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Demolition of the European ships fleet: A scenario analysis

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A B S T R A C T

This paper conducts a detailed exploration of projected trends in the demolition and recycling of the European ship fleet, in light of the dismantling capacity in Europe. Utilizing a robust predictive model based on the Weibull distribution, the study synthesizes historical data and current operational metrics to forecast trends up to the year 2050, such as ship typologies, their average age, and recycling frequency. By estimating the rate and volume of ships reaching their end-of-life (EOL), the study aims to delineate the required capacity for ship recycling in Europe over the coming decades. The analysis reveals the key factors influencing the demolition trajectory and provide essential insights for future planning and policy formulation in the field of ship recycling. The study also underscore the importance of developing adaptive strategies in ship dismantling catering to the anticipated shifts in fleet composition and evolving environmental regulations, offering a foundation for informed decision-making and policy development in the maritime industry.

1. Introduction

Throughout its operational lifespan, a ship undergoes three distinct phases: (i) design and construction, (ii) transport and maintenance operations, and (iii) demolition. Ship demolition is the process of dismantling a ship at the end of its operational lifespan. There are various techniques for ship demolition, including demolition proper, disarmament, abandonment, destruction, and recycling. The choice of terminology for the end of life (EoL) ship can vary depending on the context. The Basel Convention and its guidelines use the term "ship dismantling," while NGOs and associations prefer "ship breaking." The IMO and European regulations use the term "ship recycling," while the metal reuse sector uses the term "ship scrapping." In this article, the term "ship recycling" is used to simplify terminology and maintain consistency.

Ship recycling refers to the process of dismantling ships to extract and recover materials [22] and it is typically seen as the best method to dispose of a ship when its service life is coming to an end [55]. Ship recycling is a very profitable and inherently sustainable activity, crucial for ensuring the correct disposal of decommissioned ships and the recovery of materials and resources (K. A. [23]. The economics of ship recycling is driven primarily by market factors such as freight rates, the price of steel scrap and the costs of maintaining an aging fleet, the price offered by shipyards for the purchase of Light Displacement Tonnage (LDT), the cost of demolition and the demand for recycled steel [57], the light weight of a vessel is the weight of the hull, including machinery and equipment. The length, breadth, depth, and displacement are also very important factors for buying and selling an unserviceable ship. However, the decision to scrap a ship is influenced by other factors such as technological development, new global market needs, regulatory standards and the entry of new ships into the fleet [44,65].

The selection of a demolition location is principally influenced by the monetary value a facility offers for the metal, as perceived by shipowner or the "cash-buyer" intermediary [26]. This value is influenced by the demand for recycled steel in the area concerned and the costs of recycling operations. The market demand and the scrap prices offered by the shipyards are closely linked to the price of steel and the costs of the recycling activity [41]. Fig. 1 shows the decisions that form demand and supply for ship recycling.

Another crucial factor in choosing the demolition site concerns the recycling policy adopted by the shipowner, which must reflect the environmental and social standards required by various international regulations. It is worth noting that both NGO and public opinion are increasingly closely monitoring this sector. The adverse opinion of these

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parties can have significant repercussions on the company's image and reputation [27].

The destination of ship recycling, but especially the method of recycling, has raised significant concerns as the various demolition techniques used have diverse costs and environmental and social impacts. Beaching, widely used in Bangladesh, India, and Pakistan, involves dragging the ship onto the beach to be dismantled and has serious concerns for worker safety and environmental pollution [6]. Landing, used mainly in Turkey, involves the ship colliding with a shore or concrete berthing to facilitate dismantling operations [55]. Alongside, commonly used in China, the EU, and the United States, involves dismantling the ship piece by piece while it is immobilized on a pier. Finally, dry-docking, the safest and most efficient method, is carried out in closed dry docks, but the associated costs and dimensions limit its use [67].

Currently, the main destinations for ship recycling are located in South Asia, with two key factors driving this trend: low labour costs and the profit from selling ships, as the beaching method is economically more favourable [40]. Bangladesh, India, and Pakistan, together represent over 80% of the gross tonnage dismantled globally, Turkey represents 9% of the total ship demolition, and only 5% of recycling takes place in OECD countries [34]. The popularity of Southeast Asia as the primary location for ship demolition is also attributable to its key role in providing the main source of steel [1], significantly contributing to the development of the local industry and creating employment opportunities. The increasing demand for steel and the expansion of urbanization are further factors justifying the preference for these areas for ship demolition [30]. Additionally, the regulation and policies regarding standards and prohibitions are more lenient compared to those of OECD countries, thereby facilitating the activity.

However, the coasts of South Asia are witnessing an industry whose environmental and health balance urgently needs to change; such pressures are due to the fact that the dismantling techniques and the standards of recycling facilities are not in line with international standards for worker safety, marine environmental protection, and hazardous waste management [3,7,8]; M. S. [25]; [39]; [68].

The management of the EoL of ships and the recycling of the related materials represents a global problem, characterized by persistent difficulties [36]. The ILO identifies shipbreaking as a highly dangerous occupation globally [28]. The attention to toxic substances, working conditions, and improper recycling practices, have led political actors to develop over time efficient regulatory frameworks in terms of the management of recycling facilities, safety at work, and inspections. The increase in national and international regulations over time has led to a slow improvement in shipbreaking yards with regard to health and safety [51,53]. However, given that it is a heavy industry with a significant workload and with serious and variable risks, it is necessary to constantly update safety inspections and risk assessments [43].

The most representative legislation is the International Maritime Organization (IMO) Convention for the Safe and Environmentally Sound Recycling of Ships (HKC). The HKC aims to ensure that ship recycling does not pose risks to human health or the environment. In addition, the HKC specifies the technical and documentary requirements regarding the design, construction, operation, preparation, and the establishment of an adequate mechanism for the application of ship recycling, which incorporates certification and communication requirements [29]. After 26 years of waiting, in the summer of 2025, the HKC will officially come into force.

The European Union, aware of the importance of its fleet in terms of gross tonnage owned globally, has always been at the forefront in assuming a responsible attitude towards the cross-border movements of its EOL ships and the correct recycling. The management of EOL in the EU has moved from the regulation on the export of waste Reg.1013/2006 to a specific regulation, Reg.1257/2013 (SRR), which promotes the requirements of international standards for the ship recycling activity in the European area. The SRR aims to be an early implementation of the HKC. The objective of the SRR is to limit the sending of European ships to non-compliant yards. Article 2 of the SRR obliges that all ships flying the flag of the EU with a tonnage of over 500 GT must be recycled in facilities authorized by the European Commission. Article 16 of the SRR establishes the list of yards authorized for ship dismantling, which can be updated. The first publication was in 2016 and included 16 yards with an authorized annual recycling capacity of 0.3 MLTD and a theoretical capacity of 1.1 MLTD. The eleventh edition published in mid-2023 authorizes 48 facilities, located both in Europe and in a third country, the authorized capacity is 1.05MLTD and the theoretical capacity is 3 MLTD [17]. However, the SRR is the subject of controversy, the main ones being the insufficiency of the recycling capacity of the facilities located in OECD countries, the ease of circumventing the regulation, and the lack of an adequate financing mechanism.

