



# SHIP RECYCLING: CONTRIBUTION TO CIRCULAR ECONOMY AND INDEX OF OVERALL IMPACT

SATYENDRA NATH CHAKRABARTTY<sup>1,2\*</sup>

<sup>1</sup>Indian Ports Association, New Delhi, India. <sup>2</sup>Indian Maritime University, Kolkata Campus; Indian Statistical Institute, Kolkata, India.

\*Corresponding author: [chakrabarttysatyendra3139@gmail.com](mailto:chakrabarttysatyendra3139@gmail.com)

ARTICLE INFO	ABSTRACT
<p><b>Article History:</b>                      Received: 12 June 2025                      Revised: 5 October 2025                      Accepted: 2 November 2025                      Published: 15 December 2025</p> <hr/> <p><b>Keywords:</b>                      Economic impact,                      Environmental impact, Safety issues, Avoided emissions, Geometric mean, Critical indicators, Progress path.</p>	<p>Ship recycling (SR) with significant socio-economic benefits contributes to the circular economy by salvaging and reusing valuable materials. However, SR generates toxic substances which end up in coastal water and landfills, increasing environmental risks. The paper considers relevant indicators in various units under five dimensions, namely: Economic (Direct benefits), Economic (Indirect benefits), Economic (Induced benefits), Environment and Safety issues. These dimensions were combined to get unit free index <math>I_{Ship-break\ to}</math> reflecting the overall impact of ship-breaking in the <math>t</math>-th year from the base year. The index also enables assessment of progress across time, identification of critical indicators requiring corrective managerial action and can be expressed as <math>I_{Economic\ impact} * I_{Environmental\ impact} * I_{Safety\ impact}</math>. Increasing trend of <math>I_{Safety\ impact}</math> and decreasing trend of <math>I_{Environmental\ impact}</math> are signs of an improved SR process. The indices may be computed separately for national, regional, industry and firm/operation levels. Assessment and monitoring of indicators will help India's efforts to promote green SR, integrating SR with ship building, and emerging as a global leader in SR and pushing the country's endeavours to be a low-carbon, resource-efficient economy through sustainable recycling practices.</p>

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## Introduction

End-of-Life (EoL) ships contribute to the Circular Economy (CE) by salvaging and reusing valuable materials. Ship Recycling (SR) and shipbreaking are frequently used interchangeably. While SR is a broader term which includes proper management of hazardous substances, like asbestos, heavy metals, etc., resulting from dismantling of EoL ships to recover reusable materials mitigating environmental harm, shipbreaking refers to the main goal of extracting reusable materials like steel, etc. The Hong Kong Convention (HKC), adopted by the International Maritime Organisation (IMO) in 2009, provides a framework for safe and environmentally sound practices for SR, avoiding unnecessary risk to

human health and environmental degradation, and thus, transitioning the industry toward sustainable practices. HKC came into force at the global level in 2025, requiring member countries to meet its standards. However, the benefits of SR go beyond HKC compliance and integrating SR into shipbuilding can push the country's endeavours to become a low-carbon, resource-efficient economy through sustainable recycling practices.

SR offers a source of re-rolling and re-melting of steel scraps with significant socio-economic benefits and contributes to the development of the local shipbuilding industry. As per the 13th edition of the BIR Report on

“World Steel Recycling in Figures”, steel from SR helped reduce global water and energy usage, and CO<sub>2</sub> emissions by 950 million tonnes in 2019 (BIR, 2022). The steel industry, a major driver of economic growth also contributes in significant emission of Greenhouse Gas (GHG). The Indian government’s plan to increase production capacity of steel to 300 Million Metric Tonnes (MMT) by 2030, from the existing capacity of 160 MMT (approx.) will further increase GHG emission unless appropriate mitigation measures are initiated. Steel from shipbreaking helps to reduce carbon footprint as recycling steel requires much less energy and resources than producing virgin steel and thus, contribute to a more sustainable steel industry. Reduction of carbon footprint of the Indian steel industry is essential considering India’s commitment to achieve net-zero emissions by 2070 despite augmenting steel production capacity to 300 million tonnes by 2030 (Climate Group, 2024).

Steel scrap is being used worldwide as a raw material in steelworks and foundries. In addition, robust equipment with longer lifespan obtained from SR enjoys high demand from the consumer industry, ship repair and building industry. Recycled items like lead acid batteries, lubricants from waste lube oil, etc. have significant indirect utilisation. Thus, SR, while highly profitable, is inherently sustainable (Kong *et al.*, 2022). About 95% of the global SR market is dominated by Bangladesh, India, Pakistan, China, and Turkey, generating over 15 million tonnes of materials per annum from decommissioned ships (ElMenshawry *et al.*, 2024).

Prices of old cargo ships are primarily driven by steel weight. In contrast, service ships could be more lucrative due to the value of specialised equipment and machinery aboard these ships. The SR market is influenced by a number of factors like freight rates, operation and maintenance cost of old ships, price of steel scrap, light displacement tonnage (LDT) of ships, and demand for scrap metals like steel, copper, aluminium, etc. (Hossain, 2017). As per estimate, 40.2% of the world’s merchant fleet comprises vessels  $\geq 25$  years (Equasis, 2023).

