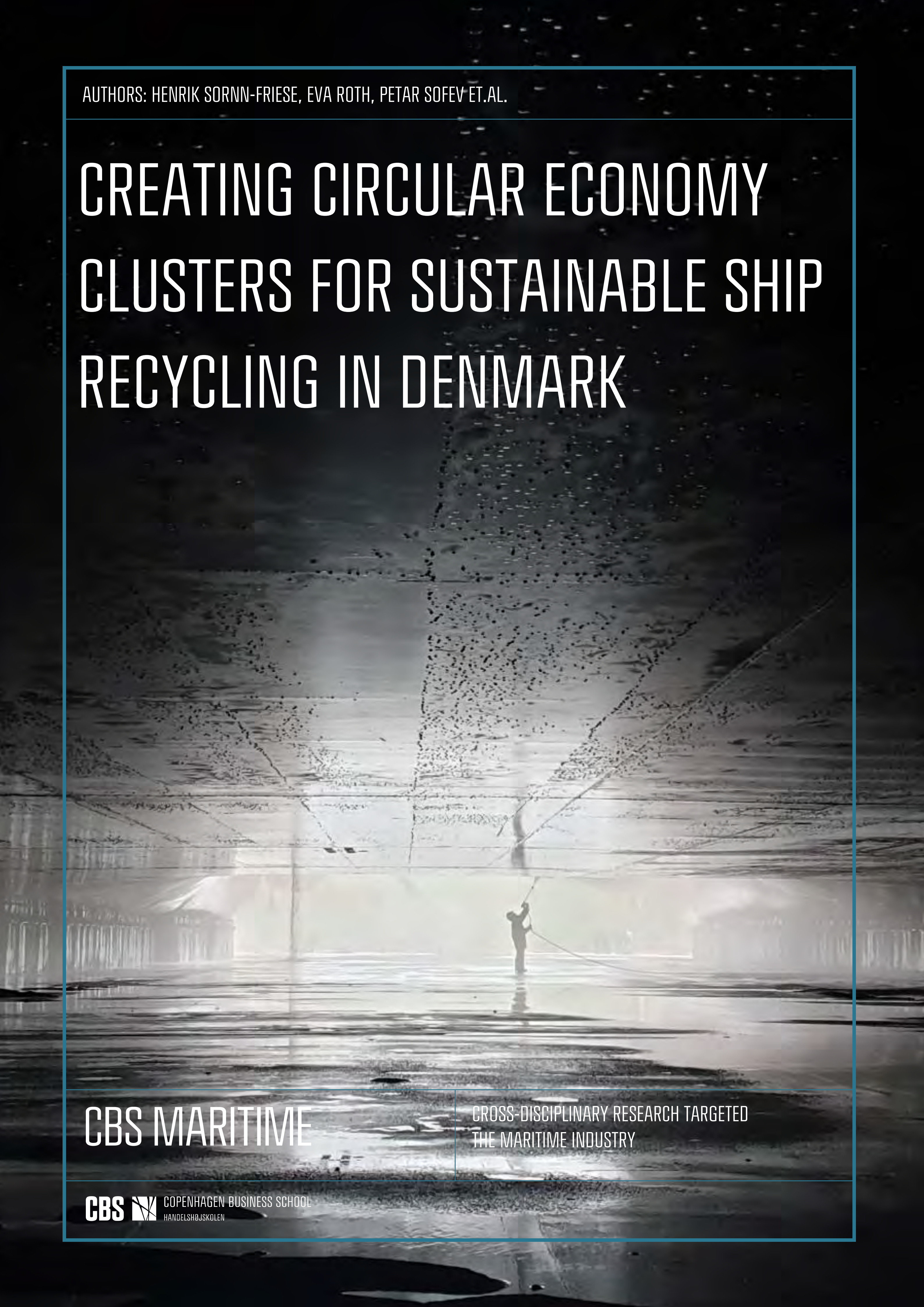
AUTHORS: HENRIK SORNN-FRIESE, EVA ROTH, PETAR SOFEV ET.AL.

CREATING CIRCULAR ECONOMY CLUSTERS FOR SUSTAINABLE SHIP RECYCLING IN DENMARK



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CROSS-DISCIPLINARY RESEARCH TARGETED
THE MARITIME INDUSTRY

CBS COPENHAGEN BUSINESS SCHOOL
HANDELSHØJSKOLEN

ATUHORS AND PROJECT PARTICIPANTS

Henrik Sornn-Friese, Eva Roth, Petar Sofev, Brooks Kaiser, Knud Sinding, Hanna Vágsheyg, Andrea Eikås, Hedda Høivik, Kevin Langhorst, Frederik Trudsøe Larsen, Tobias Olsen, Mathias Dyrhol Paulsen, Bent Lange, and Frank Stuer-Lauridsen.

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SDU
University of Southern Denmark

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INTRODUCTION: BACKGROUND AND PURPOSE

Ships have a typical lifetime of 25-35 years before repair and refitting become uneconomical and they are taken out of service and sent for scrapping. This involves removing equipment, cutting down the ship, and to the extent possible reusing or recycling the construction and building materials (mostly steel, but also non-ferrous scrap such as aluminum, copper, silver); machinery, equipment and components (e.g., main engine and propulsion, electronics and navigation equipment); ship fittings and accessories (e.g., anchors, chains, lifeboats, nuts and bolts, windows and portholes); and furniture and accommodation. Most ship dismantling today occurs in South Asia – especially in Bangladesh, India and Pakistan – where it is cheaper and where there is a booming market for recovered steel as well as a lively brick-and-mortar market for the various recovered items. However, with the entry into force of stricter international ship recycling regulation there is increasing focus on the fact that the dismantling of ships must take place in a safe and environmentally sound manner. Historically, South Asian ship recycling facilities have been substandard, with severe negative impacts on workers' safety and the surrounding natural environment. However, it should be observed that over the past five or so years, there have been tremendous developments and upgrading of many of those facilities to meet international standards, as laid out in the yet to be ratified Hong Kong Convention.

As more rules are introduced in this area, we would expect to see a further growth in high-end offerings in developed economies and an upgrade process to a mid-range level for some of the yards in South Asia. As a general result, part of the industry is believed to move from Asia to Europe and thus create new market opportunities for European ship recycling yards and related companies (e.g., recycling companies, waste handling companies, scrap dealers) that can comply with the strengthened requirements. The Danish maritime industry would have the potential to benefit from this development and generate jobs and income, while at the same time raise safety standards and meet the increasingly complex sustainability requirements.

The project reported in this book aims to explore the feasibility of advancing the circular economy around end-of-life (EOL) shipping assets and circular business models for the maritime industry in Denmark through the formation of localized *ship recycling clusters* and the development of the broader *business ecosystem* for ships and ship technology. The project thus responds to and seeks to join two distinctive institutional developments, which have conceivably significant effects on shipping, ports and the maritime industry:

1. The current institutional changes in international *regulation of ship recycling*: the Hong Kong Convention (HKC), the European ship recycling regulation (EU-SRR), and the entering into force internationally of the Basel Convention's Ban Amendment, under which EOL ships are treated as hazardous waste.[1] HKC will likely increase the costs of recycling in the global south and thus reduce their cost advantages. In tandem with the EU-SRR, which is being increasingly tightened through economic instruments and backed by financial incentives and demands from investors, banks and cargo owners, this would likely create a stronger market for the recycling of ships in

1 The categorization of EOL ships as waste rests on complex legal and economic arguments and is subject to debate. For example, with still more recycling facilities in South Asia voluntarily complying with the provisions of the HKC it is a logical question whether the Basel Convention, the Basel Ban Amendment as well as the European Waste Shipment Regulation are still relevant (Jain, 2018). In the EU-SRR it is clearly stated that EOL ships do not fall under the EU implementation of the Basel Convention: "a ship subject to the alternative control regime throughout its life-cycle under this Regulation should not be subject to Regulation (EC) No 1013/2006. Ships neither covered by the scope of the Hong Kong Convention nor by this Regulation, and any waste on board of a ship other than operationally generated waste, should continue to be subject to Regulation (EC) No 1013/2006 and to Directives 2008/98/EC and 2008/99/EC of the European Parliament and of the Council, respectively" (CEC, 2013, preamble paragraph 10). On a more basic level one may even question the logic of technically considering a ship that sails under her own power, is legally manned, and holds a compliant Inventory of Hazardous Materials (HazMat) as "waste" (Bartlett, 2021).

Europe.[2]

Under the EU-SSR all ships over 500 GT flying a European flag must now be recycled at an EU approved recycling facility. There are now 43 approved ship recycling yards on this list (34 in Europe, eight in Turkey, and one in the United States) of which several are capable of recycling large vessels. Some South Asian yards have applied for listing, but so far unsuccessfully. The Basel Action Network (BAN) has asserted that with the EU and the OECD ratification of the Basel Convention's Ban Amendment in December 2019, the ship recycling yards in South Asia cannot legally be placed on the EU's list of approved ship recycling destinations (Ovcina, 2020). In addition, a bilateral EU agreement with a South Asian nation regarding shipbreaking exports could morally undermine the EU's aspirations for a European Green Deal (The Maritime Executive, 2020).

The evolving stricter international regulation of ship recycling has already led a number of leading international shipping companies to embrace policies that set increasingly higher ship recycling standards and to also live up to these policies.[3]

2. The accumulating of multi-level policy initiatives from the Danish government (Regeringen, 2018) and the EU (CEC, 2014; 2015) together with other incentives in *circular economy transition* prompts organizations in shipping, ports and maritime industry to respond by complying with new rules and to embrace new norms and expectations. The European New Green Deal is expected to further promote circular economy through new waste and recycling laws, among others, and accelerate the transition. Industry responses already include, among other things, investments in ship waste and ballast water reception facilities in ports; hazardous material inventories on ships; and reporting on vessel material and component use, as well as on discharges and emissions (e.g., Maersk's Cradle-to-Cradle Passport detailing 95 percent of all material and component use in Triple-E container ships). It furthermore includes rethinking business models and company strategies as the conventional "take, make and dispose", linear economy model of value creation deteriorates.[4] In addition to regulatory incentives there are recent examples of private incentives, such as the Ship Recycling Transparency Initiative (SRTI), promoted by international coalitions of companies and other stakeholders (e.g., Global Maritime Forum), as well as the Poseidon Principles and the Responsible Ship Recycling Standards (RSRS) for ship financing, and having the same effect of pushing the industry towards circularity.

The UK-based charity Ellen MacArthur Foundation (2013) has described the circular economy as "an industrial system that is restorative or regenerative by intention and design". It replaces the EOL concept with restoration, a shift towards the use of renewable energy, elimination of toxics, and the superior design of materials, products, systems, and business models. A key tenet in this interpretation is the replacement of the current linear flow of materials with more circular ones, so that resources can continuously perpetuate in the economy instead of being discarded as waste (Korhonen et al., 2017).

Presently, the notion of circular economy has transitioned into business and management, as the circular economy provides opportunities for companies to capture larger shares of profits in their industry, create competitive advantage, develop resilience and respond to grand business and societal challenges (De Angelis, 2020).

2 With the strengthening of international ship recycling regulations, it is conceivable that part of the market will move from the global south to companies in Europe that are able to comply with the stricter requirements. Because of its extensive experience in handling hazardous waste and the availability of a well-developed maritime infrastructure and qualified manpower, Denmark is generally believed to be well positioned in the competition for ship recycling, also compared to other European countries (see, for example, Niras, 2014).

3 The NGO Shipbreaking Platform monitors progress in international ship recycling practices and has recently published a list of such responsible shipowners (http://www.shipbreakingplatform.org/wp-content/uploads/2019/01/List-of-responsible-ship-owners.pdf).

4 As the World Economic Forum (WEF) has argued, we must even move away from recycling (a business-as-usual, linear activity) and instead invest in those activities that preserve materials (circular activities): "In a properly built circular economy, one should rather focus on avoiding the recycling stage at all costs" (please see, www.weforum.org/agenda/2019/11/build-circular-economy-stop-recycling/).

Interest in a "circular shipping industry" is growing (Rex and Sabroe, 2019; Van t'Hoff et al., 2021), particularly in consideration of the industry's accelerating decarbonization goals (SRTI, 2021). More generally, the principles of circularity and decoupling are key to achieving the Sustainable Development Goals (SDGs), as formulated by the United Nations (UN) in its sustainable development agenda towards 2030 (Sachs et al., 2019).

Our concern in the present study is not with the issue whether EU approved ship recycling yards offer enough capacity to meet the needs of European shipowners for recycling their vessels. This question has been raised by shipowner interest organizations (e.g., BIMCO and ECSA) and has sparked an intense debate with NGOs (e.g., Basel Action Network, European Environmental Bureau, Greenpeace, and Ship Breaking Platform) and recyclers (i.e., European Ship Recyclers Group). We are indifferent to this question. Instead, we adopt the perspective of the broader maritime sector (in Denmark) to which the regional regulation imposed by the European Commission, along with the growing policy interest in circular economy, presents an opportunity, as also early on recognized by some Danish ship recycling and ship repair yards (Høg, 2013). Our concern is in line with what the European Economic and Social Committee has previously observed:

"There is sufficient capacity in the EU which is no longer used for building and repairing ships but which is suitable for the decommissioning and recycling of ships. This fits in with the EU's goal of developing into a sustainable recycling society with a circular economy in which waste is turned into raw materials by means of a sophisticated and fine-meshed recycling system. In view of alternately volatile and steadily rising raw material prices and high unemployment in a number of European Member States and the fact that a number of oil rigs in EU waters are reaching the end of their economically viable life, this could be highly profitable for Europe as a whole. Moreover, an industry specialising in recycling end-of-life ships would be an opportunity for the development of maritime areas and training of both young people and the unemployed in emerging skills" (EESC, 2016, p. 9).

The largest proportion of a ship's weight consists of recyclable materials such as steel and other metals (Milios et al., 2019), promising to provide a continuous flow of raw materials in the near future. Furthermore, the prospect of shifting the current ship recycling industry towards the framework of a circular economy holds additional benefits, for example through a larger share of remanufacturing activities (Jansson, 2016). As remanufacturing retains embedded energy and ideally provides products with the same or even higher performance as new ones (Wahab et al., 2018) it could make the process of handling EOL ships more profitable and increase international competitiveness.

A relocation of ship recycling to domestic countries can thus provide economic advantages, while at the same time assuring a more environmentally safe and sustainable dismantling process. The present business environment for recycling of EOL ships does not present a level playing field for Danish companies vis-à-vis South Asia and may not be driven by market forces without strong enforcement of the European ship recycling regulation (EU-SRR) leading to lower prices to shipowners of EOL ships. The circular economic models as well as the internalization of human safety and environmentally safe practices in the business models in the EU may further increase the profitability of the ship recycling yards in Denmark, which have already implemented safety and environmental sound practices.

Our focus is on exploring the prospects for a circular business ecosystem for EOL shipping assets in Denmark. The number and diversity of ports in Denmark, the historical development of Danish shipyards, the standing of Danish maritime industry and the long history of steel and other materials recycling in Denmark imply substantial potential (resources and strategic positioning) for promoting and leading a maritime-focused circular economy model in Denmark. The transition of ship recycling areas into innovative circular economy industrial clusters and broader business ecosystems would be a vital step in the further development of the maritime industry in Denmark, while at the same time optimizing the use of resources in shipping and ports.

The report is structured in eight chapters. The next chapter lays out the conceptual foundation for the study, covering the entire lifecycle of ships and outlining the system of actors and types of exchange taking place in the different phases of the lifecycle and potentially allowing for what we call circular economy interventions. Particular emphasis is put on the end-of-life (EOL) phase of the ship lifecycle, and especially on ship recycling as a clustered activity typically taking place in port areas. In chapter 3, we describe the data and methods used in the study: we rely on a mix of methods and many types of data, and our study is in that sense wide-ranging and largely exploratory. Chapters 4-6 cover the main empirical findings concerning ship recycling in Denmark, including the ship recycling capabilities of Danish yards and recycling companies, the fleet of near-EOL ships potentially feeding into the ship recycling industry in Denmark, and the particulars of the market for materials and parts recovered from ships in the recycling process. In chapter 7, which is a far more provisional investigation, we change the focus to circular economy business models in the maritime supplier industry, focusing on providing examples of circular approaches and recent developments among Danish marine equipment manufacturers and service providers. Finally, in chapter 8 we summarize the study's findings and offer some reflections regarding the creation of circular economy hubs for sustainable ship recycling in Denmark.

CONCEPTUAL FOUNDATION

In the context of circular economy, ship recycling becomes a full lifecycle concern and not merely an end-of-life decision. Figure 1 illustrates the product lifecycle stages of a ship, including important economic exchange and other key interactions, and serves as broad conceptual basis for the present study. A ship is a moveable capital good built for transporting people or goods at sea. It goes through a product lifecycle with distinct phases: from ship design and construction over operational life to end-of-life (EOL).[5] There can be different reasons for a shipowner to decide when to scrap a ship. It most cases, the decision is dictated by changes in the freight market, but there can be other reasons, such as irreparable damages caused by collision, grounding, onboard fire or other major accidents. Ships may also be sold by a bank or another trustee in case of a shipowner bankruptcy.[6]

An EOL ship becomes the material input in the production function of the ship recycling industry (Jain et al., 2017). Ship recycling is a distinct phase with value-adding activities of dismantling, sorting, preparing and reusing of parts (e.g., materials and items and even some hazardous wastes such as slop oil or asbestos)[7], and the recovered parts can be viewed as the material output of the ship recycling industry. The demand for recovered parts depends on price and quality as well as local consumption (or options for exporting), particularly of steel. In certain cases, the ship recycling yard may also resell a ship without dismantling it.[8]

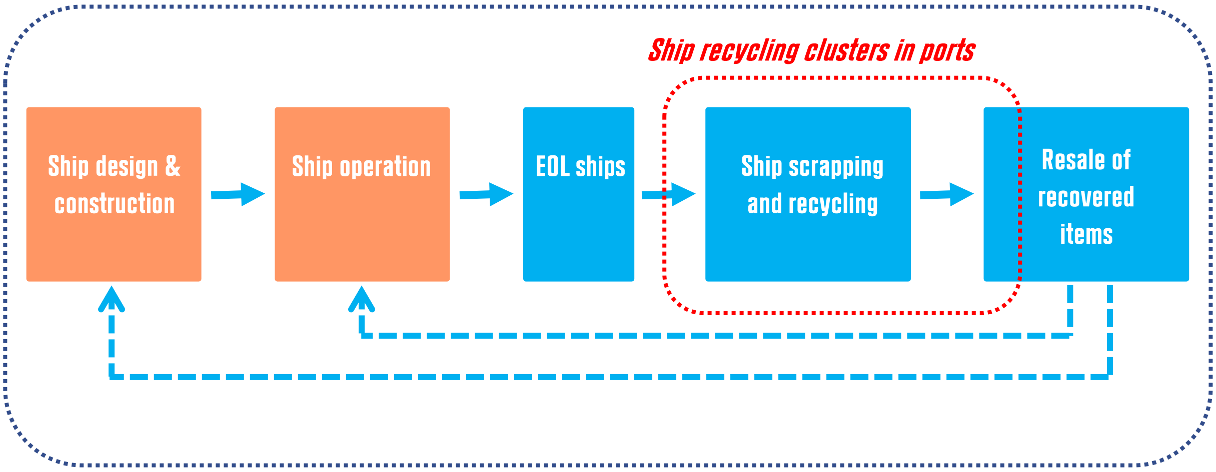
5 For the sake of simplicity, we have chosen to exclude the pre-construction stage of raw material extraction, processing and production, although this phase represents significant depletion of natural resources and also yields significant harmful emissions (Gibson et al., 2017). It is obvious that with increasing reuse of materials, components and equipment the need for raw material extraction, processing and production would decrease.