The European Union, through the adoption of the Green Deal, wants to focus its policies on a low-resource consumption economy. An integral part of the European Green Deal is the Circular Economy Action Plan (CEAP2), which is an industrial policy approach aimed at accelerating not only circularity but also the dematerialization of the economy [16]. Ship recycling is perfectly aligned with the European policies of industrial recovery and promotion of the circular economy. In fact, contrary to what one might think, ship recycling emerges as an intrinsically sustainable activity that fully reflects the principles of the circular economy. The production of steel through ship recycling is not only more ecological but also more economical. Traditional methods for steel production, such as mining, smelting, and rolling, not only consume considerable amounts of energy but are also in sharp contrast with global efforts to adopt more environmentally friendly technologies [9]. On the other hand, the virtuous recycling of steel allows for the renewal of the world's naval fleet and to maintain a balance between supply and

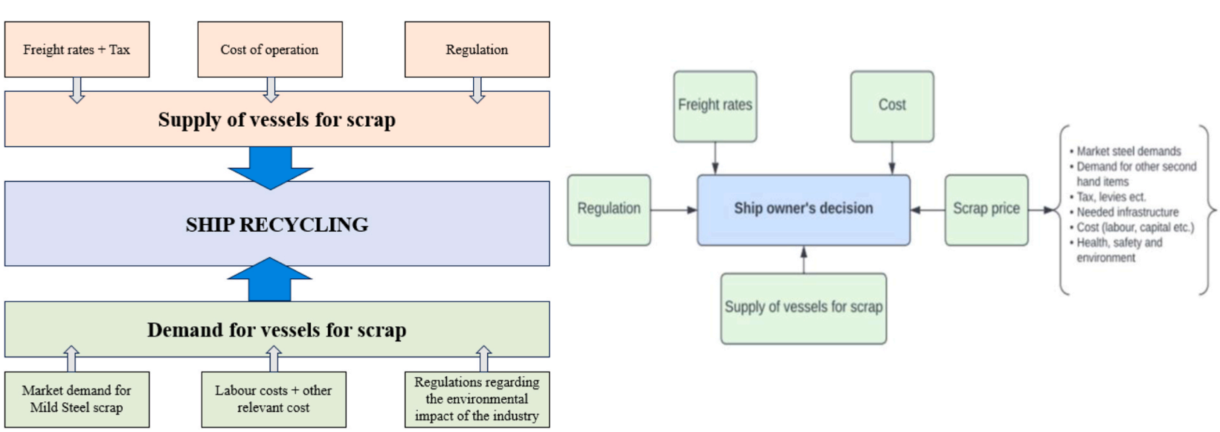

Fig. 1. Supply and demand Ship recycling and Key drivers for a shipowner's decision to scrap.

demand, but simultaneously, facilitates the recycling of millions of tons of waste materials. This not only contributes to the efficiency of the process but also supports the creation of a circular flow for the supply of resources, thus promoting more sustainable management of materials and reducing the overall environmental impact. Infact, ship recycling can be seen as an effective promoter of the development of circular business models [60]. For example, the guidelines suggested by [33] and the implementation of HKC procedures with recycling plans and eco-sustainable design are concrete examples. Furthermore, as highlighted by [46], shipyards and shipowners play a crucial role in the application of design-for-recycling strategies. Practical solutions such as the use of more efficient cutting technologies Yan et al., 2018, pyrolysis [48], material flow analysis [32], computerized models [52], and the implementation of sustainability indicators [45] indicate the sector's commitment to reducing environmental impacts and recovering resources, demonstrating the effective emphasis on circular economy thinking in ship recycling. Currently, the process of better regulation of the Ship Recycling Regulation (SRR) is underway. This review involves assessing the effectiveness of the regulation's implementation and its impact to date, evaluating the extent to which it contributes to the overall objectives of the European Green Deal, and identifying gaps in its application. However, to promote more effective legislation, it is crucial to understand the future demand for ship recycling, particularly concerning those ships within the scope of the regulation.

Predicting the lifespan of a ship is a challenging endeavor. The actual age at which ships are scrapped can significantly deviate from estimates based on historical data, due to a variety of interconnected factors. Technological advancements, changes in trade geography, energy prices, and other relevant regulations influence the operational life of ships and conditions on future decisions by shipowners regarding when to sell their vessels. For instance, Evans, [20] highlighted how capital and operational costs can influence the decision to replace ships. Buxton, [5] noted how technical and economic factors impact profitability in the demolition decision. Mikelis, [44] pointed out the existence of a correlation between transport rates and demolition prices. Knapp et al., [38] expanded understanding by using econometric models to establish a positive relationship between scrap prices and the likelihood of demolition.

Beyond economic influence, demolition behavior can be affected by other factors, including technological improvements in ships, new fuels, and environmental regulations. An example of the latter is the regulation-induced phase-out of most single-hull oil tankers prone to oil spills in f avor of double-hull tankers by 2020 [66]. The green transition is accelerating, and pressures on the maritime sector are increasingly determined by new and complex regulations and policies on emissions. In the Table 1 show an overview summary of the main norms of decarbonisation of the shipping.

The primary objective of this research is to develop accurate predictions regarding the future demolition of the European fleet by examining the demolition behavior of European shipowners and analyzing the likelihood of demolition for different types of vessels. Additionally, it aims to update the forecast estimates on the demolition of the European fleet.

International and European policies aimed at decarbonizing the maritime sector could influence the decision to demolish a ship and consequently make estimating future demolition demand even more unpredictable. In order to improve prediction accuracy, two scenarios concerning behavioral options are hypothesized through survival analysis modelling across multiple events in the implementation of decarbonization policies. This analysis aims to address the research question "what will be the forecasts for ship recycling within the European fleet by 2050?" This study not only provides an enhanced methodology but its results are crucial for understanding the quantity of ships destined for recycling and evaluating recycling capacity in relation to needs, also in anticipation of the upcoming revision of the SRR.

Table 1
Overview of the Decarbonisation regulatory framework.

Regulation	Publication Year	Enforcement Year	Term	Reduction Targets
MARPOL Annex VI	1997	2005	Short/ Medium	5% by 2023, 7% by 2024, 9% by 2025, 11% by 2026, 2027–2030 TBD
EEDI/SEEMP	2011	2013	Short	50% by 2050 compared to 2008; efforts towards phasing out GHG entirely within this century
EEDI Phase 1	2015	2015–2019	Short	running from 1 January 2015–31 December 2019, the EEDI requires a 10% reduction of carbon intensity below the relevant reference line for newly built ships.
EEDI Phase 2	2020	2020–2024	Medium	running from 1 January 2020–31 December 2024, the EEDI requires up to 20% reduction of carbon intensity.
EEDI Phase 3	2022 (Originally 2025)	2022 (onwards)	Long	Due to commence in 2025, requires an additional 10% reduction,. will be required to be 30% more carbon efficient than those built in between 2000 and 2010.
EEXI	2021	2023	Short	50% by 2050 compared to 2008; efforts towards phasing out GHG entirely within this century
Operational Carbon Intensity Indicator (CII) and SEEMP	2021	2023	Short	50% by 2050 compared to 2008; efforts towards phasing out GHG entirely within this century
EU's Emissions Trading System (EU-ETS)	2021	2023 (phased over three years)	Short/ Medium	A cap-and-trade system designed to reduce emissions through a declining cap on allowed emissions,

(continued on next page)

Table 1 (*continued*)

Regulation	Publication Year	Enforcement Year	Term	Reduction Targets
				encouraging cost-effective reductions.
FuelEU Maritime	2021	2025 (onwards)	Long	2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045, 75% by 2050
Energy Taxation Directive (ETD)	2021	2023	Short/ Medium	Encourage switch to more sustainable fuels starting 2023
Alternative Fuels Infrastructure (AFI)	2021	2025	Long	Focuses on enhancing infrastructure for alternative fuels to support the transition towards sustainable transportation modes.

2. Method

The methodology, depicted in Fig. 2, assumes that the lifespan of various ship types adheres to a Weibull distribution, a widely acknowledged approach for predicting product life and reliability. The Weibull distribution, commonly utilized for predicting product life and reliability in the design phase [47], is particularly suited to complex products such as ships. In fact, most studies that have used the Weibull distribution on complex products have provided a good approximation of the actual distribution of the lifespan [42,49,50].

The analysis of the survival of the European fleet was divided into three distinct scenarios, in order to outline different behaviours and dynamics diversified between efficiency, sustainability and regulatory compliance. For the analysis, only ships that fall within the dictates of Article 2 of the SRR were selected, that is, all European-flagged ships with a gross tonnage (GT) of 500 or more were considered. For the sample, ships built between 1990 and 2023 were selected, totalling a sample of 6.354 ships. All warships, auxiliary ships and ships owned by a member state were excluded from the sample.

2.1. Extrapolation of data

To estimate the future recycling of the European fleet, detailed information on the life cycle of ships was collected. Comprehensive life-cycle data of ships were extracted from the NGO Ship Breaking Platform and UNCTADStat databases, providing a foundation for a complete dataset of a total of 9.687 ships that were demolished between 2012 and 2022. A first operation conducted on the dataset was the categorization of the sub-types of ships into their respective appearance categories. This step facilitated the subsequent phases of the analysis. After making this division, descriptive statistics were calculated for each type. These statistics provided details on the distribution of ships within each category.

