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Abstract

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

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

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

INTRODUCTION

Circular economy, recycling and proximity

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

Until recently, circularity is predominantly backed by the recycling principle, which is ranked as 8^{th} of the 10 value retention options of CE strategy, with reuse, resale, remanufacturing and refurbishing ranked high up the order (Reike et al. 2018). In EU and other developed countries, CE and the associated 3R principles are widely applied to waste management areas, with an overarching target of achieving synergistic effects in economic growth and landfill prevention. To realize this, reuse is particularly crucial as increasing reuse will preserve structural integrity, avoiding the environmental impacts of mining virgin materials and manufacturing processes (Rahman et al. 2019). Extended Producers Responsibility (EPR) is enacted in developed countries in order to promote recycling and circularity through a monetary incentive approach. The expected repercussion of this approach is to motivate manufacturers to transform product design, enable ownership access, favor radical resource productivity and rebuilding natural capital (Rahman et al. 2019). Thus, CE involves the reemergence of 3R principles with added focus on (1) appropriate design, (2) reclassification of materials and (3) upgradability (Ellen MacArthur Foundation 2017). Gregson et al. (2015) presents a critique of CE by (1) criticizing its over-reliance on global recycling networks with little or no regard of their implications due to distancing (lack of proximity principles) and (2) ignoring the type (e.g. dirty) and ethicality (illegal trade) of the accompanied activities. They suggested adopting a moral CE that embarks on ecological modernization, environmental justice, and resource insecurity. Although potentially applicable at three levels: micro, meso and macro (e.g. decoupling in EU), CE is limited mainly in national-level and in particular sector, without concerning beyond border material flow between developed to developing countries (Nordbrand 2009). For example, Cusack (1989) pointed out that in every five minutes, a toxic shipment finds ways from developed countries to the developing countries, mostly due to reasons of avoiding high disposal costs and, instead, earning handsome profit by transporting them to the developing countries. Several studies highlighted the need to understand social, economic and environmental drivers and challenges to mitigate the hazardous waste dumping (Sonak et al. 2008, Frey 2013, Sthiannopkao and Wong 2013). While CE encourages the adoption of higher value retention options, the incentives that underlie the trans-shipment of hazardous waste towards distant 'sacrifice zone' are largely understudied. Thus, there is a missing link between CE and recycling, in which the place where recycling occurs becomes crucial. In reality, EPR was established to promote close looping within a geographic boundary, but that is limited only to certain material categories and the rest is processed beyond, with 'welcome in my backyard' as a potential driver (Sonak et al. 2008, Sthiannopkao and Wong 2013).

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

Shipbreaking

The shipbreaking industry becomes an important phenomenon for the shipping industry when ship-owners started to experience the reduced revenue at the EOL of a ship (Knapp et al. 2008). Ship-owners, mostly from the developed countries, recycle their ships in South Asian shipbreaking nations, benefitting local economy by generating employment and supplying scrap resources for the construction industry (Gregson et al. 2010, Rahman and Mayer 2015). The shipbreaking industry is not, however, without localized adverse environmental and social impacts emanating from the hazardous waste content of the EOL ships. This industry pollutes coastal ecosystems and exposes workers to occupational hazards leading to injuries and deaths (Abdullah et al. 2013, Cairns 2014).

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

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

No existing study has applied MFA to the shipbreaking system on a global scale. This study is designed to explore the relationship among the ship-owning countries (countries that own the ships during their commercial life) to the Destination countries (Countries that recycle ships: mostly Bangladesh, India, Pakistan, China, and Turkey) via flag state in relation to EOL shipbreaking.

MATERIALS AND METHODS

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

Data

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

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

Avoided environmental impacts (I) = Material recovery (R_k) X Environmental impacts/per kg of materials (I_k) ……(1); k represents each metal recovered.