6 In 2013, the Danish Fornæs Ship Recycling yard purchased the 10,000 GT ROPAX ferry RG I (IMO no. 8306577) from Finnish RG Line Oy AB, which had filed for bankruptcy. It was the largest vessel purchased by the yard until then, and the ferry was in fact in such good condition after a major refit carried out in 2005 that Fornæs Ship Recycling initially wanted to resell it.

7 Although asbestos has generally not been used in ships since 1979 it can still be found on ships registered within the EU, such as Germany (https://ww1.issa.int/events/external/Maritime2021) or Denmark (Sturlason, 2021), mostly as a material used in packaging and sealing. Asbestos is usually sealed and buried in landfills, but it can in fact be recycled into glass or ceramics and reused for other purposes (e.g., in roads or construction materials). Other types of hazardous waste, such as, slop and residual fuel oil or some heavy metals can also be profitably recovered and reused. For example, with the use of specially designed heat exchanger and recovery systems, residual fuel oil can be turned into high-value diesel products at low recycling cost.

8 As a recent example can be mentioned that Fornæs Ship Recycling in March 2019 resold the old ferry KANALEN II (IMO no. 7532090), which it had otherwise purchased for recycling.

Figure 1: A conceptual framework of lifecycle phases and coordination for EOL ships



Each phase of the product lifecycle of ships is inhabited by a specific set of players, with their individual interests and capabilities (Hsuan and Parisi, 2020), and subject to market dynamics that are both phase-specific and interdependent. More specifically, international shipping is characterized by four ideal markets: the newbuilding market, the freight market, the sales and purchase market, and the demolition (or, recycling) market (Stopford, 2009).

For the whole system to become circular there must be loop-closing both within and between the phases in the sense that scrapped parts re-enter as material input in further production (e.g., in repair or retrofitting of existing ships, in the building of new ships, or in producing other goods), thus enhancing material efficiency. Loop-closing can take place across activities that are all located within specific and narrow geographical boundaries, such as localized industrial clusters. Clusters bestow positive economies of scale in personal ties and inter-organizational networks (a.k.a., positive externalities). Such benefits arise because networked firms within clusters are able to lower coordination costs through social trust, while firms located outside of the clusters must rely on more costly coordination mechanisms (Lorenzen, 2001/2002) such as contracts, incentives, or monitoring.

Loop-closing may also take place as the interaction of activities that are neither restricted within narrow geographical boundaries nor as constituents of a particular supply chain but somehow interdependent through wider industrial systems. The latter can be analyzed from different perspectives, including technological production and innovation systems (Carlsson and Stankiewicz, 1991); national innovation systems (Lundvall, 1988; Sornn-Friese, 2000); sectoral innovation systems (Breschi and Malerba, 1997); or broader business ecosystems (Moore, 1993; Iansiti and Levien, 2004a; Jacobides et al., 2018).

We believe that the business ecosystem is a particular useful perspective for understanding the dynamics of the entire system as it provides a lens for assessing the role of the individual company (or, organization) as a recipient and as driver in the development of the system, and for seeing strategy “as ecology” (Iansiti and Levien, 2004b). In particular, keystone organizations play a crucial role in business ecosystems. Fundamentally, they aim to improve the overall ecosystems by providing a stable and predictable set of common assets that other organizations use to build their own offerings. According to Moore (1993), such organizations may change over time, but the function of the ecosystem leader is valued by the community because it enables business ecosystem members to move toward shared visions to align their investments, and to identify mutually beneficial roles.

In the context of circular economy around ship recycling, it is an open question who can be such keystone organizations. Clearly, a port authority may act as keystone by *creating and sharing value* within the business ecosystem for ships. But other types of organizations can be keystones in such a system by creating the services, tools, or technologies that other members of the business ecosystem can use to enhance their own performance. Marine consultants may develop tools for assessing the carbon footprint of marine equipment, which could be a first step for an original equipment manufacturer of marine components or systems to develop circular business models, and recycling and waste management companies may develop platforms in collaboration with customers and partners for collection, upgrading and recirculation of used materials and components in closed-loop systems (the product exchange program “Re-Made to matter”, discussed in chapter 7 of this report, may be an example of that). Several of the recycling and waste management companies active in Denmark, such as, Fortum Waste Solutions and Stena Recycling, focus on closing circular economy gaps and creating closed-loop systems in collaboration with both ship recycling yards and producers of marine equipment as well as companies outside of the maritime industry. For example, recently Stena Recycling has joined forces with ABB, Combitech, and Electrolux on a pilot project to dissemble vacuum cleaners and identify recyclable fractions, which among other things should enable Electrolux to close the recycling loop in large-scale manufacturing.

In addition, for the system to become truly circular, as outlined by the Ellen MacArthur Foundation (2013), there must be a switch to renewable energy use as well as enhanced energy efficiency in the ship recycling process, the latter either by reducing the amount of energy to carry out the tasks at hand or by enabling energy exchange (a form of reuse) between different industrial activities. While enhanced material and energy efficiency obviously preserves the primary resource base and benefits the environment (by reducing overall waste discharges and exhaust gas emissions) it also reduces recycling costs.

In each stage of the lifecycle of a ship, there is potential for closing loops through what we will here call circular economy interventions. Circular economy interventions aim to increase resource efficiency by providing services with less material production and processing. This could include reusing materials and components (e.g., rerolled steel plates in new ship hull construction), reducing yield losses, using less raw materials for the same service, life-extension of products and services, and upgrading and remanufacturing (Gilbert et al., 2017). Table 1 provides an illustration of circular economy interventions over the product lifecycle of ships.

Some of the known problems associated with ship recycling might be addressed already at the ship design and construction stage, as also recognized by the Royal Institution of Naval Architects (RINA, 2005) who encourages ship designers and shipbuilders to take due account of the ultimate disposal when designing and constructing a ship. The Cradle-to-Cradle Passport, for example, was developed by Maersk to design ships for more efficient dismantling and resource recycling. Proper design for recycling includes the use of materials that can be recycled in a safe and environmentally sound manner, the minimization of hazardous materials, structural designs that could facilitate ship recycling, and the promotion of the use of techniques and designs which, without compromising safety or operational efficiency, contribute towards the facilitation of the recycling operation. For example, building ships using composite materials instead of steel would not only reduce a ship’s weight and lower its fuel consumption. It would also potentially prolong the ship’s lifetime and reduce the input of resources in construction.

Table 1. Circular economy interventions over the lifecycle of a ship

Lifecycle stage	CE Interventions	Examples
Ship design	Reducing resource inputs	▪ Reusing steel ▪ Using remanufactured components and equipment ▪ Design for maintainability ▪ Design for disassembly/recycling
	Choosing alternative materials	▪ Composite materials* (e.g., glass reinforced polymers) for ship hull, tween-decks, hatch covers ▪ Composite materials (e.g., fibre reinforced polymers) in propeller systems, rudders, bulkheads, decks, watertight doors, pipes, ventilation ducts, components in diesel engines and heat exchange systems
Construction	Reducing resource consumption and emission factors	▪ Advanced laser welding techniques ▪ Advanced systems for capturing toxic fumes ▪ Chemicals and dust collection systems ▪ Regenerative thermal oxidizers (RTO) ▪ Alternative blasting techniques
Ship operation (maintenance)	Onboard repairs	▪ Reusing materials, components and equipment ▪ Using remanufactured components and equipment ▪ Additive manufacturing
	Drydocking, ship overhaul	▪ Reusing materials, components and equipment ▪ Using remanufactured components and equipment ▪ Automation and new technology
	Retrofit, refurbishing, modernization, conversion	▪ Reusing materials, components and equipment ▪ Using remanufactured components and equipment
EOL ship dismantling	Reusing waste materials	▪ Industrial symbiosis ▪ Recycling (collecting, sorting, storing, exporting)
	Reentering parts and materials into new ships or products	▪ Recycling, reusing, remanufacturing
	Reducing resource consumption and emission factors	▪ Scrapping surface coatings before cutting steel ▪ Automation

* Lightweight composites have several potential advantages for use in ship hull such as reduced energy consumption during ship operation, or less need for anti-corrosive protective coating. On the other hand, it should be noted that some composites have low recyclability and may be difficult in recovery. In addition, there are major safety concerns to be addressed, as composite ships are more sensitive to high temperatures exposure and to fire.

Sources: Bird and Allan (1981), OECD (2010), Deshpande et al. (2013), Cerceau et al. (2015), Dinu and Ilie (2015), Jansson (2016), Gilbert et al. (2017), Jain et al. (2017a)

In addition to *design for recycling*, a broader circular economy perspective on ships would also consider *design for maintainability* to ensure accurate, easy, economic and safe maintenance of the ship and its many component parts. The Software Advanced Protection (SWAP) technology that the Danish maritime supplier Danelec Marine applies to the shipboard maintenance of VDR systems is an interesting example of designing marine equipment for efficient maintainability that allows for the reduction of downtime from potentially many days to just a few hours.

Circular economy interventions may also take place during the operating life of the vessel, either in the form of regular maintenance and repair or in the event of more profound ship lifetime extensions. Ship repair, retrofitting, refurbishing and eventually conversion for alternative uses, as well as component and materials reuse, maybe even equipment remanufacturing, are forms of circular economy interventions where not only the material is used more efficiently, but also other value is extracted through increased labor and energy efficiency (Jansson, 2016). Regular maintenance is key to keeping a smooth running of ships, but breakdowns do occur where machinery or electronic systems must be repaired either while the ship is at sea, or immediately upon arrival in the next port.[9] Since nowadays the number of crew onboard ships is dramatically reduced, and since the space for carrying spare parts is limited, breakdown maintenance may require the services of technicians visiting the ship to solve the problem. On some, admittedly very rare, occasions it may even be necessary to fly out service technicians and spare parts, perhaps even large machinery, by helicopter to the ship. To save precious time in such situations, damaged machinery may simply be replaced by new machinery rather than being repaired. Thus, efficacious preventive and predictive maintenance systems and procedures are essential circular economy interventions during ship operation. Also, installing additive manufacturing (3D printing) technologies onboard ships is a promising type of circular economy intervention, which has already been successfully tried out by the US Navy (Zanardini et al., 2016). 3D printing of spare parts while at sea may serve to reduce the time to supply spare parts and components from the shore and to eliminate unnecessary actors and lead time, and it holds the potential for extending the operational lifetime of equipment through onboard repair (and reduce inefficient disposal of otherwise functioning parts).

SHIP RECYCLING AS A CLUSTERED ACTIVITY IN PORTS

With the EU-SRR now in place and with the possible ratification of the HKC in near future the selection of a suitable ship recycling facility will be vital for EU registered EOL ships above 500 GT. Similar to the requirements for decommissioning offshore structures, such a recycling facility must be located in a sufficiently industrialized area with a mature transport network, a robust and certified downstream waste management network, and all the required (regional and national) licenses in place (BIMCO, 2018). In addition, there must be ample physical space for storing scrap and good access to a downstream processing and potential refurbishing of materials and items recovered in the ship recycling process. In view of such requirements, ports are ideal locations for ship recycling facilities as well as for the promotion of circular economy more generally (De Langen and Sornn-Friese, 2018). The more advanced a port is in fulfilling such requirements, the more appropriate a location it becomes for the ship recycling yards catering to sustainable recycling.

The European recycling facilities included in the EU list of approved yards, except those in Turkey, are all located in port areas and in close vicinity to cities, and for good reasons.[10] Ports constitute logistics nodes at the interface between land and sea transport and play an increasingly important role in the management and coordination of material and information flows in global value-driven, maritime supply chains (Robinson, 2002; Carbone and De Martino, 2003). This role of ports as nodes of transport is well-established in the port economics and management literature (De Langen, 2020). In this role, ports provide an essential part of the infrastructures needed for sustainable ship recycling, including piers, basins, stacking or storage areas, warehouses, equipment (particularly cranes), and sometimes even suitable drydocks.[11]

As a complement to the transport node perspective, a cluster perspective is currently developing within port economics and management, addressing the additional development of ports as clusters of industrial activities where interdependent firms cluster together in port regions

9 Classification societies impose redundancy requirements to critical ship components and systems to assure that a ship can always perform required functions and make it safely to the next port, and emergency salvage at sea is thus rare.

10 It should be noted that the Turkish yards approved on the EU list are all located in Aliağa in the Aegean Region, which is in the countryside and not in close vicinity to ports and port cities. Instead, it is in close proximity to a number of large steel works that use the scrap iron and steel from ships as raw material. The deep waters and the low tidal range in the region make Aliağa suitable for ship recycling.

11 For example, in 2013 the Port of Odense in Northern Funen bought the neighboring Lindø Industrial Park from A. P. Moller-Maersk, and in 2016 fully merged the park with the port with the aim to continue the considerable shipyard activities in the area. With the takeover, the port also acquired the large drydock (90 by 315 meters) with an effective drainage system ideal for repairing and recycling large ships. The drydock is now on long-term lease to the ship repair and recycling yard, Fayard.

with various forms of co-ordination and resource sharing as a consequence (De Langen, 2020). Industrial enterprises tend to locate in ports with the aim to benefit from external economies deriving partly from proximity to co-located companies across a range of different industries and partly from the infrastructure and management services of the port itself (Notteboom et el., 2020). Some European frontrunner ports (e.g., Port of Amsterdam) have started working strategically to lead the transition towards the circular economy and are devising various incentives aiming to attract selected circular and renewable industries to the port area (De Langen et al., 2020).

Port clusters may form around different industries, such as the chemical cluster in the Port of Rotterdam, or they may be more general and complex systems of organizations collaborating across industries to deliver a product or a service, as it is known for so-called eco-industrial parks. Eco-industrial parks rely on industrial symbiosis, which is a cooperative approach to competitive advantage based on the physical exchange of materials, energy, water, and/or by-products between co-located but otherwise functionally separate industries (Chertow, 2000). To distinguish industrial symbiosis from other types of economic exchange, Chertow (2007) suggests that at least three entities (none of which are primarily involved in the business of recycling) must be involved in exchanging at least two different resources. An example of this could be a wastewater treatment plant providing cooling water for a power station and the power station, in turn, supplying steam to an industrial user.[12]

In Denmark, we believe there are thriving or latent *ship recycling clusters* particularly in the ports of Esbjerg, Frederikshavn, Grenaa, and Odense. The potential for creating circular economy clusters for sustainable ship recycling in Denmark is closely linked to the presence and interaction of a diverse set of companies, some of which are co-located in the ports and others active in the broader business ecosystem, allowing for a multitude of circular strategies and business models to be pursued and complemented by each other. Since the current ship recycling practices in Denmark are mostly centered around the recycling of scrap steel and used marine equipment and other items, a strengthening of remanufacturing activities would seem particularly promising for making sustainable ship recycling in Denmark more profitable, as remanufacturing would be a means to both reducing costs and increasing revenue.

THE BUSINESS ECOSYSTEM FOR SHIPS

Ship recycling clusters are part of the broader system unfolding over the product lifecycle of ships, as outlined above. The players in the different phases of this chain are to an extent interdependent and their interdependencies require coordination - either through more or less anonymous market exchanges or through some sort of planned and managed coordination. In the coordination of the entire system there are players involved who are directly nested within the product lifecycle (such as recycling and waste management companies, marine repair companies, maybe even marine equipment suppliers), but there are also indirectly linked players who can nevertheless influence what is going on (e.g., port authorities, Port States, classification societies, NGOs).

The business ecosystem perspective is useful for understanding such coordination and the advantages that it can bring. By the notion of business ecosystem, we refer to the complex system of organizations collaborating across industries to deliver a product or a service, and all other organizations that have the power to support or confine the ability to deliver that product or service. A sustainable business ecosystem can be a source of competitiveness for firms as well as a manageable resource for gaining a competitive advantage. This implies a shift in firms' strategic focus from the performance of individual firms to the development of business ecosystem-based strategies (Lin and Wang, 2015; Markus and Loebbecke, 2013).