To obtain a complete overview of the European naval fleet currently in service, the IMO's Global Integrated Shipping Information System (GISIS) database was consulted. All information on the ships was extracted, such as weight, flag, type, tonnage, length, size, and year of construction. A combined cross-check of the data collected on the ships was carried out with the MarineTraffic AIS system. This allowed to determine whether the ships included in the dataset continued to sail under the European flag, in order to have a sample that is well representative of reality. At the end of this process, the ships were classified according to their typology.

2.2. Theory calculations

This study estimated the lifespan distribution of ships currently in service in the European fleet using the Weibull distribution function. The distribution of the sample with respect to the Weibull distribution is shown in Fig. 3.

The information and formula for Weibull's distribution is as follows:

$$\boldsymbol{p}(\boldsymbol{t}) = \frac{a}{b}\left(\frac{t}{b}\right)^{a-1}\exp\left[-\left(\frac{t}{b}\right)^{a}\right]$$

P(t) represents the probability that the ship will be demolished in a period t. The parameters a and b represent the shape and scale of the distribution that can be fitted to the actual data. For easier under-

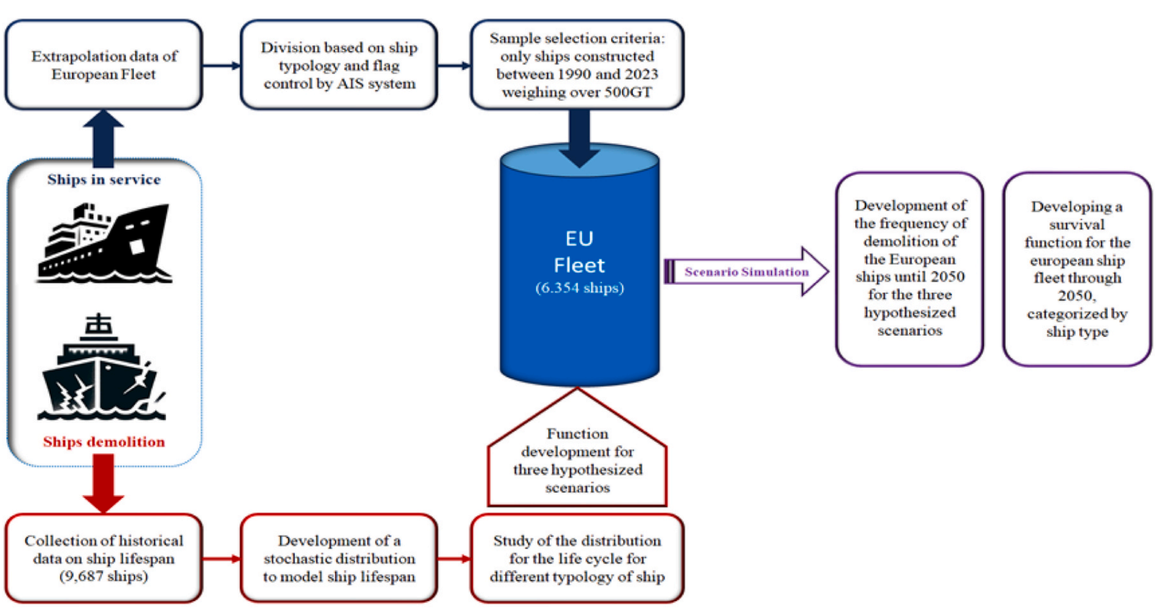

Fig. 2. Research process.

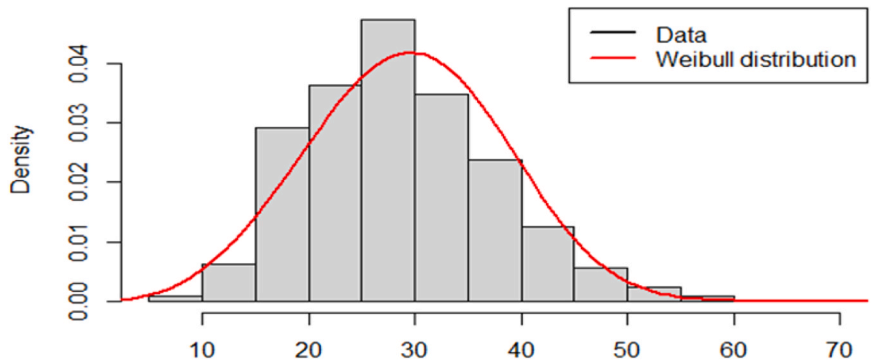

Fig. 3. Weibull distribution.

standing, the parameters a and b can be converted to more specific variables l and m, maximum and most frequent values found in the service life of ships, based on the following equations:

$$T < l = 1 - \exp[-(\frac{t}{b})^{a}]$$

$$m = \frac{b(a-1)^{1/a}}{a}$$

The values l and m obtained were then adapted to the European ships currently in service.

2.2.1. Hypothesis of scenarios

Predicting the end of life of ships is indeed a complex endeavor, given the multifaceted nature of the shipping industry and the myriad factors influencing its dynamics. These factors encompass macroeconomic fluctuations, geopolitical considerations, volatile raw material prices, and financial uncertainties, all of which contribute to the intricate landscape of the maritime sector. Furthermore, the evolving regulatory landscape, particularly concerning environmental concerns, adds another layer of unpredictability to the forecast of future demolition trends in the European maritime fleet. In light of these challenges, we have devised two distinct scenarios to capture the range of potential outcomes regarding the future demolition of the European fleet. Leveraging parameters derived from the Weibull distribution, these scenarios encapsulate various hypotheses regarding future demolition trends. To evaluate the probabilities associated with changes in demolition decisions, we have employed a logistic modeling approach, complemented by a corresponding to significant milestones in the implementation of environmental regulations. At each milestone, a logistic equation is utilized to update the probability of demolition. In addition to the logistic modeling approach, we consider the use of the binomial distribution to model the decision-making process regarding ship recycling. The binomial distribution is particularly suitable for scenarios where there are only two possible outcomes, such as whether a ship will be demolished or upgraded. The binomial distribution is defined as follows:

$$P(X = k) = \binom{n}{k} \times p^{k} \times (1-p)^{n-k}$$

Where n represents the number of trials; k signifies the number of successes, where 1 indicates the ship's demolition and 0 indicates its upgrade; p denotes the probability of success, reflecting the estimated likelihood of demolition in the given year. By analyzing the probability of demolition in a given year, based on conditions such as regulatory pressures, informed predictions can be made about the probability of demolition at various times. This approach allows for a more diverse understanding of the dynamics that guide demolition decisions for the European ship fleet

3. Result

The prediction and estimation of a ship's EOL are challenging due to the absence of a universal calculation formula. The decision to demolish a ship is often conditioned by the economic factor, that is, when the ship is considered uneconomical [5], moreover the ship EOL can vary depending on the type, design, performance, maintenance and structural fatigue [10].

However, a key hypothesis influencing the demolition demand is the average age of ships. Several studies have already investigated the impact of the average age of ships on demolition demand. For instance, Yin & Fan, [65] analyzed the demolition forecast for the entire global fleet, considering a set average age of 25 years for all types of ships. Solakivi et al., [56] examined the European fleet, assuming an average age of 25 years for ships and predicting variable demolition cycles ranging from 20 to 30 years depending on market conditions. Rahman et al., [49] estimated a mean lifespan of 30 years for all types of ships. Held et al., [21] applied the life expectancy of ships demolished from 2016 to 2018 to predict future demolitions, using models that also consider ship size and type. Are analyzed past demolition models and demonstrate how future demolitions would unfold if ships continued to be scrapped. To ensure accuracy in the prediction model, appropriate age-specific weights are assigned for each ship type, analyzing demolition behavior over a historical decade (2012–2022).