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

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

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

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

Categorization of vessels

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

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

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

Data Quality and Issues (Robustness of the estimate)

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

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

RESULTS AND DISCUSSION

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

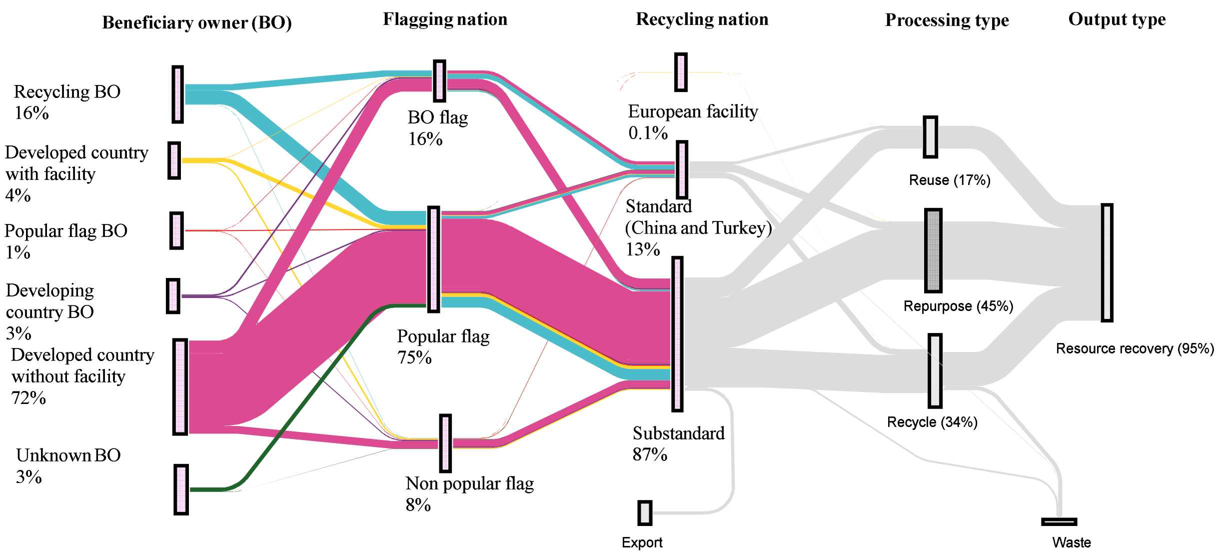


Figure 1. Global material flow of EOL ships processing in 2016 in LDT.

After dismantling the EOL ships, substandard facilities reused 17% of the total scraps that are certified (American Society for Testing Material grade) steel, mainly in the form of machinery and rolled 45% in induction furnaces to produce high quality, certified bar and other steel products. The lower quality scrap (34%) is melted and rerolled to make uncertified rebar. About 95% of the total scrap is recovered for domestic use with about 2% waste, which varies depending on where the ships are dismantled. These high recovery percentages, with more reuse and repurpose mix and less recycling makes the processing stage important for global sustainability.