We will refer to *the business ecosystem of ships* to capture the dynamics. It is difficult to draw the precise boundaries of a complex business ecosystem for circular ship recycling, but in general outline it would include a number of related groups of organizations interacting in the different stages of a ship's lifecycle, including shipyards (also new-building and repair yards); classification societies and other third party verifiers; the ports where the shipyards are located and dismantling takes place; related port companies (e.g., scrap dealers, waste management companies, and recyclers); shipbrokers; maritime

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12 The Kalundborg eco-industrial park is often mentioned as a prime example of industrial symbiosis. It involves material and energy exchanges between four co-located industrial plants: the Asnæs power station, a Statoil petrol refinery, a Novo Nordisk pharmaceutical plant, and the Gyproc plasterboard plant. Other prominent examples are found in Dunkirk (France), Landskrona (Sweden) and Quebec (Canada). In China, eco-industrial parks are a key element in the country's overall industrial transformation. More than a hundred such parks have been selected in China for transition to circular economy, including several regional maritime clusters.

equipment suppliers, including original equipment manufacturers (OEM) and service suppliers; the port state and various other regulatory bodies. Figure 2 provides a simplified graphic illustration of the business ecosystem of ships, as conceived here.

specialized in safe and efficient collection, transportation, treatment, and recycling or disposal of minerals, liquids, chemicals, gases and other waste streams. There are many competent recycling companies located in Danish ports, including the large and geographically spread companies HJ Hansen, Rimeco, Stena Recycling and Uniscrap as well

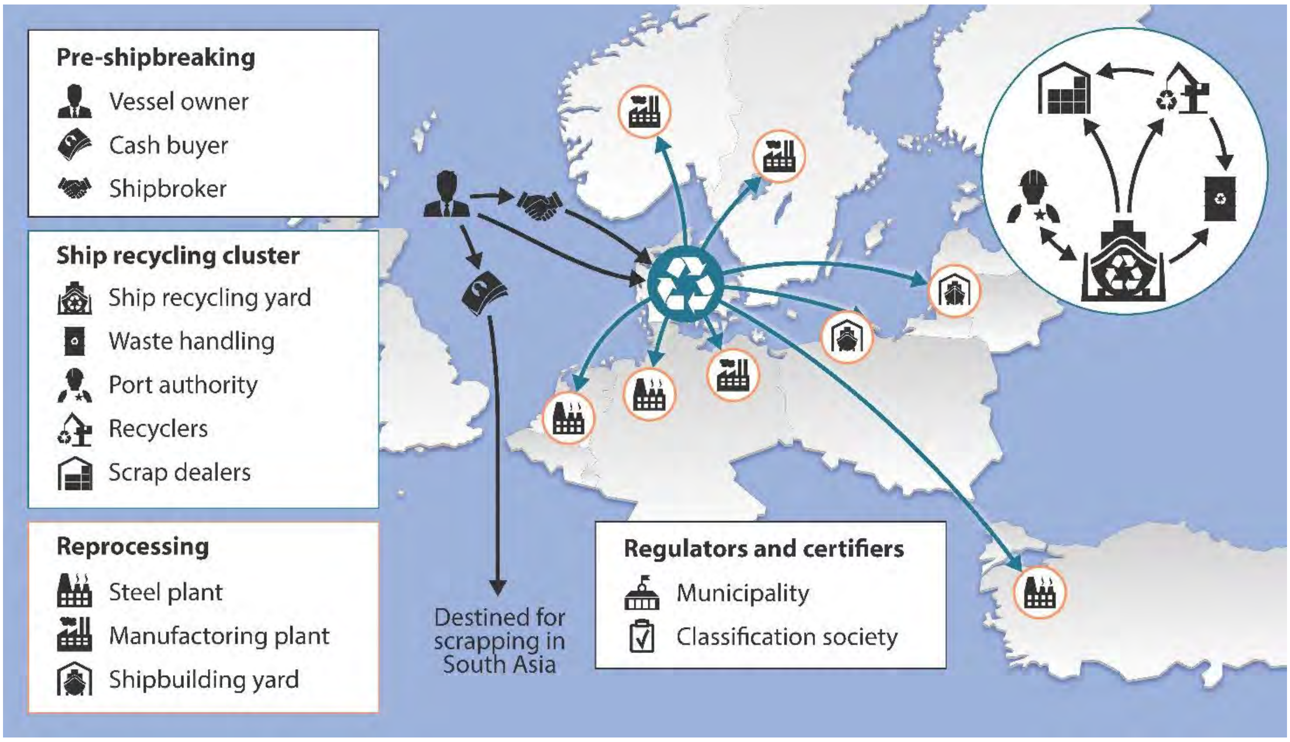


Figure 2: The Business Ecosystem of Ships

A shipyard is a dedicated and specialized, typically enclosed, area where ships are built, repaired or recycled. There is not a clear demarcation of newbuilding yards from repair yards as they to a large extent rely on the same type of equipment, know-how, and facilities (e.g., slipways and docks). Especially newbuilding yards may home-in on repair when the newbuilding market experiences low points. Similarly, repair yards may redirect activity to ship recycling jobs as a means to utilize docking capacity, although ship recycling jobs are generally less profitable than repair and conversion jobs.

A ship recycling yard is typically a simpler facility that cannot readily be repositioned for ship repair or newbuild activity. Some of them can handle most of the ship recycling operation in-house – including dismantling, sorting, shredding, and waste handling – but most rely on subcontractors with specialized knowledge and cutting-edge machinery, especially competent metal scrap recyclers and dealers, who trade scrap metal for profit, and waste management companies, the latter of which are

as scores of smaller and more local businesses. Waste management is also an engrained industry in Denmark with companies servicing car repair workshops, construction sites, industrial plants, and ships. The larger waste management companies (e.g., AVISTA, Fortum Waste Solutions and RGS Nordic) have incineration plants, offices, storerooms, recycling centers and refineries located throughout the country.

HJ Hansen, Rimeco and Stena Recycling are occasionally directly involved in ship recycling, providing expertise and metal shredding and recycling equipment in supplement to the physical facilities provided by the shipyards. For example, Fayard is a Danish ship repair and conversion yard that sometimes take on ship recycling projects in consortium with the recycling company H. J. Hansen and the waste management company Fortum, and Stena Recycling has an existing partnership with Fornæs Ship Recycling in the Port of Grenaa working as a subcontractor for the handling of hazardous waste.

METHOD AND DATA

The present feasibility study is exploratory, open-ended and non-exhaustive. It builds on the combination of existing theories and concepts, as outlined above, and examines an important and potentially lucrative emergent phenomenon, which may take future directions not yet known. Our aim is to better understand this phenomenon and investigate its potential in the context of the Danish maritime industry. In the present report we summarize our findings from especially three separate sub-analyses: 1) an analysis of Danish ship recycling yards; 2) an analysis of EOL ships potentially available for recycling in Denmark; 3) and an analysis of the resales market for EOL ships and recovered ship materials and items. In addition to these three sub-analyzes, we also report from a draft analysis of the potential of maritime suppliers to develop new circular business models around sustainable ship recycling.

We investigate a broad and diverse data material, relying on an overall qualitative and flexible research design. We collected data from company archives, websites and annual reports; other archival data (e.g., the environmental approval licenses that Danish ship recycling yards operate under), descriptive industry statistics from reliable sources; a qualitative, online survey of own design aiming to study industry practices and beliefs; site visits and observations; personal interviews based on semi-structured, open-ended questionnaires; and joint stakeholder consultation meetings with a focus on concepts and preliminary findings. In addition, we used a range of existing resources, including press releases, newspaper articles and publicly available reports. Such an approach is very time-consuming, as it requires the building of trust-based relationships with the involved stakeholders as well as thorough analysis of a comprehensive data set.

Some of the data used require a bit more elaboration:

- In the fleet and yard analyses we have relied extensively on IHS Markit's Sea-web database. Sea-web contains more than 600 data fields derived from the IMO ship, company and registered owner numbering system.[13] It is the largest maritime database available, covering approximately 220,000 ships of 100 gross tons (GT) or above. However, the historical data on recycled ships included in Sea-web are incomplete, since many ship sales and scrapping are not properly reported or registered. This is especially the case for the smaller ships, including many fishing vessels, that are typically recycled in Denmark. To the extent possible, we have therefore supplemented the Sea-web data with available data from the ship recycling yards' own websites as well as coverage of Danish ship recycling in the maritime press. Given that the data are erroneous, we must emphasize that the reported numbers on especially ship recycling activity in Danish yards are conservative estimates and that the actual recycling activity in Denmark may be (much) higher.
- We have obtained extensive qualitative data through semi-structured interviews with stakeholders in Denmark and internationally, used particularly for the yard and market analyses. These have included in-person and telephone interviews with Danish ship recycling yards and recycling companies: Fayard, Fornæs Ship Recycling, H. J. Hansen, and Smedegaarden. We furthermore had telephone conversations with Norddjurs Municipality. We conducted observational studies of Smedegaarden, including an extensive tour of their facilities followed by a debriefing conversation. Subsequent to preliminary analysis of our results additional questions were sent to the yards with the aim to exhaust the empirical evidence. One yard responded with detailed, written response.

13 The IMO registering and numbering system was introduced under the SOLAS Convention to improve maritime safety and security. It evolved from the Lloyd's Register of Ships, which covers all ships of 100 GT or above, however with some exceptions: only self-propelled ships are registered, fishing vessels are often not included, floating docks are not included, and yachts are not included (but Lloyd's has introduced a separate Register of Yachts).

Finally, the relevant municipalities provided us with publically available, but difficult to locate statistical information about the operations of some of the yards.

- Outside Denmark, we have conducted in-person semi-structured interviews with the NGO Shipbreaking Platform, the EU Commission (DG Environment), and the industry associations EUROFER and the World Steel Association (Worldsteel). We attended a symposium on ship recycling, organized by the Japanese government at the IMO in London in May 2019, where we had informal exchanges with several key international stakeholders.
- We conducted several multi-stakeholder sessions throughout the study period, with participation of Danish yards, ports, maritime suppliers, shipowners, interest associations, and relevant authorities. At the stakeholder sessions we presented our ongoing research and preliminary findings and received valuable feedback from practitioners.
- We developed a comprehensive online survey that was subsequently distributed by Danish Maritime to its members, but unfortunately, we did not manage to receive responses to the survey. We therefore developed a shorter version of the survey and invited selected members of Danish Maritime that we identified as either mentioning circular economy efforts on their website or as having a potential for engaging in circular business models. We also contacted these companies over the phone. We received four elaborate responses to the shorter survey. To cover a broader segment of the maritime supplier industry in Denmark, we extracted information from the websites of additional companies and also supplemented with secondary data from the maritime press (Lloyd's List, ShippingWatch, Søfart, TradeWinds) and the regular daily press (using Infomedia as search engine).
- Given the obvious limitations of this process our analysis of maritime supplier turned to be more exploratory than originally intended.

SHIP RECYCLING YARD ANALYSIS

Due to the country's limited natural resources, recycling has always played a central role in Denmark, and specifically the recycling of ship equipment has been systematized and been a profitable business for several Danish companies for many years. There is also a long tradition for scrapping ships, sorting and recycling ferrous and non-ferrous scrap in Denmark. Going back thirty to forty years vessels were being scrapped in Rømø, Esbjerg, Lemvig, Hanstholm, Hvide Sande and many other harbors and ports in Denmark. The business model was the reverse of today's business model: back then, the owners of the vessels paid the yards for the scrapping service, whereas nowadays, the yards buy the vessels either directly from the original vessel owner or from a cash-buyers.

NLMK DanSteel, Ltd. (established as Danish Steel Works, Ltd. in 1940 with shipowner A. P. Møller in a leading position) has played a central role, as this plant was started with the purpose of securing a reliable supply of large quantities of high-quality steel to the many Danish shipyards building large steel ships. It was constructed on a filled seabed in the city of Frederiksværk, a location chosen due to the city's harbor, the steady source of fresh cooling water from lake Arresø, a sufficient electricity supply from the Kyndby Power Station, and access to a workforce with experience from metal work. It had its own port for ships calling from provincial ports. In contrast to steel production in many other countries, its steel production was not based on iron ore but on steel scrap. Still today, the steel production at NLMK DanSteel is based on recycling through the imports of steel slabs (mainly from Russia and Ukraine) that are rolled into sheets.

SHIP RECYCLING IN DENMARK

European shipyards are active in building complex merchant and naval ships as well as advanced technology for offshore oil, gas and renewable energy and other blue economy sectors (e.g., seabed mining, aquaculture). Also, more than 300 European yards are active in repair, maintenance and conversion. Together, these companies employ at least 285,000 people in Europe and produce an annual production value of approximately 320 billion DKK, according to SEA Europe, the Shipyards' & Maritime Equipment Association of Europe (www.seaeurope.eu). There is an additional but unknown number of European yards specialized in shipbreaking, with currently 34 of them included in the EU list of approved ship recycling facilities.

Denmark is among the largest ship recycling countries in Europe and among top 15 in the world in terms of the number of ships recycled. It is also one of the countries with the most approved ship recycling facilities on the EU list, including Fayard located in Lindø Port of Odense; Fornæs Ship Recycling in Port of Grenaa; Jatob Aps. and Modern American Recycling Services (MARS) in Port of Frederikshavn; and Smedegaarden and Stena Recycling A/S in Port of Esbjerg.[14] MARS was established in late 2019 and it is thus the most recent addition to the vessel recycling industry in Denmark. It has been constructed specifically to handle large ships, semi-submersibles, jack-up rigs, all sizes of offshore production facilities and associated jackets, and it has already attracted a few impressive assignments mainly from the offshore industry. In over just a year, MARS has grown from 11 to more than 100 employees. Within the next year, the yard expects to employ above 150 people, which is considered the minimum scale necessary for an efficient business.

14 Jatob is the Danish yard most recently included in the EU list, as it was approved by the municipality of Frederikshavn on March 9, 2020.

Box 1. Ship Recycling Methods

Beaching

Beaching relies on large tidal differences. The ship is sailed onto tidal flats during high tide and secured in place, typically by flooding the ballast tanks. It is then dismantled from bow to stern, often cutting through bulkheads leaving the hull open to sea (vertical cutting). The use of cranes is limited, and the dismantling is conducted with the "gravity method" (cut pieces are allowed to simply fall from the ship) with potential dangers to workers. This method is applied in India, Pakistan and Bangladesh. A few upgraded yards with horizontal cutting methods and impermeable surfaces in cutting zones are now found in India and Bangladesh.

Dry Docking

This is basically the reverse of shipbuilding. The ship is sailed into a dock and the water is pumped out. Dry-docking prevents leakage of pollutants to the environment during the scrapping process and health and safety issues as well as worker rights are generally adequately addressed. Since a dry dock is very costly to build and maintain, dry-docking is rare in recycling of commercial vessels and primarily applied in western countries typically for government-owned vessels. The Danish ship repair yard Fayard occasionally recycles ships in its state-of-the-art dry-dock.

Slipway or landing

Here, ships are sailed directly up to or even onto the coast where the slipway is constructed. Slipways are typically located at sites with low or no tide providing better control of accidental spills. The ship is pulled onto the concrete cement slap and is dragged further up on the shore as it is lightened. The dismantling process uses mobile cranes onshore or from barges and there are typically impermeable surfaces for safe handling of materials. The coastal slipway is the main method in applied in Turkey.

Afloat or alongside

Ships under recycling are moored alongside a quay and this method is typically found in sheltered and calm waters such as in harbors or rivers, which makes spill control and remediation measures easier to apply. The method applies a top-down dismantling process (horizontal cutting) and employs heavy lift cranes. The method was the main approach applied in China and it remains a prominent method in Europe in combination with slipways.

The Danish break-yards are very different from those found along the beaches in South Asia, not only in their dismantling routines and requirements as well as their physical layout and facilities but also in their location characteristics, and especially in the fact that they are located in ports with direct access to slipways, docks and quays and benefitting from the co-location of co-specialized port companies (e.g., recycling and waste handling companies and scrap dealers) to whom there is specific complementarity. The location in Danish ports furthermore means that they generally have fine, year-round sailing conditions and easy access to larger cities and hinterland infrastructure. Given the co-location and complementarity linkages of the shipyards, other port companies and possibly also the port management body, we may see ship recycling in Denmark as an essentially localized, industrial cluster activity.

Table 2 gives an overview of those Danish ship recycling and repair yards and recyclers approved on the EU list, including information on their primary business activity, method of ship recycling, and their actual, licensed capacity (as measured by their maximum ship dimensions).

DRYDOCKING

Table 2: The capacity of Danish EU listed shipyards

	Primary business	Method of recycling	Max. ship dimensions (meters)			Max. annual output (LDT)
			Length	Width	Draught	
Fayard	Ship maintenance and repair	Drydock	415	90	7.8	
Fornæs	Ship recycling	Alongside, drydock	150	25	6	30,000
Jatob	Ship recycling	Alongside, slipway	150	30	6	30,000
M.A.R.S.	Ship recycling	Slipway	290	90	14	
Smedegaarden	Ship recycling	Alongside, drydock	170	40	7.5	20,000
Stena Recycling		Drydock	40	40	10	

Source: Based partly on information contained in the official EU list of approved ship recycling facilities and partly on the companies' websites.

Inclusion in the EU list means they are approved to recycle a vessel of any type whatsoever operating or having operated in the marine environment (i.e., all commercial floating assets and submersibles, as well as vessels stripped of equipment or being towed).[15]

In addition to the shipyards on the EU list, there are currently ten other shipyards in Denmark, active in the building of smaller and specialized ships and/or in maintenance, repair and conversions of all types of ships. Some of these yards are co-located with the EU listed yards in the Danish ports and can thus be said to belong to what could potentially develop into successful ship recycling clusters (given the future co-location of adequate recycling companies with proper equipment). These include Esbjerg Shipyard, Grenaa Shipyard, and Orskov Yard (the latter located in the Port of Frederikshavn). The remaining yards (Assens Shipyard and Faaborg Yard on the Island Funen; Søby Shipyard on the Island Ærø in the Southen Funen Archipelago; Hvide Sande Shipyard not far away from Esbjerg; Thyboron Shipyard at the North Sea inlet to the Limfjord in northern Jutland; Hirtshals Yard at the northwestern Jutland; and Karstensen's Shipyard in Skagen, the northern tip of Jutland) are located outside of the ship recycling clusters but may play important roles in the broader business ecosystem for ships within Denmark. Orskov Yard is by far the largest of these, capable of handling ships with a draught of 7.1 meters and up to 215 meters long and 34 meters wide. It owns several drydocks, floating docks and a mobile crane with a lifting capacity of up to 70 tons in addition to mobile shore power units.