The survival age of ships was assessed by consulting the demolition history from the NGO Ship Breaking Platform database. To obtain an accurate representation of the actual life cycle of European ships, has been disaggregated the dataset providing a clear representation of the duration of the ships. Table 2 presents the calculated descriptive statistics for the EOL phase across different ship types.

The table provides a detailed overview of the EOL age for the various typology of ships. Each typology is characterized by various central tendency, providing a key to understanding the central distribution and dispersion of the dimension within each type. There is a variation in the life cycle age for the different types of ships. The average life cycle of

Table 2
Descriptive statistics of the end-of-life (EOL) of the ships for typology.

	μ	Median	Mode	σ^2	σ
Bulk Carrier	27	28	30	50,50	7,10
Container Ships	24	23	19	55,36	7,44
Fishing Vessel	36	37	37	60,14	7,75
Offshore Ships	33	36	37	133,15	11,53
Passenger ship	36	34	30	93	9,94
Ro-Ro	33	32	30	81,17	9,06
Speciality Vessels	39	39	42	152,95	12,36
Tanker Ships	30	30	30	71,07	8,43
Other Ships	34	38	39	126,15	11,23
All ships	**32**	**29**	**30**		

Source: Author's elaboration

Bulk Carriers is 27 years with a mode of 30, which shows a moderate dispersion of its service life. In comparison, Container Ships, with an average of 24 years and a wider distribution, indicate greater variability in their longevity. Fishing Vessels, with both median and mode at 37 years, show superior consistency. Offshore Ships, with an average of 33 years and a median of 36 years, suggest a variation in longevity, highlighted by the mode at 37 years. For Passenger Ships, the average of 36 years and the median of 34 years suggest a distribution influenced by some ships with a longevity below the average, also highlighted by the mode at 30 years. Ro-Ro, with an average of 33 years and a median of 32 years, show variability in longevity, with many ships at 30 years. Tanker Ships have an average duration of 30 years, highlighting comparable stability. Speciality Vessels, with an average of 39 years and wide heterogeneity, are the longest-lived type of ship. The study's findings indicate that the EOL age of ships is a multifaceted issue, influenced by various economic, technical, and environmental characteristics of the ship.

3.1. Descriptive statistics European ship fleet

Maritime transport has played a pivotal role in the history of the European Union. For centuries, half of the global fleet of ships was under the control of European shipowners or registered in their own registers [59]. The European Union, while not maintaining the same competitiveness, retains a significant role as a hub in global trade traffic and ship ownership [62].

The set of European ships collected reflects the current profile of the European fleet in service, with 70% of the ships having exceeded 10 years of service, indicating a fleet aging situation. The most frequent flags in the sample of the European fleet are Greece and Malta, followed by Cyprus and the Netherlands. While analysing the GT owned by individual country, it emerges that Cyprus, Malta, Italy, Greece and Germany have the highest percentage. In terms of the most recent fleet, Denmark has the largest number of new ships. The distribution of the sample by type of ship, tanker ships represent more than 32% of the sample, followed by container ships at 25%, Bulk Carrier at 19% and Ro-Ro ships at 13%. In addition, the data analysis shows that on average Bulk Carriers are the heaviest type of ship. An additional aspect is that the Ro-Ro, Fishing Vessels and Other Ships types are the oldest among the various types.

The results of the sample on the age profile of the European fleet by country are shown in Fig. 4, while Fig. 5 shows the age class by typology of ship.

3.2. Surviving European fleet

The analysis of descriptive statistics indicates an anticipated decline in the European fleet over the coming decades, largely attributable to aging. The results of this study can provide a contribution to European policy makers, allowing them to gain a clear vision of future trends in European ship demolition. This understanding in turn could be essential to improve SRR intervention policies or to make significant updates to recycling plants. Offshore ships, special vessels, other ships, and fishing vessels were excluded from the survival calculation because, as shown in table1, they have higher data heterogeneity and variability than other types of ships. These types of ships were excluded from the calculations. The following are the results obtained from the three hypothesized scenarios.

3.2.1. Weibull scenario

In this scenario, it was hypothesized that the ship reflects the life cycle adaptation. The shapes and scales for each typology of ships were studied, providing an accurate and specific analysis for each type of ship and finally adapted to the current European naval fleet in service. Fig. 6 illustrates the survival analysis of the European naval fleet, conducted using the Weibull distribution model.

The overall trend reveals a complex and dynamic picture. Until 2033, a constant trend is observed, with a generalized decrease in GT that will intensify in the following years. As for the peak of demolition, it is expected to occur in a differentiated way for each type. The type most affected by this scenario is container ships, which will reach its highest demolition rate between 2034 and 2043, and a complete demolition of this type is expected by 2050. Bulk carriers will also suffer a significant decline, reaching their demolition peak in 2036 and 2043, respectively,

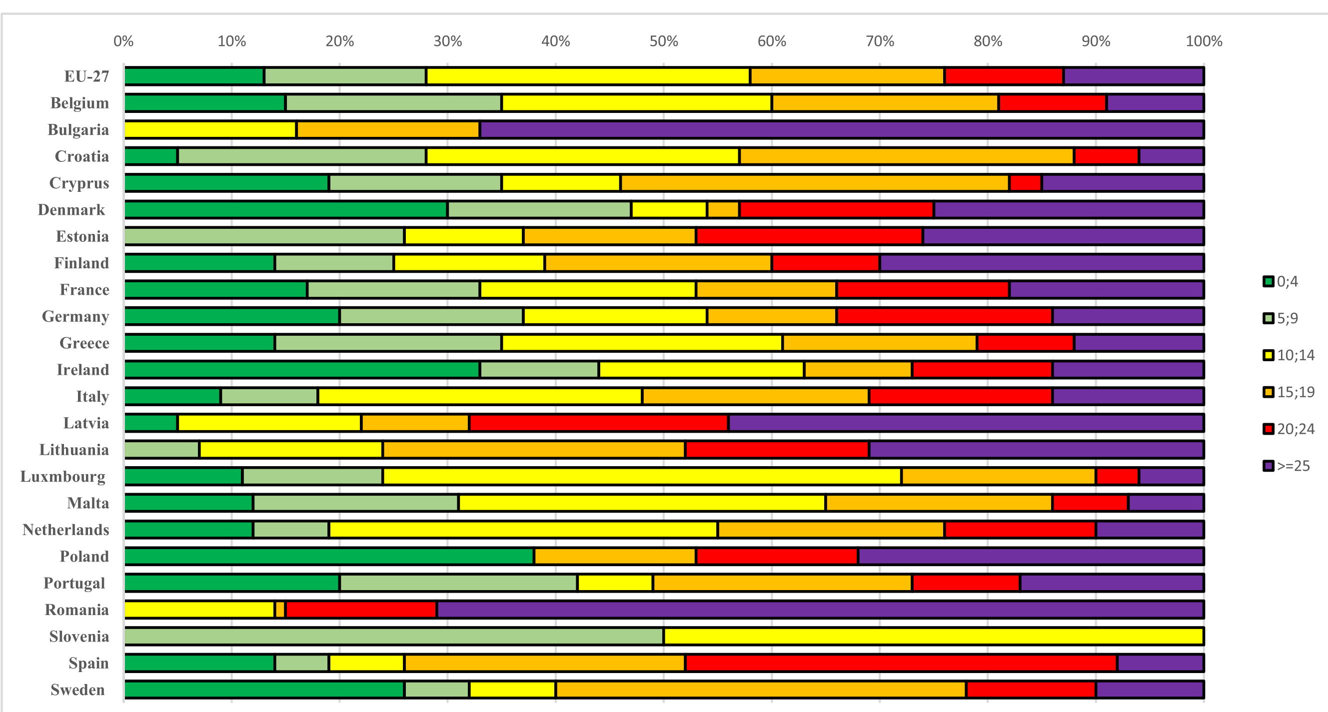

Fig. 4. Age profile of current fleet by Country Source: Authors Elaboration.

