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Solutions for large batteries for waterborne transport

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D1.2 – Market evolution and potential within 5, 10, 15 years for different marine applications

Report details

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Project Abstract

The goal of the SEABAT project is to develop a full-electric maritime hybrid battery concept that is based on:

- Modularly combining high-energy batteries and high-power batteries,
- novel converter concepts and
- production technology solutions derived from the automotive sector.

The modular approach will reduce component costs (battery cells, convertors) so that unique ship designs can profit from economies of scale by using standardised low-cost components. The concept will be suitable for ships requiring up to 1 MWh of storage or more.

Public summary

The recent worldwide interest on the environmental issue has led to a dramatic increase on the battery use on board different types of vessels. In this context, the main purpose of this document is to identify the current state of the marine battery market and develop a forecast of its evolution with a 15-year horizon.

Therefore, the activity of this task of the SEABAT project is aimed to:

- identify the current state of the technologies available on the market where, as shown in Figure 43, it can be seen that the NMC LFP and LTO lithium battery technologies are the most used at the moment,
- identify the current state of the shipping market, represented by the number of units under construction and performing a forecast for the next few years, as proposed in paragraph 3.6,
- identify the state of the near innovations for the battery systems and propose a preliminary roadmap of battery development, as shown in Figure 10,
- Developing a market forecast of the battery market for maritime use with 15 years of time horizon, as summarized from Figure 90 to Figure 95.

From the previous analyses it can be defined how, in order to be competitive with the future market in the next 15 years, it is necessary to develop a standard of battery module for marine use that can meet the needs of different applications. Medium and large-range applications (from 1 MWh upwards) will be the proponent ones on the next market. For this reason, the batteries must guarantee modularity, flexibility and safety such that they can be easily integrated on board different types of ships with different system configurations.

Contents

1 Introduction

The public interest on the environmental issue has led to increasingly stringent regulations on greenhouse gas (GHG) emissions due to human activities. The maritime transport of goods accounts for more than 70% of the world trade in terms of value and 80% in terms of volume [1]. According with recent studies, the international shipping emitted in 2012 about 796 million tonnes of CO_2, which is close to 2.2% of the total emission for that year [2], [3]. However, the mid-term forecasting shown that by 2050, a grow between 50% and 250% in CO_2 emissions is possible, depending on the future economic growth and energy development.

In this context, also being one of the major human activities, it seems to be possible to significantly reduce the environmental impact of the international shipping. In the perspective of reducing the vessel's environmental footprint and the energy waste, already since 1983, the International Maritime Organization (IMO) has released regulations in order to minimize pollutant emissions [4]. Nevertheless, it is only since 2011, with the 62nd session of the IMO's Maritime Environmental Protection Committee (MEPC), that stringent mandatory measures have been adopted to reduce emissions of GHGs from both new buildings and already operating ships [5].

Several areas of action have been identified to improve the shipboard energy performances, such as: hull shapes optimization, the introduction of energy-saving devices, structural optimization, light weight constructions and fuel efficiency strategies for ships in service and the installation of Energy Storage Systems (ESSs) both for the "fully electrification" or the optimum management of the on-board power generation units in a "hybrid energy storage system" configuration [7], [8].

These rules have encouraged all stakeholders in maritime field to adopt innovative solutions to improve ship's efficiency. As a result, there are significant reductions in fuel consumption, utility costs and air pollution.

Nowadays, the extensive electrification of transportation systems has become an appealing technology compared to the conventional concepts, even for marine applications. In this perspective, the widely known all-electric ship (AES) solution, presents a large variety of devices, technologies and operating strategies that could lead to a more flexible, efficient and sustainable design and management of ships, [9] - [12].

In the context of AES, where both the propulsion and the hotel loads are powered by the on-board power system, this high variation in power demand is even more significant. In fact, in those conditions, diesel generators (DGs) often work far from their optimal working point. As a result, an increase in costs, fuel consumption and emissions may be pointed out.

Therefore, as it happens in many land applications where there are uncertainties related to the power generation profile due to weather conditions (e.g. wind and solar power generation plant), also on board many vessels it may be advantageous to install energy storage systems. ESS can be used in order to cover the fluctuating load variations and to increase both the efficiency, reliability and flexibility of the entire power system, or, in the "fully electric configuration" can powered directly the vessel and will be recharged through the national electricity grid, significantly reducing greenhouse gas emissions.

The main objective of this contribution (T1.2 in Figure 1), within the SEABAT project, was to identify, analyse and describe the current state of the international battery market both on a global and on the maritime perspective.

In the following tasks of SEABAT, this analysis will be supplemented by considerations and the development of a roadmap for the future development and use of batteries in the maritime sector. In this perspective, a forecast analysis on the next 5, 10 and 15 years of the battery market is proposed in this document.

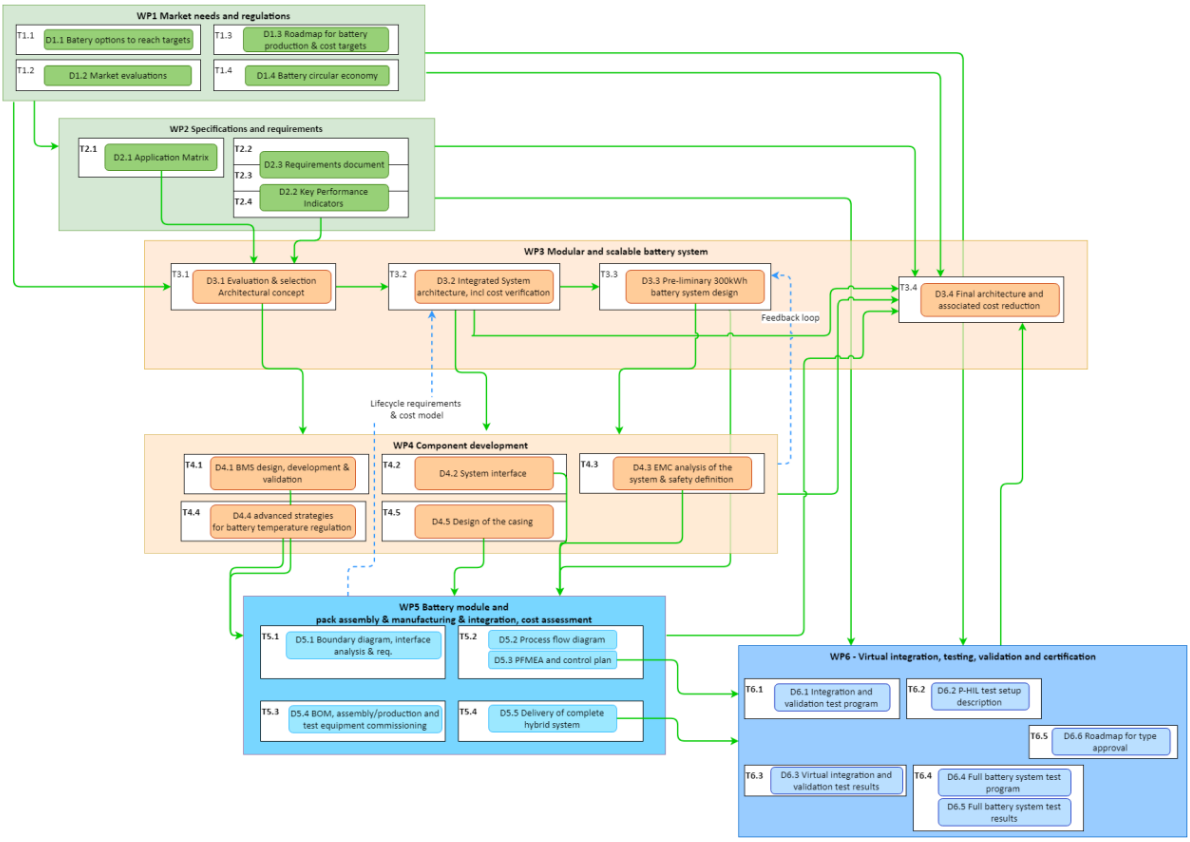


Figure 1 - Work package structure

1.1 Purpose of the document

The main objective of this Deliverable is to identify, summarize and provide a medium-long term forecast on the maritime battery market. This analysis will be used as starting point for the development of a roadmap for the use of batteries in the maritime sector (T1.3 of the SEABAT project).

With this aim, the document proposes a general overview of the existing technologies and opens a window on upcoming technologies that may be of interest to the maritime sector. Furthermore, a general analysis of the current state of the international and on the maritime market evolution for batteries is provided. These consideration have been used as a benchmark for the development of a 5, 10 and 15 year forecast analysis of the battery market.

1.2 Document structure

This document has been divided as follows. **Chapter 2** provides a brief description of the methodology agreed and applied between the Work package partners to divide the research work, identify the bibliographic material, organize specific meetings for each research area, collect the contributions of the partners, review the contributions and integrate them into the this document.

Chapter 3 presents the main results of deliverable 1.02 activity. In particular, the chapter will present an overview of the current state of art of battery systems and open the door to the possible next technologies of interest for the maritime sector. Furthermore, the current state of the global and of the maritime battery market is presented, and a 5, 10 and 15 years forecast analysis has been developed and here proposed.

Finally, **Chapter 4** draws some conclusions and proposes recommendations for the next tasks of Work Package 1.

2 Methods

The methodology identified, agreed and applied for the development of this activity and of this document envisaged the implementation of several phases, the main ones being:

1. Organization of specific meetings and committees (steering and technical committee) for the different tasks of the project's WP1, to identify the main technical activities and follow their development.
2. Identification of the skills of the partners involved and consequent assignment of contributions and activities based on the same skills.
3. Development by the task leader, in agreement with the partners, of the preliminary index of the document and assignment to the partners of the areas to be developed.
4. Identification of possible sources of technical, environmental and bibliographic information, with relative sharing between the partners of the information and selected databases.
5. Development of the technical contributions by the partners in charge for each point to be developed in the document.
6. Preliminary review of contributions by the task leader and update of contributions.
7. Collection of technical contributions and their integration within the deliverable D1.02.
8. Review of the preliminary document by the partners and subsequent updating of the document by the task leader in function of the information received.
9. Final emission of the document D1.02 by the task leader.

The following topics have been developed and proposed below.

2.1 Market description and segmentation

To tell something about future markets, first the current market needs to be described in terms of number of vessels, age, installed power and length. Data from IHS Seaweb as well as Clarksons is used. Analysis of this data is performed using Power BI. All figures show the fleet size of active vessels with IMO number built by an European builder by domicile unless explicitly mentioned otherwise. For clarification, these vessels do not represent the fleet by European country built. Vessels that are for instance built in Asia by an European company are this way included in the numbers. Vessels that may be built in Europe by a non-European shipbuilder are not. This analysis is important in the context of the SEABAT project to define the main needs which, to date, are directing the market and battery developments in a specific direction, with both technical and economic impacts.

From a technical point of view, the performance improvements that new technologies can guarantee will lead to a greater use of batteries and, consequently, to a lower price of the systems, with a consequent effect of scale on the entire market.

2.2 Forecast

The developing global macroeconomic outlook on economic growth, production, energy consumption (and developing changes to the energy production mix) provide the basis for the forecasts. These values, in turn, inform expectations for maritime trade volumes in dynamic global shipping routes and patterns.

This forecast is reporting on newbuilding requirements. Newbuilding requirements reflect the expected growth of the fleet and are forecasted for individual ship type and size. These estimates take into consideration the average age of the fleet segment and the rate of vessel scrapping.

Forecasts are made based on global forecasts and corrected for European market share with the assumption that this market share remains stable over the time of the forecast. Several acknowledged market reports and sources are used where needed.

2.3 Partners involved and contributions

The partners involved in the development of this document are:

- **Fincantieri SI**, as WP and Task leader, contributor for the battery market analysis and forecast for cruise vessels, naval vessels, special vessels, Roro-pax ships;
- **Damen**, as contributor for the battery market analysis and forecast for fishing vessels, tugs, yachts, general cargo, patrol and inland vessels;
- **SOERMAR**, contributor for the battery market analysis.

3 Results

The main objective of this paragraph is to define and describe the current state of the art for the various battery technologies, also briefly introducing the potential technologies for next use on board the ship. Starting from these considerations, the current state of the battery market, both global and specific for marine use, has been analyzed and summarized here. With this information it was possible to develop a forecast of the marked future at 5, 10 and 15 years for different types of ship. Finally, a preliminary assessment for the possible GHG emissions reductions has been developed and is summarized here with the main results obtained. It is to be noted that in paragraph 3.2 a specific focus on lithium battery technology is presented, this being the most widely used and promising technology currently for marine applications

3.1 Battery energy storage system available technologies

A Battery Energy Storage System (BESS) is a type of energy storage device the uses batteries as its underlying storage technology. A battery energy storage system is more than just a battery and requires additional components that allow the battery to be connected to an electrical network [1] for powering electrical devices such as flashlights, mobile phones, and electric cars. When a battery is supplying electric power, its positive terminal is the cathode and its negative terminal is the anode. The terminal marked negative is the source of electrons that will flow through an external electric circuit to the positive terminal. When a battery is connected to an external electric load, a redox reaction converts high-energy reactants to lower-energy products, and the free-energy difference is delivered to the external circuit as electrical energy. Historically the term "battery" specifically referred to a device composed of multiple cells; however, the usage has evolved to include devices composed of a single cell.

Basically, each battery technology can be classified as primary cells (non-rechargeable batteries) or secondary cells (rechargeable batteries). Bellow, a brief description of these two categories is presented and a table with the most important primary cells and secondary cells, with the most common application of them is presented and the end of this section. Finally, a brief description of the commercial types’ batteries (secondary cells) is presented.

3.1.1 Primary cells

A primary cell is a battery (a galvanic cell) that is designed to be used once and discarded, and not recharged with electricity and reused like a secondary cell (rechargeable battery). In general, the electrochemical reaction occurring in the cell is not reversible, rendering the cell unrechargeable. As a primary cell is used (see Figure 2), chemical reactions in the battery use up the chemicals that generate the power; when they are gone, the battery stops producing electricity. Primary cells are made in a range of standard sizes to power small household appliances such as flashlights and portable radios. Primary batteries make up about 90% of the $50 billion battery market, but secondary batteries have been gaining market share. About 15 billion primary batteries are thrown away worldwide every year, virtually all ending up in landfills. Due to the toxic heavy metals and strong acids and alkalis they contain, batteries are hazardous waste. Due to their high pollutant content compared to their small energy content, the primary battery is considered a wasteful, environmentally unfriendly technology. Primary cell common batteries are the alkaline batteries and the aluminium-air batteries. Primary cells are of no concern in the context of the SEABAT project.

A variety of standard sizes of primary cells. From left: 4.5V multicell battery, D, C, AA, AAA, AAAA, A23, 9V multicell battery, *(top)* LR44, *(bottom)* CR2032

Figure 2 - Example of primary cells batteries (source: https://en.wikipedia.org/wiki/Primary_cell)

3.1.2 Secondary cells

A rechargeable battery, storage battery, or secondary cell, (or archaically accumulator) is a type of electrical battery which can be charged, discharged into a load, and recharged many times, as opposed to a disposable or primary battery, which is supplied fully charged and discarded after use. It is composed of one or more electrochemical cells.

Rechargeable batteries are produced in many different shapes and sizes, ranging from button cells to megawatt systems connected to stabilize an electrical distribution network. Several different combinations of electrode materials and electrolytes are used, including lead–acid, zinc-air, nickel–cadmium (NiCd), nickel–metal hydride (NiMH), lithium-ion (Li-ion), Lithium Iron Phosphate (LiFePO4), and lithium-ion polymer (Li-ion polymer).

Rechargeable batteries typically initially cost more than disposable batteries, but have a much lower total cost of ownership and environmental impact, as they can be recharged inexpensively many times before they need replacing. Some rechargeable battery types are available in the same sizes and voltages as disposable types, and can be used interchangeably with them.

Based on the objective of this document and the objective of the SEABAT project, the secondary cells are the batteries on which we will focus, due to their growing demand and the value they can bring to innovation projects.

In Table 1, a summary of possible applications and the corresponding battery technology traditionally associated is presented, divided for primary cells and secondary cells, respectively.

Table 1 - Types of batteries

PRIMARY CELLS OR NON-RECHARGEABLE BATTERIES	SECONDARY CELLS OR RECHARGEABLE BATTERIES	BATTERIES BY APPLICATION
Alkaline battery	Aluminium-ion battery	Automotive battery
Aluminium-air battery	Flow battery	Backup battery
Atomic battery	Lead-acid battery: VRLA battery, AGM battery and gel battery	Battery (vacuum tube)
Chromic acid cell	Glass battery	Battery pack
Galvanic cell	Lithium-ion battery	Battery room
Lithium battery	Lithium metal battery	Battery storage power station
Lithium air battery	Magnesium-ion battery	Bio-battery

Magnesium battery	Metal-air electrochemical cells (lithium-air battery, aluminium-air battery, …)	Button cell
Mercury battery	Molten salt battery	CMOS battery
Nickel oxyhydroxide battery	Microbial fuel cell	Commodity cell
Organic radical battery	Nickel-cadmium battery	Electric vehicle battery
Silver-oxide battery	Nickel hydrogen battery	Flow battery
Solid-state battery	Nickel-ion battery	Home energy storage
Zinc-air battery	Nickel metal hydride battery	Inverter battery
Zinc-carbon battery	Nickel-zinc battery	Lantern battery
Zinc chloride battery	Organic radical battery	Nanobatteries and nanowire battery
	Polymer-based battery	Local battery
	Polysulfide bromide battery	Polapulse battery
	Potassium-ion battery	Photoflash battery
	Rechargeable alkaline battery	Reserve battery
	Rechargeable fuel battery	Smart battery system
	Sand battery	Watch battery
	Silicon air battery	Water-activated battery
	Silver-zinc battery	Wet cell
	Silver calcium battery	Zamboni pile
	Silver-cadmium battery	
	Sodium-ion battery	
	Sodium-sulphur battery	
	Solid state battery	
	Super iron battery	
	Ultra-battery	
	Zinc ion battery	

In recent years, the battery technology has improved significantly. At present, the Market offers many different cell types, and many others are currently under development. Some of the most adopted and promising solutions for ongoing and current applications are described in the following section.

3.1.3 Lead Acid and Sodium Technologies

3.1.3.1 Lead Acid

The lead-acid technology is the oldest one. The cell consists of a positive electrode of dioxide and lead and the negative electrode of sponge lead. The two electrodes are separated by a micropore material and immersed in an electrolytic solution of diluted sulphuric acid [14].

Typical values for the energy density are 30-50 Wh/kg, and the cell voltage is around 2V. Nowadays, this technology is adapted, e.g., for starting the car's internal combustion engine (12 V, 40 Ah) or as backup power in Uninterruptible Power Supply (UPS) applications. This technology offers a low cost per cycle, around 0.10 $. The maximum discharge rate is 3C. The principal advantages are the low cost, low auto-discharge, and high tolerance regarding the charge and discharge. The disadvantages are the low energy density, limited life, and slow charge [15]. This technology is considered to be very safe since the electrolyte and active materials are not flammable. The main advantages and disadvantages of this technology based on the Literature review are listed in Table 2.

Table 2 – Advantages and Disadvantages Lead-Acid batteries.

Advantages (Lead-Acid)	Disadvantages (Lead-Acid)
- Very low cost - Very safe, since electrodes and electrolyte are not flammable - Commercially available worldwide - High specific power	- Low specific energy - Low energy density - Low cycle life

3.1.3.2 Sodium Sulphur (NaS)

The Sodium Sulphur battery is composed by molten sodium in the positive electrode and sulphur in the negative electrode. They are separated by a ceramic electrolyte composed by solid beta alumina. The electrolyte allows only positive sodium ions to pass through and combine with the sulphur to form sodium polysulphides. In the discharge phase, the positive ion of sodium goes through the electrolyte and the electron goes to the external battery circuit. The cell voltage is around 2 V. The battery must be at 300° C to allows the process [16]. The main advantages and disadvantages of this technology based on the Literature review are listed in Table 3.

Table 3 - Advantages and Disadvantages NaS batteries.

Advantages (NaS)	Disadvantages (NaS)
- High power - High energy density - High efficiency - Temperature stability - Low cost of raw materials - Commercially available	- Unsafe: Fracture of beta alumina leads to violent reaction - High operating temperature (300° C) - Molten sodium electrode - Uses 10-14% of its own capacity to maintain the operating temperature. - Expensive due to manufacturing process, insulation requirements and thermal management

3.1.4 Zero Emission Batteries Research Activities (ZEBRA) or (Na-NiCl2) Technologies

The ZEBRA batteries present molten sodium in the anode and a metal chloride in the cathode, (e.g. $NiCl_2$ or $FeCl_2$). The electrolyte is solid beta alumina.

One of the main characteristics of these batteries is that they are tolerant to overcharges (an uncommon feature for batteries). This capability is obtained by impregnating the cathode also with $NaAlCl_4$. Table 4 lists the main advantages and disadvantages of this technology [1].

Table 4 - Advantages and Disadvantages ZEBRA batteries.

Advantages (ZEBRA)	Disadvantages (ZEBRA)
- High power - High energy density - High efficiency - Temperature stability - Low cost of raw materials - Commercially available - Safe: No gassing	- Unsafe: Fracture of beta alumina leads to violent reaction - High operating temperature (300oC) - Molten sodium electrode - Uses 10-14% of its own capacity to maintain the operating temperature when not in use - Expensive due to manufacturing process, insulation requirements and thermal management

3.1.5 Nickel-based battery Technologies

The nickel-based batteries address a group of cell technologies that employ nickel, i.e., nickel cadmium (NiCd), nickel metal hydride (NiMH), nickel iron (NiFe), nickel zinc (NiZn) and nickel hydrogen (NiH). All these batteries are characterised by aqueous electrolyte, potassium hydroxide (KOH) solution and hydroxide ions (OH-) as energy carriers.

A common characteristic of this family of batteries is that equal amounts of OH- ions are released and absorbed by the electrodes during the charging/discharging, thus, the ionic concentration is not diluted during the electrochemical reaction. This differs, e.g., from lead-acid, where the sulfuric acid is diluted when discharged [1].

3.1.5.1 Nickel Cadmium

Nickel-cadmium battery is a mature technology that is widely used, e.g., in UPS applications.

Nickel hydroxide/nickel oxyhydroxide (Ni(OH)2/NiOOH) is used as cathode material and cadmium (Cd) in the anode. The electrolyte is an aqueous solution of potassium hydroxide (KOH). This technology is economically priced and presents the lowest per cycle cost. There will be some hydrogen production during chagrining of the last voltages. Good ventilation is important in the room to avoid explosive concentrations of hydrogen. NiCd has a memory effect that causes a loss of capacity if not given a periodic entire discharge cycle. Some of the advantages and disadvantages of nickel-cadmium batteries are included in [1].

Table 5 - Advantages and Disadvantages Nickel-cadmium batteries.

Advantages (Nickel-cadmium)	Disadvantages (Nickel-cadmium)
- Very low cost - Electrodes and electrolyte not flammable	- Low specific energy - Low energy density - Explosive hydrogen gas during charge - Memory effect

3.1.5.2 Nickel Metal Hydride (NiMH)

Nickel Metal Hydride (NiMH) battery uses nickel hydroxide/nickel oxyhydroxide (Ni(OH)2/NiOOH) as cathode material, and a hydrogen absorbing alloy and cadmium hydroxide (Cd(OH)2) for the anode. The electrolyte is also an aqueous solution of potassium hydroxide (KOH).

During the operation, NiMH could produce hydrogen, thus, good ventilation is important in the room to avoid explosive concentration. NiMH is one of the most readily available rechargeable batteries for consumer use. It is used for the most in the same applications as NiCd.

With respect to the NiCd It can reach a 40% higher specific energy, but it is more delicate and trickier during the charge phase. It also presents high self-discharge, e.g., a NiMH battery can be fully self-discharged in a few weeks. Some of the advantages and disadvantages of the nickel metal hydride batteries are included in Table 6 [1].

Table 6 - Advantages and Disadvantages NiMH batteries.

Advantage (NiMH)	**Disadvantage (NiMH)**
- Low cost - Electrodes and electrolyte not - flammable	- Low specific energy - Low energy density - Release of hydrogen gas during charge, with potential for the creation of explosive atmosphere - High self-discharge rate

3.1.5.3 Nickel Iron

The nickel-iron battery (NiFe) uses nickel oxide-hydroxide (NiOOH) cathode and an iron (Fe) anode with potassium hydroxide (KOH) electrolyte. It produces a nominal cell voltage of 1.20 V. NiFe is resilient to overcharge and over-discharge and can last for more than 20 years in standby applications.

NiFe has a low specific energy of about 50 Wh/kg, has poor low-temperature performance and exhibits high self-discharge of 20–40%/month.

Some of the advantages and disadvantages of the nickel iron batteries are listed in Table 7 [1].

Table 7 - Advantages and Disadvantages NiMH batteries.

Advantage (NiMH)	**Disadvantage (NiMH)**
- Long lifetime - Resilient to vibrations and high - temperature	- Low specific energy - Low energy density - High cost - High self-discharge rate - Poor low temperature performance

3.1.5.4 Nickel Zinc

The Nickel-zinc (NiZn) battery is similar to nickel-cadmium in that it uses nickel oxide hydroxide (NiOOH) as a cathode and an alkaline electrolyte. However, can produce a higher cell voltage, 1.65V, thanks to the zinc (Zn) anode.

The specific energy is 100 Wh/kg and can be cycled 200–300 times. NiZn has no heavy toxic materials and can easily be recycled. NiZn suffered from high self-discharge and short cycle life caused by dendrite growth, which often led to an electrical short. This has been a topic of research.

Some of the advantages and disadvantages of the nickel zinc batteries are included in Table 8 [1].

Table 8 - Advantage and Disadvantage NiZn batteries.

Advantage (NiZn)	Disadvantage (NiZn)
- No toxic materials - Low cost - High power output - Good temperature operating range	- Low specific energy compared to lithium-ion - Low energy density compared to lithium-ion - Dendrite growth - High self-discharge rate

3.1.5.5 Nickel Hydrogen

Nickel Hydrogen (NiH) battery has a nominal cell voltage of 1.25 V, and the specific energy is 40–75 Wh/kg. The advantages are long service life, even with complete discharge cycles, good calendar life due to low corrosion, minimal self-discharge, and remarkable temperature performance of –28°C to 54°C (–20°F to 130°F).

These attributes make NiH ideal for satellite use. Scientists tried to develop NiH batteries for terrestrial use, but low specific energy and high cost worked against this endeavour. Some of the advantages and disadvantages of nickel-hydrogen batteries are included in the following Table 9.

Table 9 - Advantages and Disadvantages NiH batteries.

Advantage (NiH)	Disadvantage (NiH)
- Long lifetime - Minimal self-discharge rate - Good temperature operating range	- Low specific energy compared to lithium-ion - Low energy density compared to lithium-ion - High cost

3.1.6 Flow battery or Redox battery Technologies

Flow batteries generate a voltage between two electrodes as electrons move through an electrolyte. Whereas in conventional batteries (such as lithium-ion), the electrodes comprise of metal or carbon, and the electrolyte remains fixed between them; flow battery works by pumping a charge carrying fluid, the electrolyte, which is stored in tanks, through the separated electrodes to generate this voltage and current [5]. The electrolyte at the anode is called analyte, and the electrolyte at the cathode is called catholyte.

The advantage is that the battery's energy capacity is limited only to the size of the electrolyte tanks and can be, theoretically, infinite. The power capability is also easily increased by simply adding more cell stacks as the battery's energy and power are entirely configurable.

Additionally, the system's lifetime may be significantly prolonged by comparison since it is not subject to the same degradation mechanisms found in more traditional batteries. Though the present system's risks for mechanical failure than traditional batteries would not be subject to, these repairs are minor in scale and likely familiar to service technicians. These systems have low flammability risks.

The main disadvantage of such batteries is the low energy density of 20-60 Wh/L and specific energy of 20-35 Wh/kg. The high price of electrolytes also hider the application in many fields. Hence it is considered suitable for stationary applications and not electric vehicles or vessels. Although the fluid itself is highly acidic and can generate more toxic substances, such exposure risks are common throughout the industry. They are better understood than some of the risks posed by batteries such as lithium-ion. These risk conditions are typically brought about by unfavourable state of charge (SOC) or temperature (thermal) conditions and can thus be prevented under nominal operation.

The Vanadium Redox battery presents some benefits relative to other flow battery technologies.

Fundamentally, the electrolyte is chemically identical on both the positive and negative side of the system; there is no safety issue of cross-contamination of the systems, and the reaction is only mildly exothermic.

Additionally, this feature allows significant SOC balance issues between tanks to be resolved by simply pumping electrolyte from one tank to another. Lastly, because energy is stored through vanadium ions existing in different oxidation states, there is no electroplating or deposition of material or ions. Thus, there is a significantly reduced risk of short circuit or degradation from loss of active material. Some of the advantages and disadvantages of the flow batteries are included in the following Table 10 [1].

Table 10 - Advantages and Disadvantages of flow battery.

Advantage (flow battery)	**Disadvantage (flow battery)**
- Can decouple energy and power characteristics - Easy to scale up energy and power capabilities - Low flammable risk	- Very low specific energy and energy density - Toxic fluids

3.1.7 Lithium-ion Batteries Technologies

Lithium-ion batteries are characterized by cells based on the use of ion-conduction electrolyte located between the two electrodes. The electrolyte consists of lithium salts dissolved in organic carbonates. The two battery electrodes are separated by a porous membrane necessary for electrical insulation. During the charging and discharging process, the lithium-ions migrate between the electrodes and are intercalated in the active materials. During the discharge, the lithium is deinterlaced by the negative electrode and there is a release of electrons. Note that both aluminium and copper are used as current collectors respectively for the positive and negative electrode. The active materials of the positive electrode are, for example, mixed oxides, while those of the negative electrodes are mainly composed of graphite and amorphous carbon. In these materials' lithium is intercalated.

During discharge, as shown in Figure 3, the lithium ions migrate from the negative electrode through the electrolyte and the separator and reach the positive electrode. At the same time, the electrons, as carriers of electrical energy, migrate from the negative electrode through the electrical connection to the electrode positive.

During charging, this process is reversed, and the lithium ions migrate from the positive electrode through the electrolyte and the separator to the negative [20].

Lithium-ion cells have a high voltage (3.6 V), so fewer cells are needed to power an application with respect to the case of lead and nickel.

Lithium-ion (Li-ion) batteries are generally chosen for applications where energy density and light weight are the main requirements. However, the characteristics of high energy density, long service life of cycle, and low self-discharge have made lithium-ion preferable for many other applications.

Among the disadvantages, there are the high costs and the need for specific protections that limit the voltage and the current.

Lithium-ion batteries differ mainly in the use of different cathode materials. Among others are Lithium Cobalt (LCO), Lithium Manganese (LMO), Lithium Phosphate (LFP), Lithium Nickel Manganese oxide of Cobalt (NMC), Lithium Nickel Cobalt Aluminium oxide (NCA) and Lithium Titanate (LTO). Some applications use several batteries together to improve performance; most electric vehicles, ad example, use a combination of LMO and NMC.

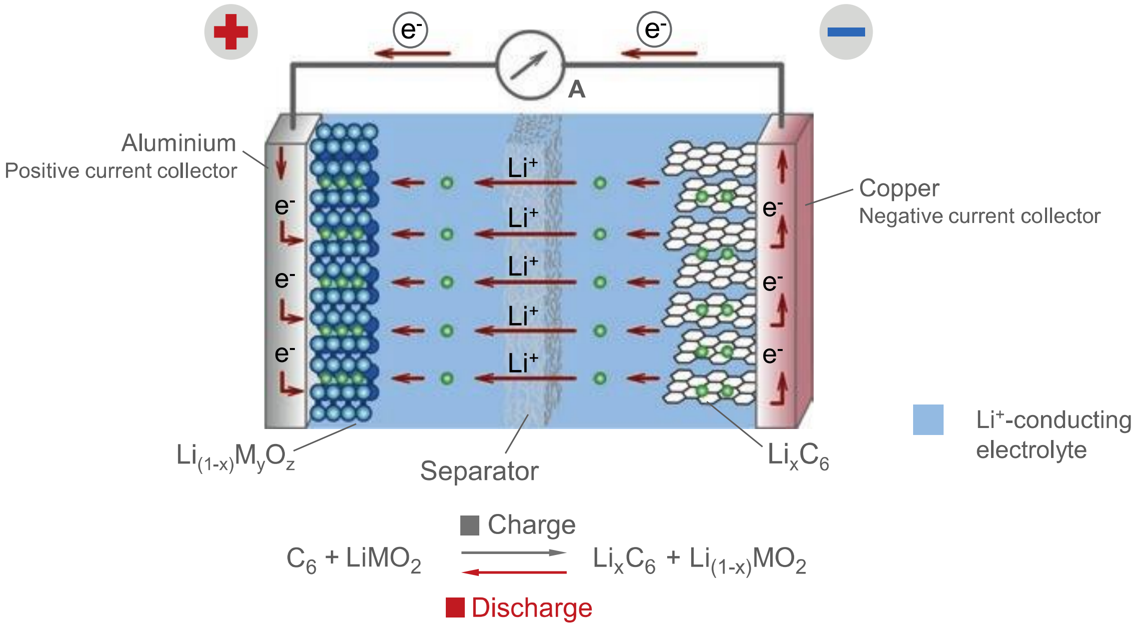


Figure 3 - Discharge process of a lithium-ion battery [20].

Table 11 highlight some of the advantages and disadvantages of the lithium-ion battery technology.

Table 11 - Advantages and Disadvantages of lithium-ion batteries.

Advantage (Lithium-ion)	**Disadvantage (Lithium-ion)**
- Highest specific energy of commercially available batteries	- Flammable electrolyte
- Relatively high cycle life	- Potentially limited availability of materials
- The highest energy density of commercially available batteries	- Cost

3.2 Summary of the existing Lithium-ion batteries

In this paragraph, a specific focus on lithium battery technology is presented, this being the most widely used and promising technology currently for marine applications.

Lithium-ion batteries are generally identified according to their specific cathode chemistry. Precisely, lithium-ion batteries typically adopt specific cathode solutions (such as NMC, LFP, LMO, NCA) and standard anode chemistry (carbon or graphite-based). An exception is made in lithium-titanate batteries (LTO), which take their name from the material used in the anode, the titanate.

The combination of different chemistries allows targeting different capabilities. In the following, a review of the most common cathode and anode materials and their specific properties is proposed.

3.2.1 Cathode material

3.2.1.1 Nickel Manganese Cobalt Oxide (NCM or NMC)

NMC is one of the more recent cathode developments. It is, at present, the market leader for large format applications and is increasingly replacing LCO and LMO in consumer electronics. Its strength is the combination of attributes of the constituents of nickel (high specific energy), cobalt (specific energy), and manganese (doped in the layered structure to stabilize it).

The relative composition and quantities can be tweaked to produce different properties concerning power density, energy density, cost, and safety, and customize the cells to specific applications or groups of applications.

NMC can also be mechanically mixed with LFP or others in the cathode to produce yet another customization of properties. Lastly, NMC is also theoretically capable of the highest electrochemical potential (cell voltage), which is primarily limited by the electrolytes used today. NMC batteries can have different properties of energy or power, depending on how the elements of Nickel, Cobalt, and Manganese are engineered. E.g., the NMC cells addressed as NMC 433 use equal parts of Ni, Mn; the cells addressed as NMC 811 use 80% Ni, 10% Mn, and 10% Co. There exists also many other solutions in between the previous two such as NMC622, NMC 532 and NMC 514.

The variation of the amount of Ni, Mn, and Co affects the cost, capacity, and stability. E.g., lower percentage of cobalt reduces costs and increases the energy density; on the contrary, higher percentage of Co significantly increases the cell cycle life (see Figure 4).

Notice that, Literature often refers to this chemistry as NMC or NCM, nevertheless, it is important to keep the order correct when referring to different balances.

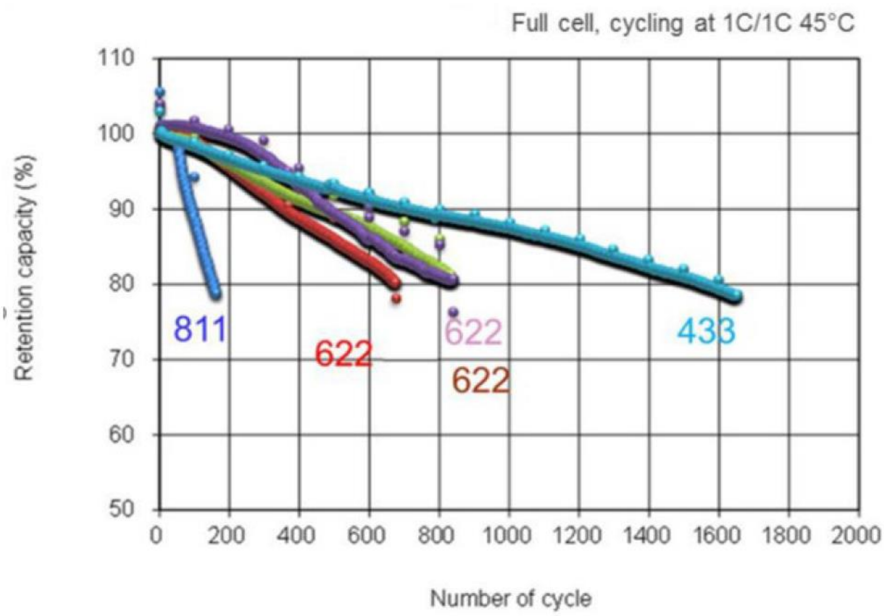


Figure 4 - Life time comparison between NMC 811, 622, and 433 [1].

3.2.1.2 Lithium Iron Phosphate, LiFePO4 (LFP)

LFP differs significantly from most other cathode chemistries due to its structure, phosphorous olivine rather than a layered metal oxide as in NMC. A dominant benefit of this is the lack of an oxygen source at the cathode, potentially reduce the risk magnitude during thermal runaway. These cells are additionally often more resilient to temperature fluctuations.

The specific energy of LiFePO4 is relatively low, and the electrochemical potential (voltage) is lower, reducing the cell's driving force. The power capabilities of a LiFePO4 based battery cell are inherently low. However, high power cells can be obtained doping the LiFePO4 material with small amounts of other materials, conductive coatings, and nanostructured active material particles, e.g., LiFePO4 [1].

3.2.1.3 Nickel Cobalt aluminium, NCA

NCA is generally similar to NMC but has minor changes that make it more suitable for specific applications. Aluminium can improve energy density and calendar life characteristics, while its primary sacrifice relative to NMC concerns cycling characteristics (degradation). NCA batteries tend to use a higher percentage of Nickel with respect to the NMC, as reference, a NCA battery may have a cathode composed of 80% nickel, 15% cobalt, and 5% aluminium.

Aluminium nominally provides some stability, similar to what is achieved with equal ratio NMC batteries compared to high nickel content NMC batteries [1].

3.2.1.4 Lithium Cobalt Oxide, LiCoO2 (LCO)

The main advantage of LiCoO2 is its relatively high energy density. However, it typically displays lower power (rate) capabilities and shorter cycle life. Impedance increase over time is also a significant concern with LiCoO2 based cells. Cobalt oxide suffers from safety concerns due to the reduced thermal stability and exothermic release of oxygen at elevated temperatures – producing a self-heating fire resulting in thermal runaway concerns. LCO type cells are very common in consumer electronics rechargeable batteries where a three-year life span of a few hundred cycles to 80% of its original capacity often is sufficient [1].

3.2.1.5 Lithium Manganese Oxide Spinel, LiMn2O4 (LMO)

LMO is somewhat unique cathode chemistry, being a spinel structure, which provides a significant benefit in terms of power capabilities. The compound has additional safety benefits due to high thermal stability.

However, it has a significantly lower energy capacity than cobalt-based compounds and is known to have shorter life characteristics, especially at higher temperatures. Several material modification possibilities exist to improve the cycle life of LMO compounds [1].

3.2.1.6 Comparison between active cathode materials

Cathode materials are suitable for different applications with different requirements. The choice of the cathode material depends on the electrochemical properties, costs, duration, and safety features. Figure 5 shows a qualitative comparison of four li-ion batteries using different cathode materials. The chemical composition of the considered cells is reported in Table 12.

Table 12 - Active cathode in the market.