RECYCLING ACTIVITY

In the 10-years period 2010-2019 Danish yards recycled (at least) 183 ships, according to a conservative estimate based on data from Sea-web. These were particularly general cargo ships, fishing vessels, safety vessels, supply ships, survey vessels, ro-ro passenger ships, and one fully cellular, geared container vessel (Royal Arctic Line's 283 TEU ice strengthened ARINA ARCTICA, IMO no. 9100255). A closer inspection of additional data sources reveals that the recycling activity in Denmark has in fact been higher over the period. Danish yards have recycled a much larger number of smaller ships, according to information extracted from the yards' own websites and other external communication, especially fishing vessels, tugboats, rescue vessels, small passenger ships, and a few naval vessels. A detailed scrutiny of the yards' own communication even shows that some larger general cargo ships, not figuring in the Sea-web database, were recycled at Danish yards in the period.[16]

15 The EU-SRR does not apply to warships, naval auxiliary, or other ships owned or operated by a state and used, for the time being, only on government non-commercial service.

16 For example, the 499 GT Danish flagged LIVARDEN (IMO no. 7310818) recycled by Jatob Aps. is not included in the Sea-web data field for scrapped vessels. Instead, it can be located in the Sea-web data field "Not-in-service", but this field includes many ships currently out of service that have not been recycled, thus making it impossible to directly identify recycled vessels.

Table 3: Ships above 500 GT recycled at Danish shipyards (2010-2019)

Danish Shipyards	No. of ships	Size range (DWT)	Average age
Fornæs Ship Recycling	113	1,600 – 108,000	37 years
Smedegaarden	42	700 – 24,000	37 years
Jatob	26	900 – 22,000	34 years
H. J. Hansen (HJH)	2	1,200 – 1,600	36 years
Total	183	700 – 108,000	36 Years

Source: Sea-web

Almost all the vessels reported in Sea-web (181 out of 183) were recycled by three of the EU listed yards: Fornæs Ship Recycling, Jatob, and Smedegaarden (see Table 3). In addition, H. J. Hansen – a generalist recycling company with special competencies in the recycling of ferrous and non-ferrous scrap, located in Lindø Port of Odense – recycled two small cargo ships in 2011 and 2012[17]. This was done in close collaboration with Fayard, who provided drydocking facilities, and the waste handling company Kommune Kemi/Nordgroup (now Fortum Waste Solutions) who would transport the waste separated from the ship by trucks to its high temperature incinerator in the nearby city Nyborg.

Fornæs Ship Recycling has recycled three out of five of the larger ships recycled in Denmark over the period, corresponding to about 63 percent of the tonnage (in DWT), and also the largest ships (up to 108,000 dwt). The average age of the ships being recycled were 37 years. Smedegaarden was the recycling destination for both the oldest and the youngest ship recycled in Denmark in the period; the 58 years old, UK-flagged standby safety vessel OCEAN SWIFT (IMO no. 5288396) recycled in 2015, and the twelve years old SAMSKIP AKRAFELL (IMO no. 9271963), a grounded 5,565 deadweight tonner flagged in Cyprus (recycled in 2015).

Table 4 shows the types of ships recycled at Danish yards over the 10-year period. Because ships are complex and usually highly customized products built on a project-like basis, the variety in completed ships is high and they are often quite unique. There is hence great variation in the requirements to their dismantling, which must rely on specialized skills and distinctive procedures.

17 In 2013, H. J. Hansen also recycled three small corvettes from the Danish navy: Niels Juel, Olfert Fischer and Peter Tordenskiold. These do not figure as scrapped in the Sea-web database.

Table 4: Types of ship recycled at Danish yards (2010-2019)

Ship category	Ship types	No. of ships
Dry cargo	Bulkers (including cement carriers)	3
	Container Ship (Fully Cellular)	1
	General Cargo Ship	57
	Palletized Cargo Ship	7
	Pontoon	1
	Ro-Ro Cargo Ship	1
	Vehicles carrier	1
Tankers	Chemicals	1
	CO2	2
	LPG	2
	Products	1
Harbor and ocean work crafts	Anchor Handling Tug Supply	6
	Research Survey Vessel	12
Fishing Vessel	Trawlers	26
	Fish farm support vessels	1
Offshore vessels	Offshore tugs	4
	Platform Supply Ship	16
	Standby Safety Vessel	25
	Crane vessel	1
RORO and ROPAX		11
Other	Exhibition and theatre ships	4
Total		**183**

Source: Sea-web

The yard practices and price-setting of salvaged equipment builds on experience and – as the market is not transparent – the tacit knowledge possessed by a few individuals. The general impression by one of our respondents is that competing ship recycling yards tend to look for accessories such as generators when bidding for an EOL ship, as often the profits are made from reselling such salvaged items. The turnover of stocked items can be substantial, but stockpiling requires long-term financing and storage facilities.

Photo: Søfart, January 23, 2018
Alongside at the Fornæs Ship Recycling yard

Figure 3 shows the yearly distribution of ship recycling at the three dedicated ship recycling yards over the period. The peak year was in 2013, when at least 28 EOL ships were recycled at Danish yards. This followed a period of increasing ship scrapping worldwide in the wake of the financial crisis, which had led especially northern European short-sea shipping in the doldrums. The Danish ship recycling yards benefitted from the crisis and had to expand their capacity. In 2012, Fornæs Ship Recycling invested in a new warehouse and office building and the year after it built a new slipway, which doubled its capacity from 15,000 lightweight tons to about 30,000 lightweight tons annually.

business strengths of the dedicated ship recycling yards, and the expected strategy of these would be to invest and grow their ship recycling businesses. For ship repair yards, on the other hand, a growing ship recycling market would be only mildly attractive and especially in the present context of regulation-driven conversion and retrofitting (particularly the installation of scrubbers and ballast water treatment systems), which deliver a much greater contract value than traditional ship repairing projects (Shen, 2020). From a general shipyard industry perspective, we may thus claim a "hierarchy" among shipyard contracts, with recycling typically figuring at the bottom.

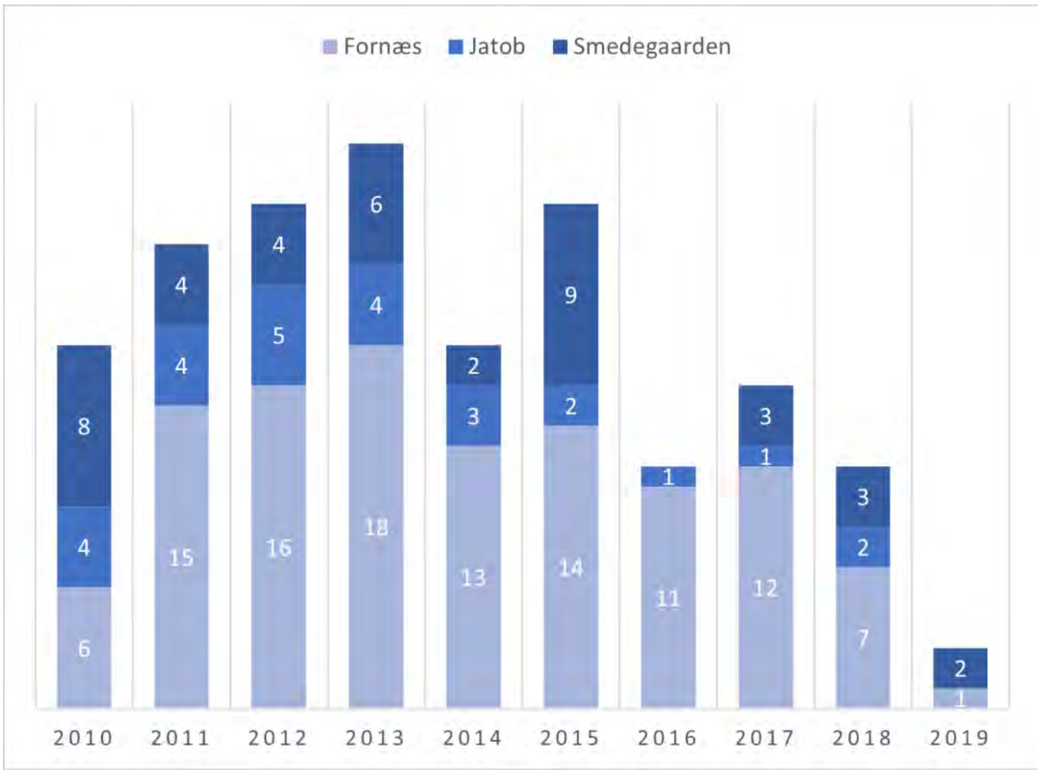


Figure 3: EOL ships recycled at the core Danish ship recycling yards, 2010-2019
Source: Sea-web

What is attractive depends on the yards' relative advantages

The question of whether sustainable ship recycling is an attractive business for Danish shipyards cannot be answered universally, as it depends on the unique combination of resources and capabilities that each of the yards possesses. In general terms, a growing northern European ship recycling market would match well the

From our assessment of the Danish ship repair and ship recycling yards we may ascertain three representative ship recycling business models characterized as:

- Service model (steel value): Dedicated ship recycling yards buy vessels and scrap them as cheaply as possible to cash in on steel price. The service model in seen in the pricing strategy, where the yard's bidding for a vessel is based on

breakeven estimation considering only the possible revenue from re-selling the steel scrap (reselling of recovered items is a nice additional benefit but is not necessarily reflected in the pricing strategy). The business model is one of focusing on selling large quantities of materials (mainly steel) at low marginal revenue. Smedegaarden and Jatob are examples of ship recycling yards following a service model, and the model also largely characterizes MARS.
- Second-hand trading model (reusable items value): Dedicated ship recycling yards buy vessels at a price that is often above the revenue that can generated from reselling the steel scrap. Instead, profits made primarily from reselling the salvaged machinery, equipment and components, ship fittings and accessories, and furniture. Sometimes entire sections can be salvaged from a ship and resold on the world market (e.g., the bridge). The ship recycling yards do not typically themselves recondition or upcycle salvaged items, but they may sell specific types of salvaged items to second-hand dealers who repair or even recondition the items and sell them on for profits. Fornæs is the clearest example of a dedicated Danish ship recycling yard pursuing the second-hand trading model, losing money on the scrapping operation but earning (sometimes very good) money in the second-hand market for salvaged items (see, e.g., Fischer, 2018).
- Opportunistic model (capacity driven): This model combines existing newbuild or repair yard capacity with available recycling competences. Newbuilding and repair yards are generally reluctant to block a drydock or a quayside for a vessel to be recycled, if it means that a more profitable activity is then excluded. However, a ship recycling contract can be lucrative if yard capacity is available. Fayard is a good example of this model, as it occasionally repurposes its docking facilities from ship repair and conversion retrofitting to ship scrapping. Fayard does not itself possess the needed recycling equipment and know-how but contracts with HJ Hansen and other specialized, co-located companies. The use of the costly drydock makes speed essential in the process. Revenue comes primarily from selling metal scrap while typically only few items are salvaged for direct reuse.

The business models found in global ship recycling are more complex and the supply chain significantly more specialized:

- Service model: This model is typical for the Turkish market (and was for the Chinese market), which benefits from a mature, domestic scrap steel market and several downstream service providers for bulk items: slop, fuel, combustibles, waste.
- Second-hand trading model: Especially in Bangladesh and India the reusable items from vessels are brought into the marketplace via a great number of merchant’s outlets. Specialized recycling companies (e.g., for light fixtures, cables or furniture) may even be active part of the onboard recycling process, paying the yard-owner for the privilege and the items recovered.
- Opportunistic model: This model is also found in South Asia but typically involving existing, but dormant ship recycling beaching yards rather than ship recycling facilities with an established recycling infrastructure.

In the international market a cash-buyer is most often involved, literally buying the vessel from a shipowner and re-selling it to a ship recycling yard in a matter of weeks. In some cases, a shipowner uses a shipbroker to scan the market for second-hand value of vessels. Nowadays, the parties in such transactions typically use BIMCO’s Standard Contract for the Sale of Ships for Green Recycling (RECYCLECON), which incorporates some key provisions from the HKC and hence may serve to allocate the parties’ private liabilities and protect them from and public liabilities (Tsomaeva, 2021).

The shipowner typically still owns the vessel until a sale is completed – be it for further trading or recycling. Some shipowners (e.g., Boskalis, Hapag-Lloyd, Maersk) take a very active role in the entire ship recycling process to guarantee that their vessels are recycled in a safe and environmentally sound manner, including carefully selecting proper recycling facilities and investing in their upgrading as well as undertaking on-site monitoring of the dismantling process with own teams oof employees.[18] An emerging EOL ship sales model is used by a growing

18 Schøyen et al. (2017) provides numerous examples of how selected Norwegian shipowners actively engage in the different steps of ship recycling to rate and select ship recycling facilities and monitor the entire process to assure the work is done in a responsible manner.

number of responsible shipowners (but still few), where the ship remains on the books of the shipowner until pre-recycling decontamination of the ship has been completed, or even while the ship is being recycled in the yard and finalized in a safe and environmentally sound manner. Almost two decades ago, the Anglo-Dutch container shipping operator P&O Nedlloyd developed internal company procedures for decontamination of its EOL ships, undertaking this activity before selling off the ships for recycling (American Shipper, 2003).

The P&O company unit responsible for the "green recycling process" was subsequently spun-off as the independent ship recycling service provider Sea2Cradle. This development has led to a new branch of service companies specializing in helping shipowners selecting a high-standard recycling yard, completing the sale of a vessel in a proper fashion, offering shipboard preparations and providing supervision during the recycling of a vessel. In addition to Sea2Cradle, the Norwegian companies Grieg Green (part of the Grieg Shipping Group) and Wilhelmsen Ship Management (part of the Wilh. Wilhelmsen Group) are prominent examples of third-party ship recycling service providers.

Interestingly, in Europe new business models are being tested.

- Trafalgar Wharf, a British shipyard located in the upper reaches of Portsmouth Harbour, has developed a "for hire business model": shipowners bring in their own repair and refitting teams and just hire the shipyard area and facilities for a period. The yard provides all the facilities shipowners need for repairing and refitting smaller vessels, such as powerboats and super yachts, including on site workshops, mess rooms and office space. It may be feasible to develop a for hire model also for ship recycling, catering to shipowners who wish to keep the ship until the recycling has completed and possibly working in liaison with an independent ship recycling service provider (e.g., Sea2Cradle or Grieg Green).
- A "fully integrated ship repair and recycling model" is being developed by the Norwegian Green Yard Kleven. Green Yard was a dedicated ship recycling yard, but recently it bought the financially distressed Kleven shipyard and with the purchase supplemented its recycling activities with more traditional shipyard work. It is now a fully integrated yard active across all subsectors, from newbuilding over repair and maintenance to recycling.
- "The networked yard" is operating in Denmark with Fayard/HJ Hansen under an opportunistic business model, but the model with a close-knit network of recognized suppliers and downstream services is also found in Europe, e.g., in the UK, Netherlands and Belgium.

FLEET ANALYSIS

The development of circular economy clusters for sustainable ship recycling in Denmark would require a certain, critical mass of EOL ships available for recycling to be introduced as raw material or resource into circular economy flows. For a start we may observe that the world fleet is growing, both in terms of number of ships plying the world's oceans and seas and particularly in terms of tonnage (ships are generally becoming bigger), and that it has been growing impressively over the past at least forty years. Thus, according to UNCTAD statistics the tonnage of the world merchant has grown from 672,142 DWT in 1980 to more than two million DWT today. Over the past ten years, since 2011, the number of ships in the world fleet has grown from a little more than 83,000 ships to almost 100,000 ships today. This implies that global ship recycling is a growing market, and that it will keep growing for at least the next 25-30 years. Traditionally, many smaller EOL ships are recycled at yards in Europe, while most large ocean-going ships are still sold for scrapping to ship recycling yards in South Asia. The EU-SSR provision that all ships over 500 GT flying a European flag must now be recycled at an EU approved recycling facility could have the effect that increasingly also the larger ships will be recycled in Europe.

In this chapter, we identify and describe what we consider the relevant fleet of EU-flagged ships above 500 GT approaching end of operational life and hence to be scrapped in the not-too-distant future, potentially at a northern European ship recycling yard. The data collected for the fleet analysis provide a snapshot of EOL ships of 500 GT or bigger potentially available for recycling at the end of 2019. In addition to the ships included in the analysis must be added the significant portion of vessels below 500 GT that are also available for recycling at Danish yards.

We include a broad range of ship types, including dry cargo ships (e.g., barge carriers, bulk carriers, container ships, general cargo ships, heavy lift ships, reefers, ro-ro ships, and specialized ships such as car, livestock and timber carriers), liquid cargo ships (e.g., chemical tankers, crude oil tankers, LNG carriers, LPG carriers and product tankers), combination ships (OBO's and CLEANBU), offshore vessels (e.g., accommodation barges, crane barges, drill ships, FSO's and FPSO's, pipe layers, production platforms, semi-submersible drill ships, and supply ships), passenger ships (e.g., channel and coastal ferries, cruise ships, harbor ferries, and liners), harbor and ocean work crafts (e.g., cable layers, dredgers, pilot crafts, tenders, and tugs as well as salvage, light house and buoy vessels), fishing vessels (factory ships, trawlers), yachts, and sailing vessels. All of these are ships for which the EU-SRR applies. In addition, we included naval ships (aircraft and helicopter carriers, hospital ships, mine vessels, patrol ships, support ships, and warships), although the underlying market dynamics and handling requirements for recycling naval ships are special.

Although all EOL ships in the world fleet are generally up for grabs and for every ship recycling yard to bid for, we believe that the likelihood for commercial ships to be recycled in Denmark increases the closer to Denmark the ships are currently registered. This view is supported by a recent survey commissioned by BIMCO and showing that EU member state ship recycling facilities tend to either provide bespoke local solutions to a niche recycling market, or focus on offshore decommissioning (Marprof Environmental Ltd., 2020). In addition, particularly smaller shipping companies in Europe will, besides from the requirement to scrap at an approved yard on the EU list, consider the operational costs of sending their EOL ships to far away ship recycling yards. Thus, a Danish shipping company will search for ship recycling opportunities in their vicinity. When the Danish offshore shipping company Esvagt a few years ago chose to recycle two ships at the Fornæs Ship Recycling yard they justified their decision partly by the cost savings from not having to sail the ships to a ship recycling in Turkey (Taylor, 2018).

We therefore divide the EU fleet into three groupings, with group 1 being flagged closer to Denmark.