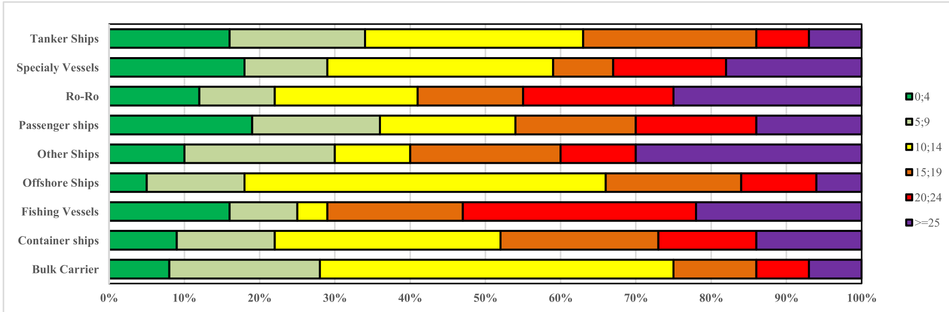

Fig. 5. Age classes by typology of vessel Source: Authors Elaboration.

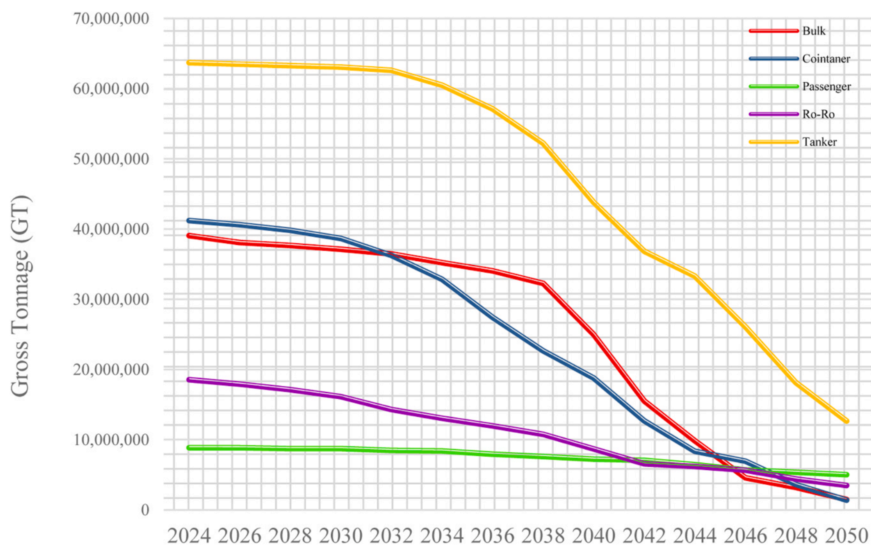

Fig. 6. Weibull Scenario.

in this time frame almost 50% of the current Bulk in service will be demolished. Tanker ships show a constant trend until 2036, but with an intensification of demolition in the following years, with a forecast of a 60% loss of aggregate GT in the time frame between 2038 and 2047. Ro-Ro and Passenger show greater resilience than other types, with a less marked decrease in the period considered. However, both categories will reach their demolition peak by 2042, suggesting that there will also be considerable pressure on these types in the coming decades. The time frame in which the highest demolition intensity occurs extends from 2033 to 2045, with a constant but accelerated decline during this period. The results obtained for this scenario are of the same magnitude as the existing literature [21,49].

3.2.2. Scenario analysis

The evolution of the regulatory landscape for decarbonization introduces an element of unpredictability in forecasting future trends in

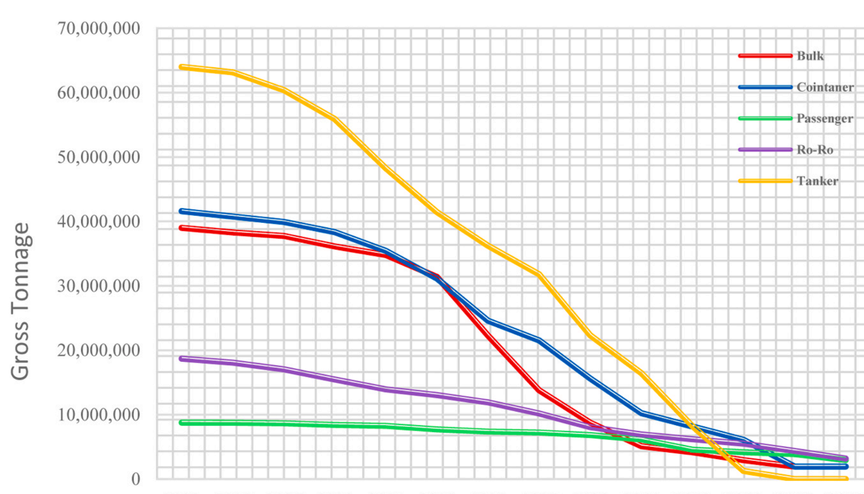

Fig. 7. Low scenario.

ship recycling. Two scenarios have been developed to reflect extreme behaviors in decision-making regarding ship recycling: the low scenario and the high scenario. Each scenario is closely linked to short, medium, and long-term decarbonization goals. These scenarios provide insights into how different approaches to regulatory compliance could shape the future of the maritime sector, introducing new projections on whether ships should continue to be demolished at the same age as in the past.

In the Low scenario, shipowners might prefer demolition over environmental retrofitting to comply with decarbonization objectives. This scenario suggests a strategic preference for demolition as a direct response to the initial phases of regulation implementation. A marked increase in demolition activities is anticipated, especially as regulatory pressures intensify between 2025 and 2035. The analysis predicts a complete reduction of the European fleet's gross tonnage by 2045, with 80% of the current fleet expected to be demolished.

Graphically represented in Fig. 7, the surviving prediction by ship type for the Low scenario indicate a steady increase in the demolition of all ship types over the years. A detailed analysis reveals specific trends for each category. For "Bulk" ships, a consistent decrease in gross tonnage is observed, with the demolition peak expected around 2030 and potential complete depletion by 2047. "Container" ships follow a similar trend, with their gross tonnage steadily decreasing and demolition peak estimated around 2032, suggesting possible exhaustion by 2045. Passenger ships show a gradual reduction in gross tonnage, with the demolition peak anticipated around 2040, potentially maintaining a limited presence until 2050 but with a significant decline. "Tanker" ships exhibit a marked decrease in gross tonnage, with a demolition peak around 2026 and expected complete demolition by 2045. "Ro-Ro" ships display a steady decrease in gross tonnage, with their demolition peak estimated around 2031, potentially remaining until 2040 but with significantly reduced presence. Tankers and Container ships are the most affected by this scenario, with their near-complete decommissioning expected by 2045.

In the High scenario, a continuous process of refurbishing is simulated to extend the ships' operational life and comply with short, medium, and long-term regulatory objectives. Here, shipowners might favor upgrading to meet standards rather than opting for demolition. This scenario represents a preference for retrofitting and life extension over demolition, depicted in Fig. 8.

The GT trend of ships shows a consistent pattern with a slight decrease until 2038. Bulk ships are most impacted by this scenario, expected to reach their demolition peak between 2042 and 2048, suggesting a near-total dismantling of this category post-2050. Container ships also experience a significant decline, with their demolition peak anticipated in 2039 and 2045, respectively. Tanker ships maintain a stable trajectory until 2038, followed by an intensification of demolition in subsequent years. For Ro-Ro ships, a steady course is observed until 2038, followed by a decline. Passenger ships experience a less marked decrease, with the most intense demolition year being 2043, further intensifying in subsequent years. The outlook until 2038 shows a contained decrease in overall gross tonnage, but more marked variations emerge in different ship types afterward, with demolition peaks concentrated in specific periods for each category.

The High scenario describes a different trajectory where shipowners initially opt for updates and retrofits to meet decarbonization goals up to 2030. This approach indicates a willingness to invest in improving ship performance to achieve short and medium-term objectives, delaying the decision to demolish. However, as the industry approaches long-term decarbonization goals, a shift towards an increased rate of demolition becomes apparent. Consequently, after 2040, a more pronounced trend of demolition emerges.

Table 3
Frequency Demolition European Gross Tonnage to 2050.