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

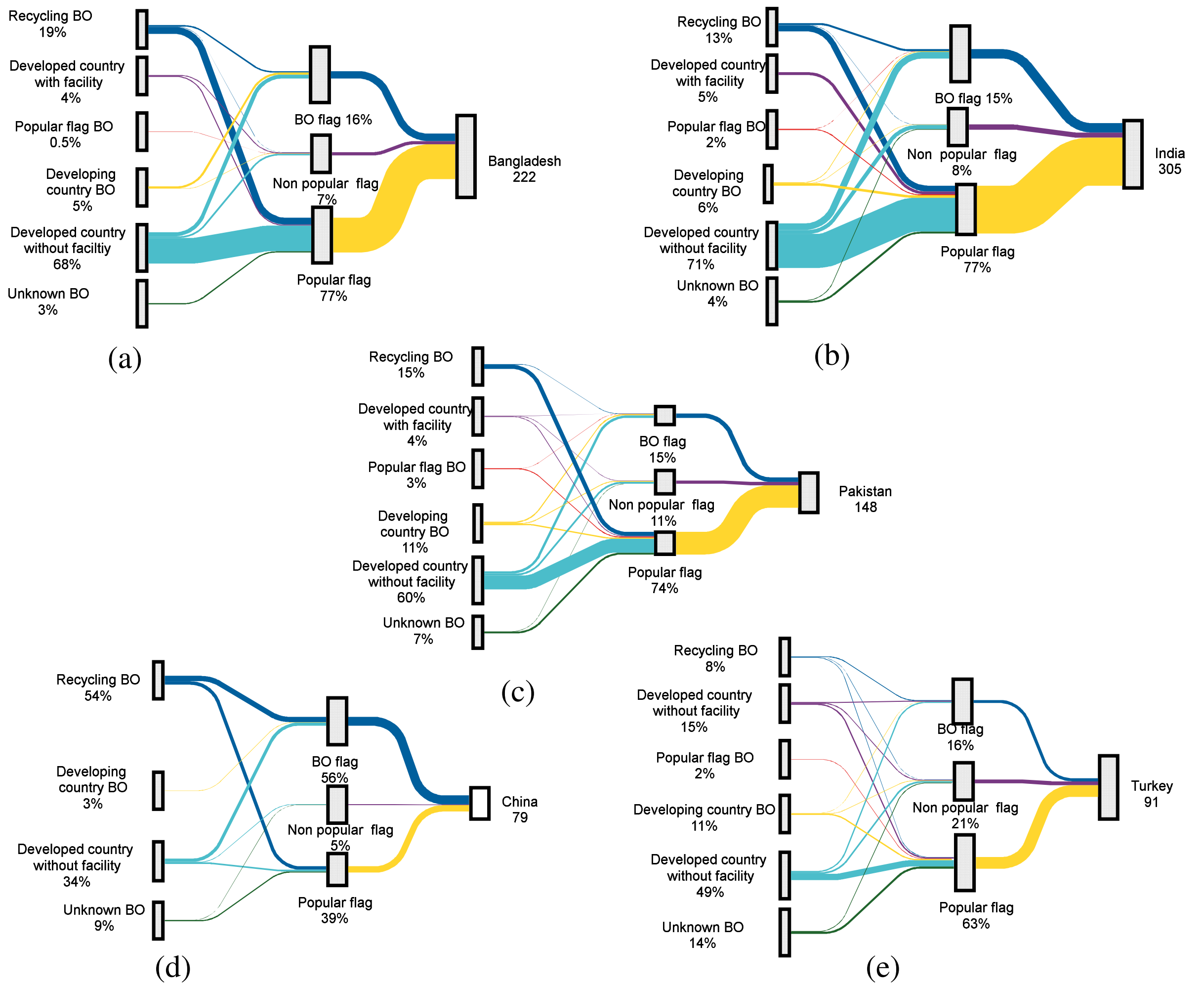


Figure 2. Source distribution of ship flow by number to five major shipbreaking nations in 2016 (Percentage calculated based on number of ships).

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

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

(a) (b)