This implies increasing availability of ships for recycling. The Global Ship Recycling Market is projected to reach \$11.5 billion by 2028, at a compound annual growth rate of 3.7% during the period 2023 to 2028 ([www.bccresearch.com/media](http://www.bccresearch.com/media)).

SR conserves energy and natural resources compared to the production of virgin metal, and contributes significantly to the United Nation’s Sustainable Development Goal (SDG)-12 relating to sustainable production and consumption. SR directly impacts revenue, supply of raw material and employment, and provides an effective way of reusing the vast amount of reusable materials from EoL ships (Choi *et al.*, 2016). However, SR also affects the environment negatively by generating toxic substances which end up in coastal water and landfills, increasing pollution risks of the air, soil and water.

The circular economy (CE) helps to reverse unsustainable linear models and generate long-term benefits since CE aims at maximising the functioning of the ecosystem and improving human well-being (Fitch-Roy *et al.*, 2019; Murray *et al.*, 2017). Unlike the linear economy, the popular CE model based on “Reduce”, “Reuse”, and “Recycle” improves resource yields by recycling materials; preserving renewable resources, generating value by reducing negative externalities (Stahel, 2016; Blomsma & Tennant, 2020) and helps nations in their endeavours to become a low-carbon and resource-efficient economy. Other principles of CE include 4R, 5R, 9R, and even 10R (Reike *et al.*, 2018).

Usable materials retrieved from ship breaking are primarily steel, steel scrap and non-ferrous metals like aluminium, lead, alloys of copper, titanium, etc. which constitute about 95% to 98% of the LDT of a ship (Jain *et al.*, 2018). In addition to reducing pressure in mining for production of virgin metals, recovered electronic and office equipment, hardware items, household appliances etc. are also reused, or recycled (Rahman & Mayer, 2015; Hiremath *et al.*, 2016). The

ASTM report gives further specifications on the quality of ship materials (ASTM, 2013). However, techniques for dismantling old ships under weak environmental and labour safety rules may result in higher discharge of toxic substances like PCB (Polychlorinated Biphenyls), PVC (Poly Vinyl Chloride), PAH (Polycyclic Aromatic Hydrocarbon), tributyltin, lead, mercury, asbestos, iso-cyanates, H<sub>2</sub>SO<sub>4</sub>, residual fuels, anti-fouling pesticides, etc. along with oil and waste-water into coastal waters and adjacent soil, creating adverse pollution effects and risks to workers' safety (EU 2016; Devault *et al.*, 2017).

Despite the existence of laws and regulations regarding environment protections and safe working conditions for shipbreaking workers, the industry in several countries continue to prefer low-cost methods that are polluting and inefficient. For example, countries with developed facilities and strict implementation of SR laws offer about USD 37 per LDT, against USD 260 per LDT offered by the Indian subcontinent without compromising profit (Barua *et al.*, 2018). There is growing consensus to minimise the negative environmental impact of SR by designing and executing green SR methods (Zhou *et al.*, 2021). Major benefits of SR include: (i) Lowering cost of steel by providing reusable parts for new ships like bars, ingots, pipes and plates, (ii) Generating social benefits by providing wages to SR workers and the multiplier effect of their expenditure accelerating the economy, (iii) Lowering usage of energy and reducing GHG emission by supplying recovered metal.

For assessment of environmental pollution from SR activities and changes over time, various indices have been proposed using arithmetic and multiplicative aggregations of chosen indicators. But existing methods differ with respect to theoretical frameworks and suffer from limitations like consistency issues, comparison consistency, subjectivity and uncertainties of human judgment, inter-related risk factors, etc. For example, in the Fuzzy

DEMATEL method, relative preferences on the agent effects opined by the experts as the input instead of actual evaluation of concentration of heavy metals (HMs) in land and water. Thus, gaps exist in evaluation of overall impact of SR for better monitoring of mitigation policies.

This paper addresses issues relating to the evaluation of indicators of SR under different dimensions and combines the indicators in various units to get the unit free multidimensional index ( $I_{Ship-break}$ ) (which reflects the overall impact of ship-breaking and helps balance socio-economic benefits with environmental objectives, ensuring a green and sustainable ship-recycling industry).

### Ship Breaking: The Indian Scenario

SR activities start with ship-breakers bidding for EoL ships from international brokers. The successful bidder takes the vessel to the ship-breaking site either under its own power or with the use of tugs. After beaching, oil from the bilges and tanks are drained, fuel tanks are cleaned, and fuel and lubricant lines are disconnected from the ship. Oily waste, including sand, rags, garbage and plastic wastes, are transported to a Hazardous Waste Treatment Storage Disposal Facility. Hazardous materials are listed, labelled, packaged and removed from SR-yard before the hull is cut by trained and equipped workers as per the guidelines of the competent authorities. Safe removal and temporary storage of the hazardous materials and their final treatment or disposal are done at certified Common Hazardous Waste Treatment Storage Disposal Facilities (CHW-TSDFs) as per HKC guidelines and/or national regulations, like the Ship Recycling Act in India, which mandates the strict monitoring of the ship-specific recycling plan to ensure adherence to safety and environmental standards.