Year	*Low scenario (GT)*	*Weibull Scenario (GT)*	*High Scenario (GT)*
2025	1.525.908	1.085.847	401.508
2026	2.499.573	1.576.733	522.060
2027	2.454.063	1.212.897	986.070
2028	4.644.182	1.226.216	1.071.049
2029	4.881.614	1.402.287	1.648.577
2030	5.528.926	1.516.163	1.160.039
2031	7.018.080	2.500.509	1.138.466
2032	7.248.990	2.836.703	1.882.442
2033	8.695.522	2.979.575	1.513.426
2034	10.066.577	3.543.133	1.963.007
2035	10.029.835	4.606.723	1.572.342
2036	10.003.123	5.872.830	1.667.509
2037	9.777.539	7.181.398	2.732.183
2038	9.314.016	8.154.453	3.383.877
2039	8.754.727	10.230.229	4.610.313
2040	7.993.079	11.734.058	5.301.482
2041	7.076.603	12.461.538	7.740.462
2042	6.267.703	12.436.361	9.217.910
2043	5.563.908	10.138.097	9.986.930
2044	5.192.536	8.400.409	11.093.761
2045	4.254.509	8.061.239	11.442.012
2046	3.228.122	7.616.249	11.166.527
2047	3.328.172	7.292.492	10.324.986
2048	768.611	6.578.023	9.418.827
2049	1.051.001	6.067.068	7.964.988
2050	939.158	4.550.410	6.882.999

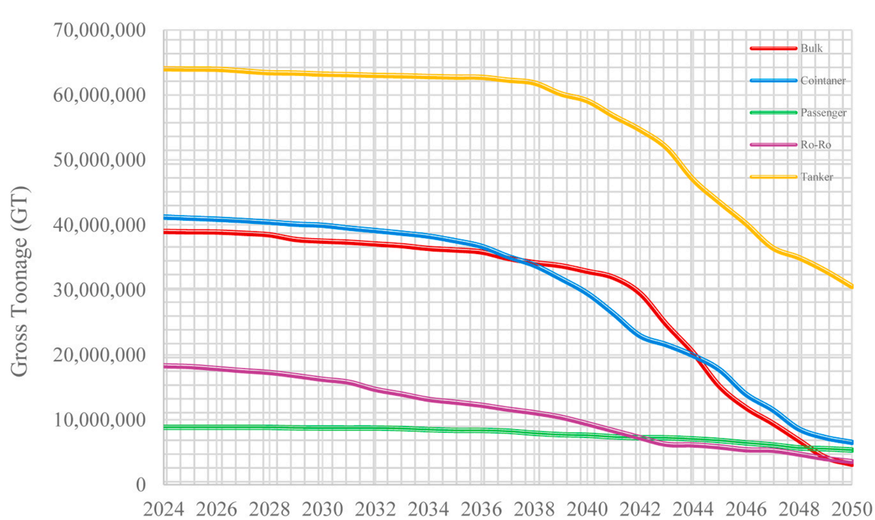

Fig. 8. High Scenario.

3.3. Frequency European ship recycling

In Table3, the total GT to be demolished in the coming years is depicted, divided into the three hypothesized scenarios. Analysing the trend over time, some interesting trends are noted. The Table 3 shows that the total GT to be demolished is expected to increase significantly in the coming years.

The Low Scenario shows a steady increase in demolition activities until 2036, followed by a modest decrease in the following years. It starts with a value of 1.525.908 GT to be demolished in 2025, recording a significant increase until 2034, which turns out to be the year with the maximum demolition peak for this scenario. Within two decades, just over 150 million GT could be demolished. After the peak of 2034, the following years show a slight decrease, reaching the minimum value in 2048 with 768.611 GT to be demolished.

The Weibull Scenario is distinguished by a more significant volume of demolitions than the other scenarios, presenting an unstoppable growth until 2043. This trend confirms that over the years, this scenario is expected to demolish a quantity of Gross Tonnage (GT) higher than the other scenarios, accentuating this trend with a marked acceleration between 2030 and 2043. Starting from an initial value of 1.085.847 GT to be demolished in 2025, a gradual increase was recorded culminating in the maximum peak in 2041, reaching 12.461.538 GT. An average annual increase of 8% is expected in the demolition activity during the period of greatest intensity. After the peak, a stabilization phase is observed in the following years, indicating careful and thoughtful management of demolitions. However, it is essential to emphasize that even in the periods after the peak, the GT to be demolished remains significant, suggesting a persistent demolition activity of ships in the post-peak phases.

The High Scenario reveals an evolution of demolitions that begins to intensify from 2038 and culminates in 2045 with a peak of 11.442.012 GT. This highlights a distinctive perspective, differentiating itself from the previous scenarios. Despite the peak occurring in 2045, it is interesting to note that the demolition activity in this scenario maintains a significantly high trend even after 2050.

4. Discussion

In this section, it is aimed to discuss the findings derived from the study on the future trends of European ship recycling, with a specific focus on the implications and limitations inherent to the methodological approach utilized. Although precise estimates and updated insights have been provided, crucial for grasping the future dynamics of the European fleet in anticipation of the next SRR revision, it must be acknowledged that there are certain intrinsic limitations to this research. Firstly, the selection of the sample is based on a current depiction of the European fleet, without considering possible changes in flag registration that could significantly affect the outcomes. Additionally, among the expected revisions of the SRR, there is the potential extension of its scope to encompass ships from shipping companies operating within European territory, irrespective of their flag. This regulatory amendment could considerably widen the number of ships subject to the SRR provisions, impacting future projections related to European ship recycling and potentially resulting in an underestimation of the findings. Secondly, a preference has been given to the age of ships, overlooking other factors that could play a pivotal role in decisions regarding ship recycling. Variables such as trends in maritime traffic, freight rates, operational cycles of ships, rates of investment aimed at enhancing the technological and environmental aspects of units, the introduction of new constructions equipped with advanced technologies, inflationary dynamics, fluctuations in the prices of raw materials, and the costs of emissions have not been considered. This methodological choice may restrict the comprehension of the numerous variables that influence the decision to demolish a ship, thereby offering a potentially partial view of future trends. However, it is essential to acknowledge that the intent of the study was to capture a current snapshot of the situation, updating estimates based on the information and conditions available at the time of analysis. The consideration of these limitations does not lessen the value of the contribution but underscores the importance of adopting a flexible and adaptive approach in subsequent research. As the economic, regulatory, and market context evolves, updating estimates and models to reflect the latest conditions becomes crucial. This will enable the provision of more accurate and pertinent perspectives to stakeholders in the maritime sector, thus supporting more effective strategic planning and informed decision-making regarding the future orientations of the SRR.

In the light of the research questions, the surge in the trend towards ship demolition appears inevitable, regardless of the scenario under consideration. The initial analysis was centred on the Weibull scenario, which facilitated an examination of the historical behaviour of ships, utilising this model to assess the probability of demolition based on historical data. This methodological approach has provided a robust empirical foundation for understanding past trends and served as a starting point for the development of further projections. From the Weibull analysis, various probabilities concerning the future of the naval fleet emerged, enabling the formulation of two distinct scenarios based on decarbonisation objectives: the low scenario and the high scenario. These scenarios represent hypotheses on how the behavioural decisions of shipowners may vary in response to environmental pressures imposed by policymakers, outlining two possible pathways for the future of ship recycling. The low scenario is predicated on the assumption of a minimal response to decarbonisation targets, where European shipowners might opt for ship recycling rather than engaging in costly modifications to comply with new environmental regulations. This trend reflects a short-term perspective, with an acceleration of demolitions anticipated between 2025 and 2035, coinciding with the implementation of various short- and medium-term regulations. On the other hand, the "high" scenario envisages a more proactive reaction from shipowners, who strive to extend the operational lifespan of their ships through technological adaptation and innovation. This scenario suggests a more significant commitment towards sustainability, although it still forecasts an increase in demolitions in the long term, due to the advanced age of the current fleet and the intrinsic challenges in prolonging the operational life of ships beyond their expected life cycles. The Weibull scenario, reflecting the past behaviour of demolition, provides an intermediate vision, highlighting a gradual but significant trend towards an increase in demolitions over time, with notable peaks between 2035 and 2049.