- Group 1 includes ships currently flying the flags of Denmark, Faroe Islands, Iceland, Norway and Sweden.[19]
- Group 2 includes ships registered in Austria, Belgium, Czech Republic, Estonia, Germany, Ireland, Finland, France, Hungary, Latvia, Liechtenstein, Lithuania, Luxembourg, Poland, Slovakia, the Netherlands, and the United Kingdom (including the Gibraltar, Isle of Man and UK ship registers).
- Group 3 includes Bulgaria, Croatia, Cyprus, Spain, Greece, Italy, Malta, Portugal, Romania, and Slovenia.

We recognize that the shipowner's decision to recycle a ship in an EU-SRR compliant ship recycling yard hinges highly on cost considerations, and that Danish ship recycling yards, in the larger picture, have difficulties in competing on price.

According to data extracted from the IHS Sea-web database, the combined EU registered merchant fleet counted about 9,800 operational ships of 500 GT or above in 2019. For the present purposes, we will look closer at the 1,736 ships that are 25 years or older, as these are the currently prospective EOL ships pending for recycling (see Table 6). The bulk of the ships aged 36-75 years still in operation are active in cargo and special purpose trades, mainly short-sea shipping. Many of these have had their operating lifetime extended once or more by refitting to accommodate current needs and standards and some may thus be fitted with up-to-date equipment.[20] A score of the ships are more than 75 years old and they are mainly exhibition vessels, passenger ships, training vessels, and yachts. With proper repair and retrofitting, continuous operation beyond design service life can offer economic profits to owners of such vessels (for exhibition vessels even without refitting). Hence, we believe that the relevant fleet of near-end-of useful life ships to consider as potential raw material in a circular ship recycling system consists of large, ocean-going vessels within the normal lifetime range (25-35 years) and all types of ships in the age range 36-75 years.

19 As an autonomous territory within the Kingdom of Denmark, the Faroe Islands are included in the analysis. The Faroe Islands are not members of the EU or the EEA but maintain close working relationship to the EU/EEA. The shipowners' association in the Faroe Islands supports the HKC and the EU-SRR.

20 For example, the IB VOIMA (IMO no. 5383158), a 66-years old icebreaker owned by the Finnish state and still operational in the Baltic Sea, went through extensive refit in the late 1970s after almost 25 years in operation. She received new hull plating, new main engines and new superstructure to accommodate the crew, and her propulsion motors and electrical systems were completely refurbished. After the refit, she was essentially as a new ship. In 2016, VOIMA went through another major refit with extensive renewal of hull and machinery equipment to secure her operational capability for another ten years (Port News, 2016). She is the world's oldest icebreaker still in service.

Table 6: EU flagged ships more than 25 years old (as of December 2019)

	Number of ships	Total GT	Total DWT
Group 1	594	2,170,156	1,586,292
Group 2	748	2,723,695	1,773,851
Group 3	394	2,122,618	1,065,518
Total	**1,736**	**7,016,469**	**4,425,661**

Source: Sea-web

A MORE DETAILED ASSESSMENT

There are 865 near-EOL ships of 25-35 years of age and 858 aged 36-75 years. Since the dedicated Danish ship recycling yards have their expertise mainly in the reuse markets for high-tech, sophisticated marine equipment and are generally less competitive in the steel market, a large share of the near-EOL ships, especially dry cargo ships, will be of less relevance for the development of circular economy ship recycling clusters in Denmark.

Table 7 tunes in on the ships in the 25-35 years age category divided into classes based on a provisional evaluation of their technological sophistication. We consider passenger and cruise ships as commonly the most technologically advanced ships, as they are subject to stricter health and safety regulations (i.e., SOLAS) and furthermore include valuable HVAC systems, luxury interior and woodwork, audio-visual equipment and other special amenities catering to passenger needs. Yacht and superyacht boats can also be highly sophisticated, but they do not contain much steel and hence their scrap value is generally low, even if the value of recoverable onboard equipment and interiors would generally be high. However, the more luxurious yacht boats tend to circulate in the secondhand market for many years, rather than being dismantled.

There are many different ship types fitted with high-tech equipment among the near-EOL vessels relevant for the analysis. They include anchor handling tug supply (AHTS), fisheries and offshore research vessels and other ocean work craft; offshore vessels; specially fitted feeders; passenger and cruise ships; and fishing vessels. There are especially many fisheries research vessels that are coming to the end of their design service life, and which may offer attractive market opportunities for Danish ship recycling yards – especially for the secondhand market for recovered items. Such ships are typically constructed in aluminum or steel and fitted with sophisticated and expensive equipment for coastal navigation, oceanographic and meteorological research, monitoring fish stock and the marine environment, and for onboard scientific purposes. Mechanical and suction dredgers may also be of relevance as they are generally within the size range of ships that can be taken in by the Danish shipyards and fitted with bow coupling and powerful pumps.

Table 7. Types of ships in the 25-35 years range (as of December 2019)

	Vessel type	Gr. 1	Gr. 2	Gr. 3	Total
Passenger	Cruise ships	1	10	6	17
	Passenger/Ro-Ro	60	59	62	181
Yachts	Yachts and superyachts	1	6	3	10
Fisheries	Fishing vessels and factory ships	77	45	16	138
	Research and support vessels	6	6	6	218
Offshore	Drilling rigs and FSO	1	2	3	6
	Supply and support vessels	3	5	3	11
	Rescue, safety and salvage ships	2	6		8
	Crane and heavy lift vessels, pipe carriers	3	4	3	10
	Anchor handling and mooring vessels	3	5	2	10
Harbor and ocean work crafts	Tugs, pilot, and coast protection vessels	1	10	4	15
	Research Survey vessels	11	15		26
	Cable repair vessels and buoy tenders	1	6	1	8
	Fishery patrol vessels	1	1	1	3
Other	Container vessels/feeders	3	7	1	11
	Reefers	8	5	2	15
	Dredgers and hoppers	4	33	6	43
	Icebreakers	1	4		5
	(Sail) training ships	1	1		2
Military	Minehunters & minesweepers	4	26	2	32
	Patrol vessels			5	5
	Replenishment tankers		7	1	8
	Torpedo recovery vessels		1		1
Tankers	LPG	1	3		4
	Chemical and product tankers	13	29	11	53
	Oil and edible oil tankers		3	1	4
	Tank barges		4		4
	Water tankers			1	1
	Bunkering vessels	1	1	7	9
Dry cargo	Aggregates, cement and stone carriers		4	4	8
	Livestock carriers	1	3		4
	General cargo ships and pontoons	69	77	22	168
	Palletized and Ro-Ro cargo ships	3	12	3	18
	Vehicle carriers	2	1	4	7
Total		**282**	**401**	**182**	**865**

Source: Sea-web

There are also small container ships specialized for arctic operations. For example, several smaller feeder vessels operated by Royal Arctic Line and registered under the Danish International Ship (DIS) register are approaching the end of their operating life and are thus potentially available for recycling at a Danish yard. These are flexible ships used for liner shipping and capable of undertaking special tasks, and they are fitted with deck cranes. Because they are currently employed in service between Denmark and Greenland, and hence operate in sensitive arctic waters, they have been refitted with valuable automatic pCO_2 measuring systems (for measuring the oceanic uptake of CO2) and sensors for sea surface temperatures and salinity.

Most of the world's container vessels today are gearless and the potential for refitting salvaged onboard cargo handling equipment on container ships is limited, but marine deck cranes can be refitted for other segments (e.g., offshore platforms, research and fishing vessels, or smaller workboats) and the global market is generally growing (Maximize Market Research, 2019).

WHAT ARE THE FACTORS THAT INFLUENCE SHIP RECYCLING DEVELOPMENTS?

Since the data reported here provide a snapshot only, they likely underestimate the number of some types of EOL ships that are available for recycling now and in the next few years, as the COVID-19 pandemic has forced many shipowners to tighten their operating costs, including laying up and scrapping of otherwise operational vessels. So far, the pandemic has caused a heave of younger and fully operational cruise ships being sold for dismantling, particularly to yards in Turkey (Street, 2020). On the other hand, the primarily demand-led post-pandemic rebound during the first half of 2021[21] has greatly increased the value of particularly container ships and most dry bulk segments and this upward trend in the value of such shipping assets is expected to continue at least until the high costs of trading spill over to the prices of goods and services and erode consumer purchasing power. Since the present high and rising price on steel has concurrently resulted in a moderate level of newbuilding orders the vessel supply and demand balance has been tightened, and we might therefore expect to see less container ships and dry bulkers being sold for scrapping in the immediate future.

Other important factors shape the market for ship recycling. While ships are generally sent for recycling when the economics of operation dictate it, regulatory changes can also have great impact on the ship recycling market, as we saw it happening with the phasing out by the regulations of Annex I of MARPOL of the single hull tanker fleet (CEC, 2007; Mikelis, 2008). Currently, the intensified focus on decarbonization and stricter international regulation of shipping emissions challenge shipowners to make modification retrofit or replace existing vessels. For example, with the energy efficiency index for existing ships (the EEXI), which was agreed upon at the in the MEPC75 meeting at the IMO in late 2020, as many as 30,000 of the world's ships will need refitting or switching too alternative fuels, according to estimates provided by DNV (Kristiansen, 2021). With the current tightness of the lending market, selling of ships for recycling may be a potential source for the shipowners to obtain the cash needed for investments in environmentally friendly ships (Paris, 2020). Notwithstanding that there are disposal alternatives to ship recycling (such as, floating storage), we generally believe that our EOL fleet assessment beyond the mediate term is conservative and in the low end of what is realizable in foreseeable time horizon.[22]

While there are hence events that will likely lead to generally increasing scrapping in coming years, also for EU registered ships, this is not necessarily to say that an increasing number of those ships will end up being recycled by EU approved yards. It is not uncommon for shipowners to either directly reflag their EOL vessels and bring them to ship recycling facilities in South Asia or sell them to intermediary brokers or cash-buyers, who then change both the name and the flag of the vessels before reselling them to South Asian ship recycling facilities (Hodgson, 2021). A recent global examination published by Shipbreaking Platform showed that several European shipowners in 2020 sent their EOL vessels for beaching at recycling facilities in South Asia. A substantial number of those ships were reregistered under last voyage flags before reselling for scrapping, including flags listed as black or grey ("flags of convenience") by the Paris MoU (e.g., Comoros, Moldova, Palau, Sierra Leone, St Kitts & Nevis, Tanzania and Togo). Previous research based on data from 2015 has shown that during their operational life around 22 percent of the world fleet flies an EU member state flag, but only eight percent of the scrapped vessels were still under European flag and hence European jurisdiction (Heidegger et al., 2015).

21 The freight rates for bulkers are currently the strongest in more than a decade, above $30,000 per day for smaller-sized vessels and above $50,000 a day for capesize vessels (Bakhsh, 2021).

22 Permanently sinking of ships in a strategic location to create artificial reefs may be another way to dispose of ships and is used with the aim to promote marine life. While sinking of ships for artificial reefs is common in U.S. territories and supervised by the U. S. Maritime Administration (MARAD), it is not generally accepted under HELCOM/OSPAR decisions (an xemption was made for the Ærøsund ferry).

Such circumvention of the EU-SRR in mainly driven by economic considerations, notably the higher scrap prices being offered by non-listed yards in South Asia (Pico, 2020). Several Northern European ship recycling yards have noted that for EU registered ships to be increasingly recycled according to the EU-SRR, more strict and stringent enforcement of the rules and sanctioning of rule violations is needed.[23]

23 In March 2018, a Dutch court penalized the reefer owner Seatrade for violating the EU-WSR, a ruling that according to Shipbreaking Platform has already raised awareness about how shipowners try to circumvent EU ship recycling regulation and fostered dialogue to enhance compliance (Adamopoulos, 2018). The Seatrade ruling in 2018 was under EU WSR because crime occurred in 2012, however, since December 31st, 2018, the implementation of Basel Convention within the EU regarding EOL is through the EU-SRR rather than the EU-WSR. The EU-SRR implements the Hong Kong Convention with its direct requirements to the safe and environmentally sound handling of the ship recycling process.

The Danish registered barge Henry P. Laden (imo no. 8646484) was built in 1930 by A&P Tyne in northeast England.

Today, the vessel is owned and operated by jd-contractor a/s and used for large-scale cable and pipeline installations in north europe

(photo by Juergen Braker, www.marinetraffic.com).

MARKET ANALYSIS

The following analysis focuses on the Danish ship recycling market in more detail, or the demolition market to use the terminology of Stopford (2009). The demolition market is one of the four main markets of international shipping, and one that could be identified as "a rough market". In most cases, the main market value of EOL ships comes from their steel content (Jain et al., 2017b), and we will therefore investigate the global steel market and how it influences the price formation of EOL vessels along with other forces of demand and supply. However, in the cases of smaller and more specialized vessels, which are typically recycled in Denmark, onboard equipment could nevertheless account for more than half of the economic value that the ship recycling yards obtain from recycling them. It is thus important to also explore the second-hand market for used equipment.

As outlined in chapter 2, ship recycling is a unique industry with a complex interaction between stakeholders at several distinct levels. From a market point of view, the ship recycling yards are both customers (they bid for and buy EOL ships) and sellers (they sell the scrap steel, other materials, and used equipment). They also serve as bridge between shipping and other (sometimes closely related) industries such as the scrap steel industry, or industries that repurpose marine equipment to be used on land (e.g., in agriculture). From a material stream point of view, the ship recycling yards also transform EOL ships, which under the Basel Convention and the BAN Amendment are legally to be considered as waste when exchanged across national borders, into two main material streams: While some parts of a dismantled EOL ship must be considered as waste the handling of which incurs economic costs (material waste stream), most of it generates economic value (material value stream) and could in some cases serve as the backbone for interdependent industries.[24]

Below analysis of the ship recycling market in Denmark describes the market characteristics and market players, identifies visible current barriers and suggests measures for resolving them. However, since the ship recycling market generally exhibits low transparency, we cannot capture the transactions between those players in greater detail and hence properly estimate the size of the market. While the price of scrap steel is generally governed by the global steel price, the actual price the shipyards receive for their scrap steel is administered in non-disclosed agreements and sometimes based on close and long-term personal or inter-organizational ties. Furthermore, there is no national or international regulation that requires the disclosure of the purchase price of an EOL vessel, just as the price of a second-hand equipment recovered from EOL ship is not publicly disclosed. The Danish ship recycling yards in fact do not publicly announce the price of the salvaged items they have on display. As one respondent explained it, this is because they know that the ship recycling yards in South Asia routinely monitor the prices that European yads charge for salvaged parts and then offer similar items on the market at a price up to ten percent lower.

The second-hand market is highly differentiated, and any actual sales price is a market price. The market in Denmark for items recovered from ships may be described as including substitute parts for primarily the agricultural sector, but it also can include rare vintage items recovered from dismantled ships that were produced in small series of which some ships are still in operation. Such vintage items are typically in scarce supply and can, if in demand, command even very high prices.

THE INTERNATIONAL MARKET FOR EOL SHIPS

EOL ships are generally scrapped in a way that generates economic value. Since the highest reclaim value of most merchant ships is their steel hull, the global recycling market for ships is based on the scrap steel value and driven by the global scrap steel market and price rather than component value. Generally, a ship is priced in USD

24 However, since the entry into force of the EU-SRR on December 31st, 2018, the Basel Convention no longer applies to EOL within the EU. What has entered in its stead are the stricter requirements to the safe and environmentally sound handling of the ship recycling process.

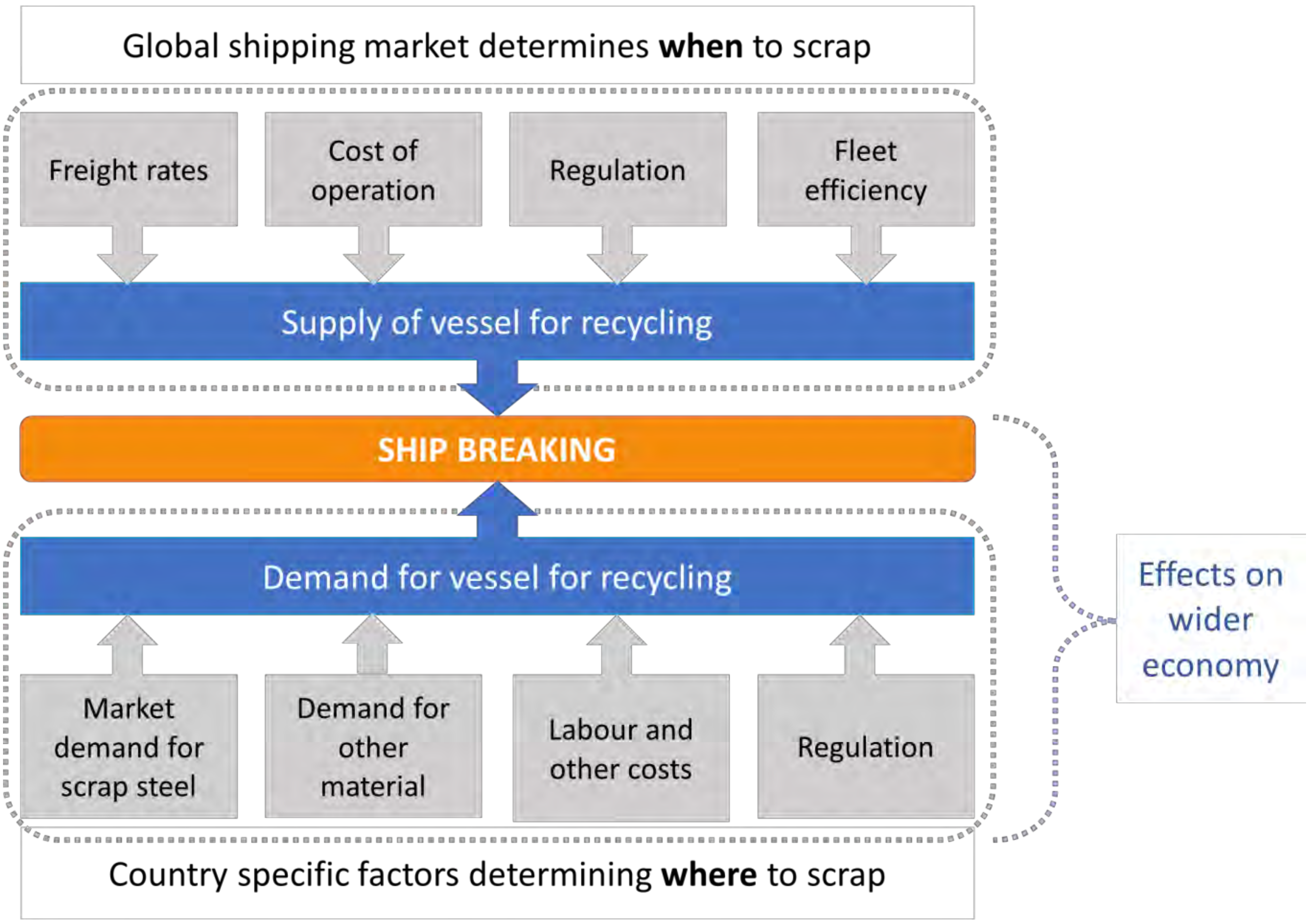
based on its light displacement tonnage (LDT) (Mikelis, 2019).[25]

The process of trading an EOL ship could vary but the most common for a shipowner is to sell a vessel directly to a yard or through brokers or cash-buyers. Cash-buyers pay the shipowner in cash and thus have a purchasing advantage over the ship recycling yards as the latter can usually only offer the shipowner a small deposit and a bank letter of credit. The shipowner first contacts a shipbroker specializing in EOL vessel sales, who in turn will contact different cash-buyers. Alternatively, the shipowner could contact the cash-buyers directly. The existence of open registers specializing in EOL ships (also known as “last voyage flags”), many of which are listed as grey or black by the Paris MoU, allows the cash-buyer who now owns the asset to re-register a ship and typically change its name before re-selling it for scrapping. Such procedures together with the use of convoluted offshore ownership structures (“shell corporations”) also adds to the challenges of identifying the true owners of an EOL vessel.