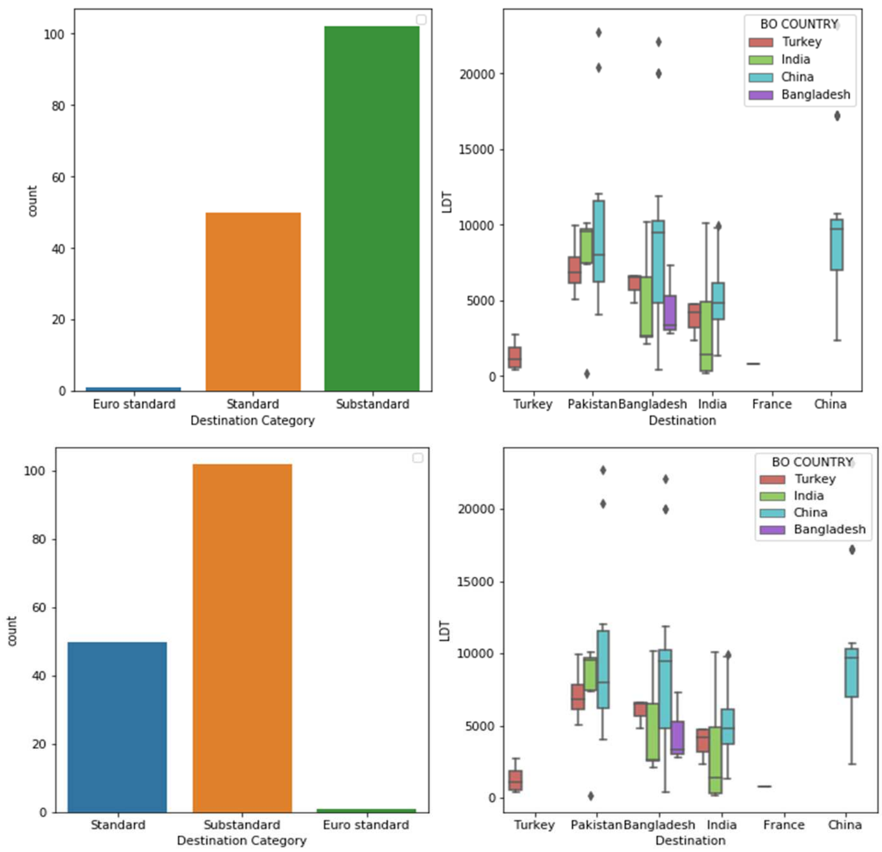


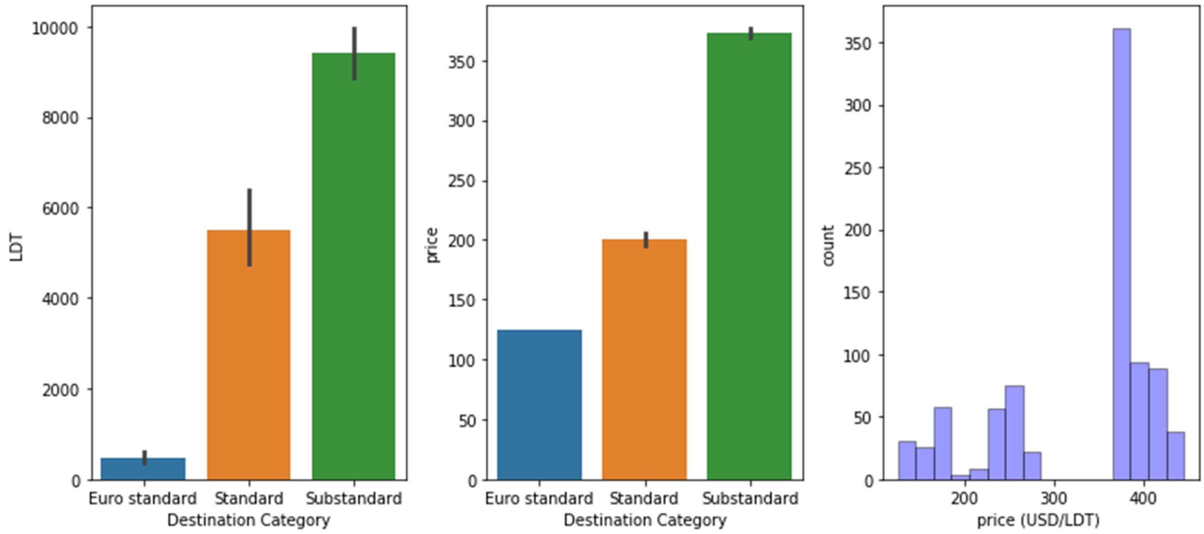
Figure 3. Analysis of Chinese, Turkish and Indian ship recycling. (a) shows the number of ships from these three countries and their destination categories; (b) shows destination nations; Bottom error bar represents minimum to first quartile of data, the rectangular box represents data from first quartile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

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

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

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

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



(a) (b) (c)

Figure 4. Price differences based on destinations

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

Domestic scrap generation and global level environmental savings

Figure 5 provides the amount of ferrous scrap and other types of non-ferrous scrap, with machinery and furniture, recovered in shipbreaking countries. A total of 7.2 million ton was dismantled in 2016 worldwide. About 79% (5.3 million ton) of ferrous scrap is recovered with about 35% (1.8 million ton) of it recovered in Bangladesh. India, Pakistan, China, Turkey and other countries recovered 30%, 22%, 10%, 3% and 0.01% respectively. Corresponding environmental savings were also estimated in table S9. South Asian nations are observed to contribute to avoid more than 90% environmental savings. Compared to the domestic processing impacts and waste disposal impacts, avoided environmental savings are much larger, with about 80% in all impact categories (Figure 6).