India contributes over 30% to the global SR sector by DWT and over 40% by numbers (mostly cargo ships) (Reddy & Manoharan, 2014). The Alang-Sosiya Ship Breaking Yard (ASSBY) in Gujarat, located 30 km (approx.) from Bhavnagar in the Gulf of Khambhat with 153 ship-breaking yards, caters to about 98% of

SR activities in India. The rest of shipbreaking activities in India are undertaken at Syama Prasad Mookerjee Port (Kolkata), Mumbai Port, Goa Shipyard Limited on the banks of the Zuari River, Steel Industrials Kerala Limited, etc. ASSBY provides about 15% of India’s total steel output (Greenpeace, 2019) plus other valuable items like onboard machinery, equipment, pumps, pipes, valves, furniture, fittings and fixtures and other scrap material, etc. The fabrication and rerolling units receive about 75% of scrap recovered at Alang and the rest 25% are used as raw materials. Thus, SR activities are in conformity with “Waste to Wealth” emphasised in the vision document of the SAGARMALA mega-project promulgated by the Government of India in the “Maritime India Vision 2030” in 2021.

Considering the willingness of SR industry stakeholders to comply with environment

sustainability norms, India has resolved to adopt a zero-residue model for SR to ensure zero leakage of liquid waste to water from underground wastewater/oily water collection at all yards. The Amrit Kaal Vision 2047 released in October 2023 articulates India’s aspiration to emerge as a global player in SR and initiates measures to provide adequate infrastructure and policy enablers, including collaboration with the EU to send old vessels from EU and OECD countries directly to Alang-Sosiya at a subsidized selling price since most of the SR yards in Alang-Sosiya are fully compliant with the Hong Kong Convention (HKC) (Mehtaj *et al.*, 2024). To get HKC certifications, yards are required to prove their ability to contain pollutants, ensure safe working conditions and adopt sound management of wastes. The number of ships recycled at ASSBY during the last five years has been given in Table 1.

Table 1: Number of ships recycled at ASSBY

Year	Number of Ships Dismantled	LDT (MT)
2023-2024 (Up to August 2023)	40	348494.88
2022-2023	131	1147480.52
2021-2022	209	1456655.12
2020-2021	187	1760641.28
2019-2020	202	162280.18

Source: Srivastava and Lahiri (2024)

Ship breaking by the beaching method is common in India due to the lower cost compared with ship breaking at dry docks, floating docks, or slipways with lock gates and waterproof floors. Labour intensive SR in India takes about 150 to 200 workers and 2 to 5 months to dismantle a ship, depending on type and vessel size. But beaching is associated with significant environmental hazards and problems to labourers’ health. International legal frameworks have been developed on shipbreaking and collection and disposal of hazardous wastes, like the Basel Convention and HKC (Bhattacharjee, 2010). The Ship Recycling Industries Association (India) was established in 1983 aimed at safeguarding the rights of its member ship recyclers and ensuring safe and eco-friendly recycling activity.

In alignment with HKC and the Basel Convention, India has come out with the Ship breaking Credit Note scheme to promote CE and strengthen the industry by encouraging investment and expansion. For a ship dismantled in an Indian ship-breaking yard, a credit notes equivalent to 40% of the scrap value would go to the fleet owner which can be reimbursed against construction cost of a new vessel at an Indian yard (Government of India, 2025). The CE concept also requires a reverse supply chain of ship-breaking industry activities, quality information throughout the industrial lifespan, assessment of efficiency of circularity progress and performance in ship breaking (Okumus *et al.*, 2024).

**Impact Assessment**

**Economic Impact**

Economic impact of SR covers direct, indirect and induced benefits, including generation of employment and wages earned. Methodologies used to estimate the economic impact of SR, like input-output (I-O) analysis (Hefner & Calvin, 2007), social accounting matrices (SAM) (Watson & Beleiciks, 2009), cost-benefit analysis (Choi *et al.*, 2016) and multiple linear regression (Tola *et al.*, 2024) vary in assumptions and sophistication, and may produce contrasting results. In addition, the assumptions need to be verified before the techniques are applied. Commonly observed economic benefits are:

- Value of recovered material which is positively related to employment with different elasticity.

- Each employed worker generates about three to four indirect jobs. However, empirical evidence of job multiplier figures is limited.
- Employment impacts vary for different types of ships dismantled and may extend beyond the regional level.
- SR industry plays a crucial role in the economy of South Asia, providing a source of livelihood for many people in the region (Ahasan *et al.*, 2021).

**Direct Benefits**

**Benefits of Ship Brokers**

Based on analysis of three examples of EoL ships, Choi *et al.* (2016) estimated weights and values of recovered materials obtained from ship breaking, details are given in Table 2.