COMPOUND	ABBREVIATION	CHEMICAL STRUCTURE
Manganese oxide	LMO	$LiMn_2O_4$
Nickel manganese cobalt oxide	NCM	$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$
Nickel cobalt aluminium oxide	NCA	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$
Iron phosphate	LFP	$LiFePO_4$

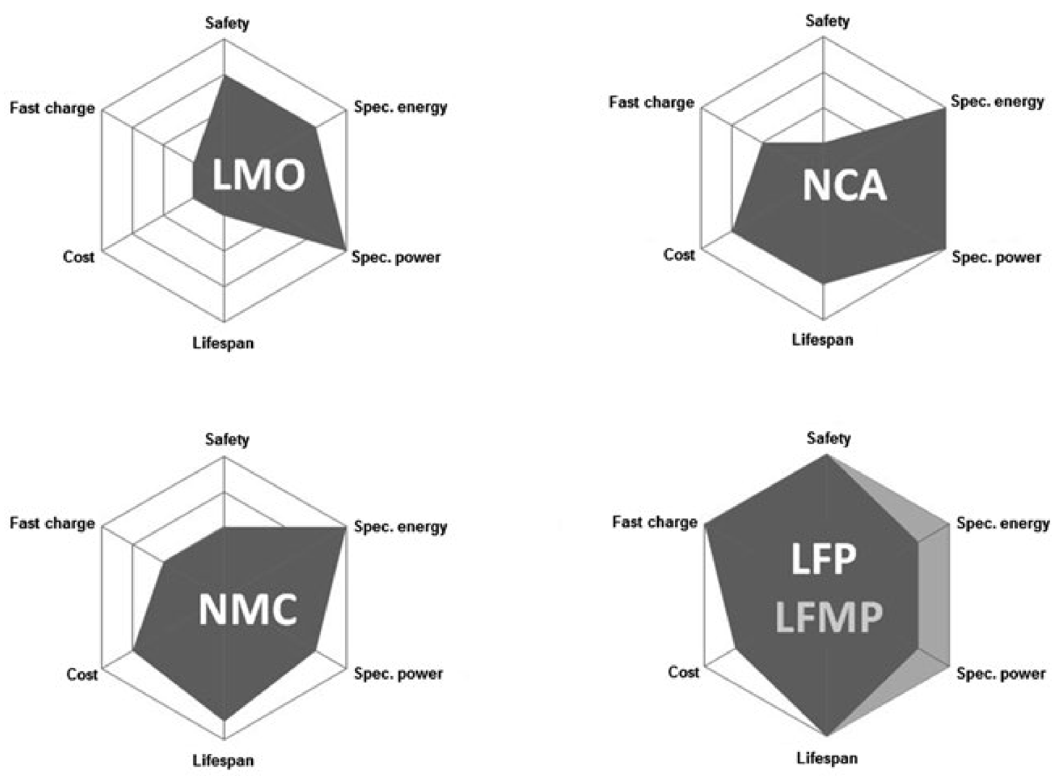


Figure 5 - Comparison between cathode materials considering safety, specific energy, specific power, duration cost, and charging time [21].

According to the proposed assessment, layered oxides are advantageous in applications where high energy density is important. Indeed, the cells that employ ions of nickel, cobalt, and manganese can reach high operating voltages and consequently high energy and/or power densities. However, the use of such materials generally increase the costs, as proposed, from Figure 6 to Figure 8 for the last 10 years, for cobalt, nickel and manganese, respectively.

Figure 6 – Cost development for Cobalt (10 years. Source: https://tradingeconomics.com)

Figure 7 – Cost development for Nickel (10 years. Source: https://tradingeconomics.com)

Figure 8 – Cost development for Manganese (10 years. Source: https://tradingeconomics.com)

The minimum cost is generally associated with the usage of cheap materials such as iron (0,057 $/kg). The lowest cost can be found in the LFP batteries.

However, these have a lower energy density than NCM and NCA, so they are not very advantageous. The oxides then constitute a safety risk, as oxygen can trigger the fire or even the explosion of the cell; the risk that does not occur with LFP.

Furthermore, LFPs shows no thermal effects up to 300 °C, while almost all cathode oxide-based materials exhibit strong exothermic effects. LFP and LFMP are non-toxic and non-hazardous to the environment, as are LMOs. This is not the case with oxide-based compounds containing heavy metals [21].

Phosphate-based batteries, therefore, appear to be the most convenient and promising for future development. LFP is the only cathode material that can be discharged and charged quickly but has not yet reached the high energy density (Wh/kg) and power density (W/kg) of oxidized cathode materials. Although with the use of manganese, LFMP the energy density and power values of the LFP can be increased by 20%.

Furthermore, it should be considered that the development of phosphate-based cathode materials is relatively young. It is therefore believed that over time it can reach the performance of other technologies.

This makes phosphate-based compounds cathode materials very promising for future high voltage applications [21].

3.2.2 Anode materials

3.2.2.1 Graphene

Graphene has high mechanical robustness, large specific surface area, desirable flexibility, and high electronic conductivity. As an auxiliary material of anode materials, it can improve the performance of lithium-ion batteries. It is believed that graphene can largely enhance lithium-ion batteries' performance in aspects of reversible capacity, cyclic performance, rate performance, and electronic conductivity. This is achieved through the reduction of the effects of volume variation and particle aggregation of the anode. Thus, existing safety concerns and cyclic instability can be enhanced with the adoption of graphene. However, wide utilization of graphene in lithium-ion batteries is not implemented due to the high expense and a lack of feasible synthesis methods in industrial production. It is expected that there is a long way to go for graphene to attain large-scale marketization [1].

3.2.2.2 Titanate

Batteries that use titanate in the anode are referred to as Lithium Titanate Oxide (LTO). The titanate increases the power level and the cycle life. However, LTO presents low voltage and consequently a significantly lower energy density with respect to other solutions such as graphene.

Considering the costs, due to the low energy density, the expense for an LTO battery is almost double of a comparable NMC. Nevertheless, the increased cycle life makes this solution often cheaper on a multi-year life span [1].

The cathode of LTO batteries can be realised with several chemistry, e.g., LMO or NMC.

3.2.2.3 Silicon

Silicon is currently in the market in systems now. Use of silicon in the anode increases energy density but significantly decreases lifetime.

Silicon allows the insertion of more lithium-ions but causes the anode to swell and contract significantly more.

This disrupts and damages the SEI formation process and lithium consumption. Much research is underway to minimize these lifetime effects, so we can better take advantage of the energy density benefits [1].

3.2.2.4 Comparison between active anode materials

Graphite is one of the most used solutions for the anode. Indeed, early lithium batteries adopted lithium metal foil as an anode (negative electrode). Despite having a high specific capacity (3,860 mAh/g) and a very negative potential that allows for cells with high voltage, this solution created numerous problems, including the complete self-discharge of the cell, the fire, or the explosion of the same [10]. Thus, the thin lithium metal was replaced by the so-called lithium intercalation material [10].

Graphite, as well as all the other anode materials, are intercalation materials.

Graphite is considered a good solution since the process of intercalation in such a material is reversible and without losses; moreover, lithium plating phenomena do not occur.

More recently, increasing attention is given to amorphous carbons (hard carbons and soft carbons) as they can give high power and energy densities and greater safety. They also have a much higher lithium storage capacity than graphite. Metal-based systems are not yet mass-produced. The addition of carbon atoms (e.g., C / Si, C / Sn) has good performance but has insufficient cyclic stability.

Lithium titanate and titanium oxide are promising as active materials for the anode. They have good cyclic stability and can provide excellent performance in terms of power and safety. However, the specific capacitance of these materials is very low, and the potential compared to lithium is very high.

Figure 8 provides an overview of the specific capacity and potential for the most important anode materials [10]. As it can be seen the potential of titanate solutions is significantly higher than graphite, and this led to cells with a lower voltage even if, as mentioned they ensure a significantly longer cycle life. On the contrary, silicon-based solutions offer higher specific capacity (or energy) while ensuring comparable potentials, even if they present a considerable reduction of the cycle life.

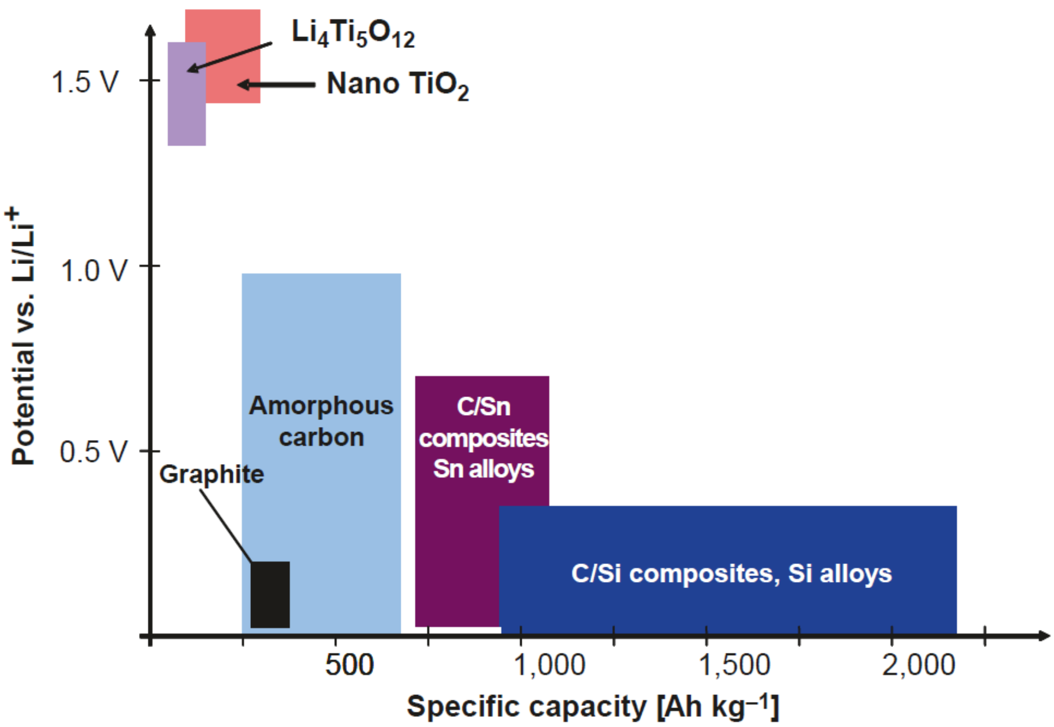


Figure 9 - Specific capacity and voltage [22].

3.2.3 Comparison of cathode and anode materials and future prospectives

Taking into consideration the above properties, the materials that are currently most interesting, depending on the application, are: synthetic graphite, natural graphite, amorphous carbon (hard and soft carbons), and lithium titanate [22].

Figure 16 presents a possible development scenario for lithium technologies [22].

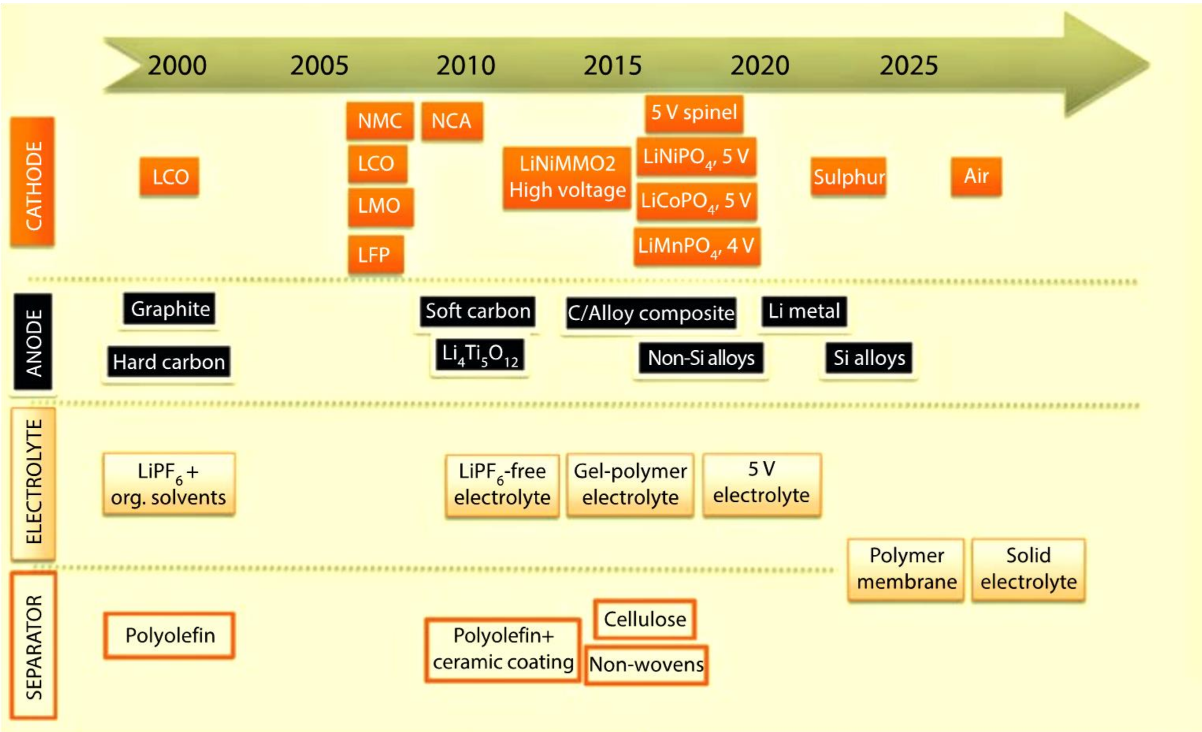


Figure 10 - Road map future development.

3.3 Overview on the next generation of battery technologies

This subsection provides an overview of presently subject technologies for research, rather than already being in the market. The selection is based on technologies that are considered promising and reasonably available in the near term. The driver for many of these technologies is the search for technologies that, relative to lithium-ion, present lower raw material cost, increase the specific energy and energy density, and improve safety. Note that the marine market is tiny compared to consumer electronics, stationary energy storage, and automotive. Hence, development is driven primarily by these other industries but with products being ultimately available to the maritime market as well.

A brief summary of the most promising technologies for maritime use, between those proposed below, is reported in section 3.3.8.

3.3.1 Solid-state lithium-ion batteries

These batteries use a solid-state electrolyte rather than a liquid, which is used in conventional lithium-ion batteries. The cathode and anode are made of the same materials used in typical lithium-ion batteries (e.g., NMC and carbon/graphite). Since the liquid electrolyte used in typical lithium-ion batteries is flammable, the safety properties are expected to be improved by replacing it with a solid-state material.

A solid-state battery gives freedom in the design of the battery geometry and improves the packing efficiency of the cells. It facilitates a long cycle life and offers the possibility of employing high-voltage cathodes. All these effects increase the practical battery energy density. The concept is shown in Figure 10. On the anode side, solid-state batteries open the door to the safe application of Li-metal, such as lithium-sulphur or lithium-air, by suppressing dendrite formation, also increasing the energy density [1].

Significant progress in synthesizing lithium-ion conducting solid electrolytes has been made. However, almost all solid-state cells' rate capability is poor, particularly those employing cathodes undergoing a high-volume change such as sulphide-based electrodes and those utilizing high-voltage cathodes.

The batteries suffer from high internal resistance for ion transfer over the electrode-electrolyte interfaces and space changes in the interfaces leading to ion depletion of the electrolyte. Several strategies have been developed to improve the interface resistances, including coating the electrodes with an oxide barrier layer enabling high-rate cycling. However, the biggest challenge regards the volume changes of the electrodes during charging and discharging, which causes loss of contact between the electrode and the electrolyte. These effects all make ion conductivity low.

If the conductivity and structural electrode challenges are overcome, solid-state batteries will increase the operational reach for the all-electric vessels – and the same would apply to maritime applications. If combined with some air-metal electrode technology, it might make the all-electric operation possible for deep-sea vessels. Some of the advantages and disadvantages of solid-state batteries are included in the following table [1].

In the last years, the company Mercedez-Benz [6] seems to have overcome these disadvantages on solid-state battery. In the new eCitaro rigid bus are installed lithium metal polymer solid-state batteries, approximately 441 kWh.

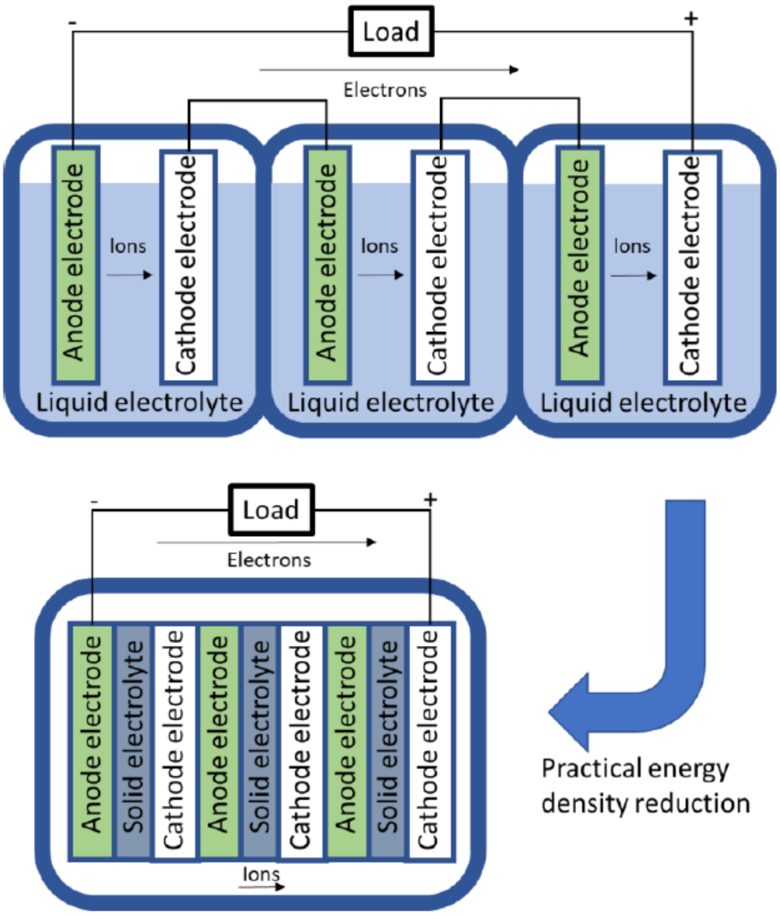


Figure 11 - Solid state battery vs conventional battery.

Table 13 Advantages and Disadvantages of solid-state lithium-ion batteries.

Advantages	**Disadvantages**
- Safe: Non-flammable electrolyte and no dendrite formation - Potential for higher specific energy and energy density - High energy density for longer range	- Low conductivity and high interface resistance - Low lifetime - High production cost - Poor cold weather performance

3.3.2 Zinc-ion batteries

These batteries use zinc ions (Zn_2^+) as charge carriers (as opposed to lithium-ions) through an aqueous zinc chloride or ammonium chloride electrolyte. A metal zinc anode is used. Different cathode chemistries have been tested, like α−, γ−, δ− Manganese Oxide (MnO_2), copper hexacyanoferrate (C_6CuFeN_6), and vanadium oxide ($Zn_{0.25}V_2O_{5 \cdot n}H_2O$) [23].

The latter type was announced in 2017, and cheap and safe, non-flammable, non-toxic materials. It has high reversibility, high C-rate, and high capacity with no zinc dendrite formation. This has notable improvement concerning safety and cost compared to lithium-ion batteries. The specific capacity has been reported up to only 85 Wh/kg, compared to 240 Wh/kg for lithium-ion.

The same cell demonstrated an energy density of 450 Wh/L [24], which is competitive with many lithium-ion batteries although some have energy densities up to 650 Wh/L, making them more attractive with regard to weight and space critical applications like a marine vessel.

Also, fundamental knowledge in the cathode material intercalation of zinc, electrolyte performance, and manufacturing process still needs to be developed and understood, and made more reliable before the technology can be commercialized. Some of the advantages and disadvantages of the zinc-ion batteries are included in the following table [1].

Table 14 Advantages and Disadvantages of zinc-ion batteries.

Advantages	Disadvantages
- Non-flammable electrolyte - No dendrite formation - Cheap to produce - Environmental-friendly	- Lower specific energy compared to lithium-ion - Lower energy density compared to lithium-ion - Not commercialized yet

3.3.3 Rechargeable metal-air

The prime motivation for using metal-air batteries is their high specific energy capacity obtained thanks to their open cathode that uses air as the reactant. The theoretical values span from 935-3463 Wh/kg. This technology has received much attention for the potential it suggests. However, it is still early in the research stage, and it is not expected to be commercialized in decades. The principle of a metal-air battery is shown in Figure 11.

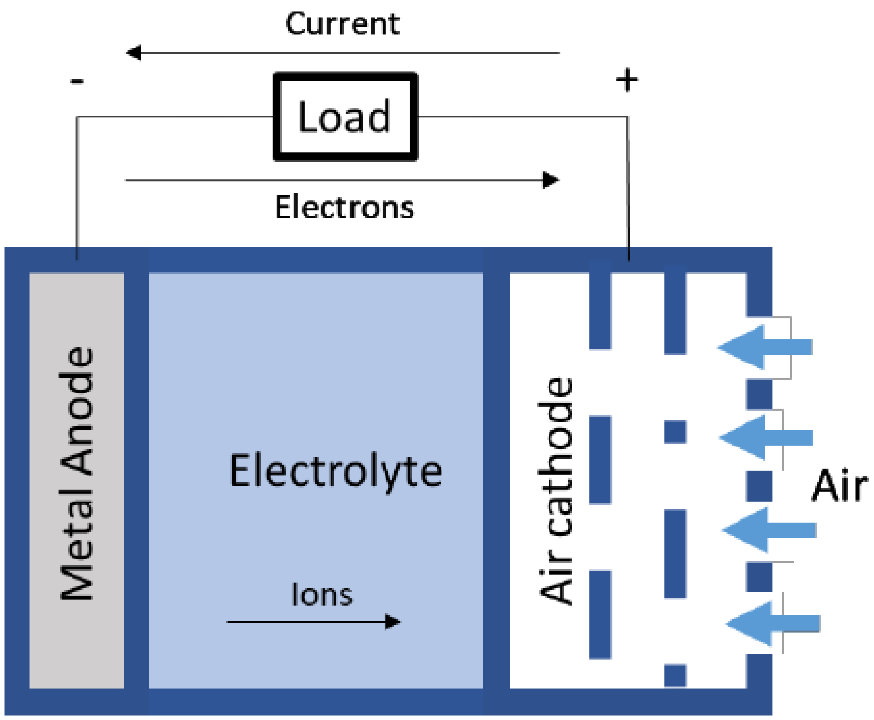


Figure 12 - Principle of a metal-air battery [1].

As it can be seen, a metal-air battery uses a metal anode and air as the cathode.

There are several types of metal-air batteries, but only Li-air, Na-air K-air, and Zn-air are considered rechargeable. Rechargeable Al-air and Mg-air have been reported but with minimal cyclic ability.

Metal-air batteries are composed of four parts: metal anode, electrolyte, separator, and air cathode. When discharged, the metal anode is oxidized and dissolved in the electrolyte. The metal ions are transferred as energy carriers through the electrolyte and separator to the air cathode. Here a reduction reaction occurs with the air.

In most cases, oxygen reacts with the metal ion, but reactions with lithium and CO2 have also been reported.

Batteries with both liquid and solid-state electrolyte are a topic for research. There are still several obstacles to overcome before these batteries can be applied (e.g., when the liquid electrolyte is used, dendrites and SEI layers are formed at the anode, increasing the risk for internal short circuit and performance degradation). Replacing the metal anode with an ion inserting material could improve these issues. Nevertheless, this solution limits the battery's specific energy. In addition, volatility of electrolyte and sluggish kinetic processes in the cathode are plaguing the researchers.

The use of solid-state batteries will avoid the volatility of electrolytes and suppress the growth of dendrites.

The conductivity of the solid-state electrolyte is very low and needs to be improved to utilize the specific energy potential in metal-air batteries. Ceramic and polymer electrolytes are promising candidates to improve this aspect. If these challenges are solved, the solid-state metal-air battery can achieve high-specific energy, energy density, and safety. This will be a game-changer with regards to the operational reach for all-electric battery vessels.

Considering the cathode structure, several materials can be used; they are carbon, titanium carbonate (TiC), nanoporous molybd (Mo2C), and nanoporous gold (NPG). In most of the studied solutions, O_2 is the desired reactant gas, since it has been observed that moisture and CO_2 in the air introduce some side reactions that need to be avoided. If air filters are applied separating O_2 from CO_2 and H_2O, this will substantially increase the weight and cost. However, some positive effects have also been reported with lithium and CO2, and a better understanding of these reactions is required [25]. Some of the advantages and disadvantages of metal-air batteries are included in the following table [1].

Table 15 Advantages and Disadvantages of metal-air batteries.

Advantages	**Disadvantages**
- Very high specific energy potential - If suitable combinations with solid state electrolyte are found, the potential safety, energy density, and specific energy benefits are huge	- Early research stage - No suitable electrolyte, solving ensuring both safety and performance requirements, is found - The cathode is vulnerable to moisture and CO2 in the air

3.3.4 Lithium-sulphur

Lithium sulphur batteries adopts Li+ ions as energy carriers as it is for lithium-ion batteries. The Li+ ions react with sulphur at the cathode giving some high theoretical values for specific energy and energy density. These values can reach 2500 Wh/kg and 2800 Wh/L, assuming complete reaction to Li2S. Hence these batteries will be very attractive for marine applications.

The cathode is made of a material that can host sulphur, several solutions are nowadays under testing such as carbon, graphene, graphene oxide, polymer additives, inorganic material composites, and metal organic framework. The anode is usually made of pure lithium metal, but also the chemistries used in conventional lithium-ion batteries are used.

Safety concerns related to these batteries, like dendrite formation, have been improved. However, this compromises the specific energy and energy density and increases the cost dramatically. Other obstacles to overcome are high electrical resistance, capacity fading, self-discharge [1].

Table 16 Advantages and Disadvantages of metal-air batteries.

Advantages	Disadvantages
- Higher theoretical capacity compared to conventional lithium-ion battery - High theoretical energy density compared to conventional lithium-ion battery - Low environmental impact	- High cost of lithium - Volume expansion and particle formation of sulphur - Low electrical conductivity - Shuttle effects - Not expected to be commercially available in decades

3.3.5 Dual-ion batteries

In all concepts discussed in previous sections, the energy carrier ions transferred between the electrodes are of a single type (i.e., Li+ ions in lithium-ion batteries or zinc ions in the case of zinc-ion batteries). In a dual-ion battery, both positive (cations) and negative (anions) charged ions act as energy carriers.

When fully charged, the anions are stored at the anode, and the cations are stored in the cathode. When discharged, both the anions and the cations are dissolved in the electrolyte.

The structure of the dual-ion batteries provides a high voltage level and consequently high energy density.

The cathode is made of graphite, while the anode can be made of lithium, LTO, or aluminium and graphite. When graphite or carbon is used both as a cathode and anode, the battery is named dual-graphite or dual-carbon. The electrolyte is molten salts.

The most common cation is lithium (Li+), but also 1-ethyl-3-methylimidazolium (EMI+) has been employed. A broad spectre of capable anions in the anode reaction is tested. Examples are hexa- or tetrafluoride guest species, e. g. PF6−, AsF6− or BF4−, hexa- or tetrachloride compounds like AlCl4−, GaCl4− or TaCl6− and oxide-based guests including SO4−, NO3− or ClO4−. Additionally, carbon-based anions with relatively large ionic radii are capable options.

When the battery is discharged, all the energy carriers are dissolved and stored in the electrolyte, opposed to, e.g., Li-ion, where the electrolyte only acts as a transportation medium. Hence, large quantities of electrolyte are needed, and it is not expected that these batteries will outperform lithium-ion concerning specific energy and energy density.

A common challenge for all these batteries is that the graphite electrode is affected by volumetric changes and exfoliation, leading to structural disorder. This is negative to safety and stability properties [14]. Some of the advantages and disadvantages of dual-ion batteries are included in the following text boxes [1].

Table 17 Advantages and Disadvantages of dual-ion batteries.

Advantages

- May utilize cheaper raw materials in the future
- May utilize globally abundant available raw materials in the future

Disadvantages

- Early research stage.
- Low specific energy and energy density compared to lithium-ion
- Electrolytes not mass produced and still expensive

3.3.6 Cobalt-free lithium-ion batteries

Cobalt is a scarce, toxic, and lustrous mineral that is found in the negatively charged electrode—or cathode—of almost all lithium-ion batteries used today. It's expensive, heavy, and linked to unethical mining practices, wild price swings, and a tenuous global supply chain. It's no wonder so many battery manufacturers want to kick their cobalt habit. But the material plays a crucial role in stabilizing batteries and boosting their energy density. Although experimental cobalt-free cells exist, they've all had major performance issues like limited lifetimes and slower charge rates—until now.

Researchers from the Cockrell School of Engineering at The University of Texas at Austin (USA) say they've cracked the code to a cobalt-free high-energy lithium-ion battery, eliminating the cobalt and opening the door to reducing the costs of producing batteries while boosting performance in some ways. The team reported a new class of cathodes - the electrode in a battery where all the cobalt typically resides - anchored by high nickel content. The cathode in their study is 89% nickel. Manganese and aluminium make up the other key elements.

More nickel in a battery means it can store more energy. That increased energy density can lead to longer battery life for a phone or greater range for an electric vehicle with each charge.

The team of researchers says they have overcome common problems with this solution (cobalt-free in batteries), ensuring good battery life and an even distribution of ions.

As mentioned above, cobalt is a toxic metal, therefore, it is not a very favourable component to use in electric vehicles, where the objective is to achieve a emission reducing. Also, for this reason, one of the objectives of the researchers, to be able to develop batteries without cobalt so that the batteries are more eco-friendly.

In this aspect, in May 2020, SVOLT (company based in China) has announced that it has manufactured a new cobalt-free NMx lithium-ion battery cells for the electric vehicles market (see Figure 13). Aside from reducing the rare earth metals, the company is claiming that they have a higher energy density, which could result in ranges of up to 800 km (500 miles) for electric cars. While also lengthening the life of the battery and increasing the safety.

Figure 13 - New cobalt-free NMx lithium-ion batteries by SVOLT

The main difference to NCM (lithium nickel manganese cobalt oxide) is the lack of cobalt in the cathode and reduced share of nickel to 75%, being the remaining 25% is manganese. To make such a setup work, the company has developed special doping and coating processes.

As a result, the NMx cells offer similar energy density tof NCM (about 5% lower, according to SVOLT), but are also about 5% less expensive. Additionally, the cycle aging, as well as the calendar (over 2,500 undisclosed cycles) aging, is reportedly improved compared to a conventional NCM type.

Table 18 Advantages and Disadvantages of NMX lithium batteries.

Advantages	Disadvantages
- May utilize cheaper raw materials in the future - Does not use cobalt and the use of nikel is reduced significantly - Available on the market	- First use for automotive. - Need to be navalized - Less energy density compared to NMC technology

3.3.7 Other technologies

The research in the battery sector is vast, and different technologies arise every year. The technologies grouped in the present report are considered to be the most promising and suitable to be used in the marine sector. Notice that other technologies could become developed enough to be included in such a list in the next future. These technologies are, e.g., Sodium-ion, Calcium-ion, Potassium-ion, Magnesium batteries, Fluoride-ion, Magnesium Sulphur, Aluminium Sulphur, Sodium-Sulphur.

3.3.7.1 Organosilicon electrolyte batteries

A problem with lithium batteries is the danger of the electrolyte catching fire or exploding. Searching for something safer than the carbonate based solvent system in Li-ion batteries, University of Wisconson-Madison chemistry professors Robert Hamers and Robert West developed organosilicon (OS) based liquid solvents in 2017.

Organosilicon compounds have attracted considerable interest as electrolytes for lithium-ion batteries because they are nontoxic, non-flammable, as well as have lower glass transition temperatures, lower vapor pressure and higher flash point than commercial alkyl carbonates. These compounds can improve the electrochemical performances and safety of lithium-ion batteries when used as electrolyte solvents or additives in the electrolytes. In this paper, the recent advances of organosilicon compounds both as electrolyte solvents and additives are reviewed. Organosilicon electrolytes containing ethylene oxide (EO) substituents with or without carbon spacer between silicon atom and EO unit are specially remarked as safe electrolytes. Organosilicon compounds as functional additives are also introduced in terms of the capabilities of passive film formation, flame-retardant, and acid/water scavenger.

The resulting electrolytes can be engineered at the molecular level for industrial, military, and consumer Li-ion battery markets.

3.3.7.2 Nanowire battery

Nanowires are thousands of times thinner than a human hair. They have a large surface for electron storage, as well as transport. Additionally, they are extremely conductive. Since nanowires are so thin, it makes them extremely fragile and susceptible to breakage. They do not do well in repeated discharges, or recharges. In a standard lithium-ion battery, the nanowire dilates and can lead to cracks.

A nanowire battery uses nanowires to increase the surface area of one or both of its electrodes. Some designs (silicon, germanium and transition metal oxides), variations of the lithium-ion battery have been announced, although none are commercially available. All the concepts replace the traditional graphite anode and could improve battery performance.

In 2016 researchers at the University of California, Irvine announced the invention of a nanowire material capable of over 200,000 charge cycles without any breakage of the nanowires. The technology could lead to batteries that never need to be replaced in most applications. The gold nanowires are strengthened by a manganese dioxide shell encased in a plexiglas-like gel electrolyte. The combination is reliable and resistant to failure. After cycling a test electrode about 200,000 times, no loss of capacity or power, nor fracturing of any nanowires occurred. The gel surrounding the gold nanowires with manganese oxide coating protects from corrosion, allowing the battery to last 400 times more cycles (see Figure 14).

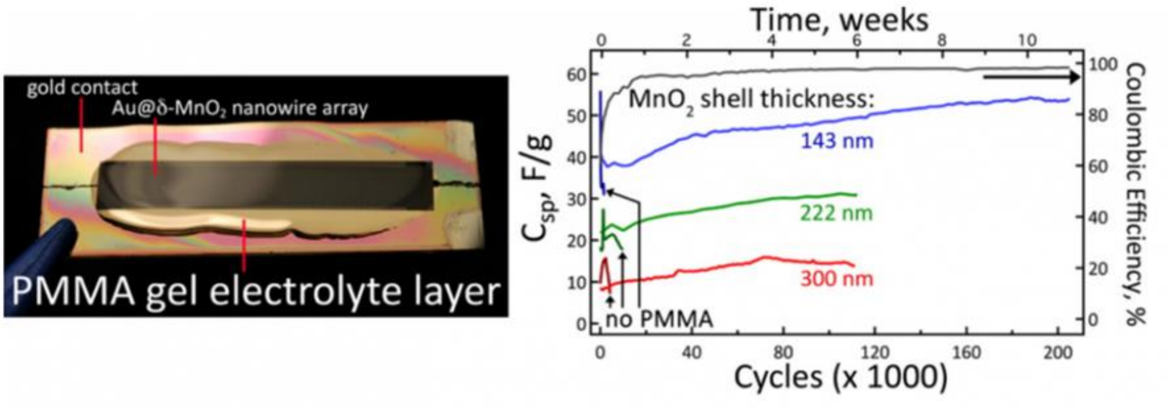


Figure 14 - Gold gel electrolyte batteries

3.3.7.3 Graphene batteries

Graphene, a sheet of carbon atoms bound together in a honeycomb lattice pattern, is hugely recognized as a “wonder material” due to the myriad of astonishing attributes it holds. It is a potent conductor of electrical and thermal energy, extremely lightweight chemically inert, and flexible with a large surface area. It is also considered eco-friendly and sustainable, with unlimited possibilities for numerous applications.

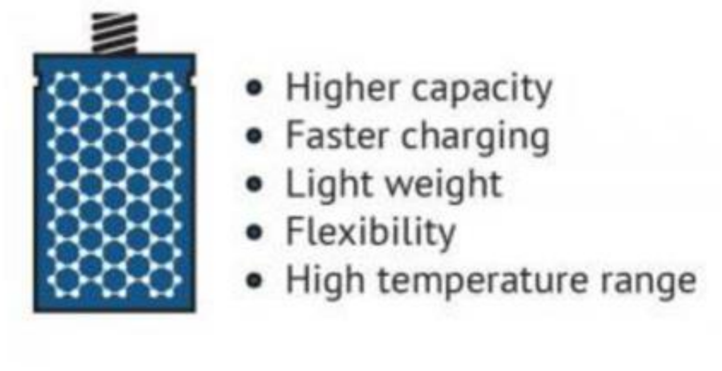


Figure 15 - Advantages of graphene batteries

In the field of batteries, conventional battery electrode materials (and prospective ones) are significantly improved when enhanced with graphene. A graphene battery can be light, durable and suitable for high capacity energy storage, as well as shorten charging times. It will extend the battery’s life, which is negatively linked to the amount of carbon that is coated on the material or added to electrodes to achieve conductivity, and graphene adds conductivity without requiring the amounts of carbon that are used in conventional batteries.

Graphene can improve such battery attributes as energy density and form in various ways. Li-ion batteries can be enhanced by introducing graphene to the battery's anode and capitalizing on the material's conductivity and large surface area traits to achieve morphological optimization and performance.

In addition to revolutionizing the battery market, combined use of graphene batteries and graphene super capacitors could yield amazing results, like the noted concept of improving the electric car's driving range and efficiency. While graphene batteries have not yet reached widespread commercialization, battery breakthroughs are being reported around the world.

Grabat Energy (Spanish company producing graphene on an industrial scale) has developed graphene batteries that could offer electric cars a driving range of up to 500 miles on a charge.

The company behind the development, says the batteries can be charged to full in just a few minutes and can charge and discharge 33 times faster than lithium ion. Discharge is also crucial for things like cars that want vast amounts of power in order to pull away quickly.

3.3.8 Most promising technologies for maritime use

A summary of the most promising emerging technologies, between those described above, is proposed in Figure 16 and Figure 17 and below.

Time to commercialisation	Battery type	Development Status	Nominal cell voltage/V	Specific Energy/ Wh/kg	Energy Density/ Wh/l	Cycle life	Notes
Available now	Lithium-ion with graphite/ silicon anodes and NCA or NCM cathodes	State-of-the-art commercial cells	3.7	240 - 270	600-650	1000 -2000	e.g. Tesla 21700 cylindrical cells (NCA) NCM 532 cathode cells pouch or cylindrical formats
		Commercial prototype cells	3.7	Up to ~300	Up to ~700	>1000	NCM 622/811 cathodes
Ready for commercialisation	Lithium-ion with pure silicon anodes and nickel-rich cathodes	Commercial prototype cells	Not specified	465	Not specified	Not specified	Amprius Si-nanowire anode cells– as demonstrated in Airbus Zephyr-S
			Not specified	Up to 450 (projected)	Up to 1200 (projected)	>570	Leyden Jar PECVD anode
	Lithium metal anode– NCM cathode	Commercial prototype cells	3.82	426 – 496	807-929	>350	Sion Power "Licerion" 6 Ah and 20 Ah cell variants
			3.8	450	838 for prototype cell, "up to" 1200 projected	>120	Solid Energy "Hermes" 3 Ah cell prototype (+projected future cell performance for larger cells)
	Lithium-sulfur	Commercial prototype cells	2.1	400 (up to 550 projected for future cells)	300 (up to 500 projected for future cells)	60-100 (100% depth of discharge) ~200 (60% depth of discharge)	Oxis Energy 14.7 Ah cell
Up to 5 years	Solid state electrolyte cells with lithium metal anode and nickel-rich intercalation cathode	Commercial prototype or pre-prototype cells	~3.8 V	400-700 (up to 1000 projected for future)	700-1100	>1000	Current and near-future metrics based on SolidPower cell characteristics. Both Ilika (UK) and Innolith (Switzerland) project 1000 Wh/kg achievable for EV-scale system based on lithium-metal anode based system. No information is provided by either developer on how this would be practically achieved
	Aluminium-air	Commercial prototype or pre-prototype cells	~1.5 – 2 V (dependant on air electrode characteristics and system design)	Up to 1300 claimed	Not specified	Not electrically rechargeable – "mechanically rechargeable" by anode and electrolyte replacement	Developers include Métalectrique (UK), Phinergy (Israel)

Figure 16 – Summary of the most promising future technologies [1 of 2] (Source: https://faraday.ac.uk/wp-content/uploads/2020/01/High-Energy-battery-technologies-FINAL.pdf)

Time to commercialisation	Battery type	Development Status	Nominal cell voltage/V	Specific Energy/ Wh/kg	Energy Density/ Wh/l	Cycle life	Notes
Over 5 years	High voltage $LiCoMnO_4$ cathode with lithium metal or graphite anodes	Small scale Laboratory prototype cells	4.7-5.3 (vs Li) 4.6-5.2 (vs graphite)	720 (vs Li) 480 (vs graphite)	Not specified	1000 vs lithium in test cells, lithium-ion cells with graphite exhibited only 100 cycles	Wang Chunsheng – University of Maryland Li-metal cells might achieve ~1300-1400 Wh/l if exhibit similar relationship between mass and volume as comparable cells
	Conversion cathode ($Fe_{0.9}Co_{0.1}OF$)	Small scale laboratory prototype cells	~2 V (average voltage for sloping discharge profile)	1000 in "half-cell" tests vs Li	Not specified	1000 cycles in half- cell tests	Most promising example data for $Fe_{0.9}Co_{0.1}OF$ nanorods given. Such systems suffer from large voltage hysteresis and typically exhibit poor cycle life in full cells
Up to 10 years	Lithium-oxygen / lithium-air	Low TRL - laboratory research	~2.9	Up to 3500 (theoretical) Up to 1000 projected for a practical system	Dependent on system	100s to 1000s (depending on depth of discharge) in oxygen.	Good cycle life has only been successfully demonstrated using pure oxygen. Potential first commercialisation as high capacity primary.
	Conversion anodes e.g. transition metal oxides, phosphides, sulfides and nitrides	Low TRL - laboratory research	Dependent on system	Dependent on system	Dependent on system	Poor cycle life	High theoretical capacity (~500 to 1800 mAh/g), but suffer from large voltage hysteresis, poor cycle life (as a result of deterioration because of structural reorganisation).
	Multivalent intercalation cell chemistries based on aluminium, calcium, magnesium or zinc	Low TRL - laboratory research	Dependent on system	Dependent on system	Dependent on system	Dependent on system	Systems tested to date exhibit poor performance vs the theoretically high capacity predicted based on the multi-electron reactions for multivalent systems. If projected high energy performance remains unachievable these systems may still offer cost benefits for large-scale energy storage application.

