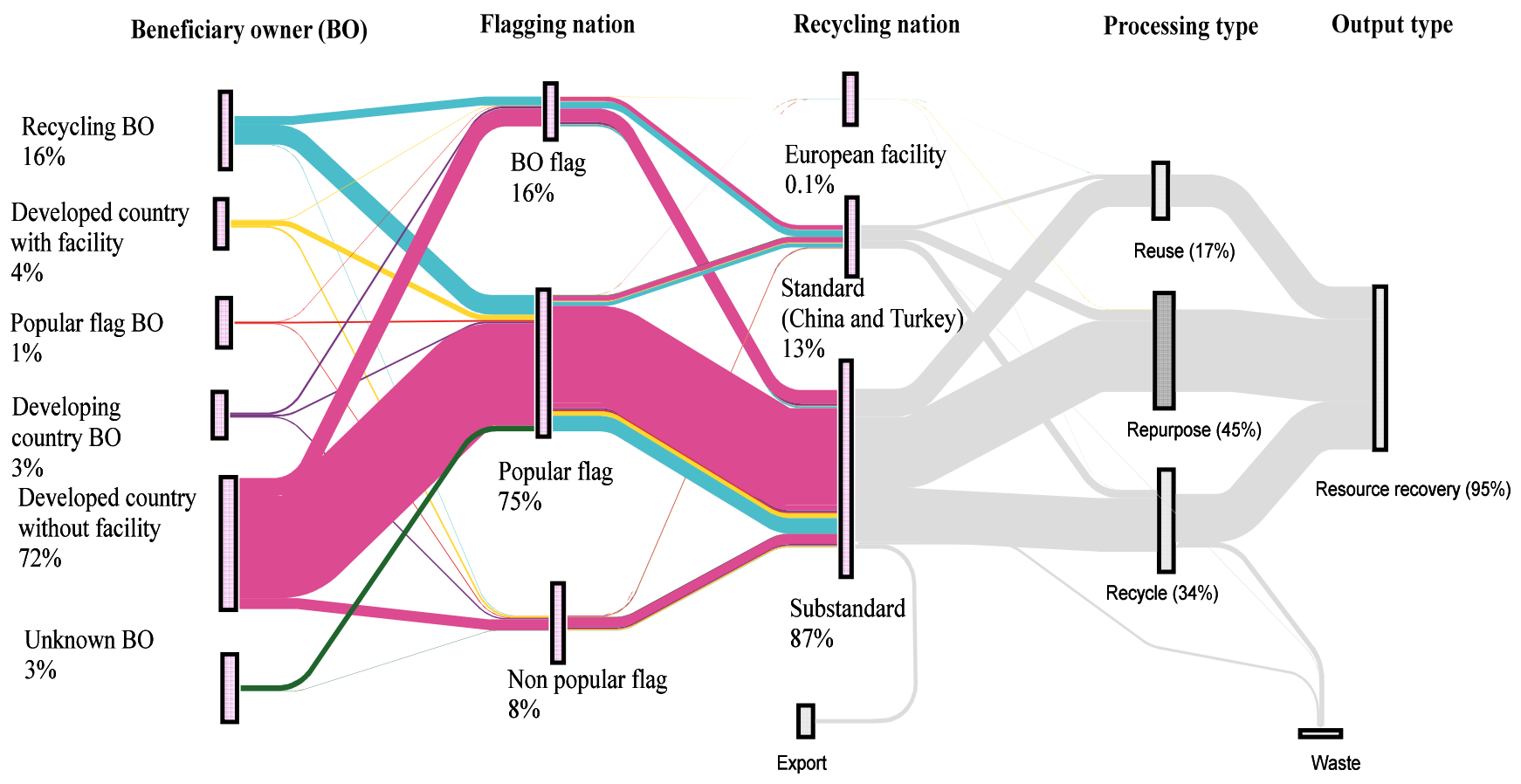
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**Global material flow of EOL ships processing in 2016 in LDT**