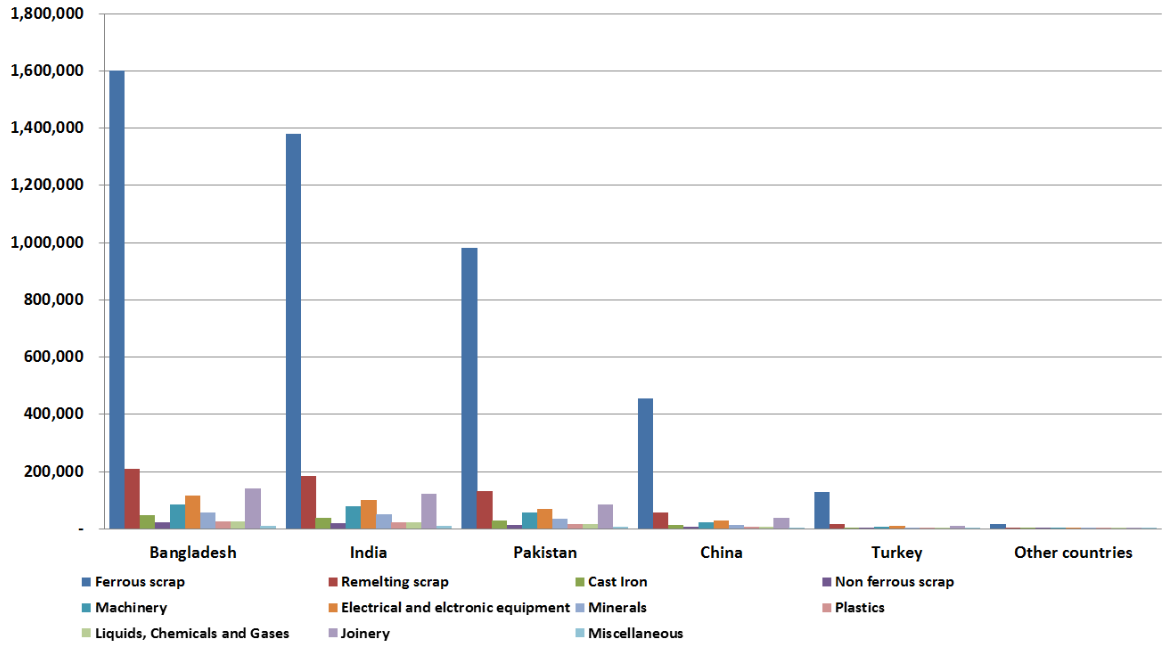


Figure 5. Scrap generation of shipbreaking industry in 2016 by country data taken from NGO Shipbreaking platform (Unit: Metric tons) [19]

Waste estimation and localized environmental impact

The quantity of waste from shipbreaking process is not easy to estimate. The waste content varies significantly with the type of ships, the age, the country in which the ships are recycled. For example, 95% of glass wool is reused in Bangladesh. Asbestos and asbestos-containing material content differs substantially depending the type of ships: Merchant ship or Navy ship. Table 2, below, shows that in India, the waste content percentage varies from 2.13% to 7.90% for refrigerator ships, while it is far below that in Bangladesh, only 0.99%, compensated for mostly by glass wool reuse. Turkey's data is, however, suspicious, with only 0.56% waste content. Instead, we relied on Neser et al. (2008) study that estimated waste percentage at 10% in Turkey. European Commission (EC) data is more reliable, as this data is collected from a US company directory (European commission, 2009). This shows that the waste content percentage is 1.86 % to 3.96 %. World bank report estimates detailed hazardous material from a merchant and navy vessel and reported waste percentage about 21% and 42%, much higher than the other estimates (Table S10).

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**				**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**	**Turkey**	**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%

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

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

According to equation. (2), disposal impact and domestic processing impact were estimated in addition to total avoided impact. For domestic processing impacts, Rahman et al. (2016) estimated specific stage wise energy use and accompanying environmental impact using life cycle assessments, dividing the process into seven stages: transportation of EOL ships; ship cutting while beached; section dragging in the yard; yard cutting; transportation to domestic rerolling mills, and rerolling process. The results were aggregated on a global scale based on 70% (3.7 million tons) of the scrap generated that undergoes induction processing for secondary steel production, leaving 30% (1.6 million tons) that require no/little energy input. The domestic impacts were then compared with waste disposal impacts and avoided environmental impacts in figure (6). In figure (6), it shows that disposal impacts are lower than domestic processing environmental impacts. Disposal impacts occupy about less than 5% in all categories, whereas domestic processing represents about 5-20%. Avoided impacts represent about 70% to 90%.