Figure 17 – Summary of the most promising future technologies [2 of 2) (Source: https://faraday.ac.uk/wp-content/uploads/2020/01/High-Energy-battery-technologies-FINAL.pdf)

3.4 Analysis of seagoing vessels

To tell something about future markets, first the current market needs to be described in terms of number of vessels, age, installed power and length. Data from IHS Seaweb as well as Clarksons is used.

Analysis of this data is performed using Power BI. All figures show the fleet size of active vessels with IMO number built by an European builder by domicile unless explicitly mentioned otherwise. For clarification, these vessels do not represent the fleet by European country built. Vessels that are for instance built in Asia by an European company are this way included in the numbers. Vessels that may be built in Europe by a non-European shipbuilder are not.
In order to describe the current market for shipbuilding, the market is segmented in fleet age, vessel type and total installed power for Vessels with an IMO number. The market for inland vessels is segmented into type. Data comes from IHS Seaweb and is visualized by Power BI.

All figures in this paragraph show the fleet size of active vessels with IMO number built by an European builder by domicile. These vessels do not represent the fleet by European country built. Vessels that are for instance built in Asia by an European company are this way included in the numbers.

3.4.1 Current fleet and sizes

In this paragraph sizes of the current fleet built by european builders in service is shown.

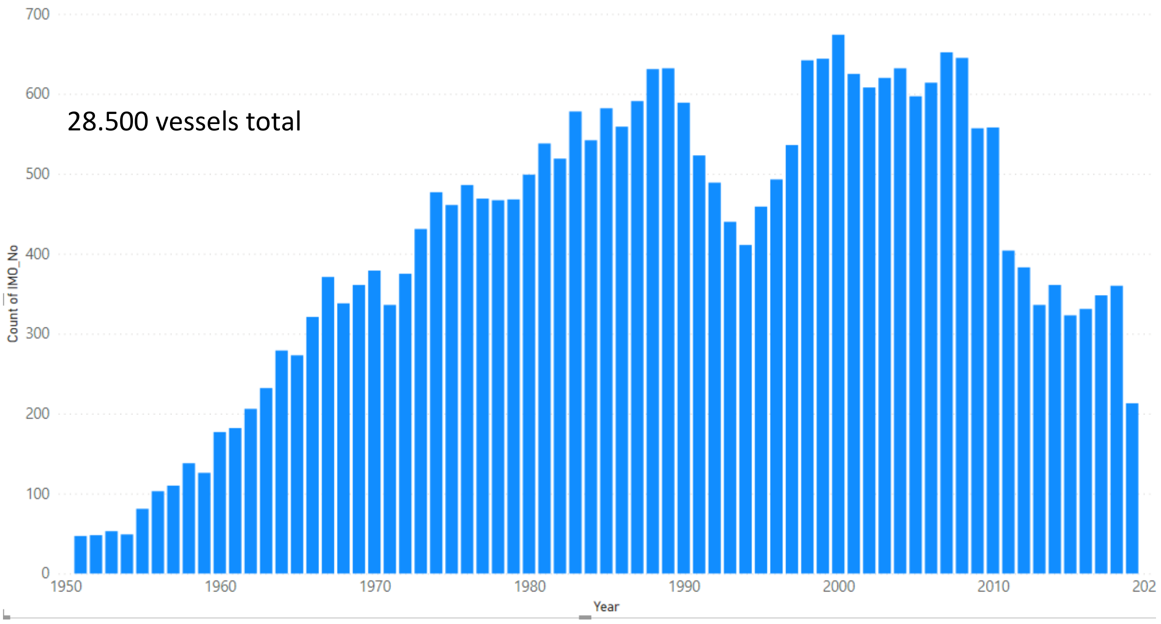


Figure 18 – Deliveries of vessels later than 1950 with IMO number European Builder and in service

In the figure below the market is segmented into length categories of 10 meter. So from 0-10 meter, 10-20 meter etc.

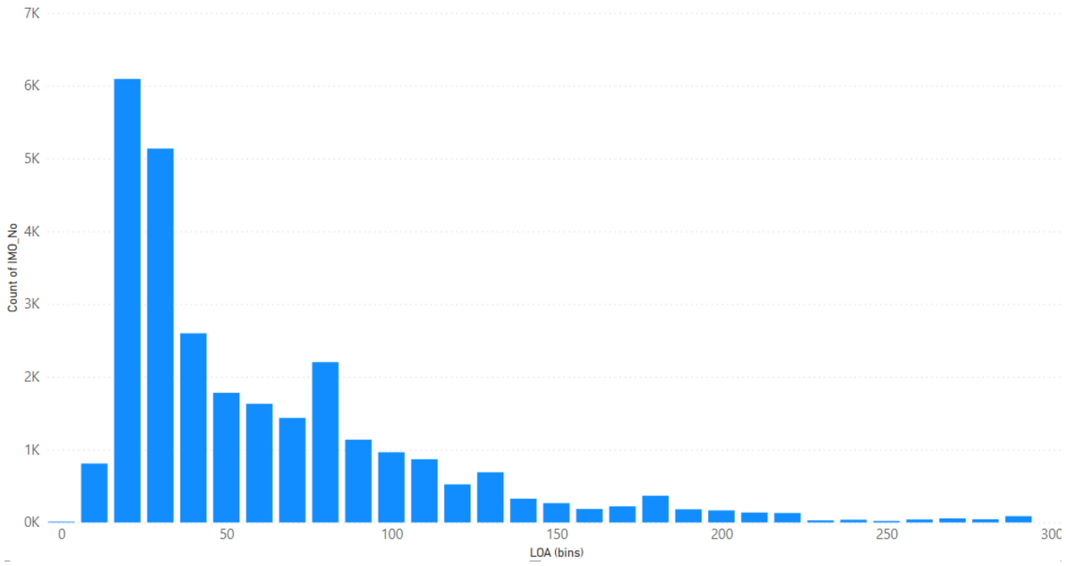


Figure 19 –Distribution of length in active fleet built by European builders

Noticeable in the graph below is that 78% of vessels with IMO number and European builder are < 100 meter length.

3.4.2 Vessel type

In this section the European builder market is segmented the vessels into service, into vessel types.

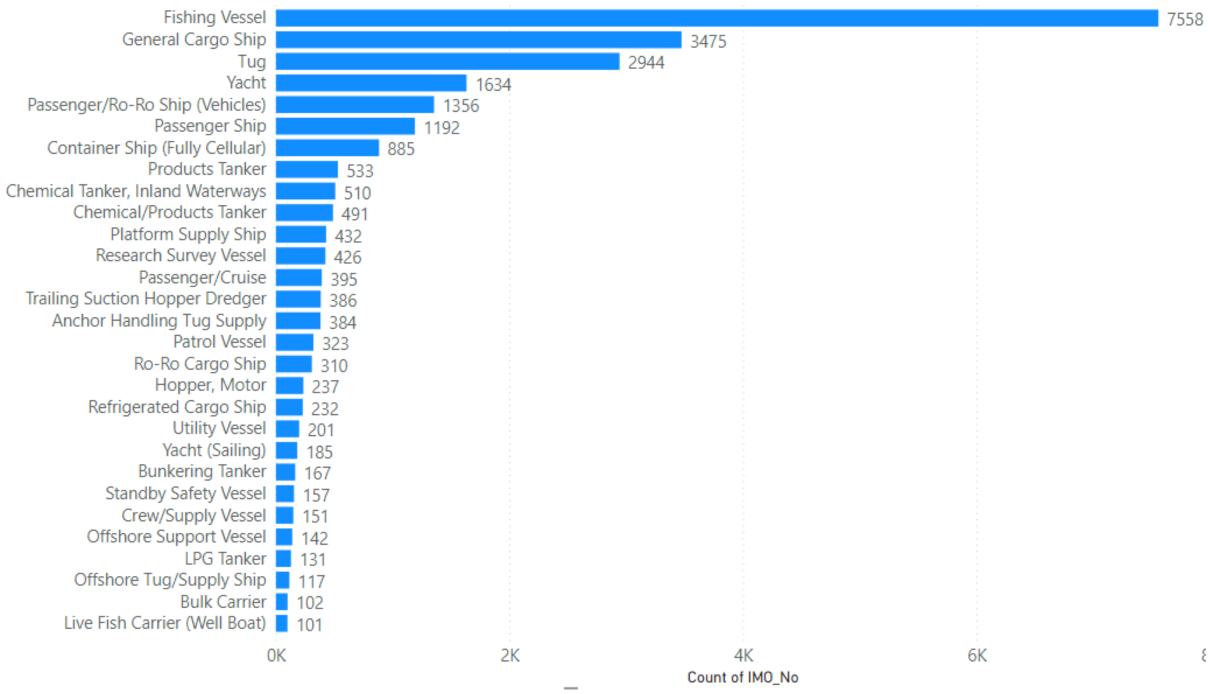


Figure 20 – Fleet size by type: Vessel types by European builder. Vessels in service

The fishing fleet counts for 26%, General Cargo fleet for 12% the Tugs 10% and yachts another 6%. First four groups summarize 54% of all vessels.

3.4.2.1 Fishing fleet in service in Europe by builder country

The demand for fishing vessels is driven by global population trends because of the main use of fish as food. The expected population growth is therefore likely to be followed by future growth in the demand for fishing activity to meet this need. Also the trend to fish farming plays a role in the type of vessel needed.

The European builder fishing fleet as per IHS Fair play currently numbers almost 7,600 vessels (some below 100 GT, but with IMO number).The total number of fishing vessels in the world was estimated by FAO to be about 4.6 million in 2020, 86% of them less than 12 m LOA and 75% in Asia.

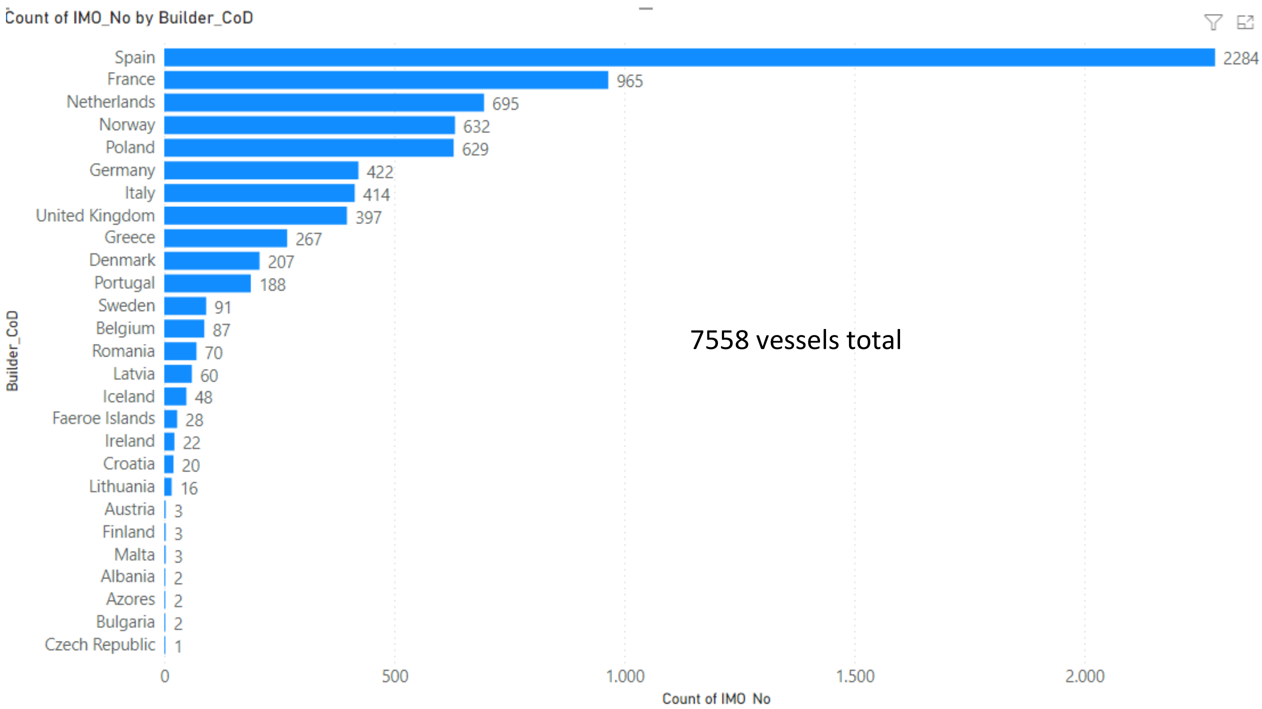


Figure 21 –Fishery fleet in service by European builder by builder country

The largest builder countries of fishing vessels in Europe are Spain 30%, France 9%, Netherlands 9% and Poland 8%.

3.4.2.2 General Cargo

General cargo is the second biggest group after fishing vessels for European build vessels.

the General Cargo fleet, as per the registers of IHS Fairplay, consisted of 15,102 ships. These are all vessels carrying an IMO number and they are classed by IHS either as “In service/commission”, “Laid up”, “In casualty or repair” or “Converting/rebuilding”. Of this total, 13,600 vessels are classed as “General Cargo Ships”. Heavy lift and multipurpose ships account for another 470 ships. The remainder of the category is made up by niche tonnage such as deck cargo ships, livestock carriers, semisubmersible heavy lift ships and the lone yacht carrier.

For a century, the general cargo ship was the workhorse of global seaborne trade. This started to change with the advent of the container ship in the late 1960s. Despite these changes to the composition of the general cargo fleet, the decline in size and market share of this fleet continued. A large part of the fleet is very old: the overall trend in recent years shows that the number of vessels scrapped quite often exceeds newbuild deliveries. As new buildings tend to be larger than the vessels they replace, a decline in terms of tonnage is less pronounced than the decline in numbers of vessels.

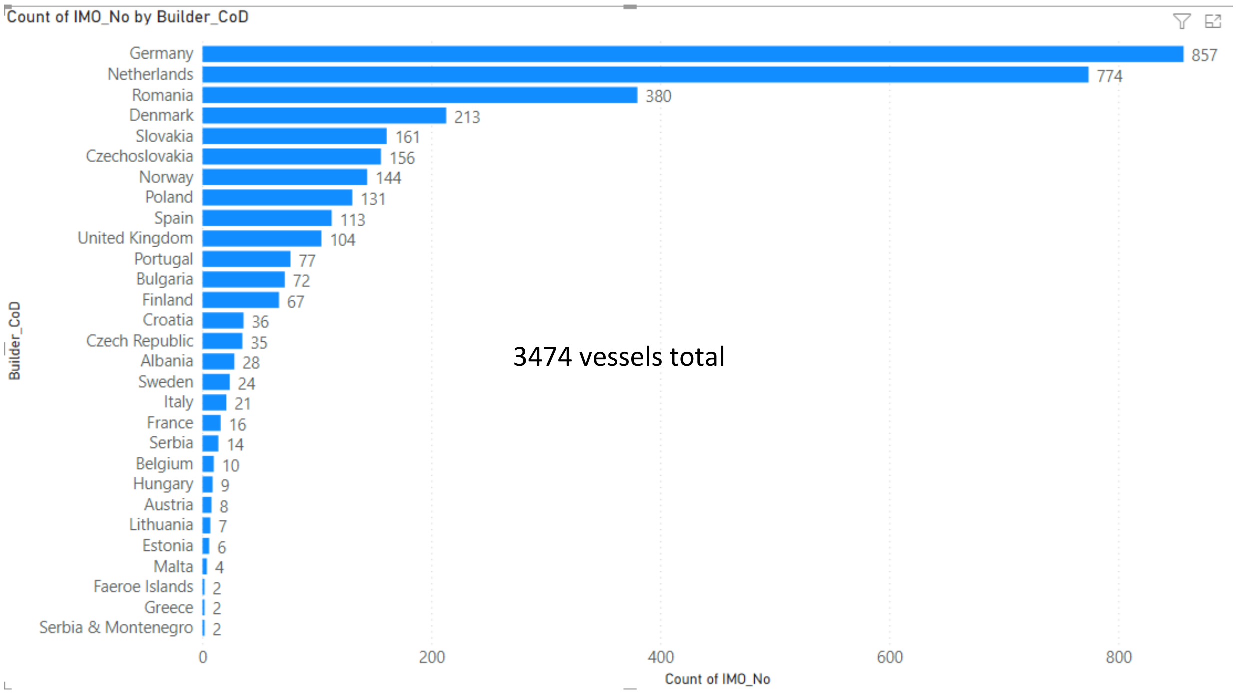


Figure 22 –General cargo fleet in service by European builder by builder country

The largest builder countries of General cargo vessels in Europe are Germany 25%, Netherlands 22%, Romania 11% and Denmark 6%.

3.4.2.3 Tugs

Growth in the fleet of tugs is driven by growth in world seaborne trade, which in turn is related to world GDP growth. Growth in world trade means more vessel movements. Most of the larger vessels require tug assistance. In order to accommodate all these extra vessel movements, a lot of ports are being expanded or newly constructed, mainly in Asia, Africa and South America. The increase is not just in vessel movements, but also in vessel size. The growth in the size of vessels to be handled has led to demand for more powerful tugs, with a higher capacity in terms of Tonnes of Bollard Pull.

Not only the rise in vessel movements is driving newbuild orders for tugs. Another driving force is fleet renewal: large port tug operators in Europe, Asia, the Middle East and the US are ordering or operating energy efficient and environmentally friendly tugs with new propulsion forms, such as hybrid propulsion (battery/diesel) or dual fuel engines fuelled by LNG or diesel. This fleet renewal by major tug operators is not directly leading to an increase in scrapping of old tugs, as tugs simply have extremely long lives, making future scrapping hard to predict. In the future tug lives will be cut short by environmental regulations, as it has also happened with some large ship types, like oil tankers and passenger ferries.

Fleet renewal, world seaborne trade, the need for more powerful tugs as cargo ships continue to grow, are expected to stimulate the tug market in the near future.

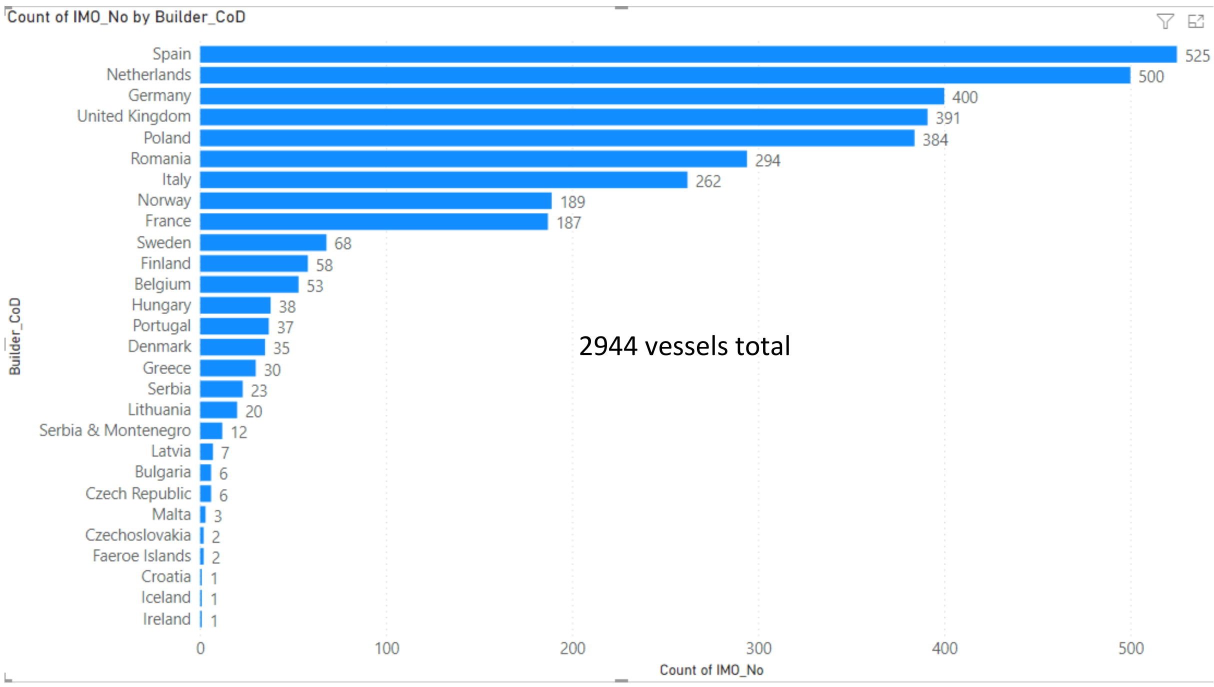


Figure 23 –Tug fleet in service by European builder by builder country

The largest builder countries of Tugs in Europe are Spain 18%, Netherlands 17%, Germany 14% and United Kingdom 13%.

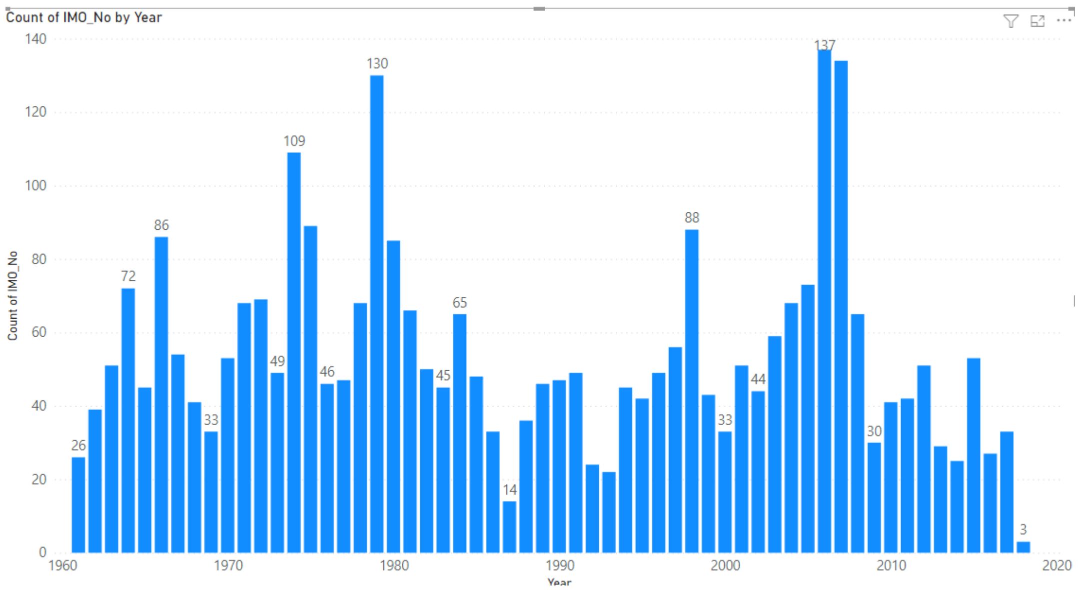


Figure 24 – Tugs in service, contracting year, by European builder

3.4.2.4 Yachts

Yachts are distinguished in Sailing yachts and motor yachts. Only motor yachts are considered in the figure below.

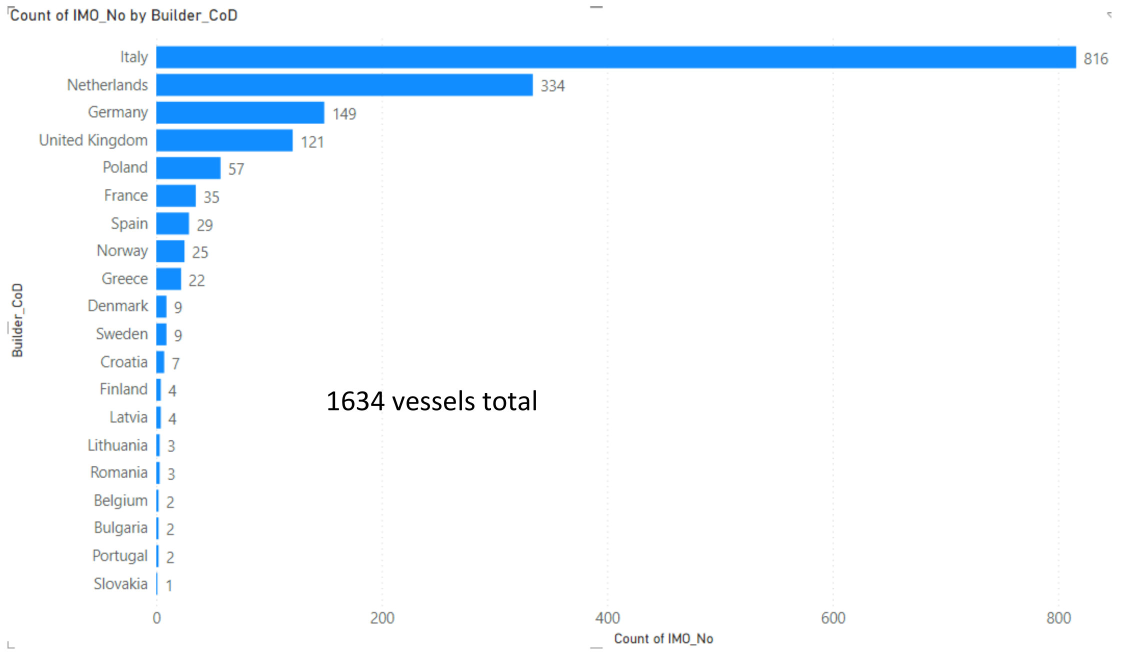


Figure 25 – Yachts in service build by European builder country

The largest builder countries of Motor yachts in Europe are Italy 50%, Netherlands 20%, Germany 9% and United Kingdom 7%.

3.4.2.5 Tankers

The tankers considered is a summary all tankers types available on the market. From LNG, to oil tanker, from water tankers to wine tankers and bitumen tankers. The European market is very small for these types of vessels considering the following figure.

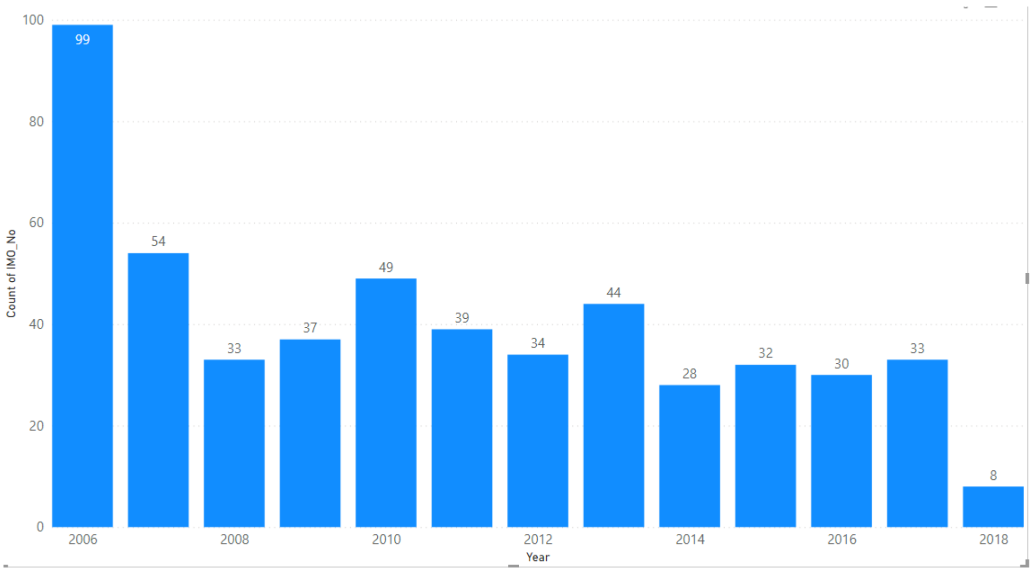


Figure 26 – Number of tankers contracted per year European builder

3.4.2.6 Bulk carriers

The market for Bulk carriers for European builders is very small.

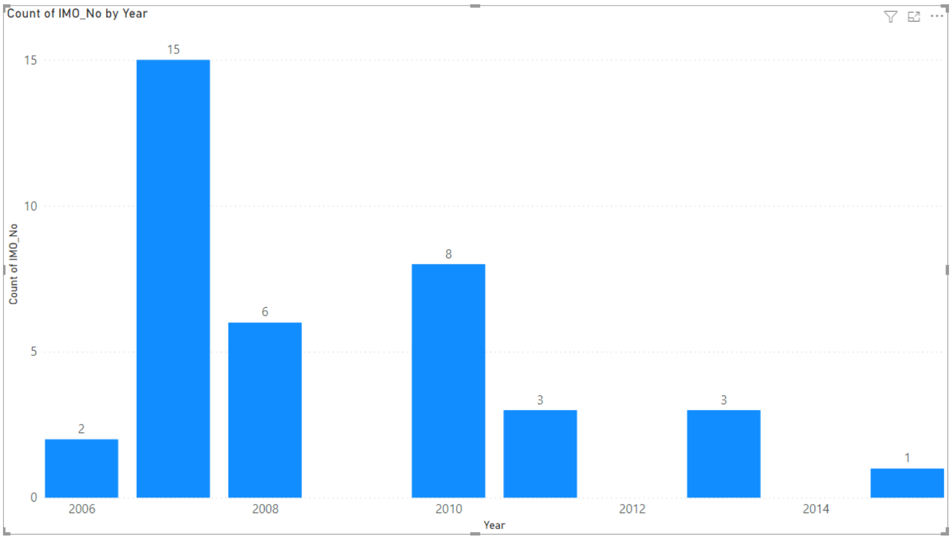


Figure 27 – Number of bulk carriers contracted per year European builder

3.4.2.7 Total installed power

This paragraph shows the vessels types segmented per installed power for the fleet of European build vessels. In the figure below the European builder market is segmented by installed power. They are grouped per 500 kw.

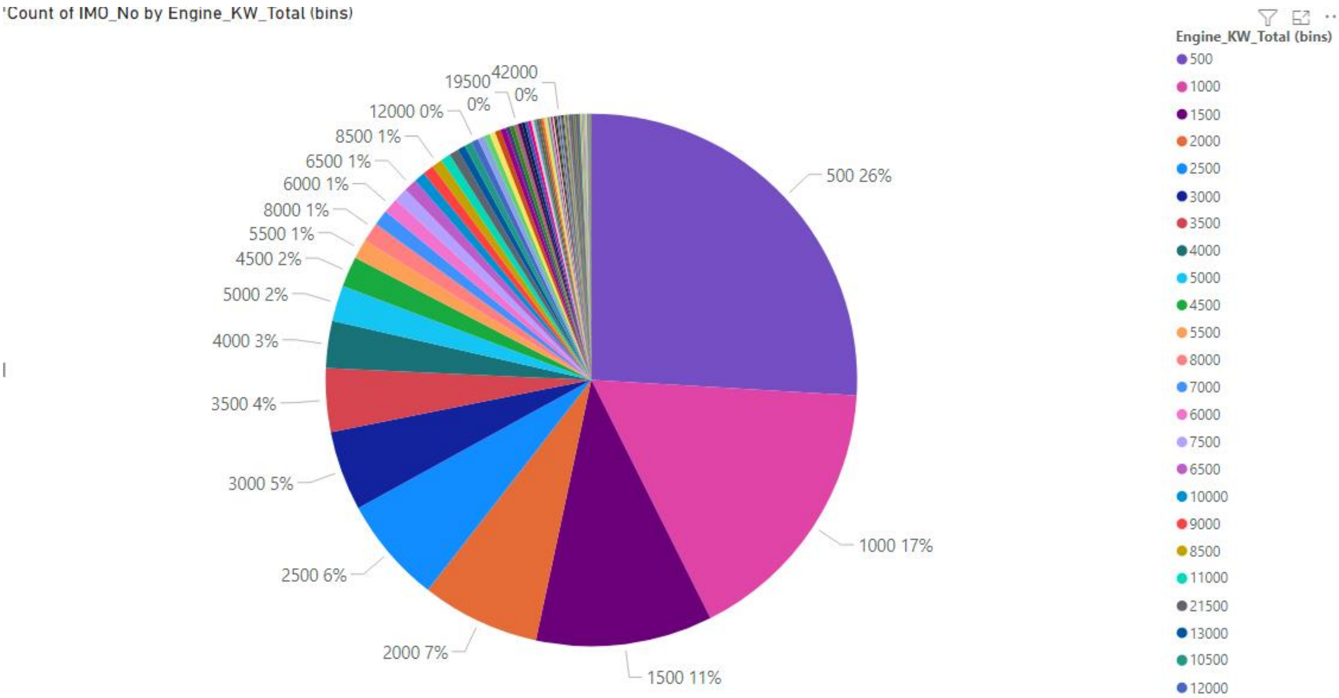


Figure 28 – Number of vessels, per total installed power European built, in service

Figure above shows that 72% of vessels are smaller than 3500kw total installed power and more than half of the vessels are below 1500kw total installed power.

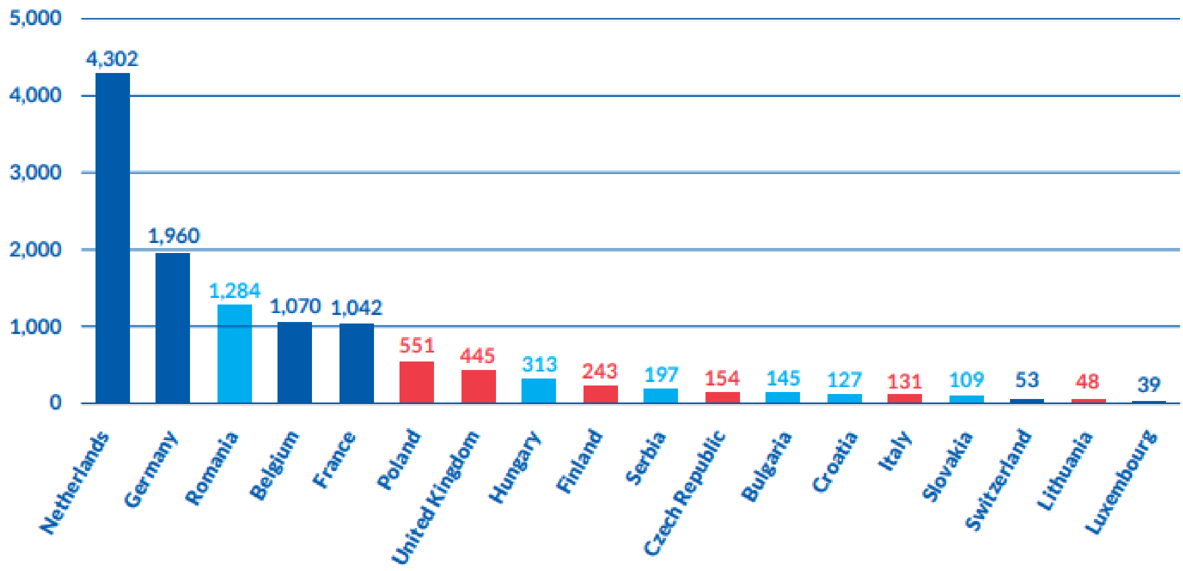
3.4.3 Inland vessels

Inland vessels make up a considerable part of the potential European market for battery driven vessels. Below figures shows the current size of the inland vessel fleet sailing in Europe.

TABLE 1: **SIZE OF FLEETS** (NUMBER OF INLAND VESSELS) **PER MACRO-REGION AND VESSEL TYPE IN EUROPE**

	Dry cargo vessels	Liquid cargo vessels	Push & tug boats	
RHINE FLEET	7,033	1,433	1,319	9,785
DANUBE FLEET	2,652	204	642	3,498
OTHER COUNTRIES*	1,546	26#	345	1,917
	11,231	1,663	2,306	15,200

Figure 29 – The size of the European inland fleet



Sources: Eurostat [iww_eq_loadcap] and sources used for Rhine countries in the table above

Figure 30 – The size of the European inland fleet by country

3.4.4 River cruise fleet

The European river cruise fleet is expanding. River cruisers could be very suitable for battery use. Battery use could enhance living conditions on board due to a reduction of vibrations, noise and exhaust gasses. It could also contribute to a greener image. Due to the regular stops at predetermined locations charging facilities could be installed. River cruise vessels are moreover often built by European builders. New vessels need to be innovative, low emissions and low draught.