The international ship recycling market is influenced by complex dynamics of demand and supply, but the pricing of EOL ships is generally based on the price (demand) for scrap steel and the supply of EOL ships, the latter of which is heavily influenced by the rates on the freight market (Stuer-Lauridsen et al., 2003). With strong freight rates is it unlikely that a shipowner will choose to scrap a vessel, unless this is influenced by other factors such as accidents, regulation, or technical issues (CEC, 2007b). Since scrap steel is the main cash-inflow for ship recycling yards, the price paid for a ship depends on its ratio of steel to other materials. Figure 4 illustrates price formation in the international ship recycling market. Often the ship recycling yard is competing for a vessel with other yards in the same country where workforce salaries, regulation on working conditions and environmental issues are comparable. The competition may be fierce, and the yards are often business-wise seen as capital-intensive, high-risk environments where especially the larger facilities in South Asia participants are betting on increasing steel prices during the recycling of a vessel.

25 Light displacement tonnage is the displacement of a ship as constructed (unloaded) without fuel, ballast and potable water, any other items that are not fixed to the ship. It is roughly equivalent to the steel weight.

Figure 4: Ship recycling demand and supply

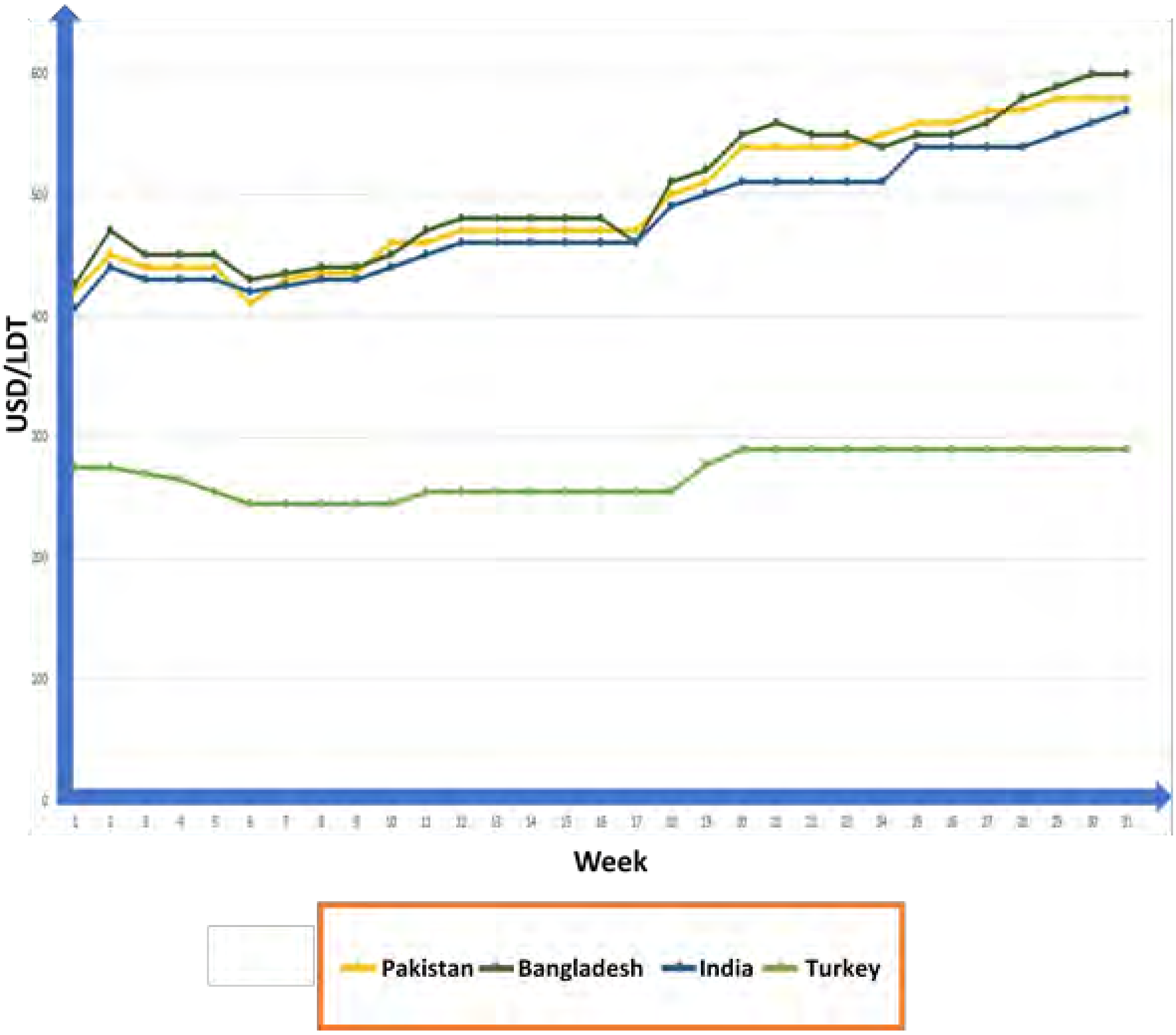


In some ship recycling countries, re-export of scrap steel is not allowed and the existence of only a domestic commercial market has led some yards to become part of local industrial and construction conglomerates. Here, the business case is more directed towards providing a robust steel supply chain for the construction industry.

Over the last couple of decades when Turkey, India, Pakistan and Bangladesh (with China on and off) have recycled more than 90% of the annual EOL fleet there has been a consistency to the regional price development (see global demolition market chart as per August 23, 2021, in Figure 5). Turkey offers approximately 50-60% of the prices offered in South Asia, a gap that has typically been 100-200 USD/LDT but has recently widened to nearly 300 USD/LDT. Pakistan and Bangladesh typically offer 5-10% more than India, but they are also taking preferably tanker and bulker tonnage where the output of re-rolled plates is larger and much simpler to recycle.

Obviously, the lower hourly pay will lower costs for the owner of a ship recycling facility, but also the suspected lax enforcement of occupational health and environmental protection in these countries may boost the business case and the lack of facilities for receiving hazardous materials may also contribute to lowering costs.

Figure 5: Example of average demolition price (USD/LDT) difference between Turkey and South Asian ship recycling yards (January 1-August 23, 2021)



Source: https://www.go-shipping.net/demolition-market

Waste streams from a vessel can broadly be divided into three main categories, listed according to the circular economy hierarchy: Re-use, Recycle, and Disposal. Waste streams that can be reused and recycled are revenue-generating, whereas materials for disposal could either incur costs (e.g., for the safe and environmentally sound handling of hazardous materials) or have neutral disposal costs (Jain et al., 2017b). Table 8 shows the material streams of an EOL ship based on the Material Flow Analysis (MFA) approach, as suggested by Jain et al. (2016).[26]

After a ship is received at a ship recycling yard, it is salvaged for as many valuable components and materials (e.g., main engine, boilers, propellers, propeller shafts, instruments, and electronics) before cutting the steel hull of the ship into metal plates that can be re-rolled and other steel items that can be remelted.

26 MFA analysis has also been applied to other industries, such as, the automotive industry (Mathieux and Brissaud, 2010) and e-waste (Kahhat and Williams, 2012).

Table 8: Main material flow categories of an EOL ship as a percentage of total LDT (based on an 11,044 LDT handy-max bulk carrier)

Economic value stream (EVS)/ Non-economic value stream (NEVS)	Material stream	% of total LDT	Weight in tons
EVS	Ferrous scrap metal	84.60	9,343
EVS	Nonferrous scrap metal	1.04	115
EVS	Machinery	6.18	683
EVS/NEVS	Electrical and electronic equipment (instruments)	1.24	137
EVS/NEVS	Minerals (toxic and non-toxic)	2.52	278
NEVS	Plastics	1.19	131
EVS/NEVS	Liquids, chemical and gases	1.03	114
EVS/NEVS	Joinery	1.28	141
NEVS	Other types of waste	0.92	102
Total		100.00	11,044

Source: Adopted from Jain et al. (2017b).

THE SHIP RECYCLING MARKET IN DENMARK

As a starting point it is worth noticing from our conversations with some of the Danish ship recycling yards and supported by evidence from Sea-web regarding the types of ships they recycle, that there is no observable case of strong competition between them. Each of the yards occupies a specific niche of the market based on their expertise. This leads us to believe that there is a strong possibility for Danish ship recycling yards and other involved market players to increase cooperation, create an efficient internal market and jointly strengthen the competitiveness and position of Denmark as a player in the global ship recycling market.

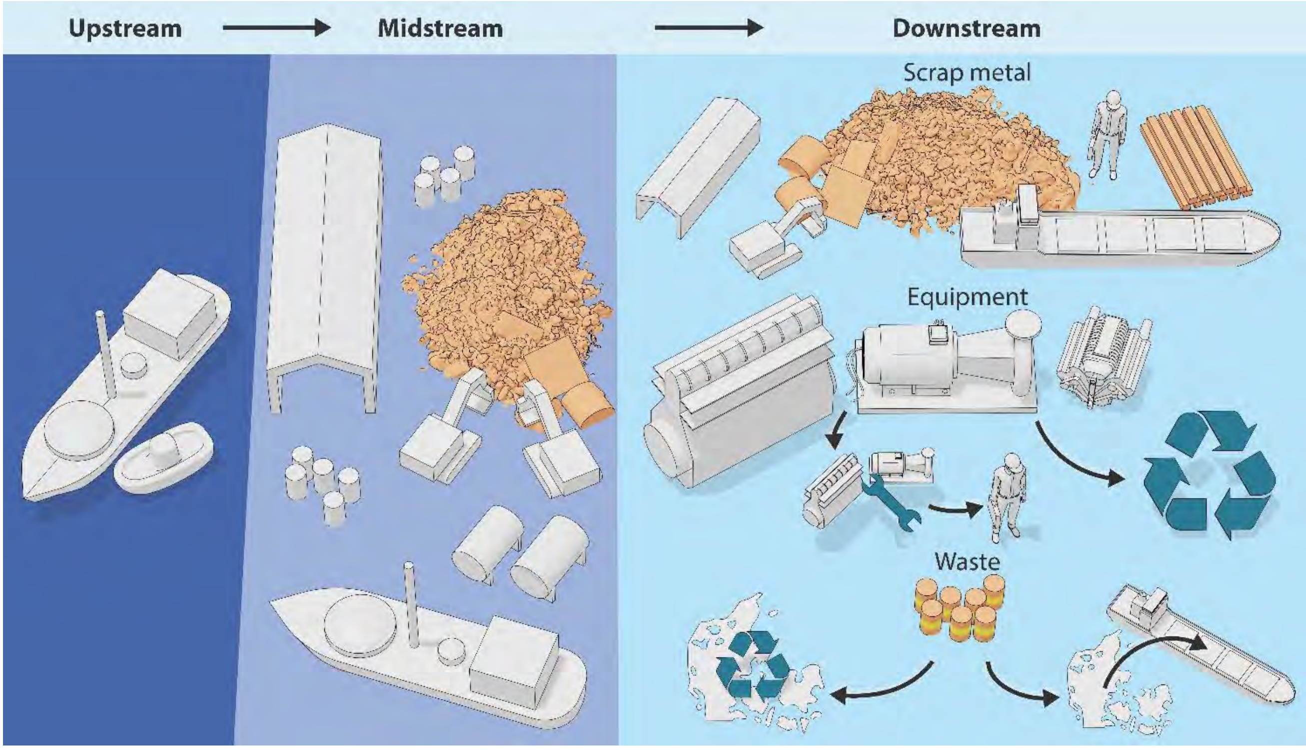
In addition, as we have already argued, Denmark has the benefit of having strong expertise within maritime and associated sectors, a flourishing second-hand market absorbing some of the material streams from EOL vessels (such as used equipment), and appropriate infrastructure in place for handling waste. On the other hand, the scrap steel from EOL vessels is generally exported as Denmark currently has limited re-smelting or re-rolling capacity. In this context, it seems appropriate to recall that, rather than relying on locally recovered materials, NLMK DanSteel currently imports all of the steel slabs that it rerolls into sheets.

To better demonstrate and analyze the specifics of the entire value chain of ship recycling, this analysis tried to build a conceptual framework around EOL, placing the ship recycling yards center stage in the dual role buyer and seller. We have identified three different stages of ship recycling, as also shown in table 9:[27]

- Upstream: Selling and buying the vessels for recycling
- Midstream: Breaking the vessels into different material streams at the yard
- Downstream: Further processing and utilizing the materials and items recovered from the EOL ship

27 This framework presented in figure 6 will likely look different in other major recycling destinations, such as, in Turkey or South Asia, but the fundamental concepts will remain unchanged.

Figure 6: : An outline of the ship recycling market in Denmark



Own illustration (graphics by Mousemover©)

The outline presented in figure 6 allows for the market players to be clearly identified and their different roles to be distinguished. For example, a shipowner has little role in the market after it has sold its vessel, either to a cash-buyer or to the ship recycling yard directly, the latter of which is quite common in Denmark.[28] However, it is important to state that this is the case in the current take-make-dispose, linear economic model. The adoption of a circular economic model will importantly reshape this outline and include further players, which are currently not specifically included (e.g., new-building shipyards or original equipment manufacturers). Furthermore, one way of mapping and clustering the downstream market within ship recycling is based on the material streams that they handle.

Table 9 summarizes our preliminary findings on the characteristics of the ship recycling market in Denmark. Our analysis reveals significant market inefficiencies. We also observe high entry-barriers, making it difficult for newcomers to enter the market and potentially limiting the level of innovation in the industry. This is because new market entrants typically compete with established players by introducing, e.g., better substitute products, or (particularly relevant in the context of circular economy ship recycling) new business models, including by the introduction of innovative technical solutions to generate value to customers (Bocken et al., 2014).

28 For example, in 2018 the Danish company ESVAGT sold and delivered two vessels to Fornæs Ship Recycling in Grenaa (https://www.offshore-energy.biz/esvagt-sells-vessel-duo-for-recycling/). Our interviews confirm that this is a common practice in Denmark, especially among the ship recycling yards purchasing smaller vessels.

Table 9: Characteristics of the ship recycling market in Denmark

Indicator	Empirical findings	Market indicators deviating from a theoretical model with perfect competition
No. of yards	Six	Yes
Product characteristics/ no. of products	Differentiated, but could be grouped into segments	Yes
Entry barriers	Capital intensive (both human and financial, e.g., specialized technical expertise needed) Conservative, low-transparency market based on: - Ties and trust (cluster) - Bazar economy - Market pricing (emerging online sales)	Yes
Regulation	EU-SRR, EU-WSR, Basel Convention, local (municipal) environmental licenses, etc.	Yes
Control setting	Price negotiated per ship and not disclosed (yards in competitive bidding) Used equipment and other waste streams usually negotiated and not disclosed	No
Competition	Price, yard capacity, specialization in certain types of vessels	Yes
Profits	Low profit margin (derived from benefit of scrap steel) – joint production On individual components (profits can be above-normal) due to scarcity and market diversification	????

The textbook economics model of perfect competition – where all firms sell identical products and are price-takers, capital and labor resources are perfectly mobile, firms can enter and exit the market without costs, and where buyers have complete information about the product being sold and the prices charged by each selling firm – only specifies the socio-economic benefits of a competitive market structure. In the context of the present study, the focus is on how the actual market functions and how it can be improved to scale the activities and increase the economic benefits of recycling material from the recycling of ships. As noted earlier, the companies scrapping ships are each part of a niche market and are each including the recycling of ships within a greater pallet of activities. The direct competition between Danish scrapyards in this segment is therefore generally low.

The fleet analysis presented in chapter 5 indicated a segmentation of the market available to each of the Danish ship recycling and ship repair yards, considering the limited physical space available to the yards within the port land area (especially storage facilities), the business model of the company, the actual ship recycling infrastructure (availability of slipways, drydocks, harbor access for the inbound and outbound shipping of scrap metal), access to capital (to buy the EOL-ships), and issues of time/speed in the process.

Entry barriers into ship recycling are generally high, and new companies – as well as systemic growth in existing companies – may have difficulties in establishing competing activities due to several market barriers. The capital requirements are very high, the tacit knowledge needed to enter the market (pricing of EOL-ships), and the non-disclosure of market prices on both input and output in the value chain is impeding growth outside existing companies. In addition, the needed land area (in ports) is not easy to come by.

Financial matters cannot be divorced from their corresponding economic context. Lack of capital may lead to alternative measures of hedging against the risk of loss. One strategy used by several of the Danish yards is to contract sales of scrap steel prior to buying an EOL-ship for dismantling. Other companies with deeper pockets or better access to financial capital may utilize the volatility in the steel-market to await better prices.