Table 2: Components of materials from a dismantled ship (indicative)

Materials Recovered	*Weight of Recovered Material (LDT %)	Value (%)
Ferrous scrap and iron plates (Re-rollable)	72 - 85	65
Re-conditioned machineries	10 - 15	25
Re-melting scrap	3	2
Non-ferrous metal	1	7
Oils including furnace oil	2	0.5
Wood and furniture	2	0.5
Burning, cutting losses and waste	5 - 8	0

Note: \*amount of material recovered is decided in terms of LDT, which equals weight of the ship excluding cargo, fuel, oil, ballast water, crew and stores. LDT is estimated as ship’s volume ( $V$ )\*Sea water density  $\gamma$  (- DWT (dead weight tonnage) where  $V = Length_{Max} \times Breadth_{Max} \times Draft_{Max} \times block\ coefficient\ (C_b)$ , value of  $C_b$  varies across types of ships, like general cargo, tanker, container, passenger, etc.  $\rho$  is taken as 1.025

Table 2 shows values of different materials that can be recovered from ships being dismantled. However, the table reveals that metal scraps and machineries constitute maximum revenue from dismantled ships. Net

economic benefit from a dismantled ship ( $E_B$ ) is total revenue ( $\sum_{i=1}^n (LDT_i \times P_i)$ ) (minus total costs, where  $LDT_i$  and  $P_i$  denote respectively LDT and price per tonne of  $i$ -th material. Choi *et al.* (2016) proposed as

$$E_B = \sum_{i=1}^n (LDT_i \times P_i) - (S + T + L + G_t + W + E + O_c) \tag{1}$$

where  $S$ : purchase price of ship;  $T$ : transportation cost;  $L$ : labour cost;  $G_t$ : government duties and taxes;  $W$ : cost incurred

towards worker safety regulations;  $E$ : cost incurred towards environmental regulations;  $O_c$ : overhead costs. Equation (1) can be simplified as:

$$\begin{aligned}
 E_B = \text{Total revenue} - \text{Total cost} &= \sum_{i=1}^n (LDT_i * P_i) - (S + O_c + G_i) * LDT_i \\
 &= \sum_{i=1}^n \sum_{i=1}^n (LDT_i) (P_i - S - O_c - G_i)
 \end{aligned}
 \tag{2}$$

Equation (1) and (2) may be computed based on actual data of the constituent factors. For theoretical purposes, (1) and (2) may consider the mid-values of the ranges. Clearly,  $E_B$  is directly proportional to  $P_i$  and  $\sum_{i=1}^n LDT_i$ .  $E_B$  may generate foreign exchange when foreign investors and buyers buy recycled materials with foreign currency.

### Workers' Benefits

Ship breaking involves a large number of workers (mostly daily paid). Major workers are gas cutters (work on the ships and at the yards), winch and crane operators, loaders and yard cleaners. At Alang-Sosiya, a gas cutter gets around ₹800 to ₹2,000 per day, a yard cleaner is paid around ₹500 to ₹1,000 per day (Srivastava & Lahiri, 2024). Alang-Sosiya employs about 40,000 workers each year, most of them are "migrant workers" who travel without their families and work at the yards for about 6 months to 2 years. For 40,000 workers, SR generates annual wages income of about ₹.56 crores (Ship Recycling Industries Association). However, it is challenging to enforce domestic labour laws in Indian SR industry due to the transient nature of the workforce.

### Indirect Benefits

According to the GDP through expenditure approach in India,  $E_B$  and also expenditure components like  $O_c$ ,  $G_i$  contribute to the country's GDP. Thus, indirect benefits of SR include government duty (import duty of EoL ships, Customs duty, licenses etc.), revenues of ports undertaking ship breaking, and the earnings SR yards from charges levied on EoL ships like for pilotage, berthing and towing, dry docking, supply of water, terminal concessions, land/estate leased, agents, etc. along with transportation cost, labour cost, cost incurred for worker safety and environmental regulations.

SR yards also create indirect employment for about a million workers in downstream industries like re-rolling mills, oxy-acetylene

plants, employment generating recycling industries like lead acid batteries, waste lube oil, plus trucking companies, railways, and other supply chain management nodes, and help to accelerate socio-economic growth of the country.

### Induced benefits

Induced benefits filter through SR-related activities other than direct and indirect employment. Steel from ship breaking generates significant savings since it is much cheaper than producing virgin steel. In India, cost of recovering 2 million tonnes steel through SR is at most ₹ 300 crore against over ₹ 6,000 crore via production of steel by blast furnace (BF) and basic oxygen furnace (BOF) technology, which require resources like iron ore, coal, refractories and other raw materials (9.2 MT), water (120 MWM), oxygen (13 MWM), electricity (4,600 M Watts), furnace oil (60,000 tonnes), plus land requirement (10,000 hectares) (Transition Zero and Global Efficiency Intelligence, 2022). In addition, one tonne of produced steel generates around 2.4 tonnes of  $CO_2$  (Hasanbeigi *et al.*, 2018), which is a major concern and is being addressed by climate policies such as EU's Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2021). India, the second largest producer of crude steel in the world, produced 144 million tonnes of crude steel in 2024, excluding about 21.6 million tonnes (15%) supplied by SR activities. In other words, steel from SR activities amounted to savings of  $[\frac{6000-300}{2} \text{ crore} * 21.6] = ₹61560$  crores in 2024. SR also lowers the cost of manufacturing new ships by providing reusable parts like bars, ingots, pipes and plates. Moreover, solid waste generation in SR is negligible as compared to ₹550 per tonne of crude steel produced in major steel plants in India. Ship breaking yards at Alang attract tourists and increase revenue from tourism-related activities, including hospitality services.

**Multiplier**

Additional income results in re-spending, generating further income and employment. The process continues and each round of spending generates more income, until the multiplier effect eventually dissipates. However, quantification of such benefits is not as straightforward as cost-saving benefits. Multiplier =  $\frac{1}{1 - \text{Marginal propensity to consume (MPC)}}$  is simple but  $\text{MPC} = \frac{\text{Change in consumption}}{1 - \text{Marginal propensity to consume (MPC)}}$  varies at different phases of business cycles and levels of income. MPC is typically lower at higher incomes. Time lag exists from the receipt of income and the consumption expenditure, and increased time lag may reduce multiplier value.