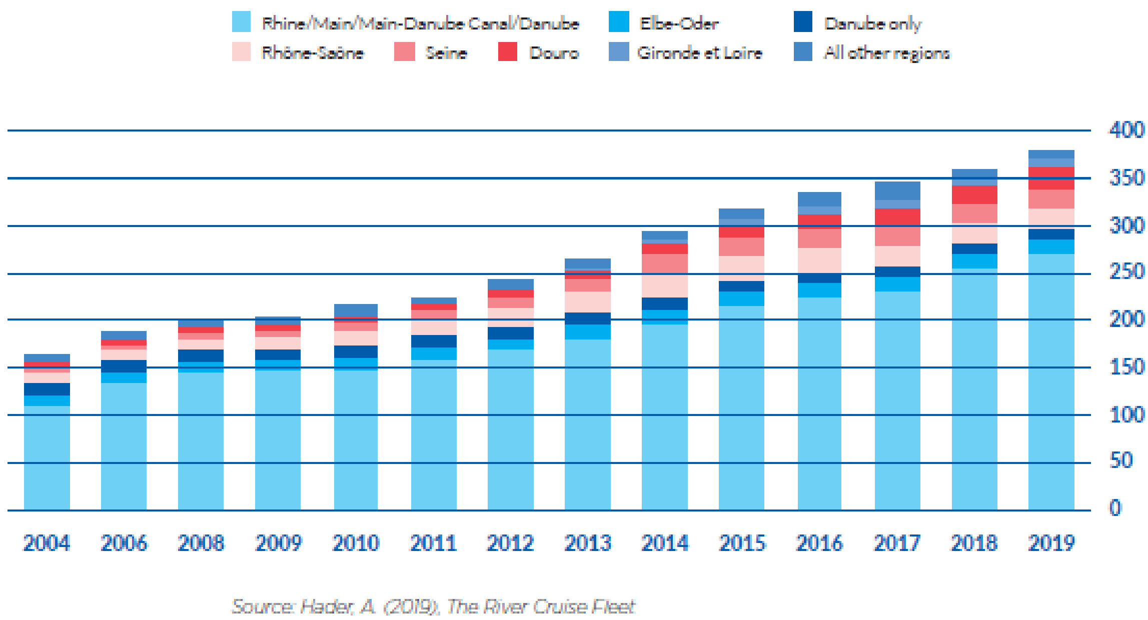


Figure 31 – The size of the European river cruise fleet

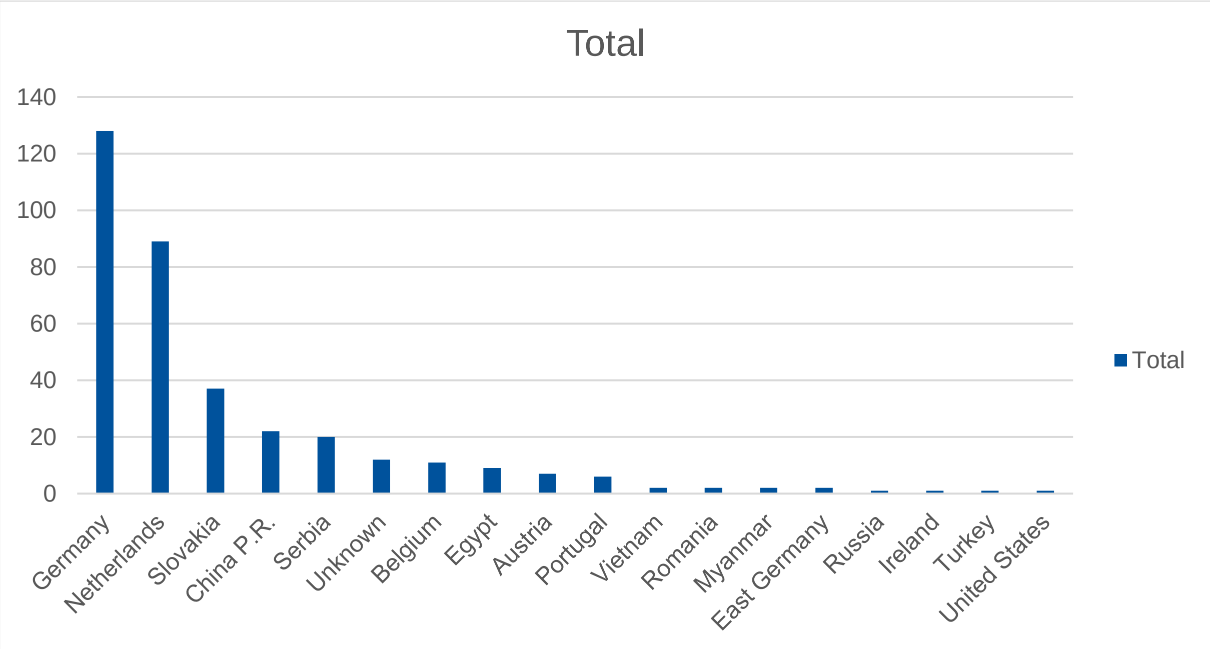


Figure 32 – Builder Countries of active river cruise fleet

3.4.5 Ship type by Installed power

From the previous analysis is emerged that the European shipbuilding market in terms of CGT is predominantly passenger oriented. In number of vessels the largest market is Fishery, followed by General cargo, Tugs and yachts. The dataset considered contains almost 30.000 vessels with an IMO number. All ships are currently active and build by an European builder. 78% of all vessels with IMO number and European builder are < 100 meter length. 72% is smaller than 3500kw total installed power. Tankers and Bulkers are almost not being build any longer by European shipyards.

The inland fleet in Europe is approximately 15500 Vessels. These vessels are currently sailing in European waters but are not necessarily built in Europe. These vessels are considered for the retrofit market and can easier be equipped with batteries because of the enhanced charging possibilities.

This subsection examines the ship types by European builder in service per category of installed power. The categories are 0-500 kw, 500-1000kw, 1000-1500kw and >1500kw. The aim is to determine which categories of ships fall within these reference dimensions.

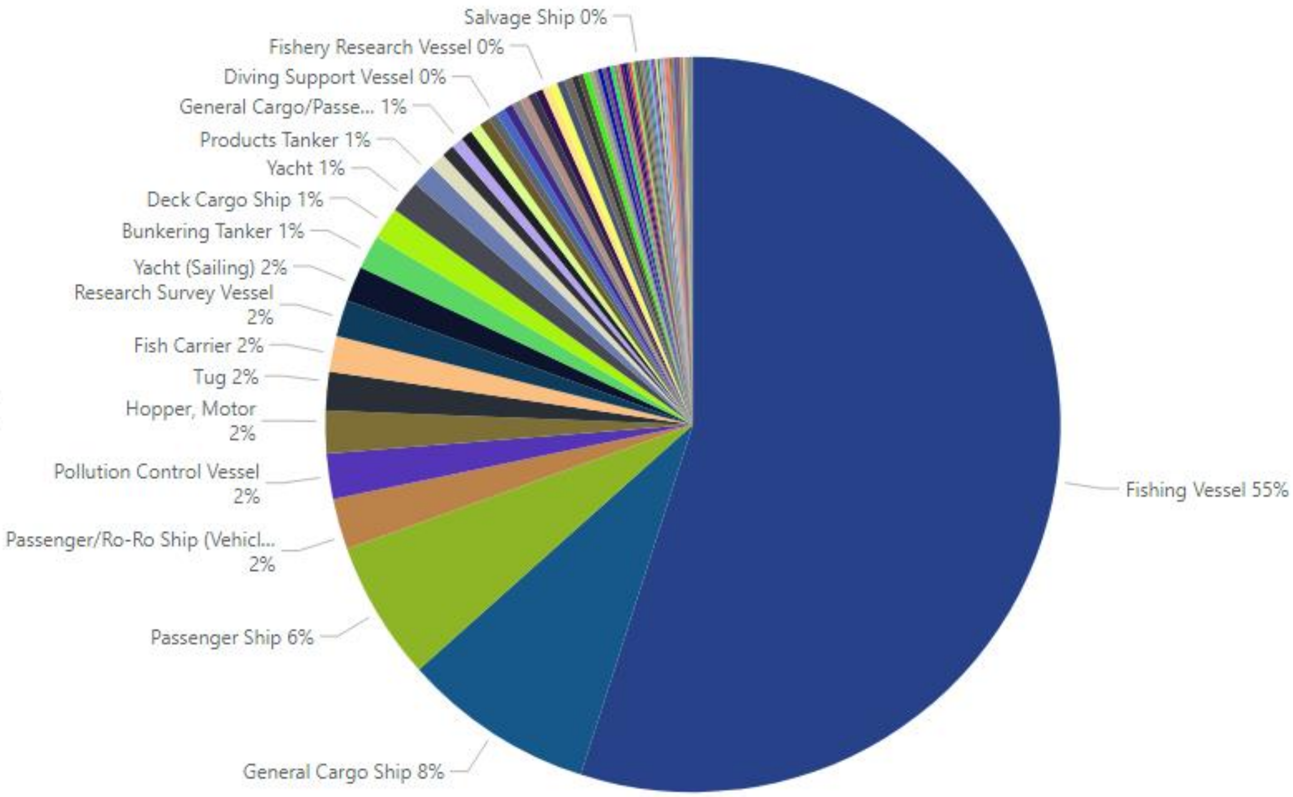


Figure 33 – Total Fleet size per Ship type, <500kw, European built

Figure above shows that the majority of vessels with installed power under 500kw are fishing vessels.

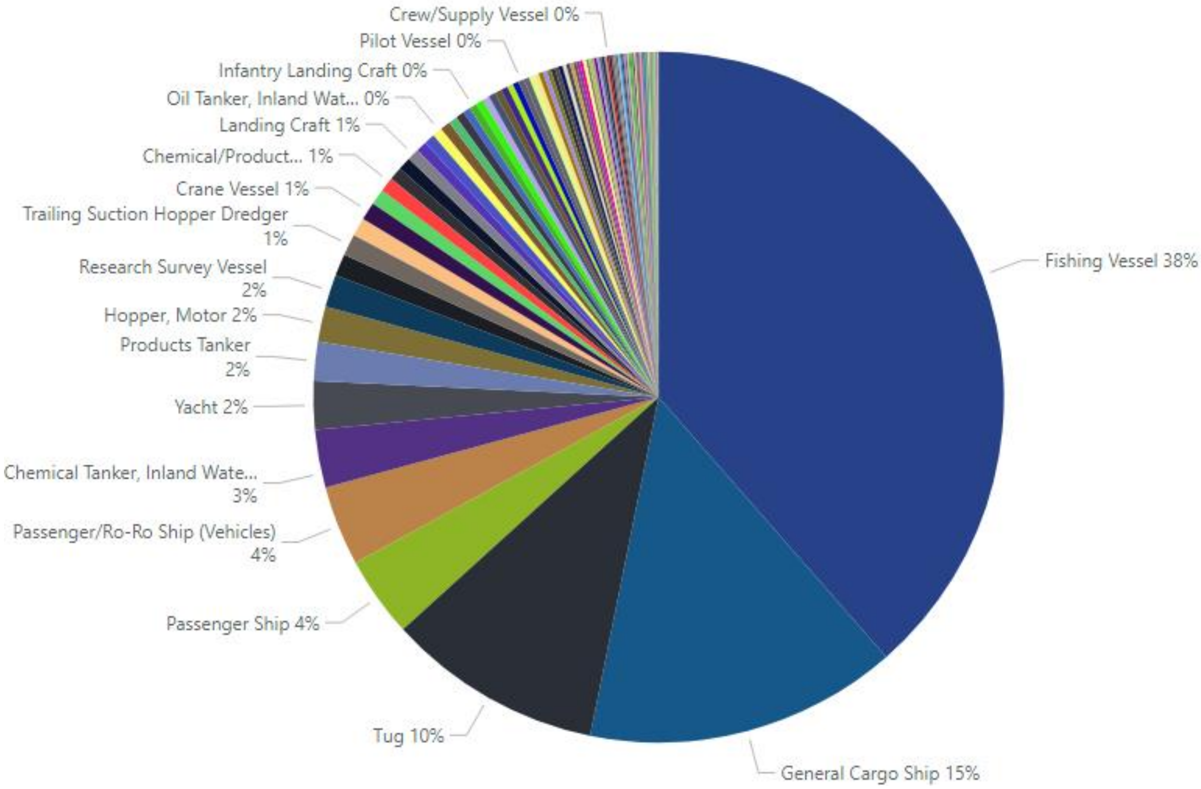


Figure 34 – Total Fleet Ship type, >500kw<1000kw

Figure above shows that that 38% of vessels with installed power between 500kw and 1000kw are fishing vessels, 15% are general cargo vessels and 10% are tugs.

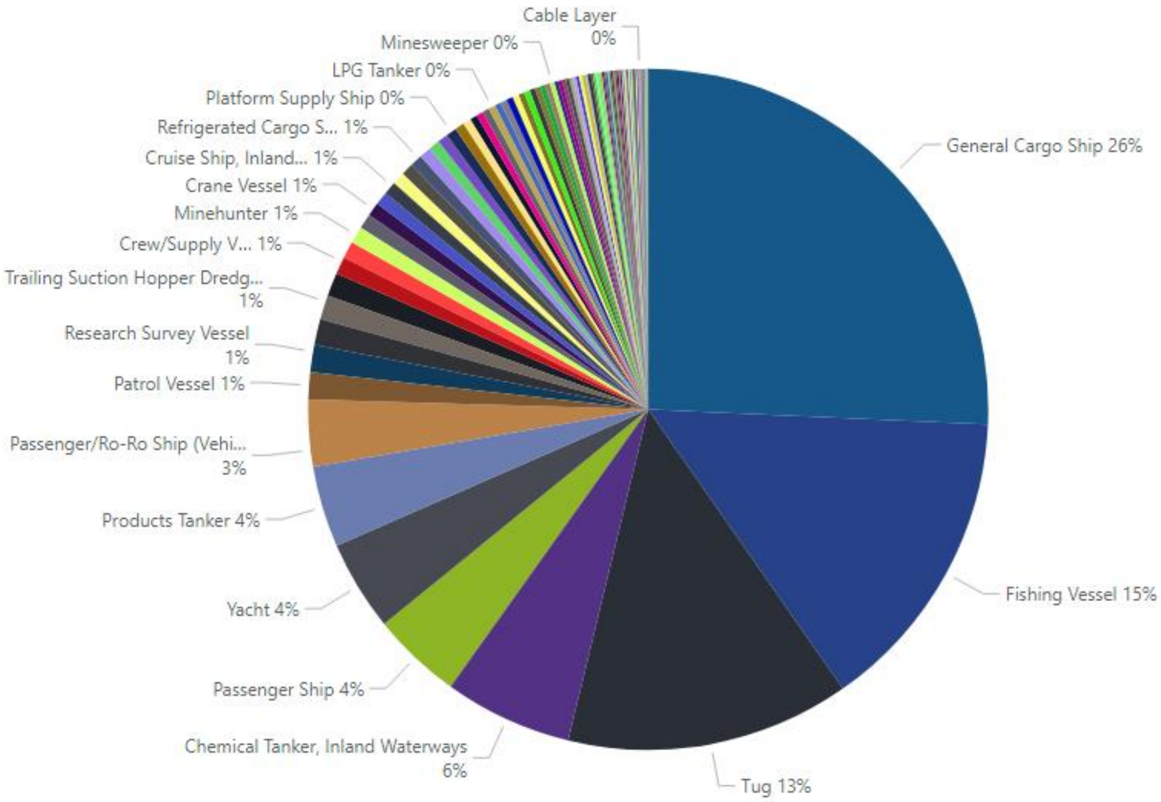


Figure 35 – Total Fleet Ship type, >1000kw<1500kw European built

The graph above shows that the majority of vessels with installed power between 1000kw and 1500kw are general cargo vessels.

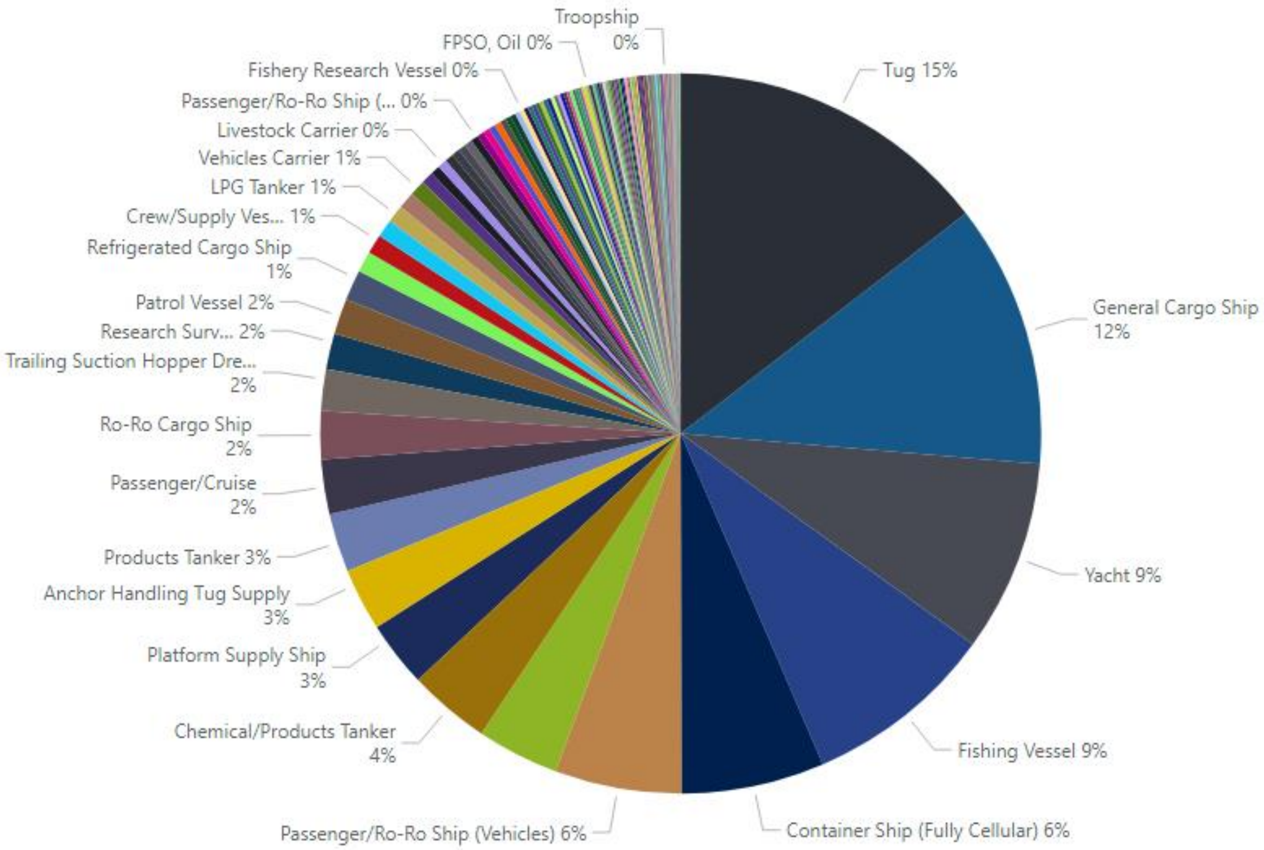


Figure 36 – Total Fleet Ship type, 1500kw European built

The graph above shows that the majority of vessels with installed power above 1500kw are Tugs.

Some data (approx. 500 vessels) is available on tank sizes. The figure below shows average installed power and tank sizes for various vessels. On the ordinate axis there is the power in KW meanwhile on the abscissa axis is the size of the tank in cubic meters.

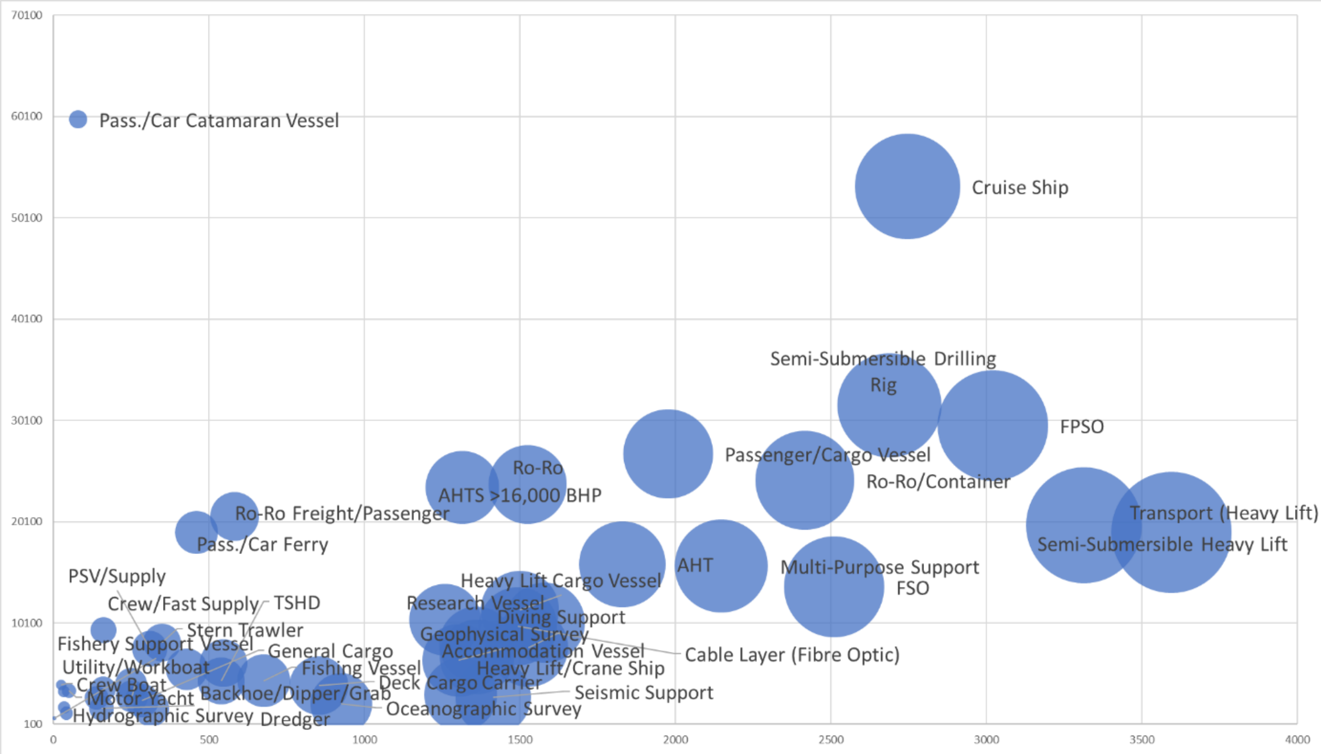


Figure 37 – Average installed power and tanks sizes per Ship type, on the

From the analysis of the power and dimension of tanks results that the vessel types that seems suitable for battery use are: Near shore fishing vessels, crew transfer vessels, tugboats, supply vessels, utility vessels, yachts. Battery use on yachts can be beneficial due to low vibrations, noise and exhaust gasses optimizing living conditions on board. Yacht support vessels could optionally be equipped with charging infrastructure. Offshore Patrol Vessels do not seem very suitable for battery use because extended ranges are a very important feature to patrol the expanding Exclusive Economic Zones. Smaller patrol vessels for coastal waters with smaller ranges or patrol vessels for harbour use could be suitable.

Inland vessels are currently sailing in European waters but are not necessarily built in Europe. These vessels are able to be equipped with batteries because of the easier accessibility of charging possibilities. Vessels with large installed powers and/or large sailing distances are less suitable for battery use.

3.5 Current battery market overview

Aim of this paragraph is to describe the current context of the battery market in general, of batteries for marine applications and of the main projects in progress that envisage the integration on board of these energy storage systems and, finally, describe the possible mode of use and market trends for the integration of batteries on different vessel types.

3.5.1 International battery market

BloombergNEF (BNEF) is a strategic research company who provides a global covering commodity markets and the disruptive technologies driving the transition to a low-carbon economy. Their expert coverage assesses pathways for the power, transport, industry, building and agriculture sectors to adapt to energy transition.

In this sense, this research institute carried out in 2020 a ranking of the producers' countries of Lithium-ion batteries, since, as already mentioned, they are the ones with the most development and applications.

BloombergNEF elaborates its ranking based on the following five key themes related to the supply chain: raw materials, cell & component manufacturing, environment, RII and end demand (across electric vehicles and stationary storage, see Figure 38).

The principal conclusions are exposed below, in order to understand which the biggest competitors in the battery market are.

Based on BloombergNEF research, China dominates lithium-ion battery supply chain ranking in 2020, having quickly surpassed Japan and Korea that were leaders for the majority of the previous decade. China's success results from its large domestic battery demand, 72GWh, and control of 80% of the world's raw material refining, 77% of the world's cell capacity and 60% of the world's component manufacturing. In 2020, Japan and Korea rank number two and three respectively. While both countries are leaders in battery and components manufacturing, they lack in the control of the raw materials supply chain, they make-up for in higher environmental and RII (regulations, innovation & infrastructure) scores compared to China.

Some Chinese manufacturers, like CATL, have come from nothing to being world leading in less than 10 years. The next decade will be particularly interesting as Europe and the U.S. try to create their own battery champions to challenge Asian incumbents who are already building capacity in both places. While Europe is launching initiatives to capture more of the raw material value chain, the U.S. is slower to react on this.

Sustainability and carbon emissions associated with the supply chain are of growing importance. Making sure that the electricity used in material processing and cell manufacturing is low-carbon is vital. France performed best in the environmental category, helped by its electricity grids low carbon emissions factor, at 28gCO_2/kWh in 2019.

In addition to making significant investments into mining of critical minerals all around the world, China is also the dominant player in materials refining. This has given it the advantage over Japan and Korea. Other countries seeking to be dominant players in the overall value chain may need to support upstream metals mining and refining development, while also formulating policies that will safeguard the environment.

Country	2020 rank	Raw material	Cell & component	Environ.	RII	Demand	2025 rank	Raw material	Cell & component	Environ.	RII	Demand
China	1	1	1	16	11	1	1	1	1	15(▲1)	11	1
Japan	2	12	2	6	7	6	2	8(▲4)	3(▼1)	7(▼1)	7	8(▼2)
S. Korea	3	17	2	9	5	2	8(▼5)	16(▲1)	2	13(▼4)	5	9(▼7)
Canada	4	4	10	4	10	11	5(▼1)	3(▲1)	12(▼2)	4	10	6(▲5)
Germany	4	17	6	12	2	2	6(▼2)	22(▼5)	6	9(▲3)	2	3(▼1)
U.S.	6	15	4	13	6	2	3(▲3)	13(▲2)	3(▲1)	7(▲6)	6	2
U.K.	7	17	6	9	4	6	8(▼1)	17	8(▼2)	10(▼1)	4	4(▲2)
Finland	8	11	13	5	3	13	7(▲1)	10(▲1)	8(▲5)	6(▼1)	3	17(▼4)
France	8	17	13	1	9	5	10(▼2)	17	12(▲1)	1	9	5
Sweden	10	22	13	3	1	8	4(▲6)	17(▲5)	7(▲6)	3	1	7(▲1)
Australia	11	2	13	21	12	8	11	2	12(▲1)	19(▲2)	12	11(▼3)
Brazil	12	3	13	2	24	23	12	7(▼4)	18(▼5)	2	24	15(▲8)
Poland	12	22	5	11	13	14	13(▼1)	22	5	12(▼1)	13	19(▼5)
Hungary	12	22	6	8	14	15	15(▼3)	22	8(▼2)	11(▼3)	14	18(▼3)
Czech Rep.	15	17	10	17	8	17	16(▼1)	17	12(▼2)	17	8	21(▼4)
India	16	9	13	19	18	11	16	13(▼4)	18(▼5)	21(▼2)	18	10(▲1)
Chile	17	6	13	18	16	20	14(▲3)	4(▲2)	12(▲1)	15(▲3)	16	23(▼3)
Vietnam	18	16	6	22	20	10	23(▼5)	17(▼1)	12(▼6)	23(▼1)	20	12(▼2)
S. Africa	19	5	13	23	17	19	20(▼1)	4(▲1)	18(▼5)	19(▲4)	17	22(▼2)
Argentina	20	12	13	6	22	24	16(▲4)	8(▲4)	18(▼5)	5(▲1)	22	25(▼1)
Indonesia	21	7	13	25	21	15	20(▲1)	4(▲3)	18(▼5)	24(▲1)	21	13(▲2)
Mexico	22	12	13	15	19	22	16(▲6)	12	18(▼5)	13(▲2)	19	16(▲6)
Thailand	23	22	10	19	15	17	22(▲1)	22	8(▲2)	21(▼2)	15	20 (▼3)
D.R.C.	24	8	13	14	25	24	25(▼1)	10(▼2)	18(▼5)	18(▼4)	25	24
Philippines	25	9	13	24	23	20	24(▲1)	13(▼4)	18(▼5)	25(▼1)	23	14(▲6)

Figure 38 - Lithium-ion battery supply chain rankings, 2020 and expected in 2025. Source: BloombergNEF

One of the most widespread applications of batteries is the electric car market and in the International Automotive Engineering Conference (7-8 November 2019, Istanbul, Turkey) talks about the current situation of the battery market and it was highlighted which were the main producers of batteries for electric cars

Today, the largest battery manufacturer is CATL with a production of 17.3 GWh in the first half of the year 2019. The Chinese company, which has more and more strategic partners, produces more than a quarter (27%) of the world total and has a 52% market share in China.

Recently, CATL has signed an agreement with BMW to become its majority supplier of batteries in the next ten years. Toyota electrics in China will also carry CATL batteries, as well as electrified models from Volkswagen (in China), Honda, Volvo, Geely, Daimler electric trucks and probably also the Tesla Model 3 'made in China'. In Europe, CATL has already started to build a battery factory, in Germany specifically, in which they intend to achieve an annual production of 22 GWh in 2022 and increase it to 100 GWh in 2025.

The world's second largest battery manufacturer is Panasonic, a partner of Tesla, which until recently held the top spot. Panasonic's production in the first half of 2019 reached 15.5 GWh, not counting that for Tesla PowerWalls and other non-car storage solutions. Panasonic manufactures the cells for the Tesla batteries at Gigafactory 1 in Nevada (USA), the largest battery factory in the world, and accounts for 22% of the market share worldwide, just over a fifth (see Figure 39).

In third place is BYD, another Chinese company that in its local market takes almost a quarter of the production. With 9.5 GWh of production, there is a notable leap from Panasonic. It should be noted that BYD manufactures batteries mostly for itself, as it also manufactures and sells everything from electric cars and plug-in hybrids to electric trucks and buses.

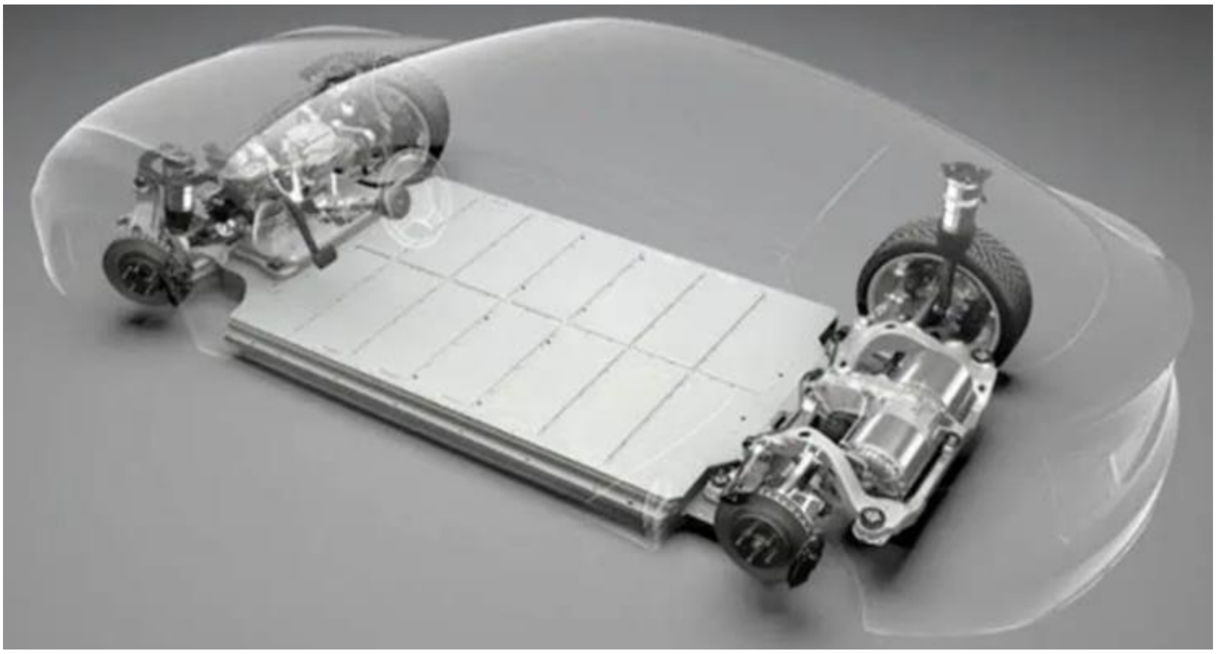


Figure 39 - Panasonic battery for electric car

In fourth position, with a production of 8.4 GWh that represents a little more than 10% of the world total, we find LG Chem. The Korean company feeds the Volkswagen Group, Volvo, Hyundai or General Motors with batteries, among others, and is the manufacturer of the batteries for the Jaguar I-Pace, the Renault ZOE and the new Ford Mustang Mach-E.

A little further from the top positions we find Samsung SDI, whose production between January and September has reached 2.9 GWh. This manufacturer is the supplier of batteries for the Audi e-tron, Volvo's electric trucks and the first Harley-Davidson electric motorcycle, among others. Behind Samsung we find AESC (whose batteries are mounted in the Nissan Leaf) with 2.45 GWh of production; Guoxuan (supplier of BAIC and SAIC, the best-selling electric brands in China) with 2.25 GWh; SK Innovation (suppliers of Hyundai and KIA) with 1.6 GWh; and finally, Lishen and EVE.

Below a summary (see Table 19) bwith the most important producers of batteries for the electric vehicle market and its clients, in the year 2019.

Table 19 - Principal manufacturers of battery in electrical vehicle market, year 2019

Position	Battery manufacturer	Country	Production (Gwh) 2019	Clients
1	CATL	China	17.3	BMW, Toyota, Volkswagen, Honda, Volvo, Geely
2	PANASONIC	Japan	15.5	Tesla
3	BYD	China	9.5	BYD cars
4	LG CHEM	Korea	8.4	Volkswagen, Volvo, Huyndai, General Motor
5	SAMSUNG SDI	Korea	2.9	Volvo, Harley-Davidson
6	AESC	Japan	2.45	Nissan
7	GUAXUAN	China	2.25	Baic, Saic
8	SK INNOVATION	Korea	1.6	Hyundai, Kia

3.5.2 International maritime battery market

The evolution in the battery market is strongly correlated to size, materials, safety, and the ability to store energy. Finding the right trade-off between these effects and at the same time maintaining a correct low production cost is the key in the search for new battery technologies.

3.5.2.1 Current market in terms of units and energy installed

Since 2008, the evolution of the marine battery market has seen a continuous growth of ships equipped with battery systems. As will be observed later in this paragraph, the first applications of these technologies concerned small boats with limited autonomy, both in “hybrid” and “full electric” mode. Recently, thanks to the continuous and significant technological innovations of battery systems, even the largest ships are starting to install large battery systems on board, mainly to improve their energy efficiency and energy management on board. The evolution of the market, in terms of installed energy for battery systems on board ship, is graphically proposed in Figure 40, divided between units in service and under construction.

In Figure 40 it is possible to highlight at least 3 points of strong discontinuity in the increase of applications (2012, 2015 and 2017), mostly linked to economic situations favourable to batteries and technological innovations enabling their use on board in a massive way.

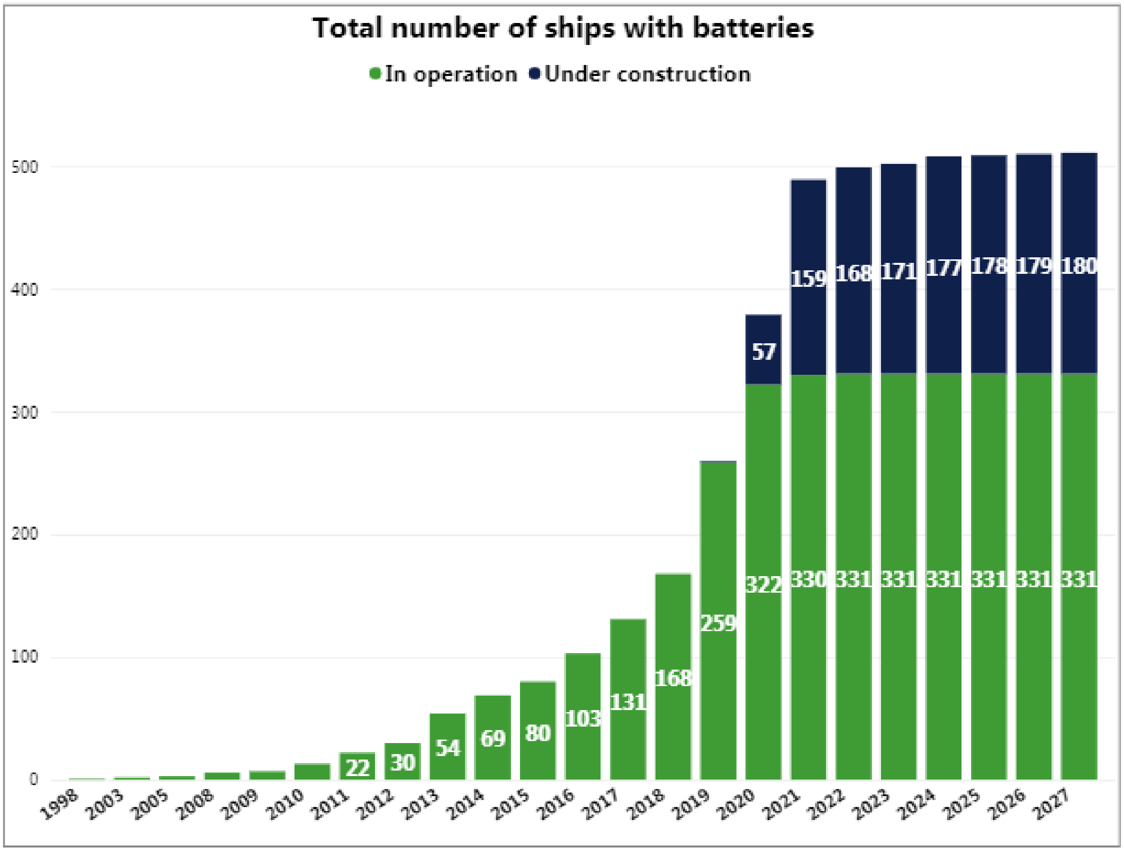


Figure 40 – Market evolution (cumulative number of ships) for maritime applications (Source: maritime battery forum)

Europe, especially Norway and France, is the leading continent for market value of onboard battery applications, as shown in Figure 41. Among these, the types of ships most affected by the introduction of these systems are ferries, offshore vessels, passenger vessels, tugs and yachts.

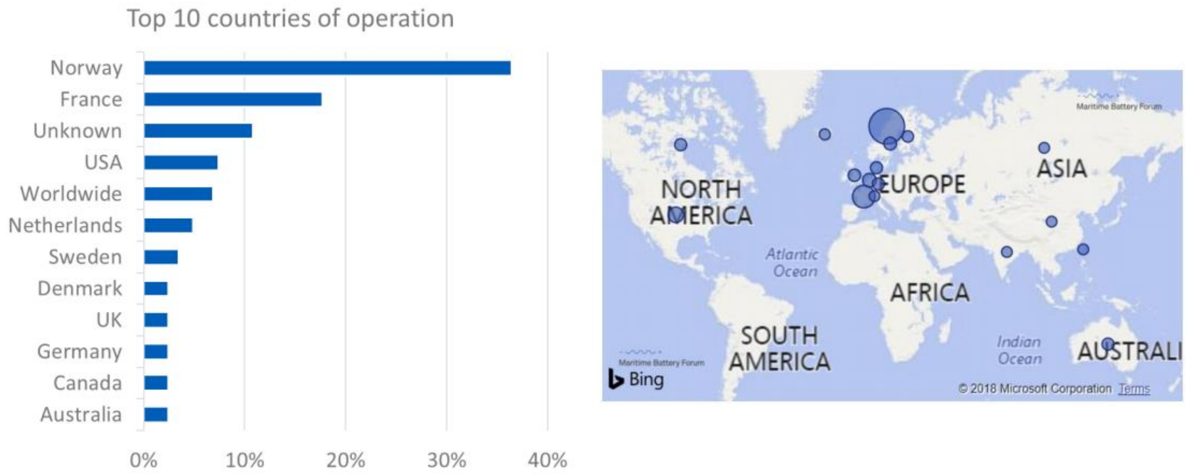


Figure 41 – Countries involved in the battery integrated on board ship (Source: maritime battery forum)

The first applications of battery systems on board ship mainly concerned the increase of the energy efficiency of power generation. For this reason, the development of hybrid systems, where the batteries are in support of the diesel generators to allow them to work as close as possible to their point of, is still today the most common application in the maritime field, as shown in Figure 42.

The recent innovations in the battery field, mainly related on the specific energy and power densities, have opened the door for further applications of battery systems in the maritime field. For this reason, as proposed in in Figure 42, there is an important number of "Pure electric, or full electric" applications, where medium-sized vessels with a short autonomy can be fully powered by the on board battery system (ferries, tugs, etc.).

Finally, "Plug-in hybrid" application have a significant share of the total market and, in the near future, will partially replace the traditional hybrid configurations, also thanks to the systematic electrification of ports and docks, which would allow the batteries to be charged during stops in port, significantly reducing the polluting emissions of ships.