The results obtained can be interpreted under an additional perspective, namely, in terms of the quantity of future material available. According to K. A. Hossain, [24], a ship can be recycled up to 95–98% of its gross weight, with steel being the major component, accounting for nearly 80% of the materials present [31]. This data underscores the significance of ship recycling as a substantial source of raw materials. Steel and other recovered materials represent a critical component for the EU's industrial policy, being at the heart of key industries such as construction, automotive, transportation, and energy [15]. The ability to recover and recycle steel scrap from ships offers a significant opportunity to reduce dependence on raw material imports and to enhance the sustainability of the European steel industry. Since only equal access to metal scrap will ensure the long-term competitiveness of European steel producers and prevent an increase in carbon emissions [11], as for every ton of steel scrap used in place of virgin steel, there is an average reduction of 1.7 tons of CO_2 emissions [58].

The steel industry ranks second in terms of energy consumption, absorbing 7% of global energy production, and first in terms of CO_2 emissions [64]. Approximately 73% of global steel is produced through primary processes, where iron ore is transformed into commercial steel through complex metallurgical processes in a blast furnace (BF) and a basic oxygen furnace (BOF), the remaining 27% is obtained from recycling scrap steel, which is melted and treated in an electric arc furnace (EAF) to produce commercial steel. In 2023, the European Union produced 136 million tons of steel, a quantity expected to increase, with almost half derived from recycled steel [12]. Scrap steel can be recycled infinitely, and the shipbuilding sector represents a global source of high-quality scrap, highlighting the interdependence between the shipbuilding and steel industries. Steel used in shipbuilding must possess specific qualities and properties to withstand the load of structures and transported cargo, ensuring navigability. The steel used in shipbuilding must be approved by a classification society based on general engineering applications, as well as the mechanical and chemical properties of the material [35]. However, due to concerns about the quality of steel with a high content of recycled material, most steel for shipbuilding is currently produced through the BF-BOF process. Challenges associated with controlling impurities in scrap steel production can compromise the final product and exclude it from shipbuilding use [37]. Additionally, current decarbonization policies in hard-to-abate sectors, such as shipping or steelmaking, emphasize the role of recycled steel in reducing emissions, promoting more eco-friendly steel production. However, the increased use of recycled steel will inevitably lead to an increase in demand, reducing the availability of scrap over the decade and altering the global supply chain. In light of our findings, in the coming decades, the increase in demolition activity will be directly correlated with the increase in availability of materials from recycling activities.This scenario foresees increased opportunities for integrating circular economy practices, allowing for more sustainable resource management in the steel industry. Implementing targeted strategies to strengthen recycling collection and processing in Europe would not only reduce dependence on virgin raw materials but also contribute to reducing the environmental impact associated with iron ore extraction and processing. Furthermore, greater availability of recycling steel could incentivize technological innovation in processes by expanding the possibility of using this material in steel-intensive industries. By integrating forecasts on future trends in ship demolition with the current steel production in the European Union and standardizing the percentage of recovered steel, according to the studies by [31] it is anticipated that the recycled steel obtained from ship demolition could contribute, in the coming years, between 1% and 8% to the annual European steel production, assuming that steel production levels remain unchanged.

The valorization of recycled steel from dismantled ships aligns perfectly with the objectives of the European Green Deal, which aims to make the EU a climate-neutral continent by 2050. Therefore, the sustainable management of steel obtained from ship recycling becomes a strategic issue for the European Union, within the framework of its broader sustainability and material self-sufficiency goals. Given the high recyclability of ships, this paves the way for strategies that not only aim to reduce environmental impact through decarbonization but also to optimize the lifecycle of material resources, to have more control over downstream waste management, and to create specific hubs for the collection and transformation of materials. For the near future, it will be necessary to study the actual quantity and its economic value from a circular economy perspective. Moreover, considering the economic implications of these practices in a context of rising raw material costs and changing macroeconomic trends that influence the decision to demolish will be crucial.

Our findings demonstrate how the coming decades will be characterized by a progressive increase, with ever higher rates, of the demolition of the European fleet. Before the introduction of the regulation, the European Commission estimated that the demolition capacity in the EU and other OECD countries was barely sufficient [13,18]. However, more recent studies further emphasize the deficit of demolition capacity considered acceptable for the near future. The most recent investigations highlight more sharply the lack of resources in the demolition sector, outlining a framework in which the current capacity is not only barely sufficient, but even inadequate to meet the expected [19]. By comparing the results of the study with the current recycling capacity, a significant gap in the ability to manage the demolition of ships in the coming years clearly emerges. In Fig. 9, the comparison with the current authorized capacity of the lists is depicted, which corresponds to 1.05MLTD, and the demolition frequency of the Weibull-scenario. The comparison was made using the LTD unit of measurement, the conversion of GT forecasts into LTD was carried out through a parameter suggested by [14], while the capacity of the facilities was considered constant over time.

The current capacity of European shipyards authorized for demolition appears to be more than adequate until 2030. However, analysing the years after that, we can see a progressive increase in the gap between the approved recycling capacity and the future estimate of ships destined for recycling. From 2031 onwards, the approved capacity is insufficient compared to future estimates. The period from 2035 to 2042 emerges as the time frame of greatest pressure, during which there is a constant increase in the gap between the approved capacity and the future estimate of ltd to be scrapped. The most significant gap between the approved recycling capacity and the future recycling estimate occurs in the year 2041, with a significant difference of 7.02 MLtd. It is in this time interval that the management of European ship recycling will have to face significant challenges. In a broader context, the analysis indicates the need for waste management policies and practices to be prepared to face a sudden increase in ship recycling, regardless of the future scenario.

The European Union is constantly committed to assessing new recycling capacities both within and outside the EU. This means that the capacity will increase, the uncertain factors are represented by the mode

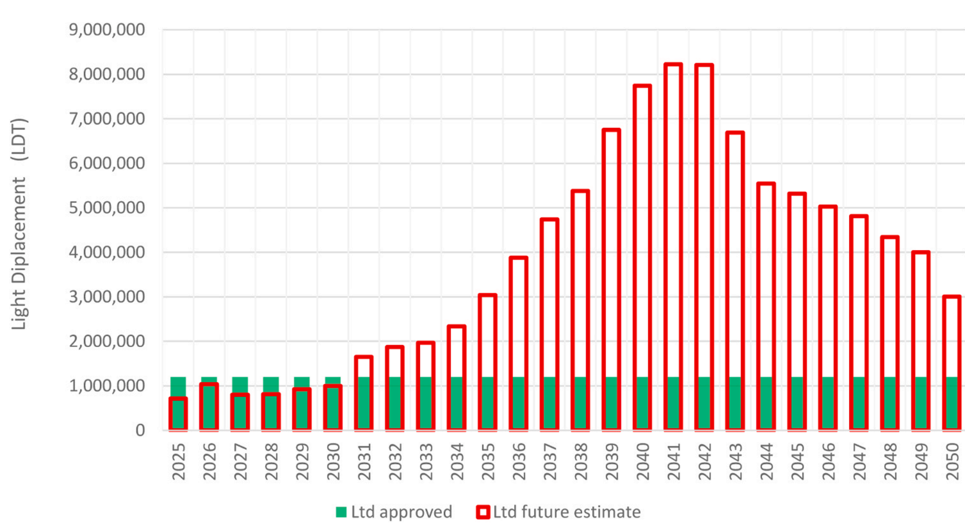

Fig. 9. Comparison of current recycling capacity of European shipyards and future recycling estimation.

of demolition and the place of implementation. A preliminary hypothesis to consider is the fact that the European Union has a significant number of shipyards suitable for high specialization activities such as shipbuilding and ship repair [4]. To identify the latent potential of the shipyards, a careful assessment of the technological and regulatory level needed to adapt such shipyards to this specific activity will be necessary. Another hypothesis <close to home> concerns the search for possible demolition yards in the Mediterranean area, which are equipping themselves for this activity [2], but solid cooperation will be necessary, taking the form of bilateral agreements for the sharing of standards and technological knowledge [63].