The general lack of market transparency is both a cost and a benefit for the companies targeting the second-hand market for recovered ship parts. Smedegaarden and Fornæs both target this market, although their business models differ (please see chapter 4). Both dismantle and extract material items targeting a second-hand market for reuse. The market they target is very diversified and non-disclosure of prices is the norm. Arguably, the competition from South-East Asia would lead to underbidding of all prices according to the
Danish sources in the market that we have interviewed for the present study. Creating a more transparent market would require building up solid knowledge of price formation in this second-hand market, useful for budgeting and bidding on EOL-ships, which is not an easy target. Such increased market transparency would come with the additional benefit of improving the choice of most profitable strategy – i.e., extracting components or shredding all material for the steel market.

The market for repair or re-manufacturing of used components is global and has attracted attention by Fornæs, as a strategy for creating a larger market outlet through networking. Their homepage specifies several collaborating companies, such as, the Norwegian ship recycling yard Fosen Gjenvinning (which is also a facility approved on the EU list), the Danish marine component repair company Skibselektro (recently acquired by HE Marine and thus becoming part of company present in many Danish ports) and the Swedish engine maintenance and repair company Persson's Maskinservice A/B, which together provides a network of companies covering all aspects of the mid-stream and downstream ship recycling market in Denmark and nearby countries.

On a final note, we wish to emphasize several key findings and tentatively suggest measures that could improve the market conditions in Denmark towards circular economy clusters for sustainable ship recycling.

ENV licenses are seen as a barrier: Danish shipyards are classified under Danish Legislation as "particularly polluting companies" and thus have to operate under Environmental Licenses issued by the municipalities within which they operate. During the interviews, some yards highlighted that they are concerned about the level-playing field within Denmark due to differences in the environmental standards they have to comply with compared to yards in other countries. However, our interview with one of the municipalities indicated that municipalities often collaborate when drafting an environmental license for ship recycling, specifically in order to create a level-playing field. A closer comparison of environmental licenses in Denmark and abroad reveals that some differences can indeed be identified but that this can often be attributed to local circumstances, such as, the yards' proximity to residential areas and other spatial characteristics, facilities conditions, and yards' facilities (e.g., for storing hazardous waste). Therefore, while local improvements can be made the focus should be put on developing a level-playing field globally.

Small margins: Similar to the scrap steel industry, the volatility of the ship recycling market makes it difficult for the yards to justify capital intensive investments, e.g., in automatization. Despite having high turnover, yards generally work with small profit margins. A visit to one of the yards revealed that scrap steel is not strictly sorted but rather stored and sold in bulk via brokers to scrap steel processing plants outside of Denmark. This means that yards that are hesitant to invest in better sorting and cleaning of scrap steel cannot charge a premium for this material, which according to an interview with an industry association could potentially make scrap steel from EOL ships highly competitive in the market due to its very high-quality and controlled composition. One of the long-established ship recycling yards in Denmark confirmed during an interview that a recent capital-intensive investment implemented with the aim to meet and exceed industry standards for efficiency and sustainability has led to persistent financial loss.

Bidding for ships: When purchasing or placing a bid on an EOL ship, Danish shipyards rely largely on their own expertise or the expertise of an experienced assessor to come up with a competitive bid and predict how much revenue the vessel can generate versus how much costs its (sustainable) recycling will incur. Despite the fact that they to some extent rely on publicly available information (e.g., the global steel price), their profit margin is largely based on tacit knowledge. We identify this as a main barrier to entry. The use of a science-based technique for assessing vessels could not only potentially allow for current market players to place more accurate bids, but also allow for new entrants into the market.

Downstream market for used equipment: When it comes to the downstream market for items recovered from EOL ships, our interviews and site visits have indicated two distinct pathways:

- ***Recycle:*** Yards can choose to scrap all inventory, including machinery, in order to simplify the process and not hold inventory. These yard's focus on the market for vessels with high steel-to-equipment ratio, including offshore structures. When they value a potential vessel to purchase, their bid is mainly based on the scrap steel market price.
- ***Reuse and resell:*** Yards choose to accurately separate any reusable equipment and sell it on the secondhand market. In individual cases, they can refurbish, especially mechanical equipment, but they do not engage in product remanufacture. These yards focus on the market for smaller, more technically advanced ships with high equipment-to-steel ratio. These yards generate more than half of their revenue from the secondhand equipment and parts market.

From a circular economy perspective, the reuse of parts is both more cost effective and environmentally sustainable but could incur a possibility of building-up inventory of old equipment that risk becoming obsolete and must nevertheless be recycled. According to one of the yards with a focus on recycling, they are, from a circular economy point of view, downgrading.

Trying to measure the downstream market in each of these two distinct cases has proven difficult as transactions are not disclosed and yards are unwilling to share any detailed information, for competitive reasons. It would be easier to measure the size of the market for the yards that generate most of their income from scrap steel, as the price they receive largely reflects the global scrap steel price. It would be much more difficult to capture the size of the market for used equipment, and not a mature and economically efficient market. This current market structure also discourages some yards from using their facilities for ship recycling and re-selling of equipment, rather than the more lucrative ship-repair market.

In some cases, an EOL ship can contain an engine or an item in high demand on the global market, potentially generating as much as 10 times the actual market value. On the other hand, some navigation equipment would have little current market value and could be stockpiled for 30 years before finally being discarded. However, the market for some used equipment spans outside of the maritime industry (e.g., pumps going to farming) where it is less likely to have negative consequence from failure.

Another issue that we have identified is that Denmark exports all its scrap steel. Indeed, Europe ranks as the number one scrap steel exporter in the world (BIR, 2017). This might not seem as an immediate concern, but as highlighted by Oda et al. (2013) future scrap steel supply will not be able to meet demand. Despite that Denmark and Europe currently utilize little scrap steel into their own production, this practice could change, possibly driven by governmental intervention to improve the ecological footprint of those industries that today use virgin iron ore as input material. It should be emphasized in this context that iron ore is in abundant supply worldwide but that it takes energy to extract and to recycle.

For recycling and circularity, the problem is essentially thermodynamic. Cleaning recycled steel of contaminants requires energy, and with enough sorting and cleaning perfectly adequate alternatives to virgin steel are possible. A key challenge is that attaining the mechanical properties of virgin steel may use up more than the energy saving originally identified from recycling. Recycling will proceed if there is a market for downcycled steel, but it will probably never be fully circular. Aspiring to greater circularity will depend on institutional arrangements and new technology, among others, for recycling flows (and on the extent to which the virgin steel industry can manage its own footprints), in particular those related to energy.

Much more analysis of additional data is needed. Our interview with a representative from Worldsteel hints at the issue by mentioning that better quality scrap is used for “flats” (car doors). This interview also noted that signals from Liquid Metal Embrittlement (LME), a type of cracking occurring in the welding of advanced steel, are often crowded out by political communication that emphasizes notions about circular economy. For circular economy in steel recycling to progress, the flow of steel being recycled needs to be separated into streams with different attributes in terms of quality. Furthermore, steel recycling is not the end of the story. How recycling is conducted may in the long run be especially important. In one sense recycling of steel is almost too easy, the structure containing steel only needs to be shredded and separated using magnets. Up to a point this is fine but certain other metals can remain and are difficult to remove after melting.

SUPPLIER ANALYSIS

The previous chapters have analyzed the fleet of near EOL ships potentially available for recycling in Denmark, the structure and competitive dynamics of the Danish ship recycling industry, and the workings of the ship recycling market. The chapters have thus focused mainly on the EOL phase of ships. However, a truly circular economy perspective must adopt a complete lifecycle perspective and include investigation of circular economy interventions and potential circular business models also in ship design, shipbuilding and operations. In the following, we therefore broaden the scope of the analysis to include marine equipment and service suppliers, as we believe sustainable ship recycling provides business opportunities to marine suppliers and that marine suppliers both thrive from and shape the business ecosystem for ships.

The transition to a circular economy will impact all industries, but especially heavy equipment manufacturers are believed to adopt circular economy thinking with an aim to bring down the costs of production and maintenance, and thus one would expect the circular economy to be high on the agenda for manufacturers and suppliers of marine equipment. A significant number of Danish marine equipment suppliers are engaged in generic repair work, from wires and cables, ship fittings, and light electrical, electronic and navigation equipment (e.g., Skibselektro and Grumsen Equipment) to engine components and entire propulsion systems (e.g., Nordhavn A/S and VMS Group). However, the initial rendering of circular economy in this industry following from our research is that still only few marine equipment suppliers take it to the next step towards circular economy by engaging in remanufacturing and eventually repurposing. This general impression of the state of the industry corresponds well with earlier studies showing that, even though remanufacturing is generally widespread among sectors that produce capital-intensive and durable goods (including other transportation sectors such as aircraft, aerospace, automotive and rail), it tends to be underdeveloped in the maritime industry (Wahab et al., 2018; Milios et al., 2019).[29] There are nevertheless good examples of Danish marine equipment providers applying circular thinking into their business and operating models, and in this chapter we will discuss some of these.

Marine equipment in Europe is a significant industry with more than 22,000 original equipment manufacturers (OEM) and suppliers delivering materials, systems and equipment to all types and sizes of ships and offshore vessels or providing naval engineering and consulting services. The industry employs more than 320,000 people in Europe and generates a production value of about 520 billion DKK annually (www.seaeurope.eu). There are currently more than 1,000 marine equipment suppliers headquartered in Denmark, many of which are world leaders within their niches and highly innovative and R&D focused. About 140 of these companies are members of the interest association Danish Maritime, and several hundred others are members of the Marine Group under the Danish Export Association[30]. In addition, many other companies not organized in Danish Maritime or in Marine Group specialize in servicing the maritime industry or have a maritime leg in their broader business portfolio. The Danish marine supplies industry produces an estimated annual gross value added of almost 40 billion DKK and together with the Danish yards employ more than 38,000 people in Denmark, directly or indirectly (COWI, 2020).

To illustrate the broad scope of the Danish maritime industry, table 10 provides an overview of the members of Danish Maritime categorized into the different types of materials, systems and equipment supplied to ships and shipyards. We initially categorized the companies in accordance with the classification provided by BALance

29 Aircraft recycling is a fairly young but fast developing industry, and there is a tendency to retire aircraft earlier in their lifecycle with the aim to harvest parts such as galley carts, trays and overhead bins for reuse in new aircraft (Leblanc, 2019). Also, reusable materials and some component parts are increasingly recovered from EOL aircraft and reprocessed to produce electronic products (e.g., circuit boards, computers and TVs).

30 Danish Maritime is the main industry association for the shipyards and marine supplies industry in Denmark. While Danish Maritime has the largest marine equipment suppliers as their members, Marine Group counts many of the additional but smaller and medium-sized companies in the industry.

Technology Consulting (2014), and then in consultation with Danish Maritime verified the categories to the Danish areas of expertise.

Table 10. Members of Danish Maritime

Area of expertise	No. of companies
SYSTEMS/EQUIPMENT	
Accommodation	5
Auxiliary systems	29
Electrical and electronics	14
Propulsion and power generation	11
Navigation/nautical and communications technology	4
Ship operation equipment	6
MATERIALS	
Steel and steel parts and other hull materials	4
Pipes and ducts	1
Paints and coatings	2
Chemicals/lubrication	1
SERVICES	
Design and engineering	26
Other/consulting	23

* The table does not include 13 of the shipyards that are members of Danish Maritime and active in 1) repair, maintenance and conversion, 2) newbuilding; and 3) ship recycling, as they were dealt with separately in chapter 4. The table does include Hvide Sande Shipyard, Steel and Service, since this yard is also engaged in original manufacturing of complex steel and aluminum structures and platforms as well as other equipment for the shipping, wind and offshore industries.
** Some members of Danish Maritime (e.g., ABB, Siemens Marine, or Wärtsilä) have several major business lines and are counted in several of the categories.

A half a hundred members of Danish Maritime provide design and engineering services, as well as other marine consultancy, and many of these have applied circular economy thinking in their business and operational models. Some examples of Danish engineering companies with circular business and operational models are MAN PrimeServ, MarineShaft, Nordhavn, and VMS Group.

Currently 30 members of Danish Maritime are original equipment manufacturers of auxiliary equipment, such as, fuel systems, marine fluid technologies, exhaust gas treatment systems, HVAC, ballast water treatment systems, firefighting equipment, pumps, sanitation, general engine room outfitting, valves and seals, and more. An additional 18 companies specialize in electrical and electronics equipment, such as, generators, batteries, lighting, electrical heating, electronic circuits, nautical equipment, communication technology, monitoring and measurement instruments, and alarm and control systems. Danish suppliers of auxiliary and electrical and electronic equipment are typically medium sized to large companies serving the shipping industry worldwide. Many of them are world leaders within their field, including ABB, Alfa Laval, Cobham SATCOM, Danfoss, DEIF, DESMI Pumping Technology, Green Instruments, Iron Pump, KLINGER Denmark, Pres-Vac Engineering, Siemens Marine, Svanehøj, and Wärtsilä Denmark. Some of these companies are pioneering new circular business models for the maritime industry, often with the broader aim to achieve carbon neutrality. We will discuss some of these in the sections below. It should be noted that for some types of especially smaller electrical and electronic equipment (e.g., circuits) the marine suppliers occasionally take back used products for reuse in other vessels. However, this is typically not as part of a circular business or operational model but out of necessity, and it is not something from which the companies can generate profits.

Ten of Danish Maritime's members are original manufacturers of propulsion and power generation systems, such as, diesel engines, boilers, turbines, gears and couplings, propeller, rudders, shaft and bearings, and auxiliary engines and boilers, and some of them are big, multinational companies dominating the industry globally (ABB, MAN Energy Solutions, Siemens Marine, and Wärtsilä). Several of these companies apply circular business and operational models, but to a limited extent and mainly for component parts rather than complete propulsion systems. While individual engine parts (e.g., connecting rod, pistons and crankshaft) require regular maintenance and can be replaced with used or remanufactured parts, the main and auxiliary engines themselves may be more difficult to reuse, or indeed remanufacture. One of our respondents, a representative from Man Energy Solutions, noted in this context that for larger vessels, primarily those of a two-stroke propulsion design, the power plant is very tightly integrated with the design of the vessel, including the design-life of power plant relative to that of the vessel. Obsolescence, to put it bluntly, generally hits the whole vessel. On top of this comes the fact that marine engines for the international shipping industry are in constant process of technological advance and only when parts for a sister ship are needed and available at the same time does it make much sense to rely on the vintage market.

Circular economy approaches in the Danish maritime industry

The question of how maritime equipment suppliers approach circularity can be seen from an input perspective, where the circular strategy focuses on reducing material and energy inputs into own production, and an output perspective, where the focus is on product life extension and the subsequent material recovery at the end of product life (e.g., through repurposing). When viewed from the input perspective, it is evident that many of the OEMs in the Danish maritime industry apply circular economy thinking in their raw material sourcing and in the production process, and increasingly so. However, the degree of commitment to circularity in sourcing, production and products and service offerings differs, from the highly intentional approach in primarily large companies supplying heavy equipment, where circularity is embedded in corporate level strategy, to the more unintentional, where the sourcing decision is discrete and rooted in price considerations.

For some companies, circularity in sourcing decisions seems more a fortuitous feature of the general market dynamics for the different materials used in marine equipment than a careful purchasing strategy of the individual OEM. For example, in manufacturing of water pumps, a company such as Iron Pump uses copper casting made primarily from recycled copper scrap, but since copper can be remelted and used directly (with little or no further refinement needed) without losing any of its chemical or physical properties it is in fact one of the most recycled metals in the world (Doebrich, 2009).[31]

Some Danish maritime suppliers apply circularity in their own production, often on an ad hoc basis when discovering how upgrading possibilities can feed into the companies endeavors to become more circular. To give an example, in 2018 Hvide Sande Shipyard, Steel and Service replaced their old wastewater treatment plant, used for treating the wastewater from washing ships before they are painted, with a modern evaporator from Envotherm capable of treating up to 150 litres of wastewater per hour. The wastewater contains paint residues, heavy metals and other chemical residues and thus improving waste management is an important step towards a circular operating model. The purified water coming out of the new evaporator is so clean that it can be reused for washing ships. In fact, the first two samples that were taken for analysis revealed that the quality of the treated water was higher than the requirements for drinking water in Denmark (for more information, please visit https://hvsa.dk/we-care-for-the-environment/).

For other maritime companies, circularity in sourcing and production decisions is a recent phenomenon rooted in the strategic apex of the company and motivated by a long-term perspective considering the company's social license to operate and grow. For example, in Danfoss, which is

31 According to the Copper Alliance, about 35 percent of global copper demand comes from recycling and in some regions of the world (e.g., China, Europe, Japan) more than half of all copper is recycled after use (https://sustainablecopper.org/circular-copper/).

one of the world's leading suppliers of HVAC and power solutions for a broad range of energy-intensive industries, including marine and offshore, the elimination of waste and the promotion of materials reuse have become a strategic concern, and Life Cycle Assessment (LCA) of the company's products is now being implemented as a management concept across all business units. Danfoss describes its circular thinking as promoting "elimination of waste and the continual use of natural resources through sharing, reusing, repairing, refurbishing, and recycling of existing materials and waste in an almost closed loop" (https://www.danfoss.com/en/about-danfoss/company/sustainability/circular-economy/).

A new product exchange program model called "Re-Made to matter" has been developed in strategic partnership between Alfa Laval and Stena Recycling and initially focusing on customers located in the Nordic region (https://www.alfalaval.com/industries/energy-and-utilities/sustainablesolutions/sustainable-solutions/sustainable-partnership/re-made-to-matter-partnership/). With Re-Made to matter, worn plate heat exchangers are retrieved from customers with a refund, recycled by Stena Recycling and reprocessed by Alfa Laval into new and improved heat exchangers, which are then delivered back to the customers. The model is truly circular in both an input perspective, as it significantly reduces virgin material extraction and processing, and an output perspective, as it allows customers to upgrade less energy-efficient plate heat exchangers to state-of-the-art, environmentally friendly products. Re-Made to matter is a decidedly strategic initiative for Alfa Laval as part of the company's aspirations to become carbon neutral by 2030.