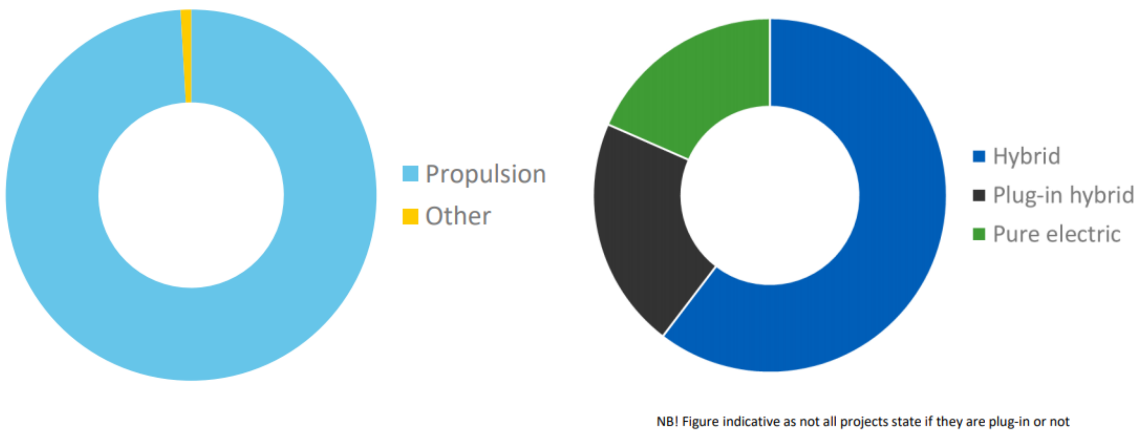


Figure 42 – Share of different applications(Source: battery maritime forum)

From a chemical and technological point of view, Nickel Manganese Cobalt Oxide (NMC) is widely the most common, due to the high performances in terms of energy and power density and relative low costs. However, in the recent years, also the lithium iron phosphate (LFP) and Lithium titanate (LTO) have increased their market share, providing different performances and costs with reference to the NMC, as proposed in Figure 5.

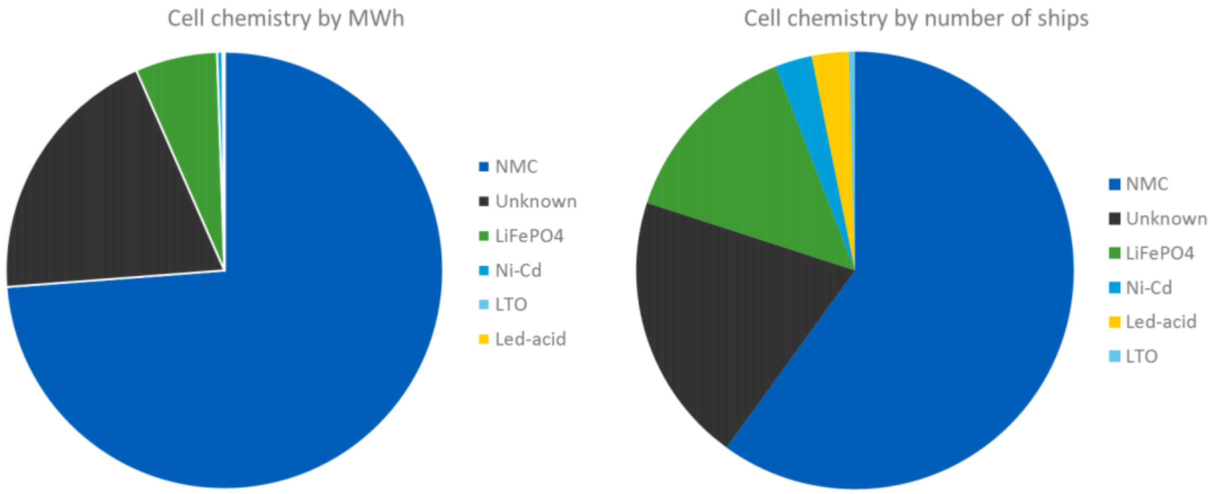


Figure 43 – Share of different battery chemistries (Source: battery maritime forum)

As a conclusion of these analyses of the current market of batteries for marine use, the total number of ships (divided by type) that have a battery system installed on board ship and the relative value of installed energy (MWh) are shown in Figure 44 and Figure 45, respectively. It is possible to highlight that, despite the similar number of units with batteries on-board, from an energy point of view ferries and passenger vessels are those with the greatest amount of energy installed per unit.

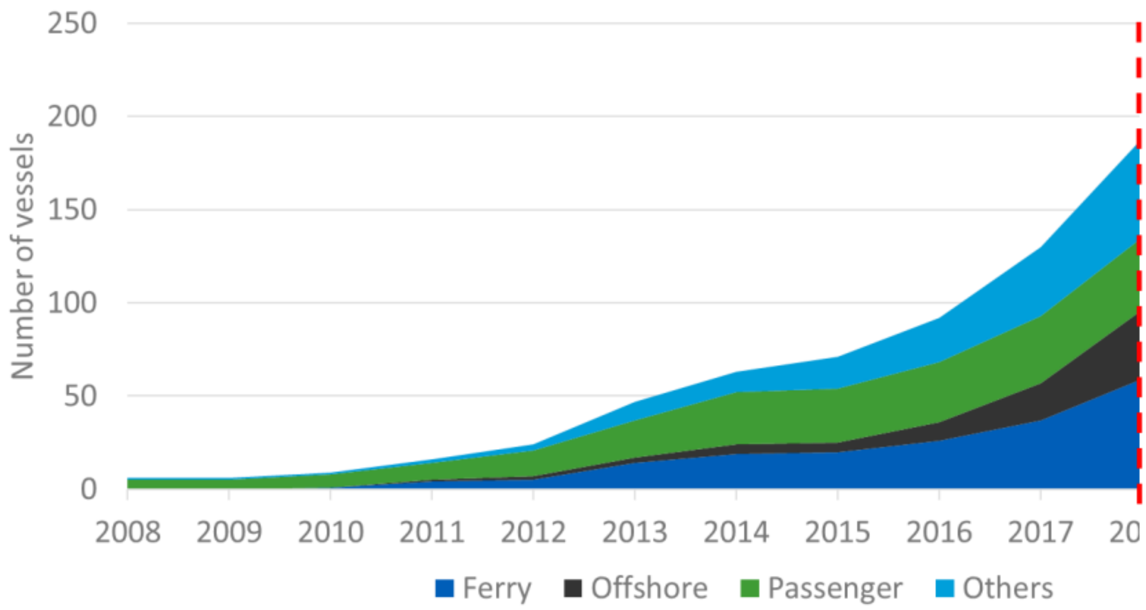


Figure 44 – number of vessel with a battery system

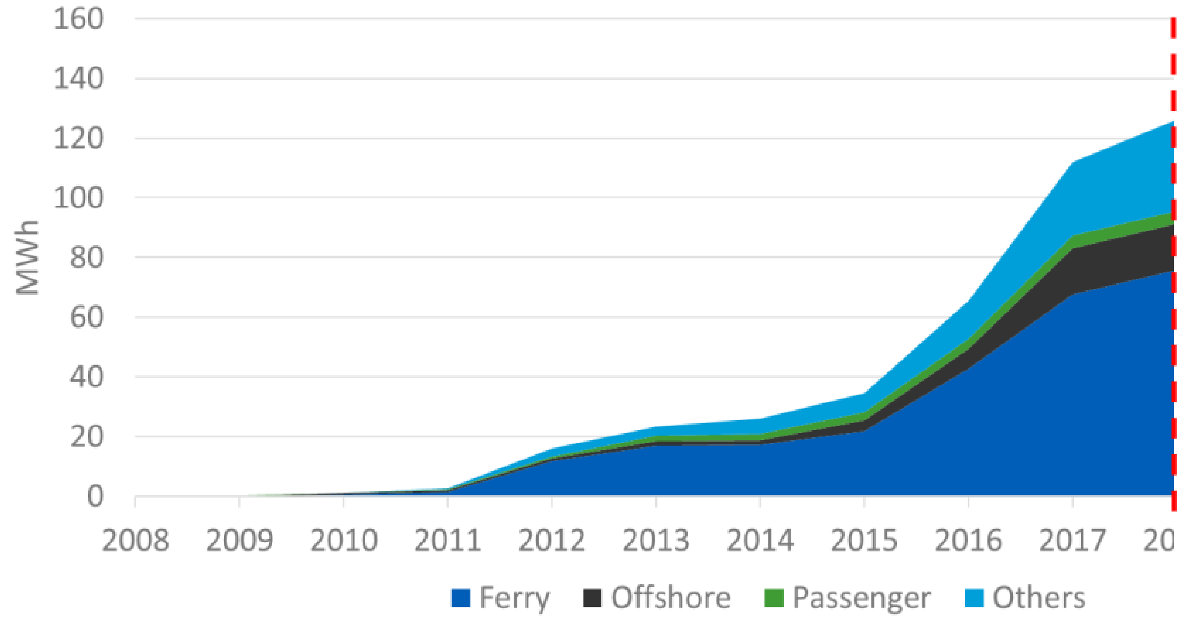


Figure 45 – total amount of energy installed

3.5.2.2 Selection of Projects

This section includes a selection of seagoing projects to get an overview of the current picture of the maritime market.

3.5.2.2.1 Alsterwasser

Alsterwasser was developed in Germany as a part of the 121 Zemship (Zero Emission Ship) project. The total project budget was 5.5 million, of which 2.4 million was co-funded by the European Union life program. A hydrogen fuelling station has been also built for this ship as a part of the project. This ship is equipped with two PEMFC systems and a DC-DC converter to stabilise the fuel cell voltage. The fuel cell system is hybridized with a lead-gel battery system to deliver the propulsion power to an electric motor without producing any harmful emissions proving to be a highly reliable power system. Twelve tanks of 50 kg of hydrogen are installed onboard the ship at a pressure of 350 bar which is sufficient for about three operational days without refuelling. The required time of the refuelling operation is about 12 minutes [27].

Figure 46 - Alsterwasser one of the first zero emission project.

3.5.2.2.2 Nemo H2

By early 2006, five companies (Alewijnse Marine Systems, shipping company Lovers, Linde Gas, Marine Service North, and Integral) concurred to set up a project aimed at the development, construction, and exploitation of a hydrogen boat, Nemo H2 (Figure A.4). The hydrogen boat was intended for the transport of passengers in the city centre of Amsterdam. The implementation of a fuel cell on a passenger boat was planned for 100 persons with a 65 kW PEM fuel cell that sails on hydrogen, a 30 to 50 kWh battery system, and 40 kg onboard hydrogen storage in 8 cylinders at 350 bar. Also, part of the project was the realization of a hydrogen filling station at the waterside with a capacity of 60 Nm^3/h [28]. The boat has a hydrogen powered propulsion system which is made possible thanks to the integration of batteries on board. The ESS improves the overall performance of the system by allowing the use of different energy sources.

Figure 47 - Nemo H2.

3.5.2.2.3 M/S Viking Lady

The first offshore supply vessel (OSV), M/S Viking Lady, owned by Eidesvik Offshore ASA, was built under a series of joint research development projects with Det Norske Veritas (DNV), Wärtsilä, and MTU Onsite Energy called the FellowSHIP project. After an integrated fuel cell of 330 kW that resulted in successful operation of more than 18,500 hours aboard in 2009, the project demonstrated the use of a 500-kWh lithium-ion battery pack to optimize the energy consumption by producing 5 MWh in 2013. The Viking Lady has become one of the world's most environmentally friendly ships [31].

The battery now installed on board is a lithium-ion battery with a storage capacity of 450 kWh from Corvus Energy. The cell chemistry of the battery is NMC. The battery acts as an energy buffer covering the intense demands that occur especially during DP and standby operations [1].

Figure 48 - M/S Viking Lady an offshore supply vessel.

3.5.2.2.4 Prinsesse Benedikte and Schleswing Holstein

The first of the Sustainable Traffic Machines projects involved the installation of hybrid propulsion and exhaust gas cleaning systems on two of Scandlines RoPax vessels; Prinsesse Benedikte and Schleswig Holstein. The vessels operate on the route between Rødby in Denmark and Puttgarden in Germany. Prinsesse Benedikte was the world's largest hybrid ferry when the retrofit was completed in 2013. The aim of the project was to combine the propulsion and exhaust gas cleaning technologies to specific requirements both of standardized ferry operations and environmental regulations (European Commission, 2014).

The project started in January 2012 and was ended in December 2015 [1].

Figure 49 - Prinsesse Benedikte and Schleswig Holstein

3.5.2.2.5 Prins Richard and Deutschland

The Sustainable Traffic Machines II, "The green link between Scandinavia and Conventional Europe", were initiated to meet the IMO's Sulphur Emission Control Area (SECA) regulations that entered into force on January 1, 2015 for ships operating in the Baltic Sea, in addition to the EU's stricter sulphur limits for marine fuels. The project involved the installation of state-of-the-art technology, hybrid propulsion on "Prins Richard" and "Deutschland", the sister vessels of "Prinsesse Benedikte" and "Schleswig Holstein", respectively. The two RoPax vessels have been hybridized since 2014 [1].

Figure 50 - Prins Richard and Deutschland.

The installed power on board Deutschland and Schleswig Holstein is 17600 and 19860 kW, respectively. The installed power on board Prins Richard is 19860 kW and on board Prinsesse Benedikte is 15200 kW. The vessels are equipped with NMC batteries. The storage capacity of the batteries is 1600 kWh for Deutschland and Schleswig Holstein and 2600 kWh for Prinsesse Benedikte and Prins Richard. The batteries were installed

on board the vessels in 2013.

The distance between Rødby and Puttgarden is 18 kilometres. The charging of the batteries takes about 30 minutes, powered by generators on board the vessels [1].

3.5.2.2.6 MF Folgefonn

In 2015 the car ferry “MF Folgefonn” was retrofitted into a full-scale hybrid and plug-in hybrid ferry. The ferry services the connection between the islands of Stord, Tysnes, and Huglo in Norway. “MF Folgefonn” is now unique in terms of having all types of electrical power solutions in one vessel; it can be run as conventional diesel electric, hybrid electric, and plug-in hybrid. In hybrid operation, the savings in fuel consumption in optimised mode is declared 10-20%. Emissions reductions by 30%, as a result of both the reduced fuel consumption and the improved operational profile for the combustion engines on board. In plug-in hybrid operation, the fuel savings will be 20-30%, and in pure plug-in operation, the potential is 100%.

Figure 51 - MF Folgefonn.

3.5.2.2.7 MF Ampere

In 2015, the Ampere was first launched to ferry passengers and cars, operating between Lavik and Oppedal, Norway. It was jointly developed by Norled, Norwegian Shipyard Fjellstrand, and Siemens. LED lighting; the heating, ventilation, and air-conditioning (HVAC) system; and propulsion motors are powered by lithium-ion batteries of 1 MWh. Another 260-kWh battery is used for charging when the ferry is in port [31]. In 2012, the Norwegian Public Roads Administration issued a tender for a competitive dialog on the development of a new technology for ferries to operate across one of the Norwegian fjords. The tender required at least 20 percent improved energy and environment efficiency.

The result was MF Ampere, which became the world's first large-size all-electric battery-powered car ferry.

The ferry has operated on the fixed route between Lavik and Oppedal in Sognefjorden, Norway, since it came into operation in January 2015.

The vessel is owned by the ferry operator, Norled, and was built at the Norwegian shipyard Fiskerstrand [1].

Figure 52 - MF Ampere.

The ferry is equipped with 10 tons of batteries with a capacity of two times 500 kWh, as well as a quick charger on shore with a capacity of 300 kWh. The ferry uses approximately 200 kWh per crossing. The batteries are placed in a rack into separate battery rooms, one of each for the front and after propulsion machinery.

The schedule of the ferry involves 20 minutes crossing, 10 minutes of quick charging in each ferry terminal, and a full charge overnight. The charging system contains two Stemmann pantographs and Cavotec plug.

When the ferry is approaching the quay, GPS signals are sent from the ferry to the Cavotec Vacuum Mooring, which sucks the ferry, with a sucking power of 20 tonnes [1].

3.5.2.2.8 OV Bokfjord

In 2015, Rolls-Royce used the battery technology on a UT 776 CDG offshore vessel with a hybrid power solution. In 2016, the Norwegian offshore vessel OV Bøkfjord was equipped with an 850-kWh battery pack on top of the conventional propulsion system to cover occasional peak loads. A containerized battery by Corvus was used [31].

Figure 53 - OV Bokfjord.

3.5.2.2.9 MS Berlin and MS Copenhagen

The aim of the project was to upgrade and to enlarge the maritime capacity of the Rostock – Gedser route.

This involved the conversion to ensure environmental and efficiency compliance. The activities included the equipment of the RoPax vessels "MS Berlin" and "MS Copenhagen" with hybrid propulsion and to do berth adaption and terminal improvements of the two ports, Rostock and Gedser. The two ferries have been in operation since 2016.

Figure 54 - MS Berlin.

Figure 55 – MS Copenhagen.

The vessels have a battery storage capacity of 1.6 MWh. The cell chemistry of the batteries is NMC [1].

3.5.2.2.10 MV Catriona

MV Catriona (Scottish Gaelic: Catrìona) is a pioneering diesel electric hybrid passenger and vehicle roll-on, roll-off ferry built for Caledonian MacBrayne for the Claonaig–Lochranza crossing. She is the third hybrid ferry commissioned and owned by Caledonian Maritime Assets, one of three such ferries in the world to incorporate a low-carbon hybrid system of diesel electric and lithium-ion battery power. The ferries are sea-going and are nearly 46 metres (150 ft) long, accommodating 150 passengers, 23 cars.

MV Catriona can accommodate 150 passengers, 23 cars. She has a service speed of 9 knots (17 km/h) and is powered by small diesel generator sets, feeding power at 400 V switchboard, which supplies power to electric propulsion motors that turn the propulsion units. In addition, two lithium-ion battery banks with a total of 700 kWh are also available to supply power to the units. The battery banks will be charged overnight from the mains. It is anticipated that renewable energy sources will be used to charge the batteries in the future, further reducing the carbon footprint.

Experience has shown that hybrid vessels can reduce fuel consumption by up to 38% compared with a conventionally powered vessel of the same size. This will result in a decrease in CO2 emissions in excess of 5,500 tonnes per vessel over their lifetime, with a similar decrease in sulphur and nitrogen oxide emissions.

Figure 56 - MV Catriona.

3.5.2.2.11 Texelestroom

Texelstroom is a sustainable, new-generation ferry built at LaNaval Shipyard, Spain, for its operator and owner Texels Eigen Stoomboot Onderneming (TESO). The ferry will operate between the islands of Texel and Den Helder, Netherlands.

The eco-friendly vessel is fuelled primarily by a hybrid diesel oil or compressed natural gas (CNG), complemented by electric batteries and solar power. It is also capable of operating solely on diesel.

The ferry project was conceptualised in 2010, the design works were initiated in October 2012, the vessel's keel was laid in December 2014, and delivered occurred in June 2016. The ferry will start operations following the completion of commissioning.

The design phase of the ferry project formed part of the larger European Union's I. Transfer Program, which aims to make ferry transport more accessible and sustainable.

The ferry is 135m-long and 28m-wide and has the capacity to carry 1,750 passengers and 350 vehicles.

It incorporates a 4,000m² main hall on the passenger deck, buffet areas, weather decks, service areas, two bridges, offices, a dining area, and other crew areas[28].

3.5.2.2.12 Tycho Brahe and Aurora

It was followed by ABB's conversion of two of Sweden's HH Ferries Group's massive ferries named Tycho Brahe and Aurora. Each ship weighs 8,414 t and has a lithium-ion battery power of 4.16 MWh for an operating route between Sweden and Denmark. They have charging systems aided by a robotic arm at the docks and deckhouse. Both ferries use the energy storage system provided by Plan B Energy Storage (PBES) and Corvus [31].

The project Zero Emission Ferries involves the conversion of two existing Scandlines RoPax vessels from marine gas oil to plug-in all electric powered by batteries. The two ferries, Tycho Brahe and Aurora, operate between Helsingör in Denmark and Helsingborg in Sweden.

These two ports are located in densely populated areas and the installation of batteries contributes to improve the air quality of the two ports, as well as reduce noise.

Figure 57 - Tycho Brahe and Aurora.

Each vessel will have a battery storage capacity of 4160 kWh. The batteries are installed in four 32-foot containers on top of the ship alongside two deckhouses, which contains transformers, converters, and cooling systems for the batteries. The four diesel engines already installed on boars will remain on the ship. They will function as a backup after the conversion to electric power.

The vessels sailing schedule involves the departure every 15 minutes. Every time the ferries are at port, the batteries must be charged with about 1200 kWh. The charging in ports takes about 5-9 minutes, which will therefore not impact the schedule of the vessels. A fully automatic laser-guided robotic arm is handling the charging of the batteries in port and connects the batteries to the grid. The robot orients itself using laser scanning. This technology is mounted in towers that are more than 10 metres high [31].

3.5.2.2.13 Elektra

In 2017, the hybrid-electric ferry, Elektra, was built in Finland. It operates on the route between Nauvo and Parainen. The 98-m-long ferry consists of 160 lithium-ion batteries with a total capacity of 1 MWh. The ferry also utilizes diesel engines to aid the onboard batteries during cold weather [31]

Figure 58 - Elektra.

3.5.2.2.14 OSV Viking Princess

Eidesvik Offshore converted the OSV Viking Princess to operate with lithium-ion-based energy storage systems. The company Wärtsilä completed the hybrid energy system using an energy storage system by Corvus.

There are 90 battery modules with a total capacity of 533 kWh. The total weight of the batteries is approximately 6,650 kg. The batteries are used to handle peak demand points to curb the engine load from dipping. The remaining energy is used to charge the batteries from time to time [31].

Figure 59 - OSV Viking Princess.

3.5.2.2.15 Guangzhou

In November 2017, China commissioned a 2,000-t electric cargo ship built by Guangzhou Shipyard for transporting coal along the Pearl River in Guangdong Province. It is equipped with two 160-kW electric propellers for a total energy capacity of 2.4 MWh using both supercapacitors and lithium batteries. The ship is capable of traveling approximately 80 km with a single charge of 2 h (equivalent to the time for loading and unloading the ship) [31].

Figure 60 - Guangzhou.

3.5.2.2.16 Gloppefjord and Eidsfjord

Gloppefjord and Eidsfjord fully battery-operated ferries, which operate on the Anda-Lote route Nordfjord on the west coast of Norway, mark another milestone in the road towards zero emission in ferry operation in Norway.

The total battery capacity onboard each ferry is two 520kWh PlanB batteries with Siemens as the electric contractor. Each ferry has two 500 KW Scania DI16 90M generators for back-up and emergency operators.

Among the ferries unique selling points is that they will only need to stop for nine minutes for battery charging in ports. Battery charging is completed via fully automatic charging stations at the quayside. The ferries are equipped with a vacuum docking device to ensure correct docking at all times with no need to run the engines and propellers at slow speeds. The ships can each transport 120 cars and 349 people [29].

Figure 61 - Gloppefjord.

3.5.2.2.17 Aranda

In 2018, the 59-m-long maritime research vessel Aranda weighed 1,734 t was owned by the Finnish Environment Institute, which retrofitted hybrid propulsion for monitoring different stations during winter. The lithium-ion battery packs provide at least 2 MWh of energy. Another offshore support vessel, SEACOR Maya, was completed in September 2018. It uses hybrid lithium-ion battery power propulsion to reduce fuel consumption and emissions. Corvus Orca Energy Storage Systems provide 533 kWh of lithium-ion battery power was installed on the vessel [31].

Figure 62 - Aranda.

3.5.2.2.18 BB-Green

The BB-Green (Battery-powered Boats, providing Greening, Resistance reduction, Electric, Efficiency and

Novelty) is a collaborative R&D project (BB Green, 2018).

The BB-Green objectives involved the development and launch of a new, innovative and competitive waterborne transport solution, which presented a step change in public service offered. The BB-Green emits zero greenhouse gases and introduced a climate friendly travel choice. The BB-Green is an all-electric vessel. The vessel has a tailor made 200 kWh Lithium-ion titanate turnkey battery energy storage system provided by Echandia. The charging of the battery takes less than 20 minutes to about 95% SOC, with the ability to reach 15000 full cycles. To optimize the operation and cycle life of the battery, the battery is connected to the cloud, storing and processing all the data. The length of the vessel is 20 metres, with a beam of 6 metres [31].

Figure 63 - BB-Green.

3.5.2.2.19 Color Hybird

Color Hybrid is a new plug-in hybrid ferry designed by Ulstein Verft in Norway. It was recognised as the world’s largest plug-in hybrid vessel when it was delivered in August 2019. The ferry was developed as part of Color Line’s fleet-renewal program to replace the company’s M/S Bohus ship.

Designed to run wholly on battery power, the vessel is recharged either via a power cable from Color Line’s shore-based Sandefjord power facility or by the ship’s on-board generators.

Steel-cutting for the hybrid ferry was held in July 2017 and the vessel was launched in April 2019. The vessel currently operates on the crossing between Sandefjord in Norway and Strømstad in Sweden. Color Hybrid was appointed as Ship of the Year 2019 in June 2019.

The vessel’s battery package offers approximately 5 MWh and can operate for up to 60 minutes at speeds up to 12k. The ferry can store up to 450m³ of freshwater and 1,500m³ of water ballast. It also includes a waste-heat-recovery system (WHR), in addition to energy-saving equipment.

It combines higher efficiency and better performance at high loads and excellent fuel consumption at low loads.

Figure 64 - Color Hybrid.

3.5.2.2.20 Legacy of the Fjords

Legacy of The Fjords includes some refinements — the vessel can be charged and loaded on both sides, and passengers can board or exit from either the port or starboard entryways. In addition, the vessel has space for three dedicated conference zones, each one equipped with projectors, screens and audio systems.

The vessel is propelled by two 450kW electric motors, enabling cruising speeds of 16 knots. Together with Brødrene Aa, the company developed a charging station called the Power Dock, a 40-metre long, 5-metre-wide floating glass-fibre charging station in Gudvangen. The station houses a 2.4 MWh battery pack for charging time of about 20 minutes. The dock also stores consumables, fuel for sister vessels, and allows black water to be offloaded for treatment on land.

Figure 65 - Legacy of The Fjords.

The evolution of the battery market for marine applications is investigated by identifying the current trends on the application of batteries and project that onto the future evolution of the identified markets of different vessel types.

3.5.2.3 Selection of projects summary

Table 20 – Seagoing Projects main characteristics

VESSEL	COUNTRY	SIZE OF VESSEL	DWT	SHIP POWER	PURPOSES	TYPE OF BATTERY	SUPPLIER	CHEMISTRY	MAIN DISTRIBUTION	APPLICATION	SIZE	YEAR	NOTES
FSC Alsterwasser	Germany	25.5 m long and 5.36 m wide	72 t	216 kW	Ferry	Lead-geal			560 V	Propulsion	200 kWh	2008	First ship equipped with fuel-cells and battery
Nemo H2	Netherlands	21.95 m long and 4.25 m wide	45 t	156 kW	Ferry	Lead-acid					70 kWh	2009	
MV Hallaig	United Kingdom	43.5 m long and 12.2 m wide	500 t	270 kW	RoRo-Pax	Lithium-ion			AC with the battery linked at 400 V DC		700 kWh	2012	270 kW only the propulsion
M/S Viking Lady	Norway	92.2 m long and 21 m wide	6200 t	8040 kW	Offshore	Lithium-ion	Corvus	NMC	11 kV AC 50 Hz		500 kWh	2013	The World's first all-electric car ferry in commercial operation
M/V Schleswig Holstein	Germany	142 m long and 25.4 m wide	9374 t	17600 kW	RoRo-Pax	Lithium-ion	Corvus	NMC			2600 kWh	2014	The first major ferry hybridization, successfully operating since 2015. Battery nominal power 3500 kW
Folgefonn	Norway	76.5 m long and 15 m wide	597 t		RoRo-Pax	Lithium-ion	Corvus	NMC	650-850 VDC		1000 kWh	2014	
M/V DEUTSCHLAND	Germany	142 m long and 25.4 m wide	9374 t	17600 kW	Ferry	Lithium-ion	Corvus	NMC	810-1050 VDC		1600 kWh	2014	The first major ferry hybridization, successfully operating since 2015. Battery output 3500 kW
Karoline	Norway	60 m long and 9.05 m wide	730 t		Special	Lithium-ion					195 kWh	2015	
M/V Prins richard	Denmark	142 m long and 25,4 m wide	8839 t	14180 kW	Ferry	Lithium-ion	Corvus	NMC	810-1050 VDC		1600 kWh	2015	Battery power output 3500 kW
MF Ampere	Norway	80 m and 21 m wide	200 t		RoRo-Pax	Lithium-ion		NMC	AC		1000 kWh	2015	The World's first all-electric car ferry in commercial operation
UT 776 CDG offshore vessel	Norway	92.8 m long and 20 m wide	4750 t	7320 kW	Offshore activities	Lithium-ion			690V 60 Hz AC		200/600 kWh	2015	UT 776 WP is supply vessel that undertakes supply duties between land bases and offshore installations
M/V Berlin	Germany	170 m and 27 m wide	5000 t	15000 kW	RoRo-Pax	Lithium-ion	Corvus	NMC	810-1050 VDC		1500 kWh	2015	The first major ferry hybridization, successfully operating since 2015. Battery output 4500 kW
M/V PRINSESSE BENEDIKTE	Denmark	142 m long and 25.4 m wide	8839	14180 kW	RoRo-Pax	Lithium-ion		NMC	810-1050 VDC		1600 kWh	2015	The first major ferry hybridization, successfully operating

													since 2015. Battery power output 3500 kW
M/V Copenhagen	Denmark	170 m and 27 m wide	5000 t	15000 kW	RoRo-Pax	Lithium-ion	Corvus	NMC	810-1050 VDC		1500 kWh	2015	The first major ferry hybridization, successfully operating since 2015. Battery output 4500 kW
MV Catriona ferry	Norway	43.5 m long and 12.2 m wide	135 t	1080 kW	RoRo-Pax	Lithium-ion					700 kWh	2016	
Bokfjord offshore vessel	United Kingdom	44 m long and 11.4 m wide	430 t	2835 kW	Offshore activities	Lithium-ion					850 kWh	2016	
Texelstroom Ferry	Netherlands	135 m long and 28 m wide	1684 t	8000 kW	Ferry	Lithium-ion					1600 kWh	2016	
Seaspan swift	Canada	148.9 m long and 26 m wide	2767 t	9000 kW	Ferry	Lithium-polymer			1050 VDC	Preventing Blackouts	546 kWh	2016	Lng and battery
Tycho Brahe ferry	Sweden	111.2 m long and 28.2 m wide	2500 t	9840 kW	RoRo-Pax	Lithium-ion			DC		4000 kWh	2017	
Elektra Hybrid-electric ferry	Finland	98 m long and 15.2 wide	542 t	1800 kW	RoRo-Pax	Lithium-ion			DC		1000 kWh	2017	Has equipped PV.
Viking Princess OSV	Norway	89.6 m long and 24 m wide	6055 t		Offshore	Lithium-ion	Corvus		650-900 VDC		533 kWh	2017	
Guangzhou electric cargo	China	70.5 m long	-	-	Cargo	Supercapacitors and Lithium-ion	-	-	-	-	2400 kWh	2017	Transporting coals along pearl river in Guangdong Province
Luciole	French	24 m long and7 m wide			Naval	Lithium-ion					156 kWh	2017	
Tianée	French	24 m long and7 m wide			Naval	Lithium-ion					156 kWh	2017	
NKT Victoria	Norway	140 m long and 30 m wide	14900 t		Cable layer						156 kWh	2017	
Gloppefjord ferry	Norway	106.2 m long and 16.8 m wide	859 t		RoRo-Pax	Lithium-ion	Simens		DC	-	2000 kWh	2018	First 100% battery supply. Battery named PlanB.
North sea Giant	Norway	153.6 m long nad 30 m wide	12705 t		Offshore	Lithium-ion			720-1000 VDC		2034 kWh	2018	
Aurora ferry	Sweden	111.2 m long and 28.2 m wide	2500 t	9840 kW	RoRo-Pax	Lithium-ion			DC		4160 kWh	2018	
Aranda maritime resarch vessel	Finland	50 m long and 13.8 m wide	-	3000 kW	Special	Lithium-ion					2000 kWh	2018	
Seven viking	Norway	106.5 m ling and 24.5 m wide	5125 t		Offshore	Lithium-ion	Corvus		720-1000 VDC		1356 kWh	2018	
SEACOR Maya OSV	United state	87.07 m long and 18.8 m wide	5116 t		Offshore	Lithium-ion	Corvus		800-1100 VDC		533 kWh	2018	
BB Green	Norway	24.8 m long and 7.5 m wide		660 kW	Ferry	Lithium-ion		Lithium-ion Titanate			200 kWh	2018	
Ouryu	Japan	84 m long and 9 m wide		6000 kw	Naval	Lithium-ion					200 kWh	2018	First japan submarine with lithium ion

Stena Jutlandic	Sweden	184 m long and 28 m wide	6559 t		RoRo-Pax	Lithium-ion				Generation and propulsion	1000 kWh	2018	Retrofit: first phase add 1 MWh, second phase 20 MWh, third phase 50 MWh
Elfrida	Norway	13.5 m long and 8 m wide		160 kW	Fishing	Lithium-ion	Siemens			Generation	92 kWh	2019	First all battery supply fishing vessel
Color Hybrid	Norway	160 m long	3258 t		RoRo-Pax	Lithium-ion					5000 kWh	2019	Ship of the year 2019
Cruise Barcelona	Italy	254 m long and 30.4 m wide	7500 t		RoRo-Pax	Lithium-ion	Corvus		790-1100 VDC	Mechanical propulsion. Battery used for hotel load	5500 kWh	2019	
Cruise Roma	Italy	254 m long and 30.4 m wide	7500 t		RoRo-Pax	Lithium-ion	Corvus		790-1100 VDC	Mechanical propulsion. Battery used for hotel load	5500 kWh	2019	
Ellen	Norway	59.4 m long and 13.4 m wide	200 t		RoRo-Pax	Lithium-ion					2150 kWh	2019	
MS Roald Amundsen	Norway	140 m long and 23.6 wide	1800 t		Cruise	Lithium-ion	Corvus		720-1000 VDC		1356 kWh	2019	World first cruise ship battery powered
Legacy of The Fjords	Norway	40 m long and 5 m wide	41 t	900 kW	Ferry	Lithium-ion					2400 MWh	2020	
Eco valencia	Italy	238 m long and 34 m wide	17000 t		RoRo-Pax	Lithium-ion			AC		5000 kWh	2020	GG5G Project
Libas NB64	Norway	86.5 m long and 17.8 m wide	3800 t	6000 kW	Fishing	Lithium-ion			AC		500 kWh	2020	
Seaspan Reliant	Canada	149 m long			RoRo-Pax	Lithium-ion					2000 kWh	2020	
Eco barcellona	Italy	238 m long and 34 m wide	17000 t		RoRo-Pax	Lithium-ion			AC		5000 kWh	2021	GG5G Project
Eco livorno	Italy	238 m long and 34 m wide	17000 t		RoRo-Pax	Lithium-ion			AC		5000 kWh	2021	GG5G Project

3.5.2.4 Current and future projects summary

Table 21 – Current and future projects main characteristics

VESSEL	COUNTRY	SIZE OF VESSEL	DISPLACEMENT	PURPOSES	TYPE OF BATTERY	SIZE	YEAR	NOTES
Yara Birkeland project	Norway	80 m long and 13 m wide		Containers	Lithium-ion	9000 kWh	2022	
Port-Liner project	Germany, Belgium			Containers	Lithium-ion	1600 kWh	2023	
BC Ferries	Canada	81.2 m long		RoRo-Pax			2022	Delivery, funded by the Canadian government
GG5G RoRo	Italy	238 m long and 34 m wide		RoRo-Pax			2020-	
P-30 project	Sweden			Passengers	Lithium-ion	180 kWh	2020-2022	
The Libas	Norway	86 m long and 17.8 m wide		Fishing		500 kWh	2020-	
Enviro	United States			Offshore supply	Lithium-ion	1450 kWh	2020-	
Yachts de Luxe (YdL)	Australian	12 m long		Yacht	Lithium-sulphur		2020-	
X-Expedition				Yacht	Lithium-sulphur		2020-	
Færøysund		77 m long		Fishing			2016-2021	
retrofitting Hagland Captain		89.95 m long and 14.4 m wide	5000 t	Bulk			2021-	First hybrid Bulk
e H2MORAY	Netherlands	64,4 m long and 6.4 m wide		Submarine	Lithium-ion	7400 kWh		
YN 19150 Project Electra	Netherlands	50 m long		Yacht				

3.5.3 Application of batteries

According to the Maritime Battery Forum there are at the moment of this writing 511 vessels with batteries installed in operation or on order. Of these 511 vessels 48% has a hybrid propulsion system, 23% has a plug-in hybrid propulsion system, 24% is fully electric and 5% is unknown.

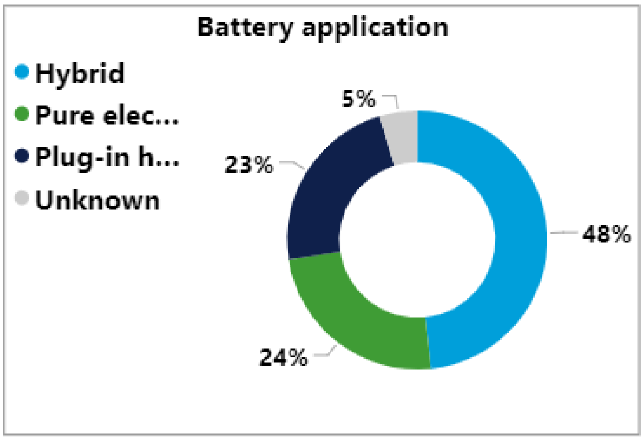


Figure 66 Types of battery applications on vessels (Maritime Battery Forum) [13]

For a vessel to become fully battery electric the required energy to fulfil its operations should be physically and commercially possible, but besides this the vessel needs to have a predictable operational profile and access to a charging facility. Plug-in hybrid vessels can have more flexibility in their operational profiles and energy requirements, but have access to charging facilities. Hybrid vessels do not have access to charging facilities and batteries will only be used to increase the overall efficiency of the ship's propulsion system (see Table 22).

Table 22 - Requirements for different types of battery applications

	Hybrid	Plug-in hybrid	Fully battery electric
Practical energy requirements	X	X	V
Predictable operational profile	X	X	V
Access to charging facility	X	V	V

3.5.3.1 Fishing vessels

Out of the total of 29150 seagoing vessels on the European market 7558 are fishing vessels. 55% of these fishing vessels have below 500 kW of propulsion power installed, 24% between 500 and 1000 kW, 6% between 1000 and 1500 kW and 15% has more than 1500 kW of propulsion power installed. The large number of vessels with relatively low installed propulsion power up to 1000 kW makes fishing vessels interesting for electrification and the application of batteries (see Table 23).

Table 23 - Overview of European fishing vessel fleet and propulsion power

	Number	Percentage
Fishing vessels	7558	100%
<500 kW	4140	55%
500 – 1000 kW	1818	24%
1000 - 1500 kW	450	6%

>1500 kW	1150	15%

There are three main trends identified in the fishing vessel market; larger new build vessels are replacing multiple smaller old vessels, the aim is for more energy efficiency due to local and international regulations and there is a growing market for fish farm support vessels.

The increase in size of fishing vessels will result in a larger power demand and possibly longer journeys both in distance and time at sea. It will therefore be not feasible for these types of vessels to become fully battery powered. These vessels also don't have regular access to a charging facility and therefore the only likely application of a battery system will be for a hybrid propulsion system. Possible use of a battery in such a hybrid system can be load levelling during fishing operations when the loads on the propulsion system can fluctuate due to the forces created by the fishing equipment. Load fluctuations on the electrical grid of the vessel will be high when the cranes or processing equipment is being operated, a battery could be used to reduce the need for additional generators online and reduce the total energy consumption. The size of these batteries will be limited as their main goal is not to provide large amounts of energy, but to reduce the load on other power sources. Therefore it is assumed that these types of vessels, if batteries will be installed on board, the size will not be likely to exceed 500 kWh.