However, as highlighted by Sarraf et al., [54], there are economic and dimensional constraints in assigning the correct demolition shipyard to various types of ships. Continuing in this sense, an effective strategy could consist of diversifying the areas of demolition based on the types of ships and the technologies required for their demolition. An additional aspect to consider is that the economic value at the end of a ship's life varies depending on the type [61]. Special attention should be paid to certain types of ships, especially those types that the EU is a pioneer in manufacturing. It will be essential to conduct thorough studies on profitability and specific operating costs for each category of ship, taking into account various factors, including the presence of valuable recyclable materials, the structural complexity of the ship, and the technologies required to address the specific challenges of demolition.

The evaluation of the SRR must primarily focus on its alignment with the objectives of the European Green Deal and the Circular Economy Action Plan, examining its application, effectiveness, and identifying gaps in implementation. A key aspect of the review will be to reconsider the regulation's scope, ensuring it applies based on the actual beneficiaries rather than the ship's flag state. The regulation should be enforced for at least two years following the sale of a ship to prevent malpractices and better identify the actual owner. Additionally, the review should tackle the certification and authorization process for non-EU shipyards, which are undergoing revisions to align with the HKC guidelines. The EU will have to determine which non-EU locations are acceptable for meeting the growing demand for ship recycling.

Implementing the HKC could lead to improved access and authorization conditions, thereby raising global ship recycling standards and benefiting the international community. However, experts and NGOs have raised concerns that the HKC does not thoroughly address many critical aspects of ship recycling, such as the creation of hazardous material inventories, the development of ship recycling plans, the authorization of recycling facilities, and the establishment of procedures to mitigate adverse impacts on human health and the environment. The HKC does not prohibit or discourage beaching methods, nor does it mandate that shipowners decontaminate ships of hazardous waste before recycling. It merely requires the minimization of cargo residues, fuel, oil, and onboard waste, and does not ban the transfer of ships containing asbestos, polychlorinated biphenyls (PCBs), or other hazardous materials to locations incapable of environmentally sound waste management. With the introduction of the HKC, an additional challenge will be resolving conflicts with the Basel Convention, which regulated the control of transboundary movements of hazardous wastes and their disposal, including prohibiting recycling EU-flagged ships in third-country facilities. Considering these insights, from a policy maker's perspective, the approach to the forthcoming SRR evaluation should be global in scope, maintaining its stringent standards to elevate non-EU thresholds.

In the coming decades, the ship recycling sector will be influenced by several factors, including regulatory changes at both global and European levels, fluctuations in the demand for secondary raw materials, and environmental pressures to reduce carbon emissions. The findings indicate a rapid increase in the number of ships being sent for demolition from the European fleet. Through the future revision of the SRR, Europe aims to play an active role in this activity and make a leap towards a possible market share. In this context, developing a scrap industry on a European scale and promoting cross-sector cooperation between steel producers and consumer industries are viable approaches to maximize the recovery and use of secondary raw materials. Envisioning a green market for the naval recycling sector translates to a market where optimizing the management of secondary raw material flows, according to an "end of waste" approach, encourages the development of business-to-business exchanges for the supply of secondary raw materials to improve upstream design and downstream recovery for new industrial processes. The idea of developing an internal European market for the naval recycling sector includes promoting a business-to-business market for the supply of secondary raw materials. This market should support innovation in upstream design processes and efficient downstream recovery, contributing to new industrial processes that comply with stringent environmental standards, also favoring the decarbonization of the economy, promoted by international and European policies. To effectively stimulate this transition, the European Union should strengthen existing regulations and introduce new economic incentives, improve the traceability of materials to maximize end-of-life value, enhance dialogue and communication among all parties, and establish coordination mechanisms to increase connectivity and information among operators. It will be appropriate to stimulate a European network for the maritime sector to catalyze the development of new commercial opportunities and technological innovation, promoting collaboration between industrial sectors within Europe. It is essential to implement hubs dedicated not only to naval demolition operations but also to the treatment, recovery, and reuse of materials present on ships.

5. Conclusion

This study aims to deliver precise estimates and updated insights into the future trends of European ship recycling. The impetus for this research stems from the imperative to enhance understanding of the impending demolition processes within the European fleet, also taking into account the imminent evaluation of the SRR. The particularly significant aspects of the research include the correct attribution of the right weight to the average life of each type of ship. This approach allows an in-depth analysis of the actual dynamics of the ship life cycle. A crucial aspect of this study is the meticulous collection of sample data, significantly contributing to a detailed portrayal of the current state of the European ship fleet. In addition, the research has distinguished itself by the analysis of three distinct scenarios that predict the future trend of European naval demolition. This analysis has hypothesized three different behaviours in the demolition decision, considering the evolving dynamics of international environmental regulations and the flexibility of demolition decisions. The research aims to address the concerns raised by [49,56] regarding the calculation of future demolition, considering the possible upcoming changes in environmental regulations that could bring forward the demolition of the fleet before expected. This perspective aims to provide a more complete and up-to-date picture, allowing a more accurate assessment of the future demolition of the EU ships fleet**.** The results of our study predict that global demand for ship recycling is likely to increase in the coming decades with high demolition cycles between 2036 and 2045. In general, it is expected that the current ships in service will be gradually removed at increasingly accelerated rates, regardless of the scenario involved. From 2030–2047, all scenarios show a marked increase in demolition activity, with an average annual rate between 6% and 9%, foreshadowing a significant expansion in the European naval demolition sector. There are significant differences in the volumes demolished between the various scenarios considered. The sum of the annual results reported in Table 2 indicates that 2042 is configured as the year with the greatest demolition activity.

This research has revealed critical insights into the future demolition trends of the European ship fleet, shaped by a complex interplay of environmental regulations and shipowner decisions. The anticipated increase in ship recycling over the next two decades calls for an expanded and more inclusive recycling approach within Europe, highlighting the importance of involving a diverse range of stakeholders. Moreover, the feasibility of ship dismantling in Europe, transcending mere recycling chain capabilities, is intricately linked to a broader spectrum of factors including national and international policies, and practical constraints such as shipyard capacities and technological advancements. This necessitates an all-encompassing approach to recycling operations, ensuring compliance across the entire lifecycle of a ship. The integration of circular economy principles and investment in advanced technologies and innovative recycling strategies, as advocated for in the upcoming SRR revision, are essential not only for operational efficiency but also for aligning with evolving environmental and market demands. These advances are crucial for the maritime sector's transition towards greater sustainability. Beyond the European context, this study's findings have significant global implications, particularly in the realms of maritime practices and environmental stewardship. The economic ramifications of these trends are profound, potentially influencing the maritime industry's economy and global trade dynamics. Moreover, the environmental impact of ship demolition and recycling practices, and their alignment with sustainable practices, is a matter of global environmental concern. From the results, it is possible to understand the future quantity of materials that will emerge from the recycling activity, and future research will focus on how the potential of end-of-life ship materials can be transformed into a valuable resource for the supply of circular markets. This aspect significantly supports the decarbonization process of the economy, particularly in strategic sectors such as the steel and shipping industries. In this context, it is essential to develop alternatives such as the identification of components that can be used as spare parts for reuse or recovery. It will be crucial to emphasize the creation of a European internal market that facilitates the supply of secondary raw materials, thus contributing to the implementation of a broader and integrated decarbonization strategy in line with the green industrial policy goals of the European Union. Considering these findings, specific policy recommendations are proposed, including the need for more stringent environmental regulations, incentives for adopting green technologies in ship recycling, and international collaboration to standardize practices. While this study provides comprehensive insights, it also acknowledges certain limitations, such as the variability in data quality and the rapidly evolving nature of maritime technologies and policies. Future research should therefore focus on these areas, further exploring the technological advancements required, the potential changes in policies, and the need for enhanced data collection and analysis. Ultimately, this research not only contributes significantly to the understanding of ship recycling within the European context but also serves as a foundational work for future studies aimed at fostering sustainable practices within the global maritime industry. The study's implications extend beyond the immediate scope, offering a blueprint for environmentally responsible and economically viable maritime practices in the era of global sustainability.

CRediT authorship contribution statement

Mattia Gianvincenzi: Writing – review & editing, Writing – original draft, Visualization. **Enrico Maria Mosconi:** Writing – review & editing, Writing – original draft, Validation, Supervision. **Francesco Tola:** Writing – original draft, Methodology, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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