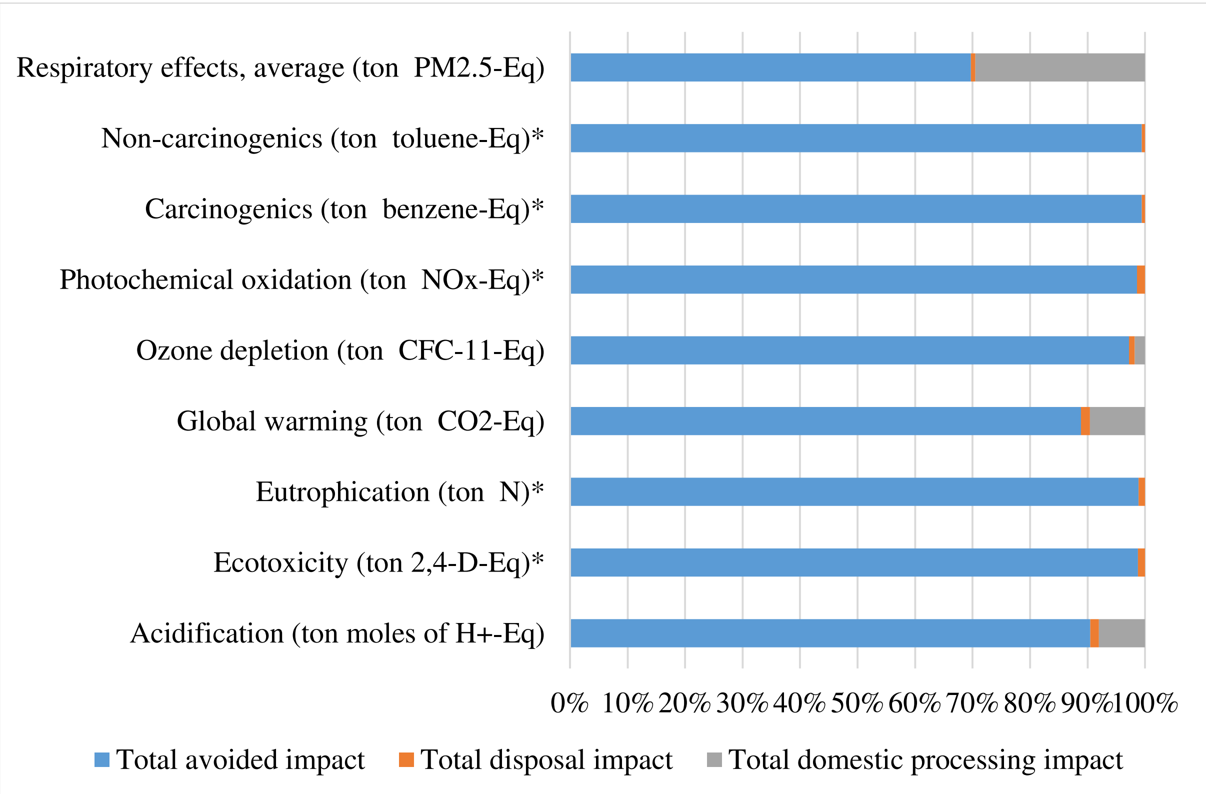


Figure 6: Environmental impact comparison of shipbreaking scrap processing in tons. Only four of the impact categories: Acidification, Global warming, Ozone depletion and Respirator

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

Implications of EOL ship material flow

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

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

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

Size-base hypothesis becomes shaky when we closely look at the dismantling pattern of recycling BO countries that have the capacity of dismantling larger ships. For example, China owned 105 ships, out of which 43 ships of average 9900 LDT are dismantled in China. In contrast, 62 ships are dismantled in substandard destinations: 32 ships of average 8400 LDT, 21 of average 5600 LDT, 10 of average 10000 LDT are dismantled in Bangladesh, India and Pakistan respectively. That means that smaller ships are sent to other substandard destinations, quite contrary to size based segregation hypothesis. Likewise, out of 25 Indian ships, 12 ships of average 2800 LDT are dismantled in India. Whereas 5 ships of average 4800 LDT, 8 ships of average 8000 LDT are dismantled in Bangladesh and Pakistan respectively (Figure 3). Average size of ships dismantled in India is 7100 LDT. NGOs generally prescribe that the capacity building of developed countries and correction of flagging loopholes can change the ship flow pattern.[17] This claim is somewhat untenable unless the reasons behind anomalous dismantling pattern among the large capacity nations are identified (Table S5).