The increasing demand for energy efficient fishing vessels is a promising development for marine battery systems. Fishing vessels operating in coastal areas will have to reduce their emissions and batteries are at this moment the most feasible method of achieving this. In comparison to the larger ocean going fishing vessels, the coastal fishing vessels usually have a more predictable operational profile and usually operate around a specific home port. This provides regular access to a charging facility. With the majority of these types of vessels having an installed propulsion power of below 500 kW or between 500 kW and 1000 kW, a full working day of fishing will be a challenge for a fully battery electric vessel. Therefore it is assumed that a plug-in hybrid system will be the most likely application for a battery system in this case. These vessels do not require high sailing speeds and therefore, depending on the specific operational profile and area of operations of the vessel, a large part of the energy demand can be supplied by the batteries. The loads on the ship's electrical grid caused by lifting equipment, pumps or other fishing operations equipment can be provided by the battery system as well. Only for larger journeys out of the usual scope of the vessel, for instance to reach a maintenance location or to change area of operations another power source will be required, such as a diesel generator. This source will then only be required to be sized according to the needs for propulsion at cruising speeds and therefore can be smaller compared to currently installed propulsion engines on similar vessels. Based on these assumptions it is estimated that with current battery technologies it will be possible to installed battery systems between 1 to 3 MWh on these types of vessels, depending on the size and operational area of the specific vessel.

The range of fish farm support vessels can vary significantly in ship size and types of operations. However, most types will have a rather predictable operational profile as they will operate on specific fish farms, which are usually located close to shore. The locations of fish farms can also result in regular access to charging facilities. Therefore a part of the fish farms support vessels will be likely to fulfil the three requirements for fully battery powered vessels; practical energy requirements, a predictable operational profile and regular access to charging facilities. Plug-in hybrid systems will however also be common for this type of vessels, as well as hybrid systems for the largest vessel sizes. Possible battery sizes are more difficult to estimate as this will vary from 100 kWh battery systems to possibly 5 MWh systems

It is assumed that the 15% of fishing vessels that currently have more than 1500 kW installed are of the type of ocean going vessel and the 6% of fishing vessels with between 1000 and 1500 kW of propulsion power installed are the smaller vessels that will be replace by newer, larger vessels. Because one larger vessel will replace multiple smaller vessels the share of large ocean going fishing vessels will be 17% of the total amount European fishing vessels. Based on the installed propulsion power it is not possible to make a distinction between the share of coastal fishing vessels and fish farm support vessels. Therefore these two groups are combined in the estimated market share, which leads to 83% of all fishing vessels will likely be of one of these two types (see Table 24).

Table 24 - Overview of fishing vessels and possible battery application

Type of fishing vessel	Possible battery application	Expected battery sizes per vessel	Estimated share
Large ocean going fishing vessels	Hybrid	<500 kWh	17%
Coastal area fishing vessels	Plug-in hybrid	1 – 3 MWh	83%
Fish farm support vessels	Fully battery electric - Plug-in hybrid	100 kWh – 5 MWh	

3.5.3.2 Tugs

Out of the total of 29150 seagoing vessels on the European market 2944 are tugs. The largest part (66%) has more than 1500 kW installed and generally tugs can have significantly large installed propulsion installations in comparison with the size of the vessel (as summarized in Table 25).

Table 25 - Overview of European tug fleet and propulsion power

	Number	Percentage
Tugs	2944	100%
<500 kW	146	5%
500 – 1000 kW	470	16%
1000 - 1500 kW	380	13%
>1500 kW	1950	66%

Tugs can be divided in 3 types of tugs with regards to their area of operations. There are ocean going tugs, harbour tugs and inland tugs. Ocean going tugs have unpredictable operational profiles, require large amounts of energy for their operations and do not have regular access to charging facilities. Therefore these vessels will only be applicable for batteries in a hybrid propulsion system. Similar to the ocean going fishing vessels, this type of battery application will most likely not have battery systems larger than 500 kW.

Harbour tugs might not have a very predictable operational profile, but the area of operations will be very limited in most cases. Depending on the size of the port at which the tug operates and the types of assists it has to perform it is possible to get a sufficient estimation of the energy requirements of the vessel to determine the required battery size. The large installed propulsion power of a tug is used less than 1% of the time during operations and tugs usually operate at below 15% of the total installed power. Charging facilities can be easily realized in the port of operations. Therefore harbour tugs are likely candidates to use batteries in plug-in hybrid or fully battery power propulsion systems. There are several plug-in hybrid and fully battery electric tugs in operation or under construction, installed capacity ranges between 200 kWh to 6 MWh, according to the size of the tug as well as the port. Both ocean going tugs and harbour tugs are assumed to be part of the group of tugs with more than 1500 kW of installed propulsion power. Therefore it is difficult to define the share of ocean going tugs and harbour tugs based on these numbers.

The inland tugs are assumed to fall in the groups of tugs with an installed propulsion power of below 1500 kW, therefore they make up for approximately 34% of the tug fleet. The operational area of these tugs will be largely predictable and charging facilities will be easy to provide due to the inland operations of these vessels. The operational energy requirements less so however and therefore the fully battery powered options are expected to be limited to specific cases and are hybrid and plug-in hybrid power systems more likely to be installed. Battery system sizes between 100 kWh and 1 MWh are expected to be practical for these types of tugs (see Table 26).

Table 26 - Overview of tugs and possible battery application

Type of tugs	Possible battery application	Expected battery sizes per vessel	Estimated share
Ocean going tug	Hybrid	<500 kWh	66%
Harbor tug	Plug-in hybrid – Fully battery electric	200 kWh – 6 MWh	
Inland tug	Hybrid – Plug-in hybrid – Fully battery electric in some cases	100 kWh – 1 MWh	34%

3.5.3.3 Yachts

Out of the total of 29150 seagoing vessels on the European market 1634 are yachts. The largest part (77%) has more than 1500 kW installed. Most yachts are designed to reach high sailing speeds, which makes the application of batteries for propulsion a challenge. However, the number of yachts with battery systems on board are increasing. Yachts have large energy requirements, unpredictable operational profiles and do not have regular access to charging stations, therefore most applications of batteries will be in hybrid systems (see Table 27). Charging the batteries with the shore power available at marinas might be considered as a plug-in hybrid system as well.

Table 27 - Overview of European yacht fleet and propulsion power

	Number	Percentage
Yachts	1634	100%
<500 kW	100	6%
500 – 1000 kW	124	8%
1000 - 1500 kW	155	9%
>1500 kW	1255	77%

Yachts have significantly large hotel loads to provide the passengers with the comfort they expect from being on their yacht. The power is now provided by diesel generators, which cause discomfort to the passengers being a source of noise, vibrations and exhaust gases. The need for a solution to have absolute silence and comfort to enjoy the luxury of yachts is getting stronger and batteries can provide this solution. Improving the efficiency of yachts is also a wish from yacht owners. Batteries are used for this to reduce the load on generators in peak shaving or load levelling applications. This makes that there are two main options for battery systems on board of yachts, large scale energy storage for maximum comfort and energy efficiency improvement by reducing the loads on generators. Relatively small battery systems can be installed to improve on board energy efficiency by installing batteries as peak shaving or load levelling applications. Battery systems in these types of applications are expected to have an installed capacity between 100 kWh and 500 kWh. For large scale energy storage to create maximum comfort on yachts the challenge is to install as much capacity as possible in the available space on board. This requires typical high energy battery systems. Depending on the size and facilities of the yacht, there is about 1 MWh to 6 MWh of energy required to run the hotel loads a full day on batteries (see Table 28). With a battery system of this size installed it will be possible to use the energy from the batteries for other applications as well, such as propulsion. This will however only be sufficient for short trips at relatively low speeds, or shorts period of boosting for high top speeds, and other sources of propulsion power will still be required.

It is difficult to determine the share of both types of battery applications on board of yachts and therefore the yachts are considered as one group further in this analysis.

Table 28 - Overview of yachts and possible battery application

Type of yachts battery application	Possible battery application	Expected battery sizes per vessel	Estimated share
Improving energy efficiency	Hybrid	<500 kWh	-
Large scale energy storage for increased comfort	Hybrid – Plug-in hybrid	1 MWh – 6 MWh	-

3.5.3.4 *General cargo vessels*

Out of the total of 29150 seagoing vessels on the European market 3474 are general cargo vessels. A large part (42%) has more than 1500 kW installed, which are the larger ocean going vessels. It is assumed that the 58% of general cargo vessels are mainly coasters (see Table 29).

Table 29 - Overview of European general cargo fleet and propulsion power

	Number	Percentage
General cargo vessels	3474	100%
<500 kW	554	16%
500 – 1000 kW	685	20%
1000 - 1500 kW	765	22%
>1500 kW	1470	42%

General cargo vessels with more than 1500 kW installed propulsion power generally travel large distances with heavy loads and therefore are not suitable for fully battery powered operations. Until standardized vessel charging facilities are realized in a majority of the ports for these types of vessels it is also not likely that these vessels will have regular access to charging facilities.

Therefore it is assumed that general cargo vessels with more than 1500 kW installed power will only be a potential market for hybrid propulsion systems if batteries will be included. Also if alternative fuels will be widely available for the marine market it can still be beneficial for increasing the energy efficiency of general cargo vessels to install battery systems in a hybrid propulsion system. The battery systems in this case are not expected to exceed 500 kWh in capacity.

General cargo vessels with less than 1500 kW installed propulsion power are assumed to mainly coasters. This type of vessel travels shorter distances in coastal regions, which provides for more regular access to charging facilities compared to the larger general cargo vessels.

Therefore it is assumed that of this type there will be besides hybrid also plug-in hybrid propulsion systems. For this type of vessels the energy demand can be very large, which makes fully battery powered propulsion not likely.

It is estimated that plug-in hybrid coasters will require battery systems between 1 MWh and 20 MWh, according to size and required autonomy, but also depending on the development of battery technology with regards to costs and energy density.

Table 30 - Overview of general cargo vessels and possible battery application

Type of general cargo vessels	Possible battery application	Expected battery sizes per vessel	Estimated share
General cargo vessel >1500 KW	Hybrid	<500 kWh	42%
General cargo vessel <1500 kW	Hybrid – Plug-in hybrid	1 MWh – 20 MWh	58%

3.5.3.5 Other vessels / patrol vessels

Two other growing groups of vessel types identified are patrol vessels and utility vessels (or work boats). In new orders for patrol vessels there is an increasing demand for batteries. This is mainly coming from sustainability goals from the governments operating these patrol vessels. Typically these vessels have high top speeds and require a large operational flexibility. Therefore fully battery electric patrol vessels are assumed not to be a realistic option and therefore these types of vessels will be either hybrid or plug-in hybrid when batteries are installed. Because weight is an important factor on fast vessels, it is expected that these batteries will not be larger than 2 MWh. For practical application of batteries on these types of vessels also not less than 500 kWh of capacity is expected.

Utility vessels or workboats come in many shapes and sizes. Operational requirements vary a lot and therefore it is difficult to estimate the type of systems and how these vessels will use batteries and therefore it is assumed that these vessels will possibly be hybrid, plug-in hybrid and fully battery electric. This vessel group contains small and large vessels and therefore battery sizes will vary a lot as well and it is assumed that battery size will possibly vary between 100 kWh and 10 MWh (as summarized in Table 31).

The share of both vessel types in this group is difficult to determine and therefore it is assumed as one group further in this analysis.

Table 31 - Overview of patrol and utility vessels and possible battery application

Type other vessel	Possible battery application	Expected battery sizes per vessel	Estimated share
Patrol vessels	Hybrid – Plug-in hybrid	500 kWh – 2 MWh	-
Utility vessels	Hybrid – Plug-in hybrid – Fully battery electric	100 kWh – 10 MWh	-

3.5.3.6 Inland vessels

Inland vessels make up for a considerable part of the European fleet. They also have a high potential for the application of batteries as they are always operating in areas where it would be relatively easy to create a charging infrastructure. Vessels traveling long distances on Europe's inland waterways will pass by locks on their journey, which could be potentially interesting points for creating a charging station. Most inland vessels are limited in speed because of local regulations and shallow water depths. The challenge for providing sufficient propulsion power is related to the currents, which one way help to reduce the power demand of the vessel, but in the opposite direction will increase the power demand.

The largest group of inland vessels are (dry and liquid) cargo vessels. These vessels can potentially benefit significantly from installing batteries for propulsion. A large network of charging facilities will be required however, but this is assumed to be feasible for inland waterways. Still plug-in hybrids will be the first step to electrification of this fleet, as long as there is no large charging network yet.

Plug-in hybrid vessels will also provide the required operational data to gain insight in the energy requirements of these vessels, to go to fully battery powered propulsion. The containerized battery concept is being investigated by multiple parties and seems promising for inland cargo vessels. It is therefore also difficult to estimate the future installed battery capacity on these types of vessels, as the containerized batteries will not be a fixed part of the ship's installation.

For the first plug-in hybrid inland cargo vessels it is assumed that a battery capacity between 500 kWh and 2 MWh will be installed. With future battery developments it is assumed that this can be expanded to approximately 6 MWh as installed capacity for these vessels. This can also be the base for when the battery capacity will be expanded by adding containerized battery systems.

Inland push and tug boats are relatively small vessels with a large installed propulsion power compared to the vessel's size. Although charging facilities might be regularly accessible for these types of vessels in the near future, full battery powered operations might be challenging with their energy requirements and size. Therefore mainly plug-in hybrids are expected for this market. Battery sizes are expected to be below 500 kWh for the smallest inland push and tug boats, but up to 6 MWh on the larger vessels.

River cruise vessels generally have longer stops compared to inland cargo vessels, which provides possibilities for charging off batteries. However, these types of vessels have high hotel load demands, which make them big energy consumers.

Therefore, it is expected that these types of vessels will be mainly potentials for plug-in hybrid propulsion systems. The usage of batteries will reduce emissions and increase the level of comfort for the passengers on board.

Large battery sizes will be required to fulfil the energy requirements and therefore it is expected that these vessels will have battery systems between 2 MWh and 10 MWh installed in the near future.

Table 32 - Overview of inland vessels and possible battery applications

Type of inland vessel	Possible battery application	Expected battery sizes per vessel	Estimated share
Inland cargo vessels	Plug-in hybrid – Full battery electric	500 kWh – 6 MWh	83%
Inland push and tug boats	Plug-in hybrid	500 kWh – 6 MWh	15%
River cruise vessels	Plug-in hybrid	2 MWh – 10 MWh	2%

3.5.3.7 Marine battery manufacturers

The marine battery market is estimated to be USD 250 million in 2020 and is projected to reach USD 812 million by 2025, at a CAGR (compound annual growth rate) of 48.1% from 2020 to 2025. The implementation of the sulphur 2020 rule and growing maritime tourism industry are among the major factors driving the marine battery market.

In the year 2018, 203 vessels in the civilian and commercial market are installed with energy storage systems that either partly or fully replace the need of fossil fuels. Two suppliers are dominating the market: CORVUS ENRGY (from Canada but with a factory in Norway) and PBES (from Canada, currently named SPBES). The two companies together account for 50% of the market's production

It´s a long way down to number three, four and five. That is French SAFT, Dutch EST-Floattech and Norwegian ZEM.

In 2017, Corvus Energy last year sold energy systems all together 50MWh capacity to 50 vessels. The second biggest supplier, Plan B Energy Storage (PBES), delivered a total of 15,3 MWh for a total of 20 energy storage systems in 2017. PBES built their production line in Trondheim and most of the engineering and sales is in Norway.

One of the new manufacturers of maritime batteries is Siemens. Siemens has developed their own batteries and is starting production in Trondheim.

Swedish Echandia Marine, that delivered the electrical systems for coastal express BB Green, has published that they are engineering both lithium-titan-oxide and nickel-metal-hybrid batteries.

Norwegian ZEM is mainly involved in powering a new generation of smaller ships and ferries, including Norsafe's E-GES electric life boat and Moen Marin's electric and hybrid fish farming vessels.

EAS provides solutions for hybrid electric and electric applications for ships, underwater vehicles and on shore harbor equipment such as diesel generator powered RTG cranes.

Kongsberg Maritime's hybrid propulsion system are mainly focused on energy efficiency for a hybrid configuration.

Leclanchè battery systems mainly focused on powering the next generation of electric and hybrid maritime vessels, helping to reduce their environmental impact and improving sustainability while also assisting with regulatory requirement compliance. On port-side, the battery energy storage systems (BESS) are used to enable fast charging while also reducing the demand on the harbour grid by acting as a buffer.

Finally, a summary table with the principal manufacturers on battery ship market are presented. It is important to know that the order in which these companies appear does not correspond to the volume of GWh production. As can be seen, unlike the electric car market, companies are more diversified (see Table 33).

Table 33 - Principal marine battery manufacturers

Marine battery manufacturer	Country
Corvus Energy	Canada
Akasol AG	Germany
EST-Floattech	Netherlands
Siemens	Germany
Spear Power Systems	USA
Echandia Marine	Sweden
PBES	Canada
Furukawa Battery Solution	Japan
PowerTech System	France
Toshiba	Japan
EverExceed Industrial Co. Ltd	China
Lifeline Batteries	USA
Saft	France
Forsee Power	France
ZEM	Norway
EAS	Germany
Kongsberg	Norway
Leclanchè	Switzerland

3.6 New buildings market evolution over the next 5-10-15 years

Global Seaborne trade is the main driver for newbuilding requirements. Given the large uncertainties and challenges that the Covid-19 pandemic imposes on the global economy it is difficult to give an outlook of what can be expected. In the optimistic baseline scenario of the IMF, the pandemic is assumed to fade in the second half of 2021, allowing for a gradual lifting of containment measures. Yet, in this optimistic scenario, the global economy is projected to contract sharply - far worse than during the 2008-2009 financial crisis. The forecast for the European Union points to a stronger initial decline 7.1% than for other parts of the world.

Another challenging factor when predicting future newbuilding markets is that the contracting of ships is highly cyclical and is strongly dependent on the state of the freight market and on the cycles in the world economy, as well as on specific demand and supply side factors, especially tonnage requirement growth and vessel demolition. Furthermore, decision makers' perception of the short and medium term outlook for the freight market, of second-hand vessel prices, as well as of newbuilding prices, has a strong impact on the demand for newbuilding's and thus on the level of contracting.

Taking above into consideration, the graph below shows the newbuilding requirements for the worldwide market expressed in millions of CGT and showing an expected long-term increase back to levels of 2008-2009.

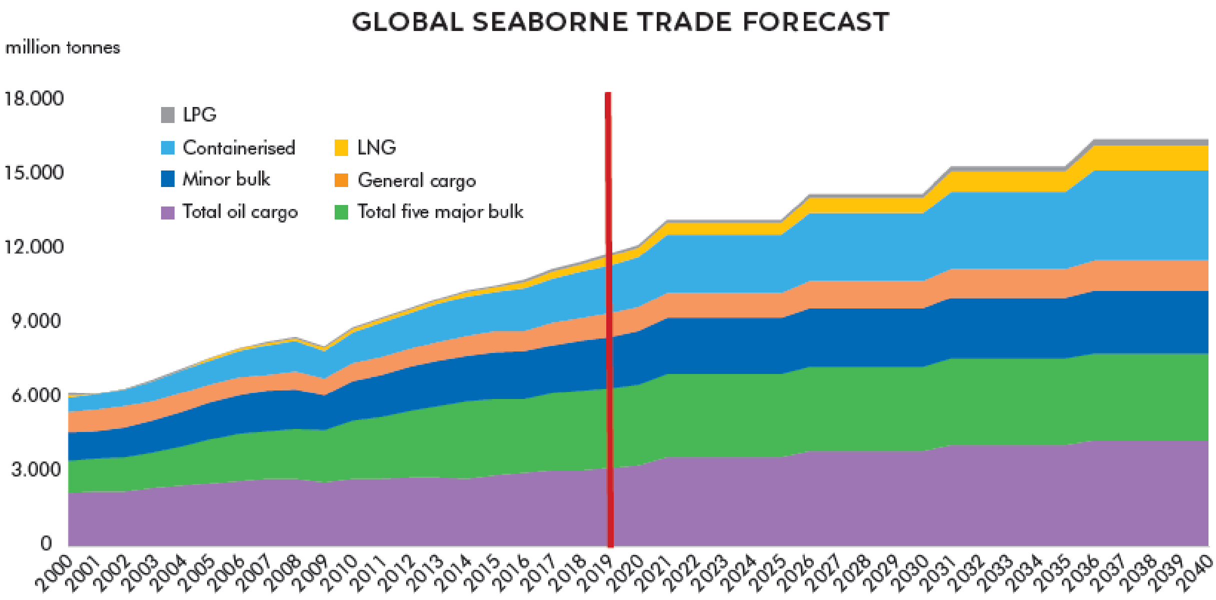


Figure 67 – Global seaborne trade forecast 2021-2040. Source SEA Europe WG MF, 2019

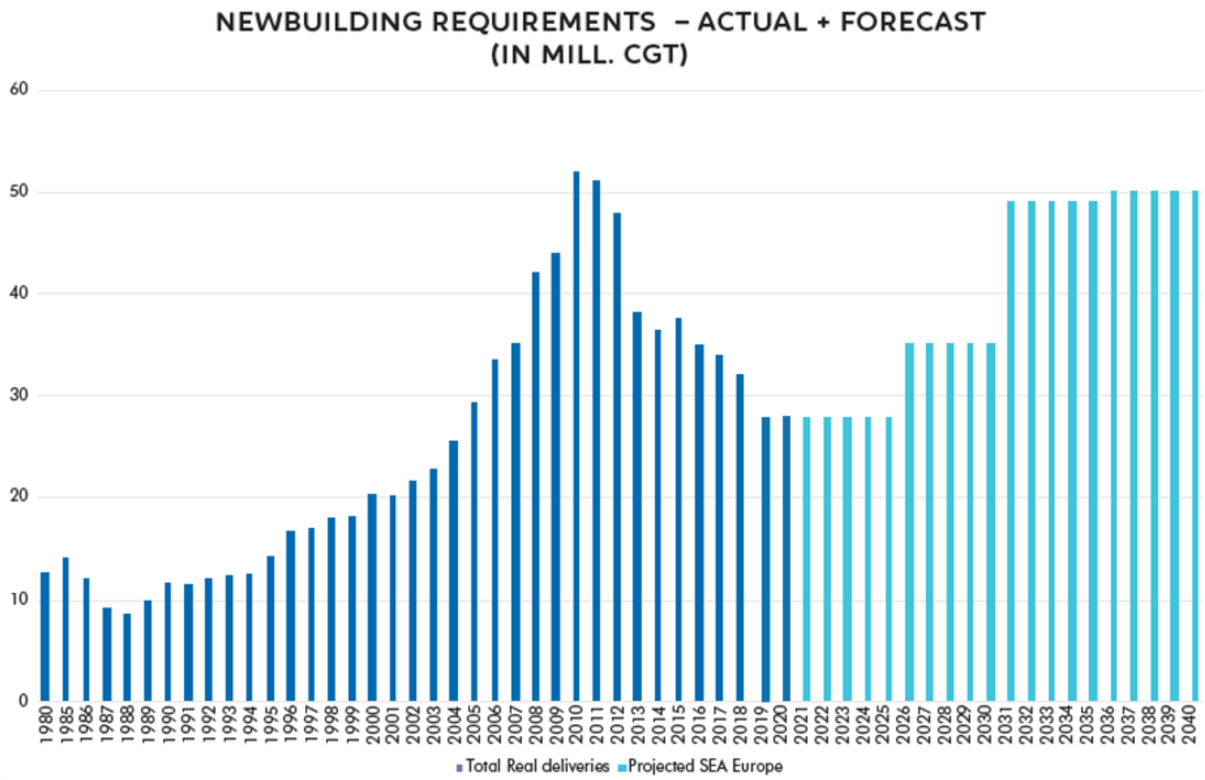


Figure 68 – Newbuilding requirements

3.6.1 Forecast Vessels with IMO number by largest vessel types.

In this paragraph the forecast of vessels with IMO number built by european builders are given by the largest 4 groups of vessel types.

The figures in this paragraph all respresent forecast for the world's newbuild requirements and should be corrected for european market share. These are mentioned per type.

In the graphs the yellow line represents the number of vessels while the blue bars represent the CGT sum.

3.6.1.1 Fishing Vessels

The future market for fishing vessels is one of the hardest markets to predict of all vessel types. This is largely due the fact that the fleet size is mostly dictated by government policies rather than market requirements. Several studies have shown that fish stocks have been seriously overfished in many areas of the world. The percentage of stocks fished at biologically unsustainable levels increased to 33.1% *(Source: Sea Europe)*

Statitics show that there has been a big increase in the average CGT in the Fishing vessels completed last years. The tendency is to build bigger ships because old smaller vessels are replaced by larger, more efficient newbuildings. The number of ships has also been reduced as it is usual to replace several ships with an only bigger one. The market is moving towards fuel efficient vessels with new types of fishing gears, more sensitive to marine environment (pulse fishing, less bycatch, etc.) and much safer for the crews. *Source clarksons forecast club 2021*

The fishing fleet is one of the oldest with an average age of 30 years. A high level of scrapping is expected in the coming years due to the need to replace the oldest units. Currently, almost 50% of the ships are over 30 years old

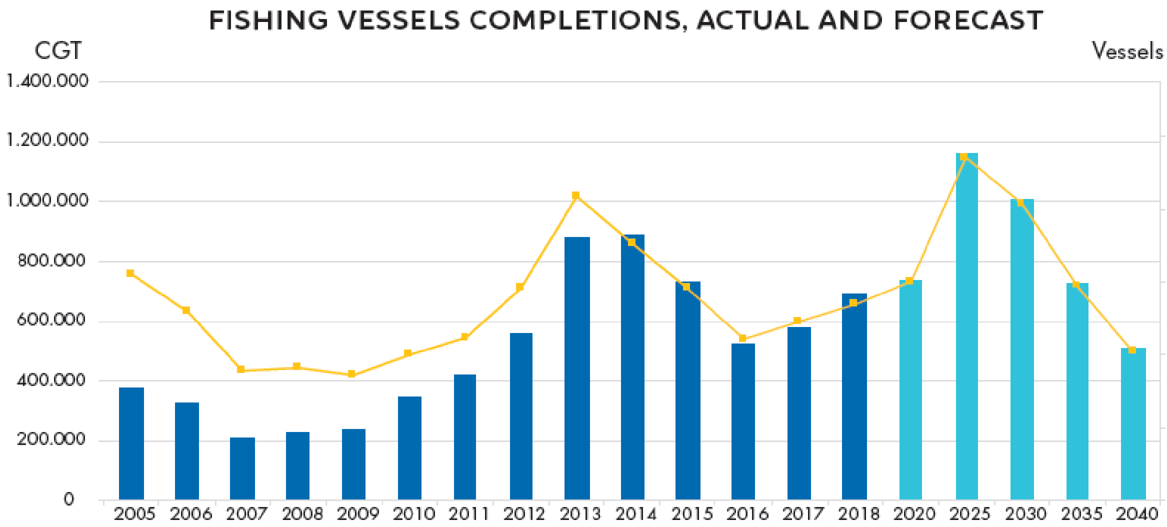


Figure 69 - *a worldwide number of fishing vessels completions, actual and forecast*

European built fishery vessels count for approximately 25% of market share. Based on IHS seaweb data total fleet. The numbers in the graph avove show worldwide numbers of fishing vessels.

A rise in the number of vessels active in fish farming is to be expected. There will still be a newbuild requirement for fishing vessels, as a certain degree of fleet renewal will be necessary to replace part of the current ageing fleet.

3.6.1.2 Tugs

Worldwide 530 tug deliveries per year in the afore-mentioned period untill 2025 is expected *(Source: Sea Europe)* European builders have approximately a 10% market share. (See also graph 3.1.5b)

For the longer term, the growth of the world fleet of tugs is expected to decrease from 2.25% to around 1.7% per year, in line with reduced growth expectations for world seaborne trade. A peak of close to worldwide 640 deliveries per year is expected in the 2026-2030 period, whereas afterward deliveries will decrease to around 620 units per year worldwide in the 2036-2040 period. Of course, expected delivery numbers could be impacted positively on the one hand by increased scrapping as a result of future environmental regulations or, more distantly, mass replacement of existing tugs by autonomous or remotely operated tugs. On the other hand, numbers could be impacted negatively by a stronger reduction in world seaborne trade growth.

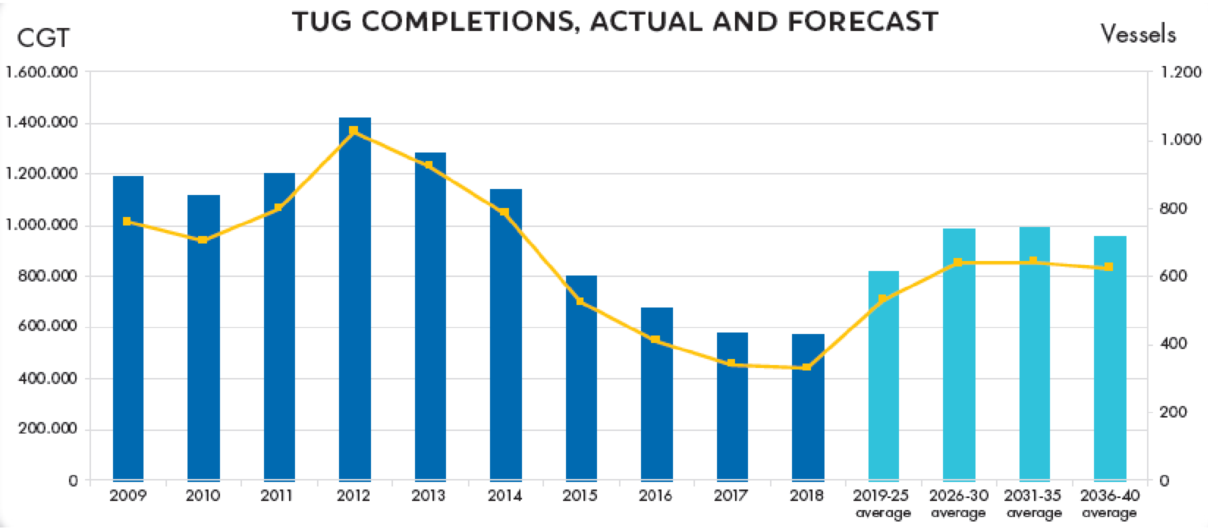


Figure 70 - *worldwide number of Tugs completions, actual and forecast*

3.6.1.3 General Cargo Vessels

In the medium term, newbuild requirements for General Cargo are expected to recover and peak at an annual average of 184 vessels or 1.71 million CGT in the period 2021-2025. In the longer run, however, the world's general cargo fleet is expected to resume the declining trend it has exhibited over the years. The forecast for the period 2031-2035 is therefore decidedly bearish, at an annual average of 112 vessels or 1.19 million CGT

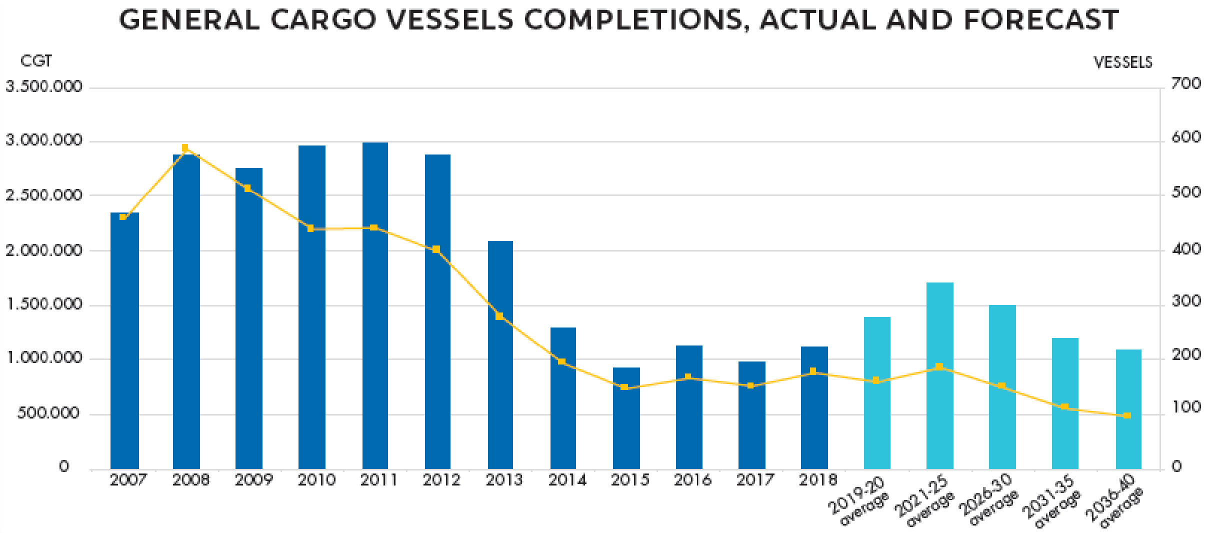


Figure 71 - *worldwide number of General cargo completions, actual and forecast*

Over the past years the general cargo vessels that are ordered at European shipyards have been declining as well as the marketshare. The market share of general cargo vessels has declined from 20% in 2006 to only 1-3% in the last years.

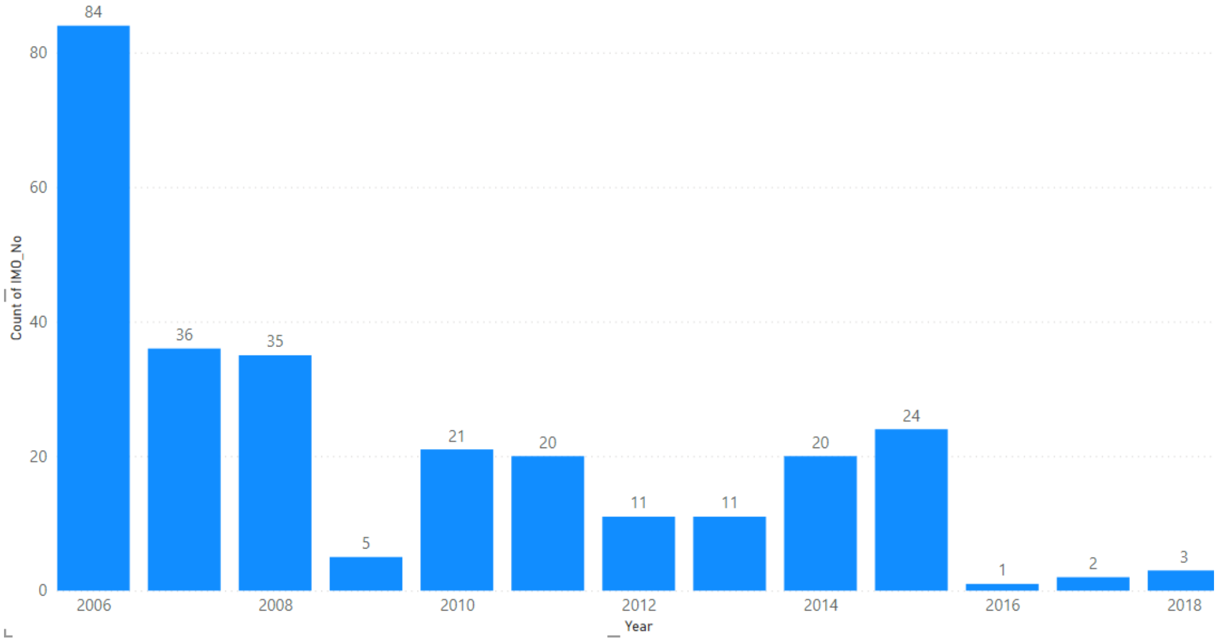


Figure 72 - *European number of General cargo contracted*

3.6.1.4 Yachts

By 2030 we estimate that the world superyacht fleet could reach 7500. *(source: the superyacht newbuilding report 2020)*

Figure 73 – Superyachs delivered over the past 10 years

3.6.1.5 Bulk Carriers

The market for newbuilding bulk carriers in Europe is very small/negletable. The world forecast for bulkcarriers looks as follows

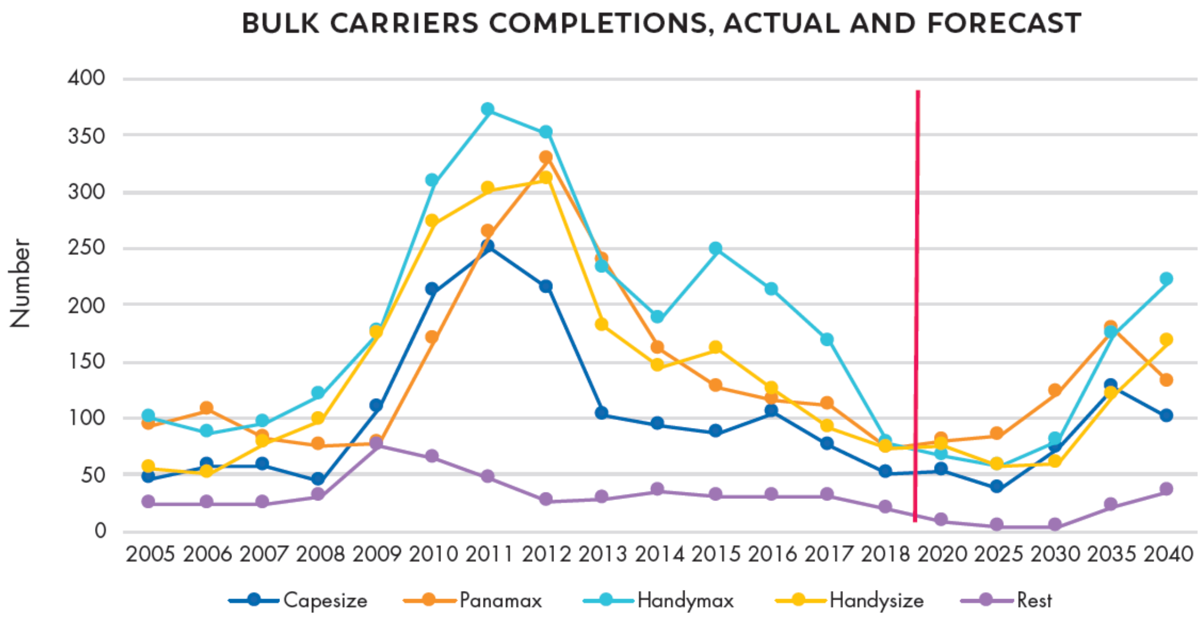


Figure 74 - *worldwide number of Bulk Carriers completions, actual and forecast*

3.6.1.6 *Tankers (oil and chemical)*

The market for newbuilding tankers in Europe is very small/ neglectable. The world forecast for tankers looks as follows

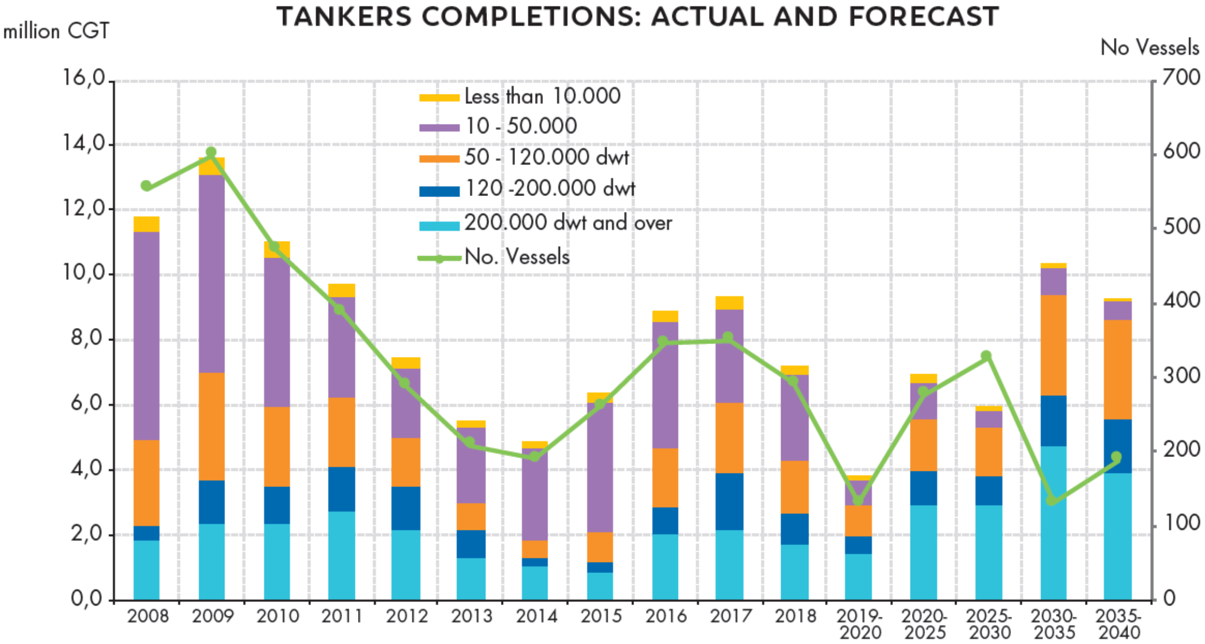


Figure 75 - *worldwide number of Tankers completions, actual and forecast*

3.6.1.7 *Tankers (LNG and LPG)*

The market for newbuilding tankers (LNG & LPG) in Europe is very small/ neglectable. The world forecast for LNG and LPG tankers looks as follows:

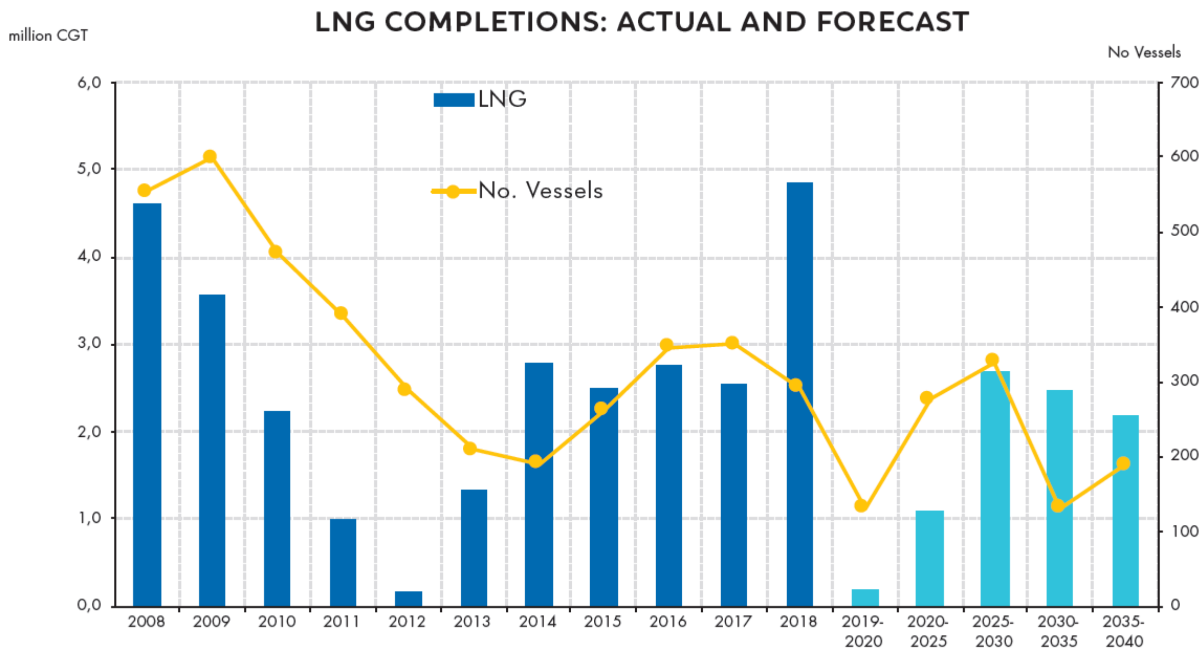


Figure 76 - *Worldwide number of LNG completions, actual and forecast*

3.6.1.8 Other vessels/ patrol vessels

The remaining group of specialised vessels is a very mixed group, consisting of a wide variety of vessel types. It is a challenging group to keep track of, as certain subgroups of vessels move in and out of this category over time in the registers. This has to do with the employment of these vessels, which is often related to other large vessel groups such as Offshore vessels, Dredgers or Naval vessels for example.