Considering value of MPC at 49.8% in India from macro time series for 1990-2020 (Kasturi *et al.*, 2023), value of multiplier ( $\lambda$ ) is  $\frac{1}{1-0.498} = 1.99$  implying that induced incomes ( $Y$ ) results in additional income of 1.99 $Y$ , or almost double.

**Environmental Impact**

Frameworks for mitigating environmental impact and safety issues in SR have been attempted by various approaches. Direct assessment of environmental pollution from SR by considering waste content in a few EoL ships may result in overestimation since all of the waste from a dismantled ship may not go into land and water. Lin *et al.* (2022) computed emission of  $i$ -th hazardous wastes from  $j$ -th type ship in  $t$ -th year for  $c$ -th country ( $HS_{c,i,j,t}$ ) as product of annual global LDT for breaking of  $j$ -th type of ship in  $t$ -th year ( $Q_{j,t}$ ); per-unit weight of  $i$ -th hazardous wastes from  $j$ -th type ship ( $F_{ij}$ ) and proportion of  $i$ -th hazardous waste in  $c$ -th country that is not treated ( $E_{c,i}$ ). However, the benefits of multiplicative aggregation over additive aggregation are not mentioned. A better approach would be to fix country and find  $HS_{i,0}$  from all types of ships in the base year and compute  $\frac{HS_{i,t}}{HS_{i,0}}$  to quantify changes in  $t$ -th year from the base year.

Sustainable risk management model using fuzzy decision-making trial and evaluation laboratory (Fuzzy DEMATEL) method for analysis of causal links among the identified sub-factors was proposed for improved safety and environmental practices in ship-breaking process (Ozturkoglu *et al.*, 2019). Best-Worst Method (BWM) using questionnaires based on fuzzy sets, showed major hazardous materials released into the environment during SR are: HM residues ( $H_4$ ), PCBs ( $H_6$ ), tributyltin (TBT), and asbestos ( $H_3$ ) putting challenges to better pollution management for reduced environmental risks (Soner *et al.*, 2022). Sezer *et al.* (2014) assessed SR hazards combining Dempster-Shafer’s evidential theory, and failure mode effects and criticality analysis (FMECA), where highest risk priority number was observed for  $H_6$  and  $H_8$  (toxins) requiring immediate corrective action for a sustainable SR process. However, BWM suffers from limitations like consistency issues and comparison consistency (Liang *et al.*, 2020). For  $n$ -number of agents, comparison of  $\frac{n(n-1)}{2}$  pairs become tedious for large  $n$ , resulting in inconsistency since all the elements of the comparison matrix involve ambiguous judgment scales that do not follow the transitivity rule. Moreover, absence of threshold for the consistency ratio, and unique best and/or worst criterion indicate limitations of BWM (Rezaei, 2018). Safer and more sustainable SR operations under management, environmental and occupational health and safety regulations were recommended (da Silveira *et al.*, 2025).

**Concentration of Heavy Metals**

Several indices are there for assessing the effect of single factor, geo-accumulation, ecological risk and resulting human health risk. Comprehensive assessment requires combining such indices by a methodologically sound approach to get a comprehensive index for analysis of overall pollution status of heavy metals (HMs). Distributions of concentration of HMs vary for different locations, and are not normally distributed for different sections of soil (Zhao *et al.*, 2022). Illustrative list of indices used to measure concentration of several HMs

include:

- Mean Metal Index (MI)

$$\sum_{i=1}^n \frac{\text{Concentration}_{i\text{-th HM}}}{\text{Max. allowed Concentration}_i} = \sum_{i=1}^n \frac{C_i}{MAC_i}$$

(Tamasi & Cini, 2004) where  $C_i$  ( $\frac{mg}{Kg}$ ) is the detected concentration of  $i^{\text{th}}$  HM;  $MAC_i$  is the maximum allowed concentration of the  $i^{\text{th}}$  HM

- Individual bio-accumulation index (IMBI) =  $\frac{1}{n} [\sum_{i=1}^n (\frac{C_i}{C_{iMax}})]$ , even if  $C_{iMax} \neq C_{jMax}$  for  $i \neq j$

and thus,  $\frac{C_i}{C_{iMax}} + \frac{C_j}{C_{jMax}}$  is not meaningful

- Toxic risk index (TRI) =  $\sum_{i=1}^n TRI_i$
- Metal Pollution Index (MPI) for  $n$ -samples =  $\sqrt[n]{(Cf_1 \times Cf_2 \times \dots \times Cf_n)}$  where  $Cf_n$  denotes concentration of  $i^{\text{th}}$  HM (Teodorovic *et al.* 2000). MPI avoids reference concentrations and eliminates extreme values that may skew the data.
- HM pollution index (HPI) uses weights which are inversely proportional to the standard value recommended to every element and is given by  $HPI = \frac{\sum_{i=1}^n w_i Q_i}{\sum_{i=1}^n w_i}$  where weight to  $i^{\text{th}}$  parameter  $V = 1, 2, \dots, n$  and sub-index for the  $i$ -th parameter  $[\sum_{i=1}^n [\frac{M_i - I_i}{S_i - I_i}]] * 100$  where  $M_i$ ,  $I_i$  and  $S_i$  denote respectively assessed value, tolerable value and allowable value (Mohan *et al.*, 1996)