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

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

Distant recycling of EOL ships exemplifies circular economy at the global level but exhibits 'ambiguity' at the national level. Globally shipbreaking generates environmental benefits, but it causes adverse effects locally that, arguably, offset the positive environmental load (Demaria 2010). Shipbreaking activities save environmental emissions that benefit global communities but require management of about 25 thousand tons of waste for Bangladesh and 50 thousand tons for India. For example, global warming potentials were avoided by 10 million tons CO_2 eq. as opposed to generating 1 million tons due to domestic processing. Similar magnitude is also saved for other categories (Table S9, Figure 6). In addition, secondary material consumption largely reduces the landfill cost otherwise incurred by the yard owner of the developed countries due to absence of secondary product demand.

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

The figure (7) shows that all parameters favor distant recycling except efficient sorting and occupational hazards. Distant recycling performs worse in occupational hazards parameter with maximum -50 points whereas proximate recycling represents only -15 points as occupational hazards are seriously treated and almost nonexistent in developed countries. Financial motivation of the owner gets maximum points 50, which favors distant recycling as opposed to proximate recycling, which scores only 8 for mainly transportation savings. Market demand for secondary steel and second hand consumerism also attain highest 50 points for distant recycling. Proximate recycling scores very low in these parameters (15 and 2 respectively). Interesting judgement came in employment generation parameter in which scores in both recycling system are quite close: distant recycling, 30 and proximate recycling, 24. This reflects that employment generation is no less important in the European nations. The global sustainability score is somewhat intuitive. Proximate recycling wins over by 16 points, mostly due to the local dismantling impacts. This score did not however consider waste landfill impacts in the proximate recycling as higher proportion of waste is expected to be generated due to absence of secondary products' demand and subsequently, be landfilled. Overall the distant recycling gets 184 points and proximate recycling gets 95. While, this score is just an expert judgement, the parameters used are quite directive in understanding the contexts of different recycling systems. Thus, it seems that suggesting for support programs for distant recycling is sustainable and cost effective.

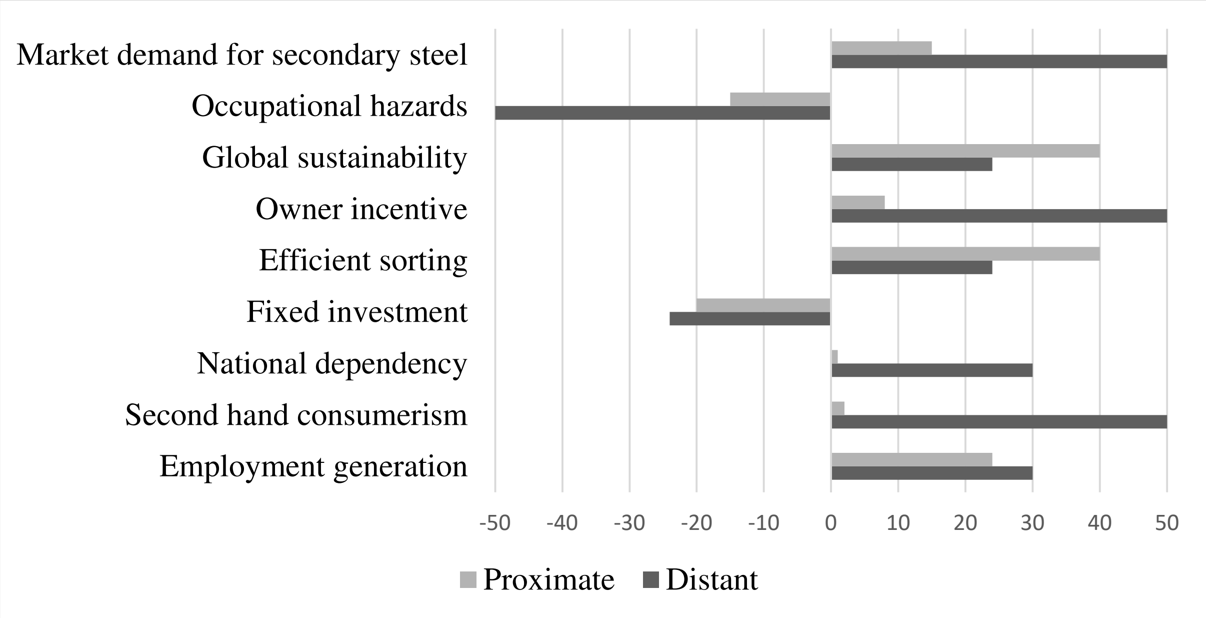


Figure 7: Evaluation of proximate recycling against distant recycling

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

Conclusion

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

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SUPPORTING INFORMATION AVAILABLE