The largest subgroup of Other Special Vessels is that of the patrol vessels. Although patrol vessels are more related to navy ships than to regular commercial vessels, many are built these days by commercial shipbuilders and to commercial standards. Also, some of the smaller patrol vessels are offered as a multi-role design which can also be customized as a crew boat or supply tender.

Production of patrol vessels is rising. Developing nations are building up their navies, while navies in the Western world are increasingly looking to deployment of patrol vessels as a more cost-effective way of performing some duties which used to be performed by frigates and corvettes, enabling the latter ship types to be deployed more exclusively on the more dangerous tasks. Trends in patrol vessels are multi role, heavier armery and range extensions/ longer at sea.

Utility vessels and work/repair vessels also form a relatively large group. These are mostly small multi-role vessels, commonly known as “workboats” and often used as auxiliary vessels in port construction, dredging and offshore construction projects. These vessels are usually equipped with a crane and an open deck and often have a catamaran hull form in order to provide a relatively stable working platform on such a small vessel. Also heavily involved in offshore energy projects are the crane vessels.

Ships owned by governments or ports, such as pollution control vessels, buoy tenders, training ships, search & rescue vessels, firefighting vessels, pilot vessels, and salvage vessels make up most of the remainder of this category.

Most of the other special ship types are built in very small numbers, with production in the low single digits each year. The most notable exceptions are the larger categories of workboats and patrol vessels. Many patrol vessels are built to the standards of a Class Society but then withdrawn from Class shortly after delivery as they are naval units. These vessels then often disappear from the vessel registers Although the production numbers of many other special vessels are relatively small, the vessels themselves are often high-value specialized vessels.

European market share for this group is around 40%.

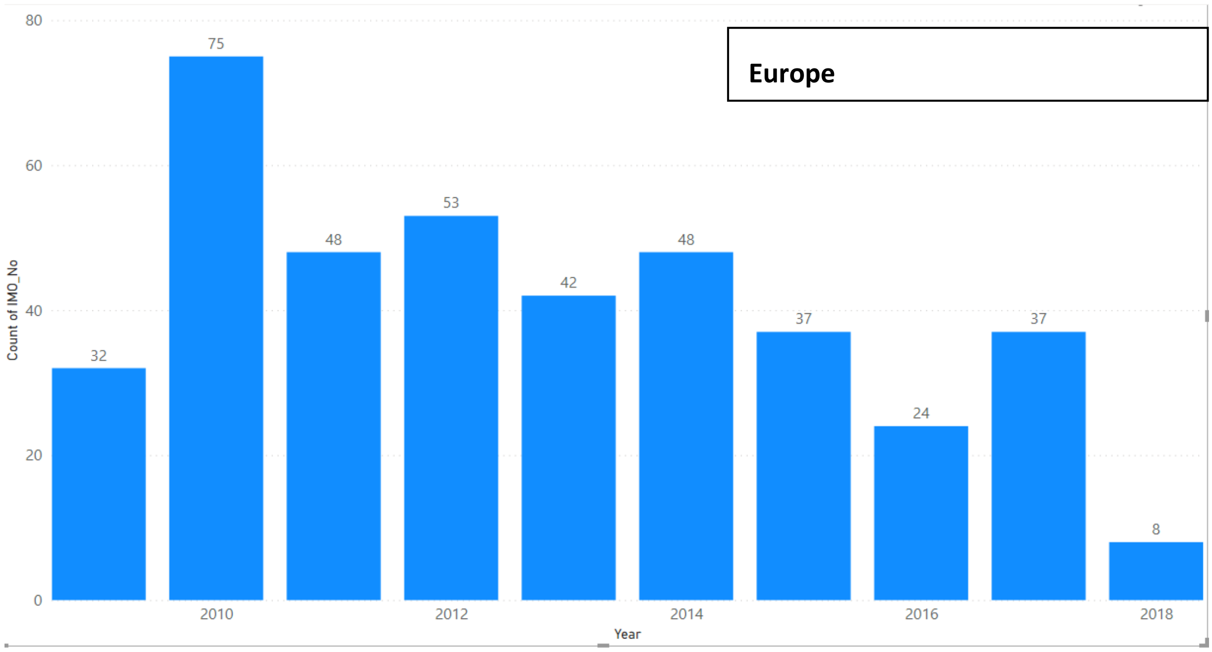


Figure 77 – European market from 2010 to 2018

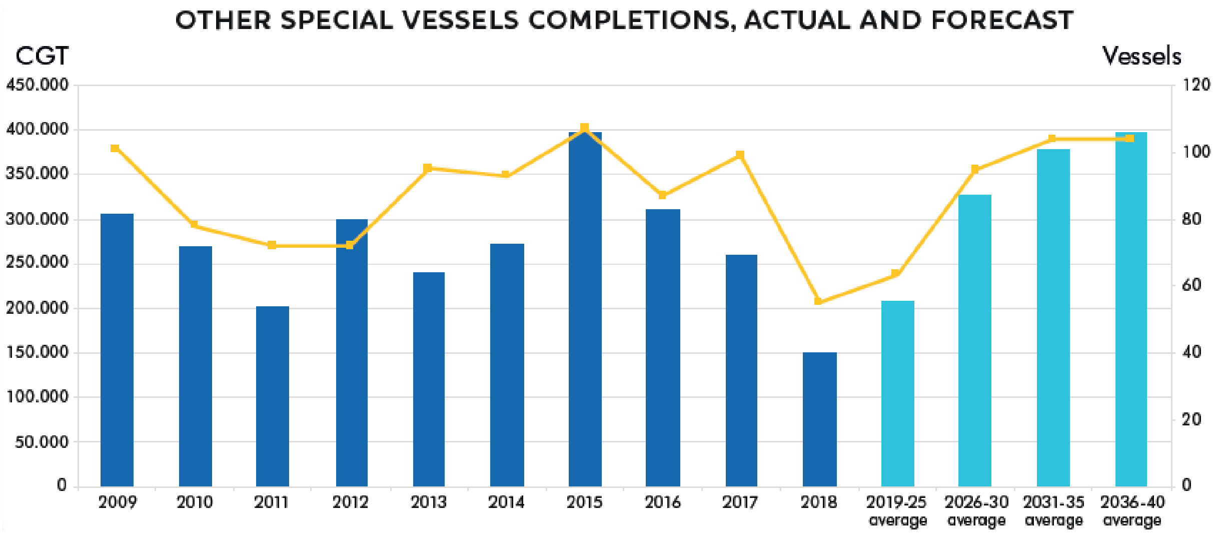


Figure 78 - *Worldwide number of other special vessels completions, actual and forecast*

3.6.1.9 Inland shipping fleet

Forecasts for the inland waterway fleet are not abundantly to be found by recognized agencies, but some guidance exists as to how the industry is faring and what its' outlook may be. The Central Commission for the Navigation of the Rhine (CCNR) publishes, amongst others, a yearly Market Observation on the European Inland Waterway Transport (IWT). In addition, in 2020, they published a special report on the effects of Covid-19 on the sector, and, as a supplement to the latest annual Market Observation, an outlook for the period 2020 – 2040. This supplement was based on a market study performed by Royal Haskoning, and led to the following outlook by segment.

Segment	Potential	Most important driving factors	Long-term trend for IWT
Chemicals	++	High degree of innovation of the chemical industry in Europe	IWT remains the preferred transport mode for chemicals
Containers	0/+	Reduction of growth rates in world trade and maritime shipping	Growth continues but with lower rates
Sands, stones, building material	+	IWT is a preferred mode of transport for shipping companies and growth in the construction sector will be positive in western Europe (WE)	Moderate growth on existing long-distance routes, higher potential for growth in urban areas
Metals and metal products	0/+	Economic growth in emerging markets leads to more demand for steel	Metals and steel transport can grow on a limited basis
Mineral oil products	0/-	Mineral oil products are still needed as a fuel in the next decade, but a gradual decline is already underway	Gradual decline in most regions but positive exceptions are possible
Foodstuffs	WE*: 0/- EE: 0/+	Decrease of livestock activities in western Europe due to nitrogen and other emissions, delocalisation of parts of these activities to eastern Europe (EE)	Decrease in foodstuff transport due to less livestock activity in WE. For EE, a more stable or even positive evolution is expected
Iron ore	WE: - EE: +	WE) A certain saturation in steel demand and less iron ore intensity in steel production EE) Stronger growth potential in steel demand	Iron ore transport is expected to decrease in WE while it is thought to increase for a certain period in EE
Coal	WE: - EE: 0/+	Phasing out of coal in the energy sector and gradual decline of coal use in the steel industry	Decrease in coal transport in WE, at least stagnation in EE

Segment	Potential	Most important driving factors	Long-term trend for IWT
Project cargo, heavy and oversize cargo	+	Energy transition (windmills), electricity demand (transformers), bottlenecks for transporting this type of cargo by other modes of transport	IWT benefits from its large space capacities for project cargo, heavy and oversized cargo and its flexibility
Recycling, circular economy	+	Industrial production is transformed by the need for a large-scale reduction of emissions	IWT is already active in the transport of recycling material and is expected to increase this activity
Biomass	+	Energy transition, need for more biofuel, compensation for reduction in foodstuff production	IWT has large capacities for transporting these materials
Hydrogen, batteries	+	In the future energy system, hydrogen can be an important element, possibly in combination with electricity and batteries	Trend is still at the beginning, transport possibly by pipeline or by containers on maritime ships and inland vessels (or by a combination of these modes). Large potential from 2030 onwards

As for the size of the fleet in 15 and 30 years from now, the Entwicklungszentrum für Schiffstechnik und Transportsysteme e. V. DST (Development Centre for Ship Technology and Transport Systems) has produced a forecast for the Switzerland based Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation, Bundesamt für Verkehr (BAV), Abteilung Sicherheit/Sektion Schifffahrt [1], who are a member of the CCNR Study Group 'Financing the energy transition towards a zero-emission European IWT sector' (October 2020).

1 https://www.ccr-zkr.org/files/documents/EtudesTransEner/Deliverable_RQ_C_Edition_1_Oct2020.pdf

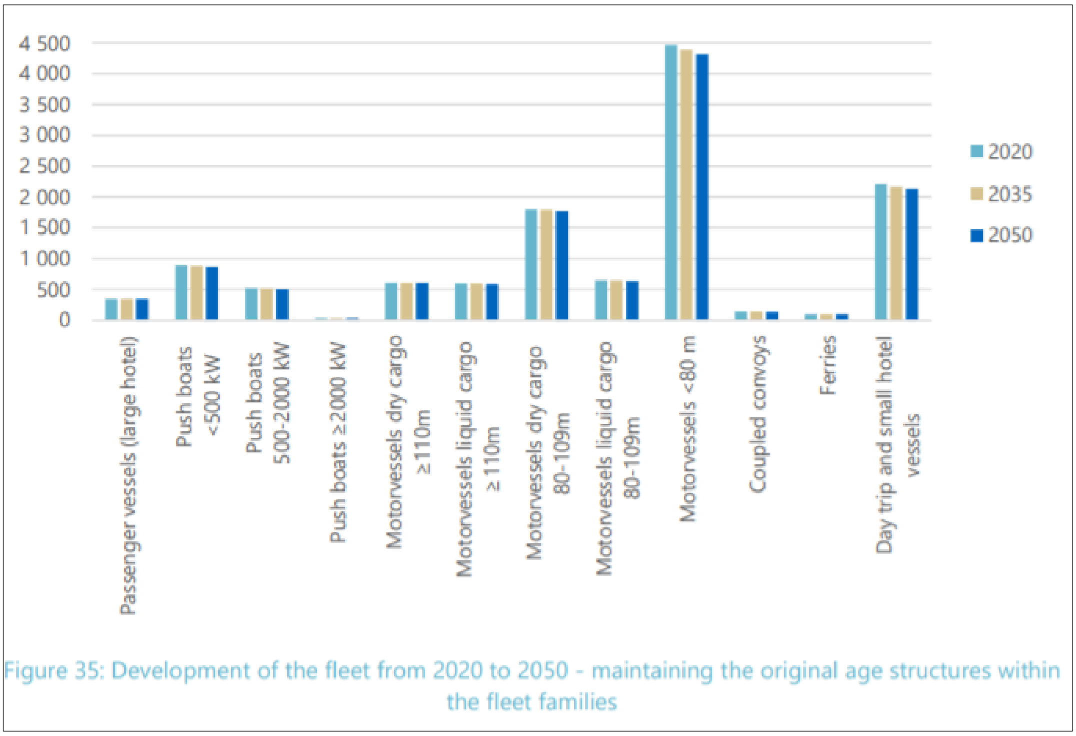


Figure 79 - *Worldwide number of inland vessels fleet forecasting*

Their forecast, shown in the above graphic, estimates a relatively stable fleet size for all inland vessel types over the period to 2050. The only fleet segment to show a (small) decrease in numbers is the category Motor vessels of <80 metres in length, which is under some commercial pressure due to the continuing trend towards larger sized inland waterway cargo vessels.

The forecast has been based on the assumption that the over all age structure of the fleet in 2050 will remain equal to the age structure seen today – logical, as inland waterway vessels (except for cruise vessels) have long service lives of even up to 50 years. For cruise vessels, an average replacement age of 30 years has been assumed, meaning that by 2050, all river cruise vessels in service will have been built in or past 2020.

3.6.1.10 Containers

The great part of the ongoing container vessels capacity is from 4000 to 10000 TEU, in terms of number of units. On the other hand, considering the number of TEU, the most common size are in the ranges 7500-10000 TEU and 12500-15200 TEU [39].

On the other hand, taking in to consideration the new orders, the most common sizes are in the ranges 18000-24000 TEU and 10000-15200 TEU. These data show a clear trend towards ever increasing dimensions and capacity in container vessels [39].

The current fleet age breakdown shows that the majority of the ongoing vessels, in terms number of TEU, are in the range between 1 and 15 years old. Another important information derived by the current fleet age breakdown is the clear increasing dimensions and capacity of the most recent ships [39]

The European share of the global container vessels shipbuilding and order book is a very little part of the global market (less than 1% indeed).In fact, most of the new buildings are produced in China, Japan and South Korea [40].

3.6.1.11 Cruise vessels

The current world fleet account for close to 400 cruise vessels, new orders are, nowadays, equal to 114 units and the European market share is close to 91% (104/114 units) [40], making European shipyards the worldwide leaders in cruise vessels building (see Figure 80).

It is of interest to highlight that, the 30 percent of the cruise vessels built since 2020 have installed a shore power connection facility. This is only one of the recent innovation aimed to reduce the carbon footprint of these vessels. Moreover, considering the future integration on board of battery ESS, the possibility of recharge these systems by means of the port (i.e. national) electric grid, could dramatically reduce the global GHG emissions due to cruise vessels activities. Finally, the possibility to take advantage of a fast charging facility would drastically increase the integration of battery ESS for these ships (Figure 81).

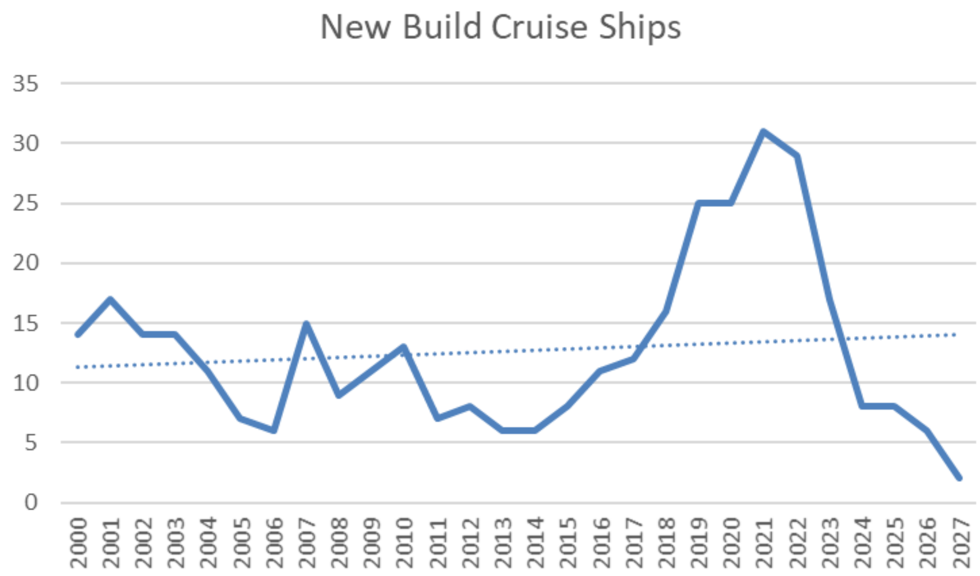


Figure 80 - *Worldwide order book for cruise vessels [40]*

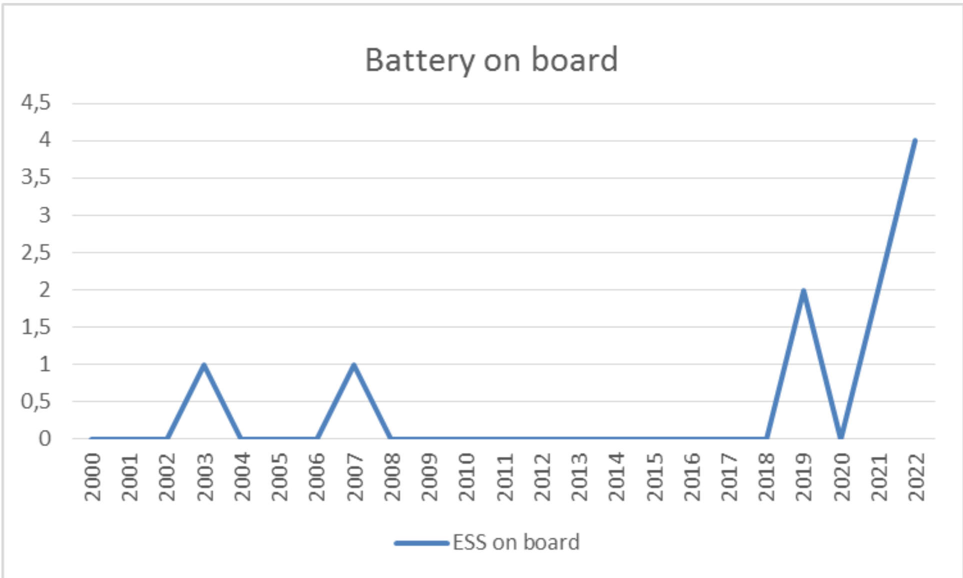


Figure 81 - *Worldwide order book for cruise vessels with battery ESS integrated [40]*

3.6.1.12 RoRo, RoRo-Pax and Ferries

A Fincantieri internal analysis on the RoRo and RoRo-Pax current fleet shows a European penetration equal to 52 percent (764 ferries over 1461 total) considering ongoing vessels. For what concern new buildings, of the total 89 units, 47 will be designed and built in a European shipyard. Within the next 5 years of time horizon, 97 of the total 283 vessels (RoRo, RoRo-pax and Ferries) will be designed and built in a European shipyard [40].

Of all the RoRo and ferries built in Europe, the 49 percent will operate in the Mediterranean area. The remaining 51 %, on the other hand, will operate in the Baltic area.

3.6.1.13 Special vessels

As special vessels are considered all the platform supply vessels, research vessels, trailing suction hopper dredger, hopper vessels, utility vessels, standby safety vessels, crew supply and offshore support vessels. The total number of ongoing special vessels, operating in the European area, is equal to 2132 units.

These vessels are particularly suitable and could take great advantage for the on-board integration of a battery ESS in the refitting case. The European retrofitting market share is very close to 100 percent, due to the high complexity of the on-board power system.

A five years market forecast for special vessels shows that, in Europe, 19 of 45 dredger will be built in a European shipyard. Similarly, 59 of 566 offshore vessels and 22 of 42 research vessels wil be built in a European shipyard.

3.6.1.14 Database definition

This section summarizes the main characteristics of the sample database for seagoing projects (Table 20) and current and future projects (Table 21). Of course, this is not a complete database of every vessel with a battery system installed on board. However, the selection of these projects could give a good picture of the current market trends in terms of energy installed and ships dimensions.

3.6.1.15 Database analysis

As it has been highlighted in the previous section, marine applications of batteries have grown considerably in the last 10 years. Many Companies consider battery technology as a sustainable solution to improve performances and to reduce polluting emissions. This section summarizes the analysis conducted on the database previously identified.

The dataset considers only a sample of ships built and intends to give a general view of the evolution of the market and of the applications in recent years.

3.6.1.15.1 Trend of installed energy

In Figure 82 it is presented the energy installed over the years, based on the sample database. The red line represents a fitting of the data. Yellow and purple lines represent two projections to 2030 based on the linear fitting of the entire set of data and the last 5 years of installations, respectively. It is possible to notice that in the last years the installed energy has increased rapidly, as it is confirmed by the projection based on recent data.

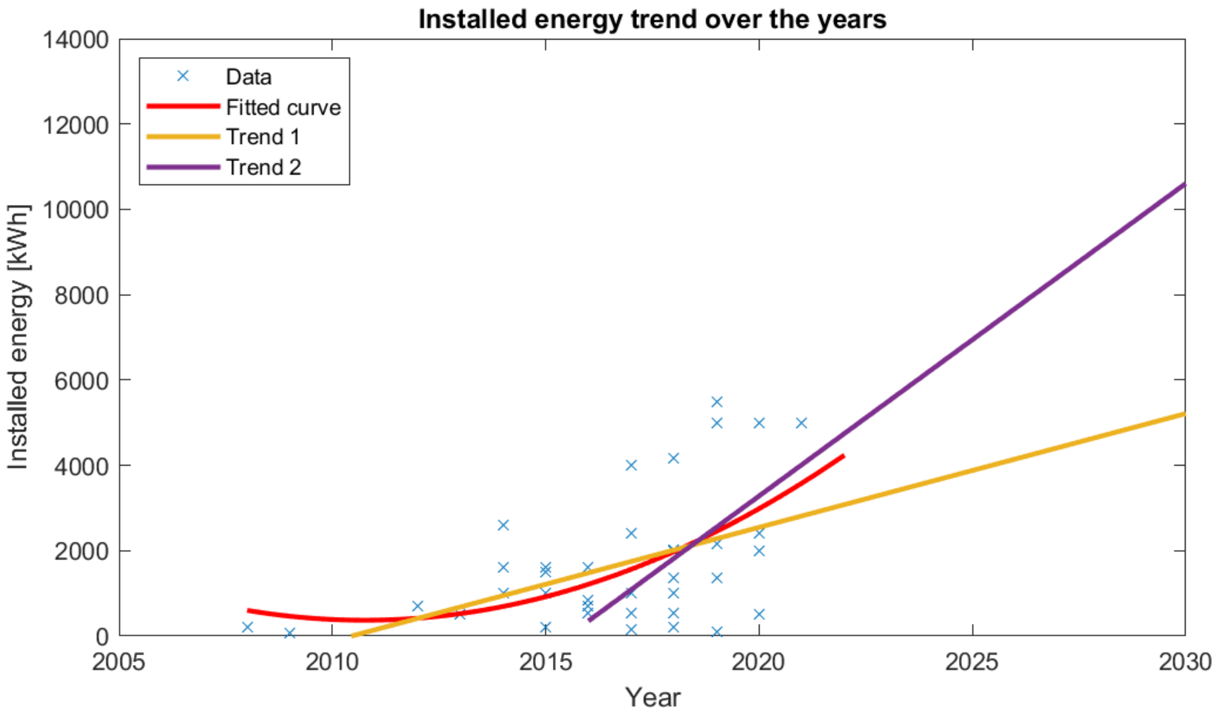


Figure 82 – Installed energy trend over the years

3.6.1.15.2 Total installed energy

In Figure 83 it is presented the sum of the installed energy per year, where it is possible to notice the rapid increase of the installed energy on board.

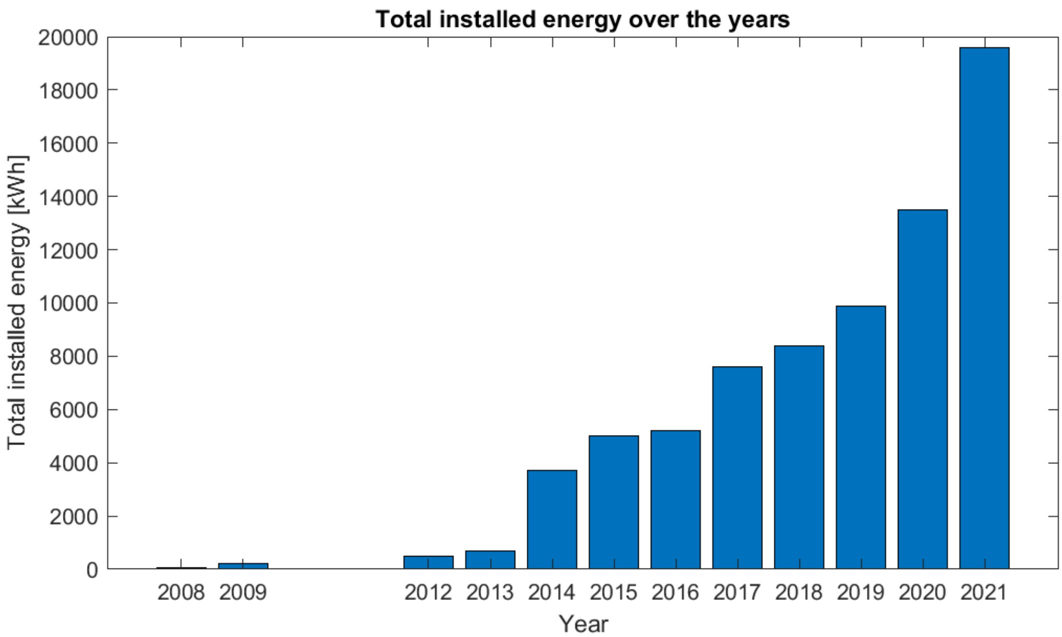


Figure 83 – Total installed energy per year.

In the early years, the ships with installed batteries were small ships, with a length of around 50 m. With the growth of battery technology and a better compromise between energy density and specific energy, the length of the ships with batteries installed has increased (e.g. The Eco Livorno RoRo-Pax is long 238 m). In Figure 84 the crosses represent the length of the vessels over the years, and the red line is the quadratic fit of the data.

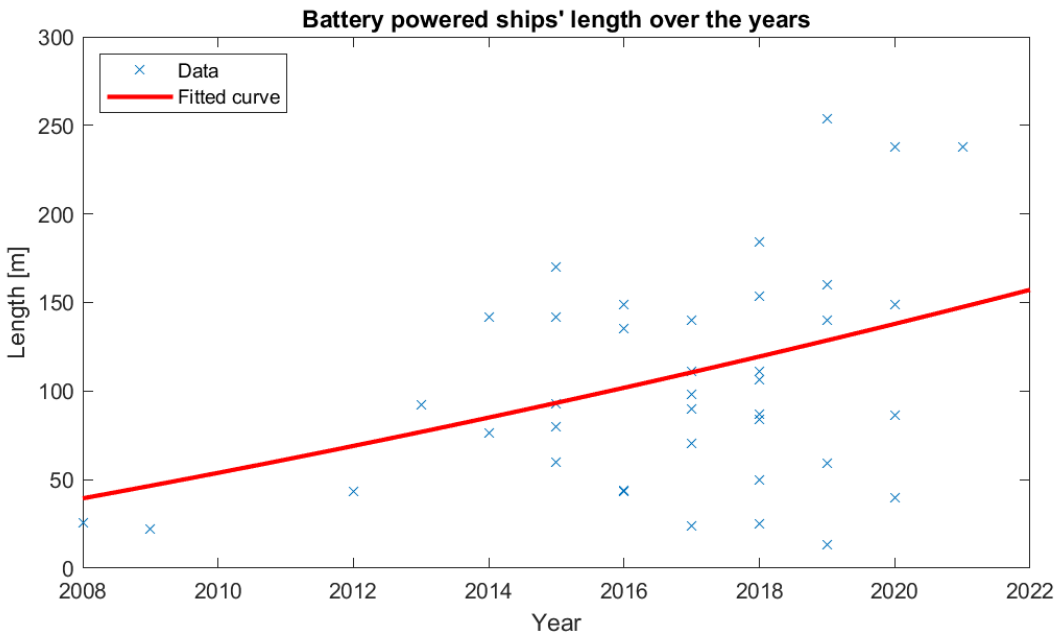


Figure 84 – Battery powered ships' length over the years.

The sample database includes ships in literature [1], [31]-[32], to validate the considerations on the trend the sample data has been compared with other research. It is possible to observe in Figure 85 the installed energy and the length over the years. Ships are sorted from oldest to newest design. It is possible to see the increase in length and installed energy as in our analysis. The sample database selected for this research considers the ships update to 2021.

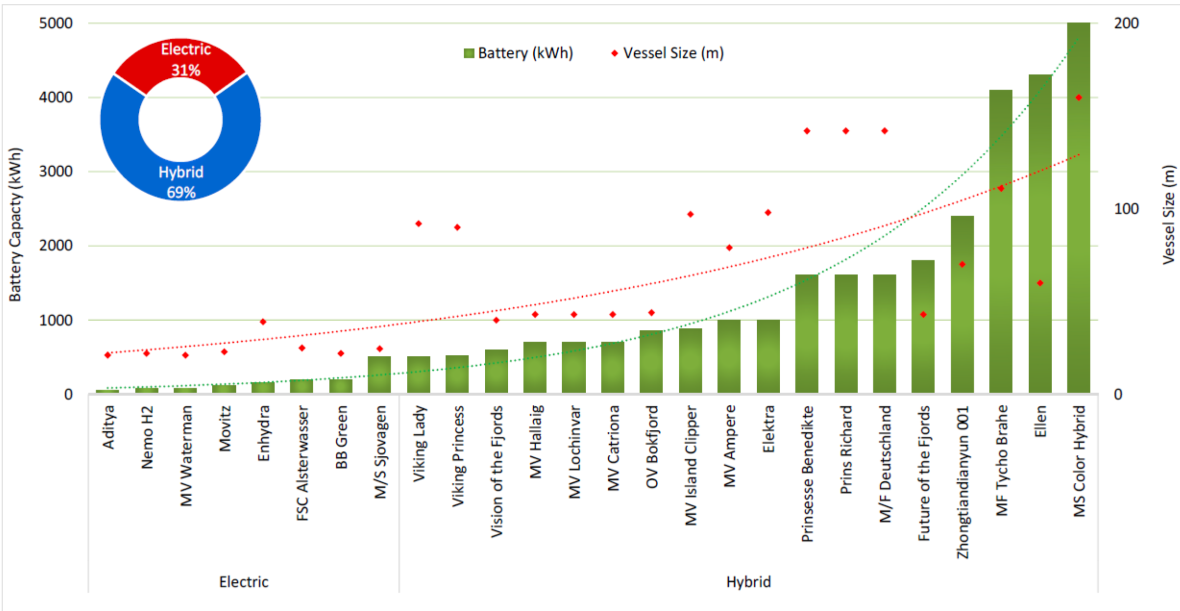


Figure 85 - Length and installed energy over the years [32].

Figure 86 shows the different types of ships in the database, the most relevant ship type is the RoRo-Pax type.

In the following report named "Customizable Battery Power System for Marine and Offshore Applications" [31] different ships type in their database are presented. The database makes a difference from Passengers ships and Ferry ships, not including the class RoRo-Pax. In the analyse of the database most of the referred Passengers ships or Ferries were associated as RoRo-Pax.

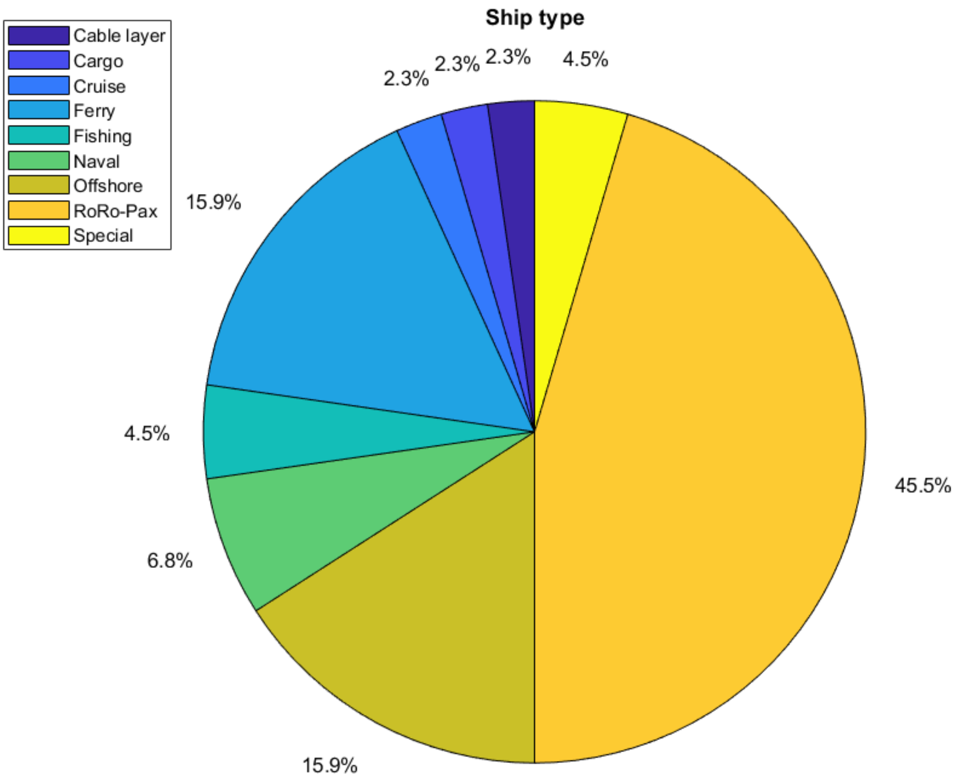


Figure 86 - Ship type.

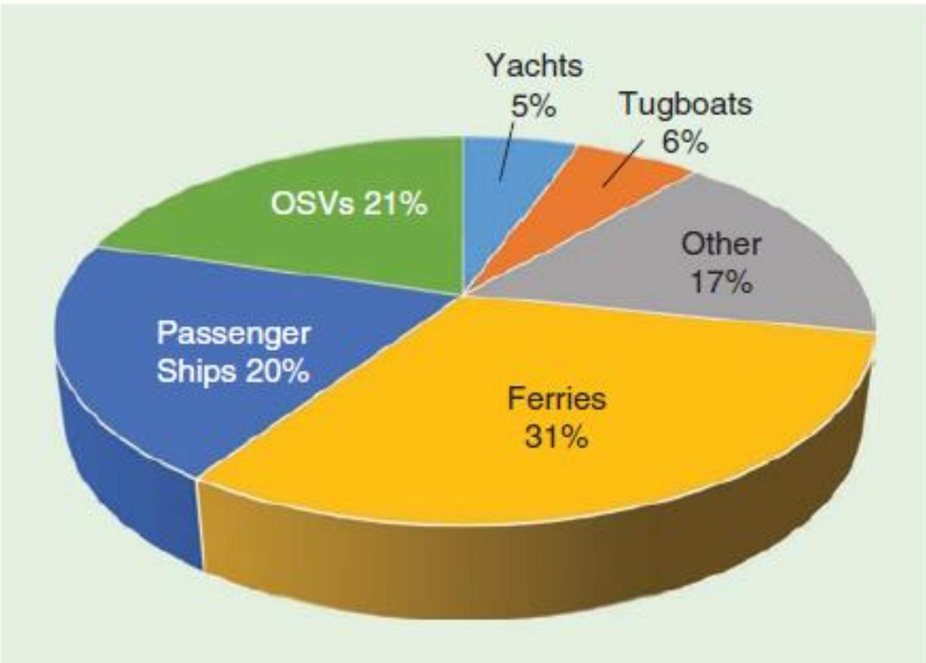


Figure 87 - The battery-powered vessels in operation or under construction in 2018.