- Geo-accumulation index ( $I_{geo}$ ) to assess pollution level for a single element by  $I_{geo} = \log_2 \left[ \frac{C_{Sample}}{1.5 \times C_{Background}} \right]$  where  $C_{Sample}$  and  $C_{Background}$  denote respectively concentration of a HM in soil and the same in the background, taken from secondary data, which can change due to natural diagenesis (Müller, 1969). Based on maximum value of  $I_{geo}$  ( $I_{geoMax}$ ) and average of  $I_{geo}$  value ( $I_{geoAv}$ ), Santos-Francés *et al.* (2017) calculated mean, SD, median and geometric mean for and Nemerow index  $I_{IN} = \sqrt{\frac{P_{geoMax} + P_{geoAv}}{2}}$

separately for each of the eight HM considered.

### Major Limitations

- $I_{geo}$  depends heavily on value of  $C_{Background}$ . For a fixed value of  $C_{Background}$   $\frac{I_{geo(1)}}{I_{geo(2)}} \neq \frac{C_{Sample(1)}}{C_{Sample(2)}}$ . For example, let for Pb be  $36.0 \text{ mg} \cdot \text{kg}^{-1}$ ,  $C_{Sample(2)} = 37$  units and  $38$  units. Then,  $\frac{C_{Sample(1)}}{C_{Sample(2)}} = 0.973684$ .  $I_{geo(1)} (0.685185) = -0.5454 \log_2$  and  $I_{geo(2)} (0.703704) = -0.507$ . Thus,  $\frac{I_{geo(1)}}{I_{geo(2)}} = 1.07574 \frac{\Delta I_{geo}}{\Delta C_{Sample}}$  is not constant. Let values of Pb concentration in  $C_{Sample(n)} = 74$  and  $C_{Sample(n-1)} = 75$ , where  $C_{Background_{Pb}} = 36.0$  like the above example. Here,  $\frac{I_{geo(1)}}{I_{geo(n-1)}} = 0.959274 \neq \frac{I_{geo(1)}}{I_{geo(2)}}$
- Better measure of  $C_{Sample}$  could be pooled mean
- Information on  $C_{Background}$  may not be available for areas taken as free from HM pollutants or areas where geochemical baseline map is in progress (Dutta *et al.*, 2021).
- Scoring systems of subjective rating scale used in HPI are rather arbitrary ranging between 0 and 1. Selection of weights in HPI can be questioned since no weighting system is beyond criticism (Greco *et al.*, 2019).
- Calculation of  $Q_i$  to evaluate HPI may give wrong results. Eldaw *et al.* (2020) provided examples where observed concentration of zinc in sample A ( $C_{Zn,A}$ ) (exceeded the same for sample B ( $C_{Zn,B}$ ) (and highest desirable limit value of zinc was in between  $C_{Zn,A}$  and  $C_{Zn,B}$ , giving a result which contradicts reality. In addition, sum of  $Q_i$  equaled the overall index even when  $M_i < I_i$ .
- If relative weight of a HM=0, influence of the HM will be absent, despite  $M_i > S_i$

- For *HPI*, standard value ( $S_i$ ) could be the permissible or desirable value of the parameter, and value of is not fixed and may be manipulated (Singh *et al.*, 2019).
- Salah *et al.* (2015) found results from *HPI* and *MI* for assessment of groundwater pollution. Limitations of combined indices were reviewed (Ahirvar *et al.*, 2023).
- Methods to assess combined concentration of several HMs lack theoretical basis, produce non-uniform results without indication of distribution of the combined/aggregated measures (Eldaw *et al.*, 2020).

The above illustrative studies differ with respect to theoretical frameworks and methods but emphasise the importance of sustainable, comprehensive frameworks for better assessment of environmental impact of SR activities and changes of the impact over time. Subjectivity and uncertainties of human judgments, inter-related risk factors,

adopted aggregation methods along with high computational intensity, inconsistencies and potential errors are major limitations of such approaches. For example, in the Fuzzy DEMATEL method, relative preferences on the agent effects are opined by experts as the input instead of actual evaluation of the concentration of HMs in land and water. Chakrabarty (2024) suggested multiplicative aggregation of concentrations of HMs to get an index satisfying index for the region = aggregation of index of all dimensions = index formed by aggregating all the indicators.

One tonne of recycled steel reduces  $CO_2$  emissions by 1.67 tonnes and conserves natural resources like iron ore (1.4 tonnes), coal (0.8 tonnes), and limestone (0.3 tonnes) (Climate Group, 2024). Assuming full utilisation of India's SR capacity of 4.5 million LDT by 2030, and considering forecasts and projection of recovered steel from SR, emissions savings was estimated by Climate Group (2024) as

$$\text{Avoided emissions}_{2024} = \text{India's Av. Steel Emission Intensity (2.54 t-CO}_2\text{/tcs)} \times 75\% \text{ of total steel recovered in 2024 (1.9 MT)} \quad (3)$$

It may be noted that ban on PCBs (Polychlorinated Biphenyls) in 1976, asbestos in 1985 and TBT in 2000, implies such wastes in ship breaking are either absent or of negligible quantity. Lin *et al.* (2022) estimated that the generation of waste from SR in India, Bangladesh and Pakistan in 2050 might be reduced by 80% or more from 2020 levels if the EU Convention and the HKC are adopted, despite an increase in SR scrap. Rahman and Kim (2020) found that SR avoids 70%-90% of environmental impacts at the cost of 1%-5% disposal impacts and 5%-20% of domestic processing impacts. Lower

environmental risks in SR may encourage flow of FDI for further economic growth.