In addition to companies creating circular business and operational models aiming to reduce material input in own production or lifetime extension of own products, there are also companies that specialize in third-party services to OEMs, providing analytics, specialized know-how and technologies for product lifetime extension and other circular economy interventions. The start-up company Reflow Maritime, for example, provides digital solutions for calculating, documenting and sharing data on environmental performance (e.g., carbon footprint) over the lifecycle of marine components as well as consultancy on how to implement circular economy principles in the maritime industry. Another example is the naval engineering and consultancy company OMT, which was established as a spin-off from Odense Steel Shipyard Lindø when the yard closed in 2012. OMT designs ships and provides a range of services for the maintenance of the onboard equipment on the ships they have designed. This includes improved proactive or predictive maintenance and onboard analytics that allows for extending the operational lifetime of onboard components and systems.

Remanufacturing

An earlier study (Jansson, 2016) outlined the challenges and benefits of remanufacturing in the maritime industry. The benefits to customers from using remanufactured equipment is that the price might be lower, and the energy footprint might be significantly smaller. The suppliers of remanufactured equipment would primarily be that if a market for this kind evolved there would be opportunities to compete with manufacturers of new equipment. Whereas manufacturers of new products need to be able to demonstrate the quality and usefulness of new items, remanufacturers need to demonstrate the advantages of their products, sometimes with an added requirement for conformance to industry standards and tolerances. Remanufacturers also need to provide compelling arguments that their items remain viable even beyond their originally stated design life.

While such a requirement to product quality and standard assurance for remanufactured items may be considered as an important barrier to circular economy in the maritime industry, which is generally considered a rather conservative industry, there are also other important obstacles that must be overcome.

A recent study of the maritime industry in Denmark and Sweden by Milios et al. (2019) identified several such interconnected economic and market, regulatory, and information and awareness barriers: 1) the rigid rules of the classification societies, 2) general lack of skills needed for reuse and remanufacture in shipyards and original equipment manufacturers as well as in third-party independent remanufacturers, 3) an insufficient take-back infrastructure for used items and lacking planning competencies for sourcing remanufactured equipment, and 4) absent economies of scale in European shipyards, making it difficult to earn profits from remanufacturing of maritime equipment and components.

Figure 7: Examples of circular business models in the Danish maritime industry

A number of Danish maritime suppliers have made repair, refurbishing and remanufacturing of marine equipment their specialty (see figure 7). Some companies have specialized in repair and installations of light equipment such as electrical and electronic devices.

- MAN PrimeServ is the aftersales service arm of MAN Energy Solutions, servicing the parent company's customers worldwide and undertaking technical assistance as well as component repair and refurbishing, sometimes even profound overhaul and testing of engines.
- MarineShaft is a medium-sized Danish marine equipment provider established in 2004. It specializes in manufacturing marine propeller shafts and repairing and reconditioning of propulsion equipment, rudders and rudder arrangements, and cranes and winches, using purpose-built machinery capable of handling all sizes of manufacturing tasks. Wärtsilä Denmark has also developed a profitable business in reconditioning and remanufacturing of propeller shafts, an activity that it undertakes in its propulsion workshop in Nørresundby. Both companies have many years of experience in cold straightening of propeller shafts, which is much faster and much cheaper than manufacturing new shafts.
- PJ Diesel Engineering is a family-owned marine supplier that already at the time of its establishment in 1978 pursued a circular business model. It specializes in repair and reconditioning of key components for large diesel engines and turbines, including fuel systems, turbochargers, governors and electronic controls, gas engine systems, turbines, power management, and engine components such as cylinder covers and liners, pistons, connecting rods, and exhaust valve cages.

Currently only one Danish marine equipment supplier has, to our knowledge, developed a business model for repurposing of the materials recovered from their own EOL products and thus keeping the materials in a circular loop, namely VIKING Life Saving Equipment – a global leader in marine and offshore safety equipment and operating procedures. Viking has entered a collaborative agreement with the Danish design company Grünbag to manufacture the "VIKING Lifebag", a sporty bag – orange on the outside and silver on the inside – made of durable fabric recycled from life-rafts. Although this business developed from a random incidence, where one of the co-founders of Grünbag happened to walk by a pile of worn-out VIKING life-rafts on their way to incineration, VIKING has over the years built expertise in sorting and handpicking the proper fabric from retrieved EOL life-rafts for reprocessing by Grünbag. The Danish cleantech recycling company Plastix has developed a similar repurposing model based on plastics recovered from the maritime industry (including recycled fishing nets, ropes and trawls). This initiative is however not carried out in collaboration with marine equipment providers but in collaboration with ports and ship recycling yards (including Smedegaarden).

There are some interesting similarities among many of those Danish maritime suppliers that are today engaged in repair, refurbishing and remanufacturing activities:

1) They have evolved from metal working and blacksmithing companies occupied in small-scale production. Each company holds many years of experience within their particular trade, and some can trace their history back more than 100 years (e.g., Aalborg Boilers was founded in 1919 and is today integrated as the Danish subsidiary of Swedish Alfa Laval)
2) They employ skilled people, including highly specialized people with expertise in the particular types of equipment that each company focuses on and more generalist mechanics such as ship fitters, machine workers, and certified welders.
3) Their production facilities are located within or in close vicinity to ports, and although the majority of the companies are expanding into other geographical locations, in Denmark and abroad, they have generally maintained and strengthened their presence in the location where they were originally established. They are embedded in the local network of shipyards and other marine suppliers within the broader port area with whom they have repeated transactions and close collaboration based on ties and trust.
4) They invest in precision tools and workshop facilities with the aim of attracting high-value, niche projects from customers all over the world. Investments in raw material stocks are also common, as this allows the companies to meet unforeseen demand (e.g., in case of equipment breakdown on a ship) and provide speedy solutions.
5) They are growing companies and they are currently consolidating their presence in several port areas within Denmark. Growth and consolidation take place either through own upscaling investments or through mergers and acquisitions.

This chapter has documented how Danish marine suppliers and original equipment manufacturers, despite the presence of several interconnected and difficult to overcome barriers, increasingly adopt circular thinking in their business and operational models, however with different levels of strategic commitment. Only few of the companies relate their circular models to ship recycling, and those who do tend to be fairly small, craftsman firms catering to the reuse and occasional remanufacturing of lighter or simpler equipment, such as, electrical and electronic devices or selected engine components. In the broader business ecosystem for ships, it does not appear attainable to create circular economy hubs around the EOL stage of shipping assets. Circularity starts already at the original ship purchasing decision in the shipowner's office. This is where the decision to go for a vessel design prepared for maintenance and eventually recycling is made and it is where suppliers are sourced that can guarantee a take-back of their equipment at the EOL. However, because of the high degree of industrial clustering of maritime companies within the ports and because of their close interaction with associated recycling and waste management companies, there is potential for integrating ship recycling into the broader business ecosystem for ships in Denmark and enter materials and parts recovered from recycled ships in the resource circulation within this system.

SUMMARY AND REFLECTIONS

The project presented in this report has explored the potential for promoting a circular business ecosystem for end-of-life (EOL) shipping assets (vessels and marine technology) in Denmark. The number and diversity of ports, the development of the shipyards, the standing and current developments of the maritime industry, and the long history of steel and other materials recycling and waste management in Denmark imply substantial potential for creating and leading a Danish, maritime-focused circular economy model. The transition to a maritime business ecosystems based on circular economy would be a vital step in the further development of the sector in Denmark, while at the same time optimizing the use of material and energy resources in shipping, ports and maritime industry.

Considering current developments in the international regulation of ship recycling and the parallel institutional promotion of circular economy in the maritime context, the project has provided a detailed assessment of the EU registered fleet of near-EOL ships potentially available for recycling in Denmark, the business models and capabilities of Danish ship recycling and ship repair yards and the dynamics of the market for materials and parts recovered from recycled ships in Denmark. In addition, the project has provided a more preliminary appraisal of the circular business and operational models that are now being developed by Danish marine equipment providers and that may be seen as stepping-stones (in the sense of building upon already proven circular economy experience and expertise) for creating a circular economy around EOL ships and marine equipment.

Denmark has a well-established ship recycling industry with clustered activities in and around four ports. Indeed, Denmark is among the largest ship recycling countries in Europe and among top 15 in the world in terms of the number of ships being recycled. Comparable to Norway, Denmark It is also one of the countries with the most approved ship recycling facilities on the EU list These include Fayard, which is located in Lindø Port of Odense; Fornæs Ship Recycling in Port of Grenaa; Smedegaarden and Stena Recycling in Port of Esbjerg; and Jatob and Modern American Recycling Services (MARS) in Port of Frederikshavn. Over the period 2010-2019 these six yards plus the recycling company H. J. Hansen have recycled more than 180 ships of many different types and sizes (notice that the actual number is in fact many times higher). The business models of these yards differ but can generally be described as either a service model focused on cashing in on steel value, a second-hand trading model focused on appropriating value from recovering and reselling components and equipment, and an opportunistic model focused largely on maximizing the use of yard capacity by accepting ship recycling jobs as a buffer against infrequently low activity in the repair, maintenance and retrofitting market.

There are currently ten other shipyards in Denmark, some of which are located within the same four ports as the EU approved yards. They are active in building smaller and specialized ships or in maintenance, repair and conversions of all types of ships, and besides from complementing the Danish yards approved under the EU-SRR and strengthening the maritime clusters in the ports, they may potentially bid for ship recycling contracts as a means to smoothening demand fluctuations in ship repair and conversion. Our broad assessment of the Danish ship recycling yards has documented considerable and growing expertise in ship recycling in Denmark but has also pointed to a certain indisposition of the smaller Danish yards specialized in ship recycling to fully embrace circular economy business models as well as hesitancy to purchase ships for recycling among yards not confined to ship recycling. The latter tend to focus on repair works and profitable retrofitting projects instead but may engage opportunistically in ship recycling.

While the Danish ship recycling industry is robust, the further development of a circular economy model for sustainable ship recycling in Denmark would require a certain, critical mass of EOL ships available for recycling to be introduced as raw material or resource into circular economy flows. Traditionally, many smaller EOL ships are recycled at yards in Europe, while most large ocean-going ships are still sold to recycling facilities in South

Asia. Under the EU-SRR all EU registered ships over 500 GT must now be recycled at an EU approved recycling facility, which could have the effect that increasingly also the larger ships will be recycled in Europe. Our assessment of the relevant near-EOL fleet, which also considers that the world fleet has been growing substantially over the past decade, suggests there is a considerable number of vessels potentially available for recycling in Denmark in near to medium-long term.

By end-2019, more than 1,700 ships of 500+ GT were older than 25 years (858 of these ships were between 36 and 75 years of age). Almost 600 of the ships were registered in Denmark or nearby countries (Faroe Islands, Iceland, Norway and Sweden). The bulk of these ships are presently active in cargo and special purpose trades, mainly short-sea shipping, and many have had their operating lifetime extended once or more by refitting to accommodate current needs and standards. We believe that our fleet assessment provides a conservative estimate of the ships potentially available for recycling in Denmark in the coming years. For example, although we are now witnessing immense post-pandemic increase in freight rates for container shipping and for certain dry bulk segments, COVID-19 initially forced many shipowners to tighten their operating costs, including laying up and recycling of otherwise operational vessels. In addition, the intensified focus on decarbonization and stricter international regulation of shipping emissions will challenge shipowners to make modification retrofit or replace existing vessels.

In addition, we would emphasize that the upgrading to international standards that we are currently witnessing for South Asian ship recycling facilities, which tends to occur with the intermediating role of European “responsible shipowners” as well as specialized and independent ship recycling service providers, would put pressure on the EU regulators to approve them for the recycling of EU registered vessels, and thus work to preserve the international division of labor among ship recycling facilities that has evolved over the past 40 years, where especially large ocean-going vessels would still be recycled in South Asia in the future, while the smaller vessels, typically deployed in short-sea trades, would continue being recycled in Europe.

We carried out a deeper analysis of the market for ship recycling in Denmark. From a market point of view, the ship recycling yards are both customers (they bid for and buy EOL ships) and sellers (they sell the scrap steel, other materials, and used equipment). They also serve as bridge between shipping and other (sometimes closely related) industries such as the scrap steel industry, or industries (e.g., agriculture) that repurpose marine equipment to be used on land. Our analysis has revealed that the ship recycling market generally has low transparency on transactions and that it is thus difficult to estimate the size of the market. We found interesting characteristics of the ship recycling market in Denmark. On a positive note, we see a generally low level of competition between the Danish ship recycling yards, which tend to occupy niches, and this could potentially translate into increasing levels of collaboration with the effect of jointly strengthening the position of Denmark in the global ship recycling market. We also see a flourishing second-hand market for items and materials recovered from EOL ships, and an appropriate recycling industry and infrastructure in Denmark for handling waste streams from EOL ships. On the other hand, we found inefficient price formation as well as high entry barriers, the latter of which may be an impediment to innovation around a circular economy model. The market analysis points to a number of potential measures for improving the market conditions in Denmark towards circular economy clusters for sustainable ship recycling, such as, adjusting local regulation to obtain globally consistent standards and requirements, and improving the process of bidding for EOL ships (e.g., by implementing rigorous methods for assessing the value of EOL ships).

In a general sense EOL vessels have considerable potential for being a source of high-grade scrap, particularly with respect to contamination from other metals, which lowers the quality of scrap from other sources. Apart from hull coatings, marine scrap can more easily be kept uncontaminated by metals such as copper. Marine scrap may possibly be recycled at higher prices that scrap of lower grade. To benefit from such differentiation, metal scrap recyclers need to implement stringent separation practices and be able to document that their scrap output meets expected specifications.

From the above analyses we may conclude that Denmark has strong ship recycling capabilities and the general outlook for the ship recycling industry is promising. However, there are also a number of barriers that this industry faces, which may set a limit to its further development towards circular economy. Besides from the issue of a level playing field internationally, not least in terms of local differences when it comes to ship recycling yards obtaining the relevant environmental and other permits, as well as the general question of social acceptance, there are some key hurdles that need to be overcome, including better traceability of individual marine components and equipment, greater transparency in the markets and pricing of certain types of (ferrous and non-ferrous) materials and recovered items from ships, certification and warranties for remanufactured items.

Reuse and remanufacturing are attractive alternatives in some respects, but such practices are constrained by imperfect information flows, often characterizing items in these categories. Some items may come from vessels at the end of their design lives, and as such be of limited value because they too are more or less obsolete. Even old items, however, may still be relatively unwearied and may represent a higher resale value than scrap value. For potentially viable items recovered in the dismantling process their value is likely to depend on the documentation that accompanies them, all the way from the original manufacturer, through one or more refurbishments. A development of the market (transparency leading to lower search costs for the customers, better budgeting for yard owners in deciding what goes for scrap and which items it pays to salvage) is therefore paramount to significant growth in the second-hand market.

We finally broadened the scope of the analysis to include marine equipment and service suppliers, as we believe that the broader business ecosystem for EOL shipping assets provides business opportunities to marine suppliers and that marine suppliers thrive from as well as shape the business ecosystem. We tentatively showed how circular thinking has entered into the business and operational models of Danish marine suppliers and original equipment manufacturers, and how circular business models are gaining traction, however with different levels of strategic commitment. Only few marine equipment suppliers relate their circular models to ship recycling, and those who do tend to be small, artisan metalworking companies specialized in reusing, repairing and occasional remanufacturing of precision components such as electrical and electronic devices or selected engine parts. However, the geographical location of maritime suppliers in Denmark, with many of them clustered within the ports and interacting with yards and other port companies, and the close interaction that both the ship recycling yards and many of the maritime suppliers have with recycling and waste management companies, is indicative of the bottom-up potential for integrating ship recycling into the broader business ecosystem for ships in Denmark.

On the whole, our study documents that the building blocks for developing a business ecosystem for ships in Denmark based on circular economy are there, but such a system would not be formed squarely around the activity of recycling EOL ships. Rather, closing loops in such a system would involve all the stages in the lifecycle of ships, and for the system to be fully circular the ship recycling activity would just be one important piece. The question of how the whole system can triggered, configured and organized, and how ship recycling can be included, is complex. A real trigger could come from shipowners requiring take-back guarantees and servitized offerings from marine equipment suppliers when ordering new ships. Danelec Marine’s redesign for maintenance of its Electronic Chart Display & Information System (ECDIS), was the result of a servitization strategy and has reduced the use of materials and components while at the same increased product reliability and extended product lifetime. It has also meant reduced vessel downtime in case of equipment breakdown. Shipowners could advocate more strategically towards the legal implementation of extended producer responsibility through which the reuse, remanufacturing and potentially repurposing of certain types of marine equipment become part of the business models of original equipment manufacturers.

As for reconfiguring and organizing the business ecosystem for ships towards circular economy, there would be a need for lead organizations to pursue keystone strategies, focusing on creating platforms, tools and practices for easing the coordination of the whole system. The study by Milios et al. (2019) advocated for a global effort to coordinate and regulate under the umbrealla of classification societies and in accordance with international conventions of maritime affairs as the most effective way to promote circular economy in the maritime industry, but keystone strategies can in fact be developed by individual maritime companies, ports and other types of organizations in the industry as well. There are several examples already of organizations in the current business ecosystem developing keystone strategies for circularity and sustainability, and ship recycling could potentially be a target of such strategies. For example, in their role of landlords the port authorities in Port of Frederikshavn and Port of Grenaa actively promote ship recycling and also invest in broader infrastructure with a major goal of attracting sustainable and circular activities to their areas. MARS is one very visible result of such investment in Frederikshavn. Recycling and waste management companies are also developing keystone strategies of relevance for creating circular economy hubs around maritime industry located in ports. Stena Recycling's "Circular Initiative", of which the "Re-Made to Matter" collaboration with Alfa Laval is but one of several real outcomes, is developing as a platform for collaboration and inter-organizational actions for creating circular and sustainable material flows.

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CBS MARITIME

KILEVEJ 14A, 2ND FLOOR, 2000 FREDERIKSBERG, DENMARK
CBSMARITIME@CBS.DK · MAIN: +45 3815 3815
WWW.CBS.DK/MARITIME

CBS COPENHAGEN BUSINESS SCHOOL
HANDELSHØJSKOLEN