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

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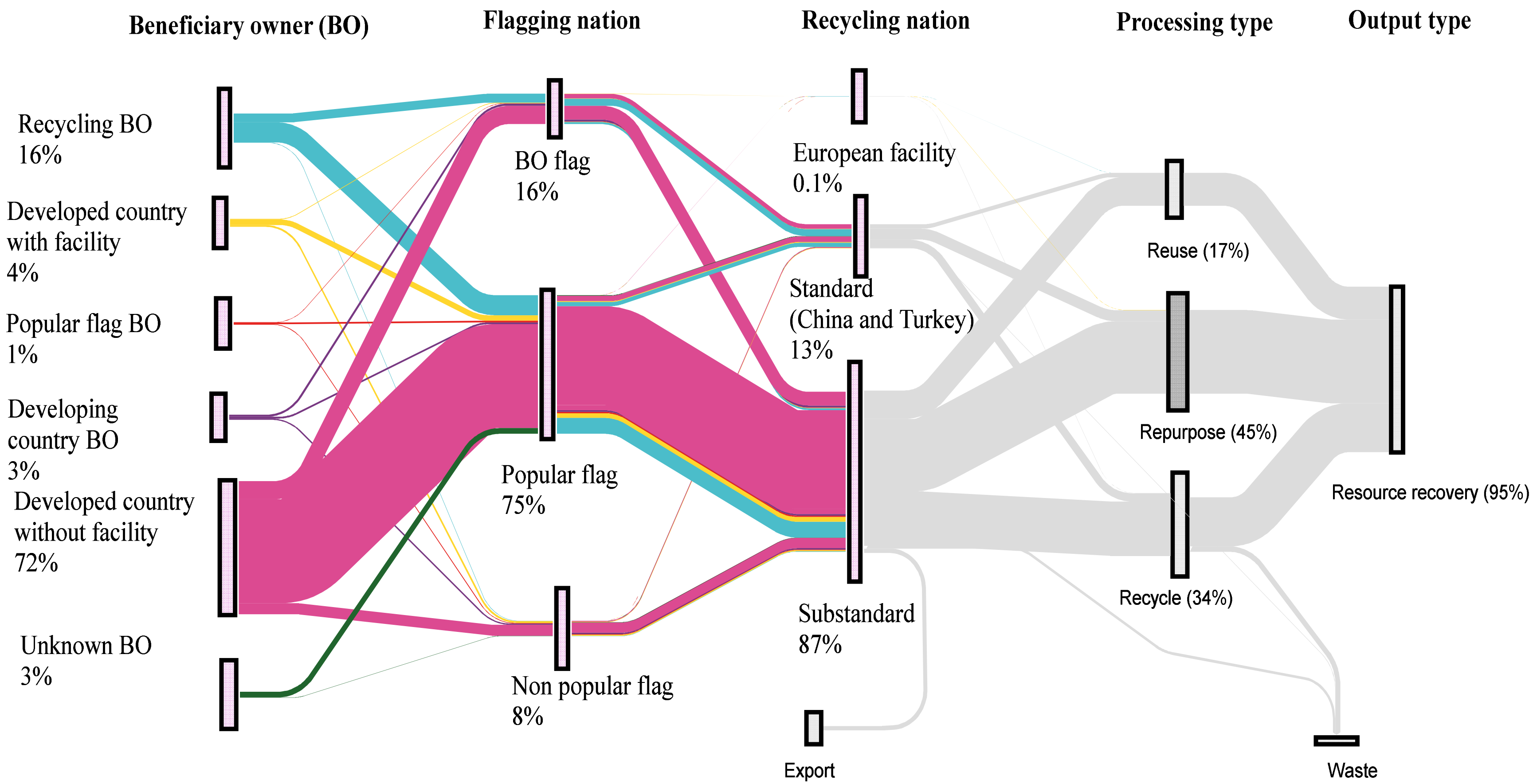

Global material flow of EOL ships processing in 2016 in LDT