However, despite various efforts, management and disposal of hazardous waste resulting from ship breaking is poorly managed and requires further actions to promote more environmentally friendly and sustainable practices.

### Proposed Method

The proposed index  $I_{\text{Ship-break}}$  reflecting the overall impact of shipbreaking considers the dimensions and indicators given in Table 3.

Table 3: Dimensions and indicators of  $I_{Ship-break}$ \*

Dimensions	Indicators	Evaluation of Indicators
Economic (Direct benefits)	Income to Shipbrokers	$\sum_{(All\ dismantled\ @ships)} E_B = X_1$
	Income to SR workers	$\sum$ Wages, allowances received by all SR workers in a year = $X_2$ $\sum$ Wages, allowances received @ by all SR workers in a year ) = $X_2$
Economic (Indirect benefits)	Government duties and taxes	$X_3$
	Revenue of ports and SR yards from shipbreaking	$X_4$
	Cost to comply with - worker safety	$X_5$
	- environmental regulations	$X_6$
	Overhead costs of all shipbrokers	$X_7$
	Total wages in indirect employment generated in downstream industries plus relevant supply chain management nodes	$X_8$
Economic (Induced benefits)	Savings in production of virgin steel.	Cost of production of one unit of virgin steel – cost of supplying one unit of steel via SR) * Volume of steel obtained from SR ( $X_9$ )
	Savings in production of equipment and materials	(Production cost of equipment and materials – cost of supplying them via SR) * Quantum of equipment and materials obtained from SR ( $X_{10}$ )
	Value of raw materials for units dealing with lead acid batteries, waste lube oil, etc.	Annual value of such raw materials supplied by SR ( $X_{11}$ )
	Value of recovered materials as input to small-scale businesses giving credibility to CE	Annual value of such products from dismantled ships sold in flea market ( $X_{12}$ )
	Additional income to trucking companies, railways, and other supply chain management nodes	Annual income for transporting dismantled ship parts by supply chain management nodes like trucking companies, railways, etc. ( $X_{13}$ )
	Revenue from tourists visiting SR sites including hospitality services	Annual income from tourism-related activities ( $X_{14}$ )
	Supporting and promoting local economies	Total income generated from nearby shops, markets and related establishments ( $X_{15}$ )
	Multiplier effect considering current MPC= 49.8% Current Multiplier ( $\lambda_c$ )=1.99	Additional income = $\lambda_c * \sum_{i=1} X_i$ ( $X_{16}$ )

Environment	Reducing CO <sub>2</sub> emissions	Avoided emissions in t-CO <sub>2</sub> /tcs of CO <sub>2</sub> emissions for steel industry and other metal industries (X <sub>17</sub> )
	Overall concentration of Heavy metals (HM) and Toxic metals (TM) in land and water	Field investigations to estimate individual concentrations of each HM and TM and aggregate them by $CI_{HM-Soil} = \frac{C_{1c} \cdot C_{2c} \dots C_{nc}}{C_{10} \cdot C_{20} \dots C_{n0}}$ (X <sub>18</sub> ) and $CI_{HM-Water} = \frac{C_{1c} \cdot C_{2c} \dots C_{nc}}{C_{10} \cdot C_{20} \dots C_{n0}}$ (X <sub>19</sub> ) where C <sub>ic</sub> and C <sub>i0</sub> denote concentration of i-th HM in current period and base period respectively (Chakrabarty, 2024)
	Other water quality parameters	BOD (X <sub>20</sub> ) COD (X <sub>21</sub> ); pH (X <sub>22</sub> )
Safety issues	Non-use of Personal Protective Equipment (PPE)	Percentage of non-use of PPE by site visits without notices (X <sub>23</sub> )
	Non-compliance of the ship-breaking code	Percentage of non-compliance of the ship-breaking code by inspection (without notices) of Central and State Pollution Control Boards (X <sub>23</sub> )
	Accidents in SR yard	$\frac{1}{No.of\ Fatal\ accidents}$ (X <sub>25</sub> ) $\frac{1}{No.of\ non\ Fatal\ accidents}$ (X <sub>26</sub> ) $\frac{1}{No.of\ dangerous\ accidents}$ (X <sub>27</sub> )

**Observations**

- $\sum_B^E$  overall dismantled ships consider number of recycled ships and their LTD. Higher value of  $\sum_B^E$  gives higher value of the index  $I_{Ship-break}$
- Each chosen variable needs to ensure positive relationship with  $I_{Ship-break}$  i.e. the higher the value of a variable, the higher is the value of  $I_{Ship-break}$ . Thus, reciprocal of each variable under accidents in SR yard are considered to ensure similar direction of the variables in the index  $I_{Ship-break}$ .