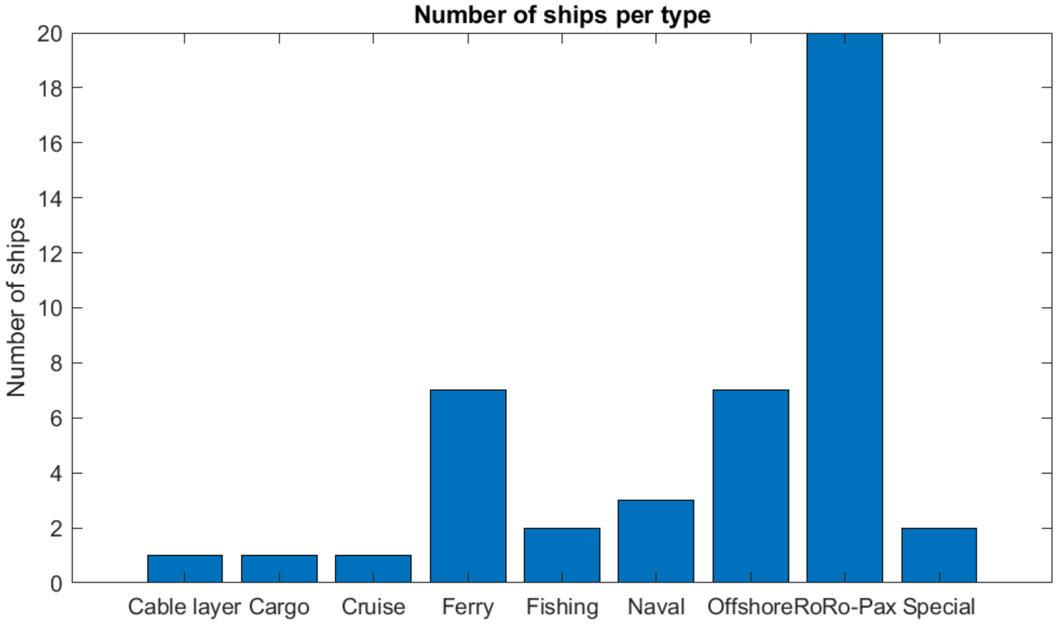


Figure 88 - Number of ships per type.

In Figure 89 the number of ship types is reported in the sample database, in the DNV GL [1] the same graph is shown with many more ships, even if the number of ships are less in our database, the ship types with the greatest impact are shown correctly.

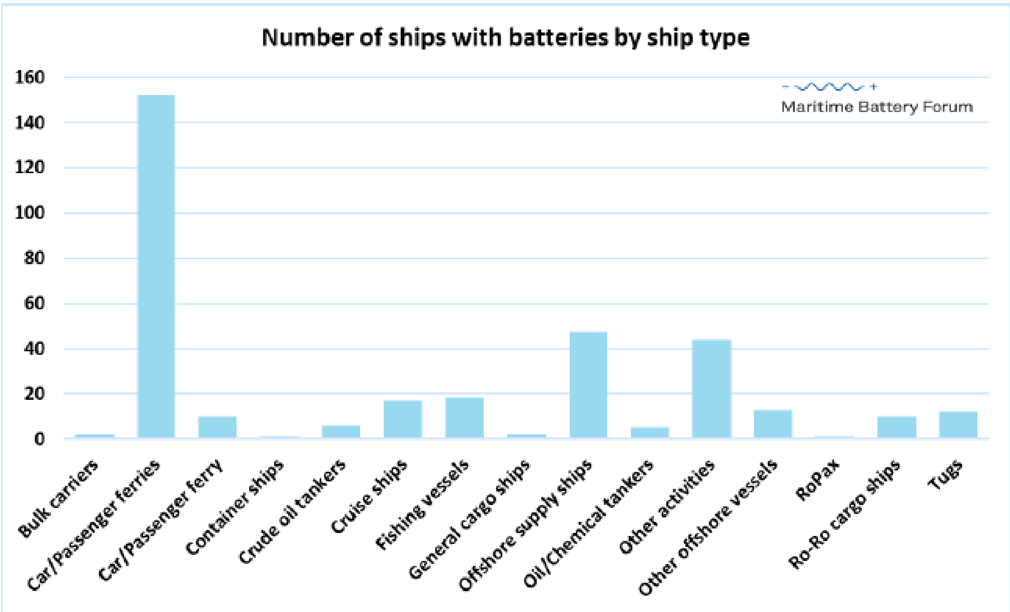


Figure 89 - Number of ships with batteries by ship type [1].

3.7 Evolution of the battery market for marine applications

In Table 34 it is reported for each ship different applications and potential benefits of batteries on board. One important aspect is related to the number of cycles per day that represents the mission of the ship and the relative strategy for sizing and charging facilities.

Table 34 - Summary table with typical values with regard to application feasibility and benefit [1].

SHIP TYPE	FUEL SAVINGS POTENTIAL (%)	MAIN BATTERY FUNCTION CONSIDERED	FACTORS WHICH CAN MAXIMIZE BENEFIT	C-RATE [1]	CYCLES [2]	CYCLES PER DAY[7]	TECHNOLOGY
RoRo – RoRo/Pax and Ferries	up to 100	All electric where possible	Low electricity costs, high port time, low crossing distance	Very high	Very High	10	NMC, LFP, LTO
Special Vessels	1-30	DP - Spinning reserve and peak shaving	Variable depending on the case	Very high	Variable	0,5	NMC, LFP, LTO, supercap
Cruise vessels	<5	Hybrid operating in all electric, ticket to trade	Ability to operate in all electric mode for an extended period	Low	Likely High	2	NMC, LFP
Fishing vessel	3-30	Hybrid load levelling and spinning reserve	Diesel sizing relative to loads	Nominal	Nominal	-	NMC, LFP, LTO
Deep sea vessels	0-14	PTO supplement	Highly variable, detailed duty cycle analysis	Highly variable	Variable	-	NMC, LFP, LTO
Cargo vessels	0-30	Crane system hybridization	Integration with genset sizing	High	High	-	NMC, LFP, LTO
Tug boats	5-15	All electric or many hybrid uses	Detailed duty cycle analysis	Highly variable	Highly variable	-	NMC, LFP, LTO
Yacht	5-10	Silent operation, spinning reserve	Detailed duty cycle analysis	Low	Low	-	NMC, LFP, LTO

3.7.1 RoRo-pax

Ferries (car and passenger ferries) represent one of the few segments that have already seen a large uptake in both “all battery powered” and “hybrid” solutions. Most of the ferries with batteries are technically hybrids, with diesel gensets on board, although many are operating on battery only during normal operation.

Ferries are in general predictable, following a relatively short, fixed route every day. This makes them suitable for all electric operations. Challenges are typically short stays in port (high charging power), extremely high cycle life and in some cases, too long stretches to make battery alone feasible with current technology.

In general, the ways of using battery on ferries can be summarized in:

1. All electric ferries, eliminating local pollution, most efficient solution.
2. Hybrid, the battery either provides a certain amount of energy or acts as spinning reserve or potentially peak shaving.

In general, ferries are well suited for using batteries. Charging infrastructure and practical volume and weight restrictions for higher power demands are more often constraints since most concepts will require high charging power (often on MW scale) during the typical 5-15-30 minute port stay.

3.7.2 Special vessels

Offshore support vessels have already seen a relatively large uptake of batteries with around 40 projects already realised or being implemented. Modern OSVs are typically diesel electric which makes them suitable also for retrofitting of battery packs.

OSVs typically have high requirements for redundancy, a typical operational scenario is near a multi-billion installation on dynamic positioning (DP). Therefore, they are running many generators in case of load spikes to assure sufficient redundancy in case of failures. With batteries this can be avoided, saving both fuel and maintenance and potentially Capital expenditures (CAPEX) since it can be possible to reduce the number of engines installed.

In general, batteries are a feasible solution for OSVs, and some oil majors (most notably Equinor) have batteries as part of the specification for long term contracts.

Batteries must handle potentially high peak loads if a generator fails. In the scenario of running one generator and battery in DP the battery must typically be able to provide enough power and energy to abort the ongoing operation.

Applicable technologies are NCM, LFP, and LTO. Given that cycling is not necessarily a key requirement (DP operation typically handles fluctuations and not cycles) for OSVs the size of battery vs C-rates and costs can, perhaps for most cases, be decided based on required energy to abort an operation in case of an engine failure [1].

3.7.3 Cruise vessels

Cruise vessels represent a relatively small segment in number of ships, but it is starting to gain in terms of requirements for reducing emissions. When the port is close to a city, batteries could be applied to lower load on generators or to avoid low loading, reducing local pollution as much as possible.

For the time being it is not seen as feasible to run a cruise at the port on batteries only (depending on the size of the vessel and duration of the stay). Shore power (cold ironing) is more likely to be the zero-emission solution.

During transit, the vessels could potentially operates based on batteries only in sensitive areas, in addition to the more general load levelling functions. Solutions like this are being implemented along the coast of Norway with Hurtigruten and Havila Kystruten installing large battery packs for going into fjords and for manoeuvring purposes. These are, however, relatively small vessels compared to the large cruise vessels being delivered now.

Batteries on cruise vessels can act as backup power (also UPS), be used in manoeuvring, sensitive area sailing, optimise the use of engines and support during various peak loads.

Cruise vessels can experience large power fluctuations during certain times of the day, however, not at a very fast rate of change to the point where engines cannot keep up. Batteries can support and simplify the variation in power fluctuations. Cruise vessels are also often manoeuvring, and they are therefore often in an operational mode where hybrid propulsion is beneficial.

Some projects are investigating using very large batteries with low c-rates for the cruise segment.

3.7.4 Naval vessels

The emergence of Energy Storage Systems in warships is an evolution of battery-supported DC systems in submarine programs. In early 1995 were noted that energy storage devices (e.g. batteries) could negate the need for multiple storage devices common to naval ships. In 1998, the possibility of using a single generator with a backup battery system was identified to increase fuel efficiency and reduce operating expenses (OPEX) and in silent operation, the battery as a power source can lead to a large reduction in acoustic noise.

The batteries as power source were not used in the naval application, more recently the benefits of ESS are more clear, which are increased survivability, energy recovery during a crash stop deceleration, black start capability following a black-ship condition, manage pulse load, and load levelling/inertia compensation to improve fuel efficiency and reduce exhaust gas GHG emissions. Moreover, the ESS is a method to provide a faster response to differential load changes as ESS are not limited by the characteristics of the prime mover, thereby facilitating the reduction of engine maintenance, and increasing service life.

3.7.5 Maritime battery market forecast 5-10-15 years

Based on the data collected and presented above for the ships currently in circulation a trend analysis has been proposed in Figure 82, describing the energy storage capacity that will be installed each year.

Therefore, considering all the data presented in the previous paragraphs, a forecast of the possible future market for marine battery applications has been developed. With this perspective, the possible applications of batteries on board ship have been divided by total installed energy, in three different categories, divided as follows:

- > 100 and < 1000 kWh,
- > 1000 and < 3000 kWh,
- > 3000 kWh.

In order to identify which type of application is the most promising for the future, it was necessary to divide the ships into three groups, according to the total installed energy for the battery systems. Obviously, in the following analyses, there may be cases in which a type of ship may fall into more than one group depending on the installed energy (i.e. typically ferries and RoRo-pax). Despite this, since the purpose of this analysis is to verify which type of battery application can dominate the future market, these approximations by type of ship are negligible.

The analyses developed envisaged three different economic scenarios:

- business as usual scenario,
- worst case scenario,
- best case scenario.

According to sections 3.6.1.1 to 3.6.1.9 the following vessel types are expected to have a yearly (approximate) amount of newbuilds in the European market according to the table below.

Vessel type	2025	2030	2035
Ocean going fishing vessels	20	17	13
Coastal fishing and fish farm support	100	83	62
Tugs (>1500 kW)	40	40	40
Tugs (<1500 kW)	20	20	20
Yachts	160	160	160
General cargo (>1500 kW)	3	2	1
General cargo (<1500 kW)	3	2	2
Patrol/utility vessels	38	42	42
Inland cargo vessels	258	258	258
Inland push and tug boats	46	46	46
River cruise vessels	13	13	13
Total	701	683	657

Table 35 Future market expectations for new build vessels in Europe (vessels per year)

The evolution of the battery market is estimated based on 3 different possible scenarios. The low scenario is based on the a situation where in 2025 10% of the newbuild vessels of the above described types will have batteries installed, this will expand to 20% in 2030 and 30% in 2035. In the medium scenario 20% of the newbuild vessels will have a battery system in 2025, in 2030 this will be 30% and in 2035 this will be 45%. The high scenario is based on the assumption that in 2025 20% of these vessels will have batteries installed, in 2030 40% and in 2035 65%. These scenarios might seem precautious, but it is assumed that other zero emission technologies will also cover a part of the market and not all vessels will be equipped with batteries.

Scenario	2025	2030	2035
Low	10%	20%	30%
Medium	15%	30%	45%
High	20%	40%	65%

Table 36 Percentage of newbuild with batteries installed, different scenarios

The battery demand forecast is calculated with an estimated average battery size based on the minimum and maximum assumed battery sizes for each vessel type. In some cases it is not exactly the average between the minimum and maximum battery size, this is based on the assumed occurrence of the different battery sizes. If the largest possible battery size is not expected to be installed often, the estimated average battery size will be lower compared to actual average between the minimum and maximum battery size.

Vessel type	Minimum battery size	Maximum battery size	Estimated average battery size
Ocean going fishing vessels	100 kWh	500 kWh	300 kWh
Coastal fishing and fish farm support	100 kWh	5 MWh	2 MWh
Tugs (>1500 kW)	200 kWh	6 MWh	2 MWh
Tugs (<1500 kW)	100 kWh	1 MWh	500 kWh
Yachts	100 kWh	6 MWh	1 MWh
General cargo (>1500 kW)	100 kWh	500 kWh	300 kWh
General cargo (<1500 kW)	11 MWh	20 MWh	8 MWh
Patrol/utility vessels	100 kWh	10 MWh	2 MWh
Inland cargo vessels	500 kWh	6 MWh	2 MWh
Inland push and tug boats	500 kWh	6 MWh	2 MWh
River cruise vessels	2 MWh	10 MWh	6 MWh

Table 37 Average battery size used for market evolution estimation

The market outlook is calculated by assuming the average battery size being installed on the number of newbuild vessels according to the low, medium and high scenarios.

Vessel type	Low scenario			Medium scenario			High scenario		
YEAR	2025	2030	2035	2025	2030	2035	2025	2030	2035
Ocean going fishing vessels	0.6	1.0	1.2	0.9	1.5	1.8	1.2	2.0	2.5
Coastal fishing and fish farm support	20	33	37	30	50	56	40	66	81
Tugs (>1500 kW)	8	16	24	12	24	36	16	32	52
Tugs (<1500 kW)	1.0	2.0	3.0	1.5	3.0	4.5	2.0	4.0	6.5
Yachts	16	32	48	24	48	72	32	64	104
General cargo (>1500 kW)	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2
General cargo (<1500 kW)	2.4	3.2	4.8	3.6	4.8	7.2	4.8	6.4	10.4
Patrol/utility vessels	8	17	25	11	25	38	15	34	55

Inland cargo vessels	52	103	155	77	155	232	103	206	335
Inland push and tug boats	9	18	28	14	28	41	18	37	60
River cruise vessels	8	16	23	12	23	35	16	31	51
Total	124	242	349	186	362	524	249	483	757

Table 38 Battery market outlook in MWh per year

On the basis of sections 3.6.1.10 to 3.6.1.13 instead, the hypotheses and data considered to develop the analysis of the these types of ships of European interest are summarized in the Table 39 and Table 40.

It is possible to highlight that thanks to the current trend of decreasing battery costs, to the increase in performance (in terms of energy, volume and weight), in the near future larger and larger ships will be interested in installing this technology, especially in configuration hybrid with current on-board power generation systems. At the same time, the increased energy density of last technologies would help short range small ships to be converted into full electric ships, opening the door to their full decarbonisation (small ferries, fishing vessels, etc.).

Moreover, after an analysis of the different ship and applications, a great variability emerged in the capacity of the batteries adopted on board the ship, demonstrating the importance of a modular and expandable system.

Table 39 – Average scenario hypothesis and parameters selected for retrofit units market.

	High	Low	MWh	AVG	EU share	Ships	MWh market
cruise	10%	5%	6	7,5%	91%	400	163,8
ferry	10%	5%	4	7,5%	52%	1456	227,1
cargo/container	5%	2%	5	3,5%	1%	5337	9,3
Special vessels	10%	5%	1,5	7,5%	100%	1931	217,2

Table 40 – Average scenario hypothesis and parameters selected for newbuilding market.

	HIGH	LOW	AVG	MWh	EU SHARE	SHIPS	MWh MARKET
cruise	10%	5%	6	7,5%	89%	108	43,2
ferry	40%	20%	4	30,0%	34%	283	116,1
cargo/ container	5%	2%	5	3,5%	1%	200	0,4
Special vessels	40%	20%	1,5	30,0%	15%	653	45,0

Starting from the information presented in the paragraphs above and the hypothesis stated (scenarios, EU share market and MWh market), a market forecast analysis has been developed and it is here presented.

The average scenario consists in forecasting a business trend as recorded in recent years. Thanks to this market trend and technological developments, together with the information collected and presented, the forecast for the next 15 years has been developed. The main results obtained, divided by application groups and by future projections, are presented in Figure 90.

On the other hand, the worst case scenario considers a market trend dominated by recessions and downward fluctuations in the maritime sector.

On the contrary, the best case scenario considers a period of continuous growth of the global market and further technological innovations that can open the doors to an ever greater penetration of batteries on board ship.

From the results proposed from Figure 90 to Figure 92, it is possible to highlight that the application with the highest growth rate in the next 15 years will be the one for capacities between 1000 and 3000 kWh, both in terms of number of units and in terms of total installed energy. In this context, projections show that in 2030, this market segment will install the same amount of energy as the largest applications. It also appears that the lower price and better performances of the batteries will make it more attractive to install medium-sized energy storage units than smaller ones.

However, for the first decade, the market will probably be dominated by the large ESS installations, even if these are less inclined to increase their market value over the time.

Finally, low capacity applications will consistently maintain their minority share of the market over the next 15 years, in terms of units of installed energy.

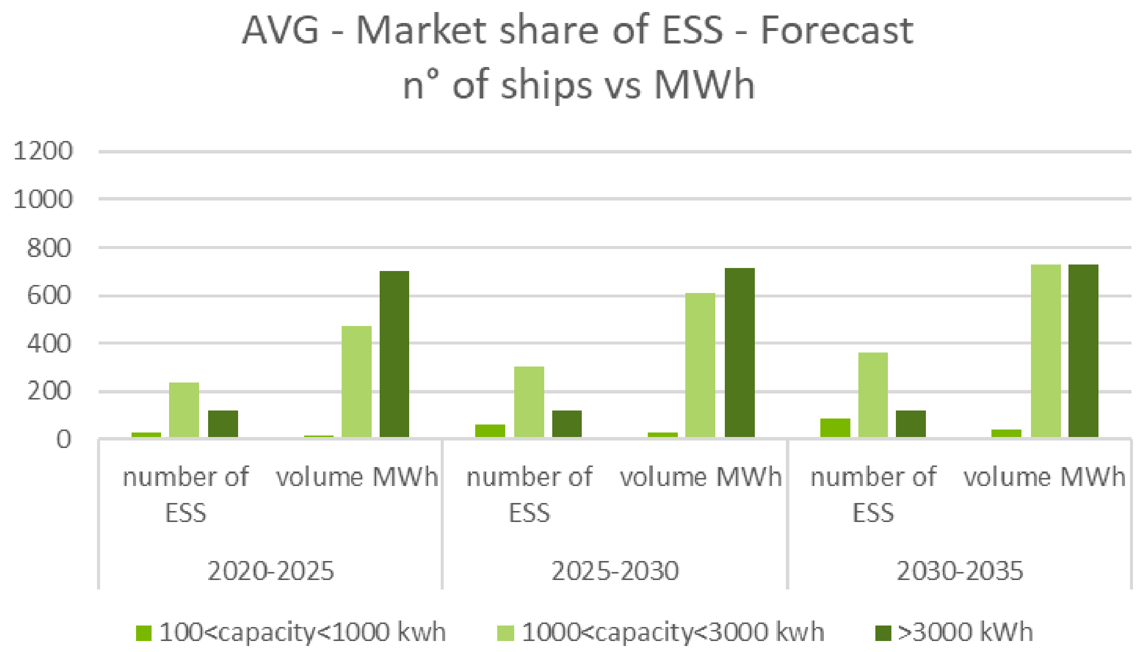


Figure 90 – Average case scenario, maritime battery market forecast at 5, 10 and 15 years ahead

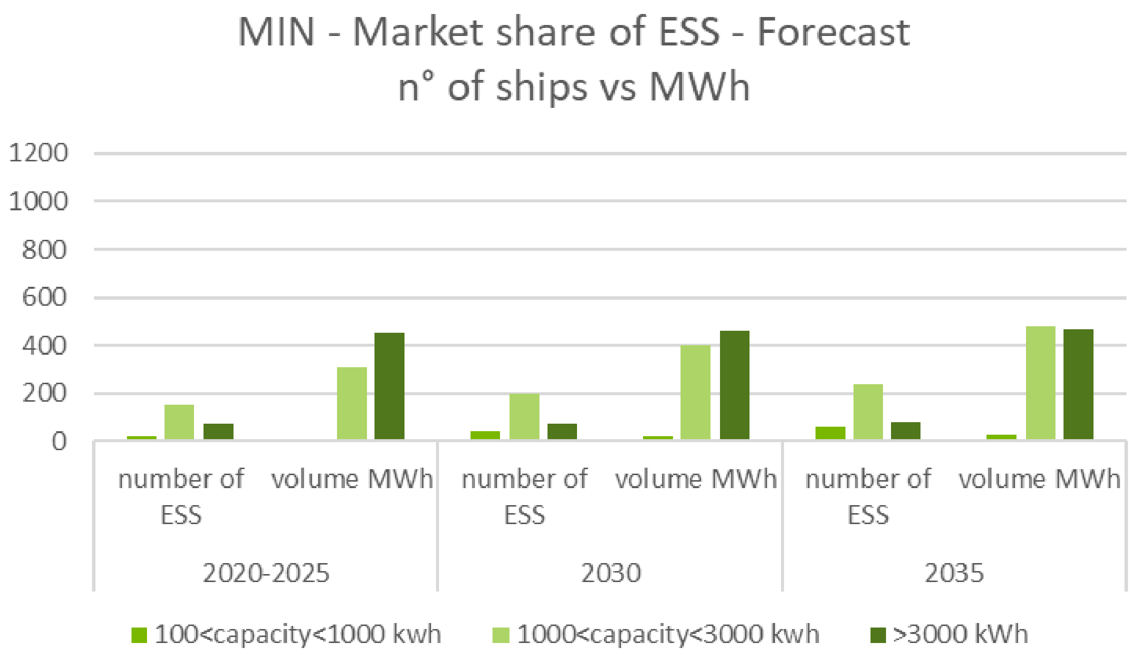


Figure 91 – Worst case scenario, maritime battery market forecast at 5, 10 and 15 years ahead

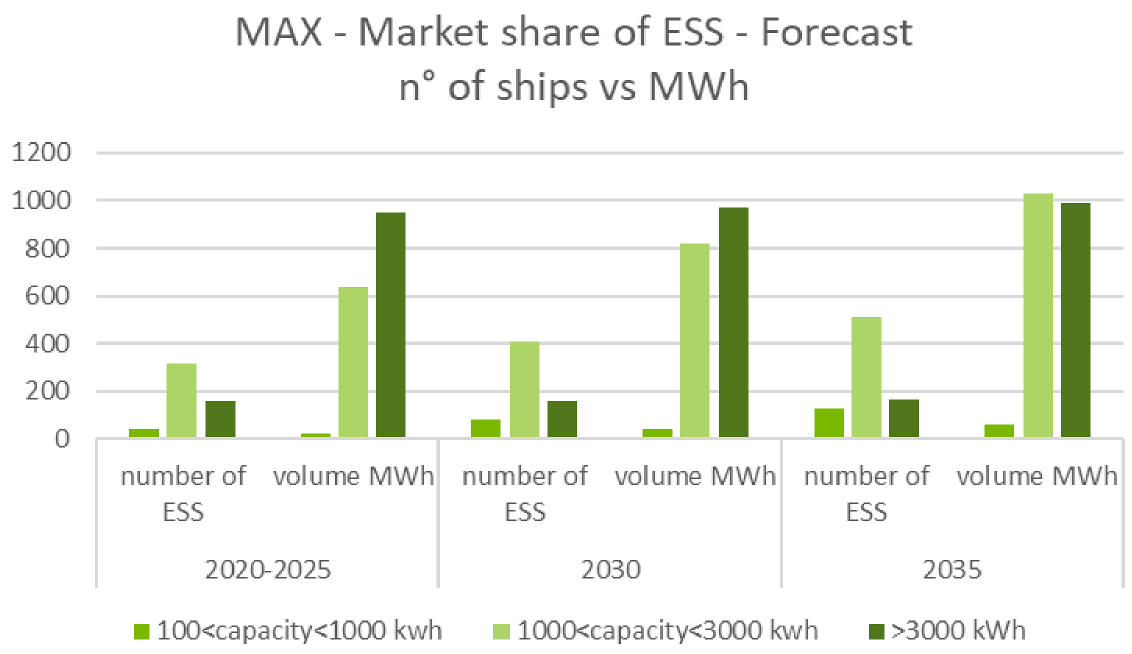


Figure 92 – Best case scenario, maritime battery market forecast at 5, 10 and 15 years ahead

From Figure 93 to Figure 95, the expected increase over the next 15 years is shown for the total installed energy for the various applications, the final numbers are the sum of the three different quantities analysed. In each scenario, it is noted that the only market bundles with continuous increase is the one between 1000 and 3000 kWh, as previously reported. The larger applications, in fact, will see a rather significant increase in the first 5 years, also thanks to recent technological innovations, both on the battery side and on the recharging systems of the same on board the ship (shore power connection) and on the land side (cold ironing in port).

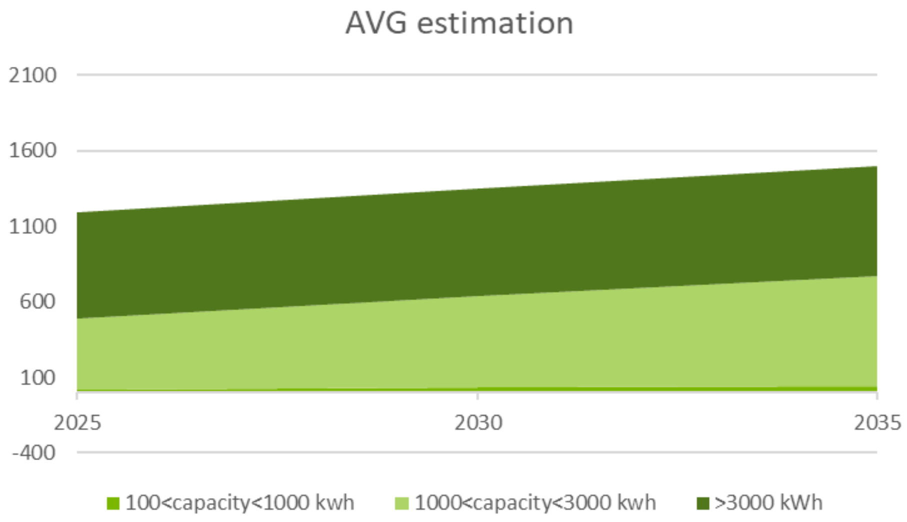


Figure 93 – Average case scenario, maritime battery market energy capacity (MWh) forecast at 5, 10 and 15 years ahead

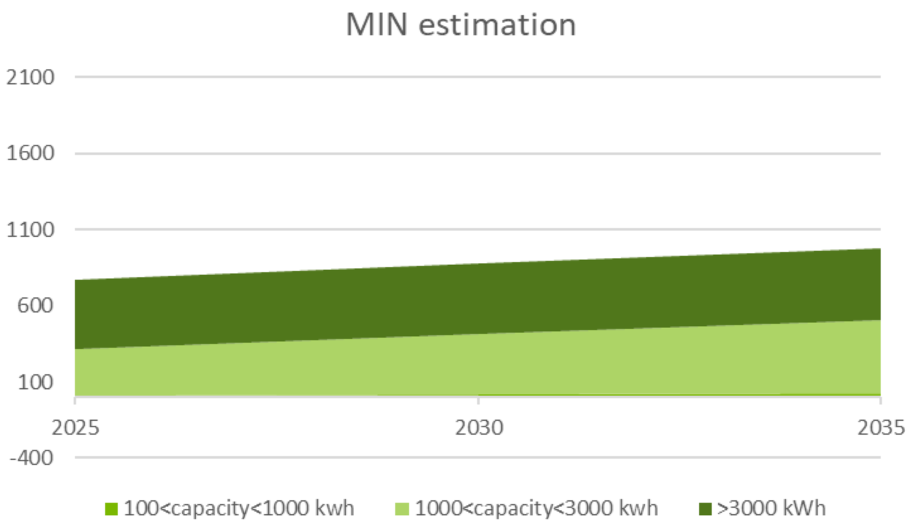


Figure 94 – Wprst case scenario, maritime battery market energy capacity (MWh) forecast at 5, 10 and 15 years ahead

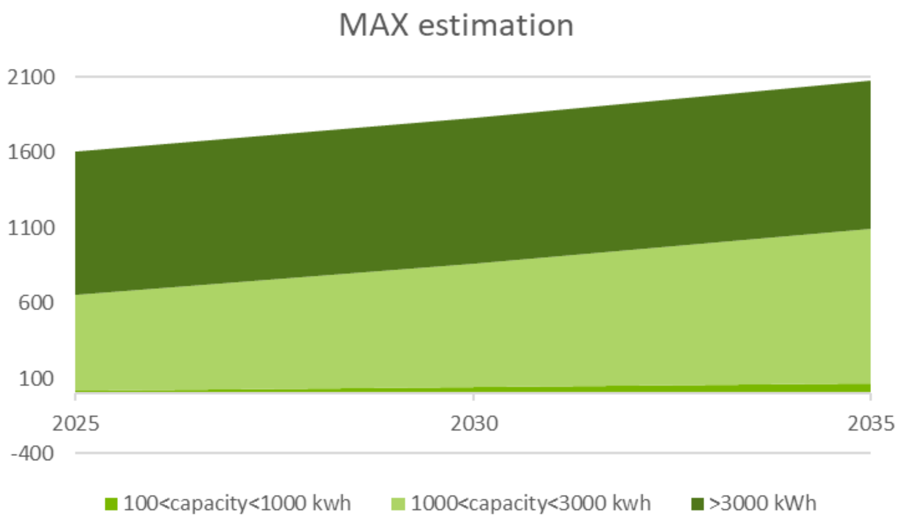


Figure 95 – Best case scenario, maritime battery market energy capacity (MWh) forecast at 5, 10 and 15 years ahead

4 Discussion, Conclusions and Recommendations

4.1 Conclusions

Main aim of this document was to identify and present the current state of the battery market, mainly focusing on the maritime battery market. This aim has been pursued and achieved by analysing market and technological trends and, finally, providing a preliminary forecast for the market evolution with a time horizon set equal to 15 years.

The analysis of the current state of the market has been divided according to the different types of ships, identified in Deliverable 1.1 of this project, in paragraph 4.3 of the same document.

This analysis of the development of the market from the early 2000s up today has highlighted some interesting aspects, also from a future perspective:

- From 2008 to 2020 there was at least 3 moments of strong increase in the installation of battery systems on board ship (2012, 2015 and 2017, as shown in Figure 40). In all of these cases, the economic context, regulations framework, the cost of fuel, the cost of battery systems and technological innovations, have contributed significantly to the market evolution.

- Europe has been the real centre of the maritime battery market. Especially Northern Europe and France have definitely contributed to the European market evolution and success. Recently, also Mediterranean countries have massively started to use these systems on board ships in order to reduce ships environmental footprint.

- On the other hand. Asian countries (China, South Korea and Japan) are, today, the main suppliers of the primary cells from which to develop the battery systems.

- Ferries, offshore vessels and passenger vessels have been the most involved units in the installation of battery systems on board.

- Right from the first years of use, the main applications of battery systems on board ship have concerned propulsion aid, mainly in hybrid configuration, in order to improve the energy efficiency of the ships involved.

- However, recently (from about 2015), the development of battery systems, with increasing energy/power density characteristics and cost reduction, together with the development in the port areas of fast dock charging systems, have allowed the increase of different configurations of the use of batteries on board the ship.
  This is the case of the plug-in hybrid configuration (i.e. compared to the classic hybrid configuration, the batteries can also be charged via a dock connection to the national electric grid) and full electric ones (i.e. there is no internal combustion engine on-board, and batteries may feed all on-board services by recharging only through the quay connections), which allow ships to operate in zero emission mode.

Starting from the previous conclusions regarding the evolution and the current state of the market, a forecast analysis on the market trends over the next 15 years has been developed (reference to paragraph 3.7).

The results of this analysis, which are summarized in Table 38, 39 and 40 (reported below for more clearness), highlighted some fundamental aspects:

- The technological innovations currently in a preliminary development/implementation phase, both with regard to innovative cell chemistry (lithium-sulphur, cobalt free cells, lithium-air, etc.) and all the different membrane configurations (mainly solid-state batteries) will certainly be cutting-edge solutions for the maritime sector. In fact, these innovations will dramatically increase the energy/power densities and performances of battery systems, which will open the door to the complete electrification and decarbonisation of medium-sized vessels with medium operating ranges (fishing boats, ferries, yachts, etc.);

- Today, small units with medium operating autonomy are moving towards complete electrification and decarbonisation, through the use of increasingly larger batteries in full electric mode.

- In the next 5 years, up to 15 years onwards, thanks to the technological innovations described, ever-larger units will start using ever-larger battery systems. The first applications on large ships will concern the increase of overall energy efficiency. In the medium term, on the other hand, technological innovations should make it possible to carry out (short) operational scenarios with zero emissions even for large ships (cruise, large ferries, cargos, etc.). In addition, the use of batteries on board these units will enable the integration of the next technologies for the complete decarbonisation of maritime transport (fuel cells, dual fuel engines, sustainable alternative fuels, etc.).

- On the other hand, small battery modules and small battery applications will have less and less market value over the next 15 years, leaving more and more space for medium and large applications.

The medium and large application range of batteries will see a considerable increase in their market share over the next 5-10 years, with their shares stabilizing over a 15-year horizon, as proposed from Figure 90 to Figure 95 in paragraph 3.7.

In this context, the development of technologically advanced battery modules with dimensions that allow easy integration on board of different types of ships, especially medium and large ones, in a flexible, efficient and safe way, is of primary importance. Furthermore, the cost of battery systems is expected to decrease significantly (see Figure 96), even in the face of the aspects listed above, favouring a further downturn in the battery market in the marine sector.

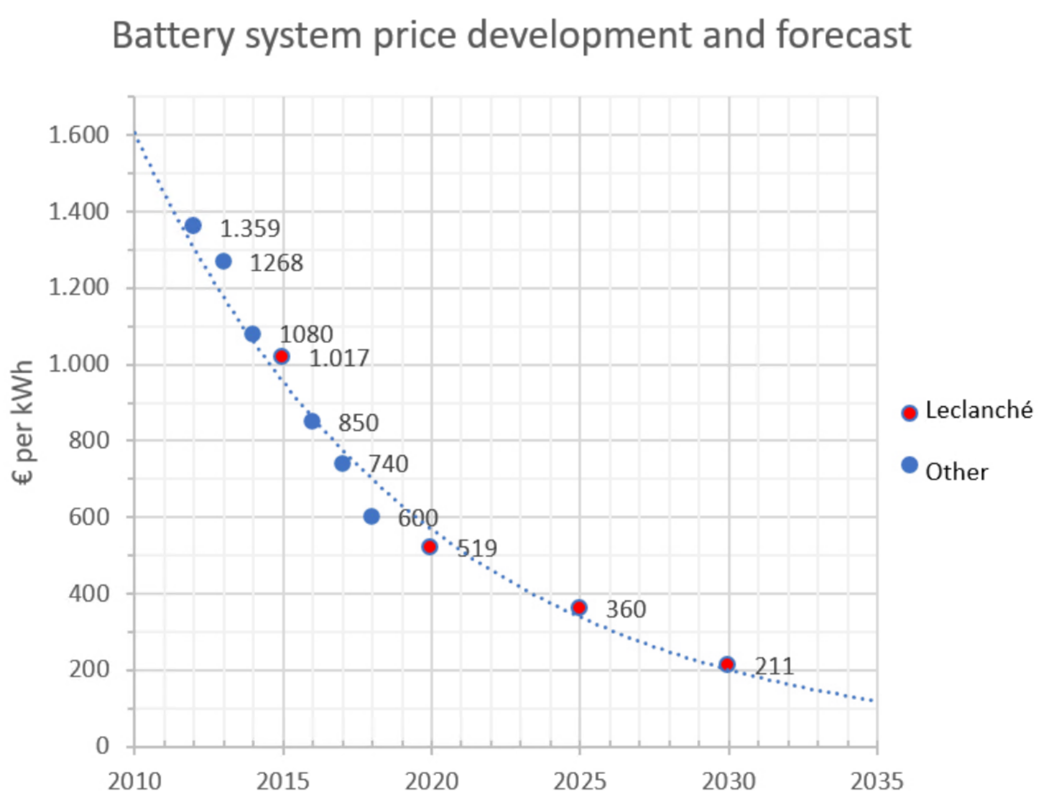


Figure 96 – Battery pack price development for maritime application (source: http://e-ferryproject.eu/)

Battery market outlook in MWh per year

Vessel type	Low scenario			Medium scenario			High scenario		
YEAR	2025	2030	2035	2025	2030	2035	2025	2030	2035
Ocean going fishing vessels	0.6	1.0	1.2	0.9	1.5	1.8	1.2	2.0	2.5
Coastal fishing and fish farm support	20	33	37	30	50	56	40	66	81
Tugs (>1500 kW)	8	16	24	12	24	36	16	32	52
Tugs (<1500 kW)	1.0	2.0	3.0	1.5	3.0	4.5	2.0	4.0	6.5
Yachts	16	32	48	24	48	72	32	64	104
General cargo (>1500 kW)	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2
General cargo (<1500 kW)	2.4	3.2	4.8	3.6	4.8	7.2	4.8	6.4	10.4
Patrol/utility vessels	8	17	25	11	25	38	15	34	55
Inland cargo vessels	52	103	155	77	155	232	103	206	335

Inland push and tug boats	9	18	28	14	28	41	18	37	60
River cruise vessels	8	16	23	12	23	35	16	31	51
Total	124	242	349	186	362	524	249	483	757

Average scenario hypothesis and parameters selected for retrofit units market.

	High	Low	MWh	AVG	EU share	Ships	MWh market
cruise	10%	5%	6	7,5%	91%	400	163,8
ferry	10%	5%	4	7,5%	52%	1456	227,1
cargo/container	5%	2%	5	3,5%	1%	5337	9,3
Special vessels	10%	5%	1,5	7,5%	100%	1931	217,2

Average scenario hypothesis and parameters selected for newbuilding market.

	HIGH	LOW	AVG	MWh	EU SHARE	SHIPS	MWh MARKET
cruise	10%	5%	6	7,5%	89%	108	43,2
ferry	40%	20%	4	30,0%	34%	283	116,1
cargo/ container	5%	2%	5	3,5%	1%	200	0,4
Special vessels	40%	20%	1,5	30,0%	15%	653	45,0

4.2 Recommendations

In the previous chapters and paragraphs, an analysis of the current state of the marine battery market was presented, according to the different types of ship and, further, the different use that could be defined for batteries on board ship.

The analysis also shows the difficulty in decarbonising this sector, mainly referring to figure XX, which shows the important dimensions of the fuel tanks, but at the same time it emerged that BESSs are fundamental in this decarbonisation process.

Considering these numbers and analyses, a 5, 10 and 15-year market forecast has been developed into the future, analysing how the market value of batteries could be for different application configurations in the maritime sector.

For future developments relating to the SEABAT project, especially as regards the development of the roadmap relating to batteries for marine use and the application matrix, it is suggested to start from the numbers presented in the two market analyses described in this document, in order to keep in mind the impact of the market on technological development and on possible integrations on board.

Moreover, it should be noted that, according to many experts in the sector, the effect of COVID-19 on the market should delay the growth dynamics for only 2 or 3 years at most, as evidenced by future forecasts regarding the expected growth.

In the paper it emerged several times how essential it is to have a BESS system that is modular and scalable, especially given the different types of applications and sizes that systems can have. The general recommendations that emerge are that it is necessary to keep in mind the evolution of cellular chemistry which in recent years is seeing large investments both public and private. In fact, already in the design phase, in addition to the scalability and modularity of the system, every single element must be designed to be improved or replaced with innovative and more performing components, in this case the chemistry of the cell, which, as we saw in paragraph 3.3, has various possibilities for development.

Finally, it should be highlighted that even the costs of battery systems could decrease significantly, both thanks to technological innovations that may use less valuable materials, and due to the economic leverage effects (already observed in the automotive field) due to the massive use of batteries for transport systems.

5 Deviations from Grant Agreement Annex 1

There are no deviations with respect to Annex 1.

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