The indicators are in different units and follow different distributions (that too unknown) with different extents of inter-correlations are not appropriate for arithmetic aggregation.

The unit free index  $I_{Ship-break}$  reflecting overall impact of ship-breaking is defined as multiplicative aggregation of ratio of for the t-th year and X<sub>it</sub> for the base year i.e.

$$I_{Ship-break0} = \sqrt[27]{\frac{X_{1t} \cdot X_{2t} \dots X_{27t}}{X_{10} \cdot X_{20} \dots X_{270}}} \tag{4}$$

or equivalently as

$$I_{Ship-break0} = \frac{X_{1t} \cdot X_{2t} \dots X_{27t}}{X_{10} \cdot X_{20} \dots X_{270}} \tag{5}$$

$I_{Ship-break0}$  in (4) to (5) can accommodate measures such as percentages, t-CO<sub>2</sub>/tcs of CO<sub>2</sub>, rupees, etc. irrespective of their score ranges, distributions and sample size.  $I_{Ship-break0} * 100$  may be considered to reflect percentage changes.

**Properties and Benefits**

$I_{Ship-break0}$  depicts overall impact of ship breaking in the current year over the base year by a continuous variable. The index significantly reduces substitutability among the chosen indicators and produces no bias for regions and satisfies:

- Time reversal test since  $I_{Ship-breakt0} * I_{Ship-breakt0} = 1$
- Formation of chain indices since  $I_{Ship-breakt20} = I_{Ship-breakt21} * I_{Ship-breakt10}$
- Replacing the base year figures by variable-wise non-zero targets will allow the index to indicate how far the country/region is from the targets.
- $I_{Ship-break_{t(t-1)}} > 1$  will give progress of overall impact of ship breaking in successive years. Plot of such progress/decline across time facilitates comparison of regions based on longitudinal data.
- $\frac{X_{jt}}{X_{j0}} > 1$  indicates improvement in the  $j$ -th variable where  $X_{jt} > 0$  and  $X_{j0} > 0 \forall j = 1, 2, \dots, 27$ . However,  $\frac{X_{jt}}{X_{j0}} < 1$  indicates that  $j$ -th variable is critical and needs managerial attention for necessary corrective action. Identification of critical variables is important for monitoring SR systems.
- Increase in  $\frac{X_{jt}}{X_{j0}}$  by 1% implies 1% improvement in  $I_{Ship-breakt0}$  if all others are unchanged
- Equation (5) implies  $\log \log (I_{Ship-breakt0}) = [\sum_{i=1}^{27} \log X_{it} - \log X_{i0}]$  i.e. an additive model following lognormal distribution for large sample size (Alf & Grossberg, 1979).

$I_{Ship-breakt0}$  can be decomposed to indices for dimensions like  $I_{Economic\ impact} = \frac{X_{1t} \cdot X_{2t} \cdot \dots \cdot X_{16t}}{X_{10} \cdot X_{20} \cdot \dots \cdot X_{16,0}}$ ;  $I_{Environmental\ impact} = \frac{X_{17t} \cdot X_{18t} \cdot \dots \cdot X_{22t}}{X_{17,0} \cdot X_{18,0} \cdot \dots \cdot X_{22,0}}$  and  $I_{Safety\ impact} = \frac{X_{23t} \cdot X_{24t} \cdot \dots \cdot X_{27t}}{X_{23,0} \cdot X_{24,0} \cdot \dots \cdot X_{27,0}}$

where relative importance of  $X_j$  on  $I_{Economic\ impact}$  is given by  $\frac{\Delta X_j}{\Delta I_{Economic\ impact}}$ . Following a similar approach, relative importance of a variable can be found on  $I_{Environmental\ impact}$  or on  $I_{Safety\ impact}$ . The

variables with high value of relative importance merit more attention from planners and monitoring authorities.

### Discussions

The number of indicators in the index  $I_{Ship-breakt0} = I_{Economic\ impact} * I_{Environmental\ impact} * I_{Safety\ impact}$  in three dimensions can be increased or decreased depending on purpose, ensuring the same direction of the variables in the index. Here, . GDP of a country can be regressed on  $I_{Economic\ impact}$  where the  $\beta$ -coefficient indicates average change in GDP for unit change in  $I_{Economic\ impact}$ . A decreasing trend of  $I_{Environmental\ impact}$  and increasing trend of  $I_{Safety\ impact}$  are signs of improved SR processes. The indices may be computed separately for national, regional, industry and firm/operation levels.

### Conclusions

India’s efforts to promote green SR, integrating SR with ship building, coupled with increasing the number of ageing fleets will help the country to become a global leader in SR and push country’s endeavours to become a low-carbon, resource-efficient economy through sustainable recycling practices and addressing the safety, health and environment (SH&E) issues. Against around 2.47 million GT of dismantled ships in 2023, India is expected to recycle 3.8 to 4.2 million GT of ships annually by 2025 and the growth is likely to continue till 2028 (Care Edge Ratings Report, 2024) thus increasing the production of domestic steel/steel scrap and create employment opportunities. However, availability of reliable data to quantify India’s potential needs to be arranged. Future empirical investigations may be undertaken on the interplay of the proposed indices and regional, national economy.

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### Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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