Marine propulsion using battery power

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Abstract: The global demand to reduce CO_2 emissions requires effort from the shipping industry which currently emits about 2% of anthropogenic global Greenhouse Gases (GHGs) and which is predicted to increase due to growth of world trade. Therefore, it is important to find new ways to reduce CO_2 emissions from shipping using new operational strategies, improved ship designs and new technologies.

Battery technologies have been developing rapidly leading the road transport industry into a greener future with hybrid and electric vehicles but such a change is not so apparent in the shipping industry. This paper provides an overview of the state of the art battery technology and important future developments that may potentially exploit batteries in future ship's power and propulsion systems.

Through case studies, the paper assesses the applicability of battery power to ships, more specifically small ones. Approximately 14,000 ships, 22% of the global commercial fleet are below 400 gross tonnes, most of which are small coastal ships, e.g. tugs and passenger ships/ferries. Existing battery-powered ship system configurations are summarised; battery developments are considered, impacts of battery application on ship performance are discussed in the paper supported by a case study.

Keywords: low carbon shipping, battery powered ships, small ships, coastal ships.

1. Introduction

Large batteries have been used in conventionally powered submarines since the turn of the 20th Century to provide submerged operation and today, with the use of an air independent propulsion plant, they are capable of staying submerged for around 3 weeks operating at speeds of about 5 knots. Whilst many small boats have adopted batteries for propulsion e.g. pleasure craft, the use of batteries in ships has been limited, mostly restricted to acting as an emergency power source with very few battery powered applications. In contrast, there has been significant increased interest in battery powered road vehicles to reduce atmospheric emission to meet increasingly stringent regulations. These vehicle designs have taken advantage of new battery technologies such as Lithium batteries originally developed for the telecommunications industry. The focus of this paper is to consider the potential of these new battery technologies to power ships.

All ships require power for two purposes: 1) to provide propulsion power, where power and speed are broadly related by equation (1):

$$P = kV^n \quad (1)$$

Where, P is the effective power; V is the ships speed; k is a coefficient that depends upon ship type, specific delivered power coefficient, and water density whilst n is mainly dependent upon hull form characteristics. For most ships the relation between P and V is near cubic. 2) to provide service power to support hotel/accommodation, cargo and ancillary equipment. Service power depends on many things such as number of crew, cargo type and operational requirement but for most ships is typically a small fraction of the propulsion power. When considering demand then it is evident that reducing speed by 50% will reduce the ship's power requirement to about 12.5% and reduce ship's energy requirement to 25% - something to keep in mind when thinking about battery powered ships.

Large intercontinental ships have tens of MW of propulsion power installed and tend to use a large two-stroke low-speed diesel engines coupled directly to the propeller. Exhaust Gas Waste Heat Recovery System (EGWHRS) located in the uptakes of the diesel engine are used to generate steam that is in turn used to generate electricity for service load. Furthermore, jacket water cooling is used by evaporators to produce fresh water from seawater. Overall the efficiency of these vessels is high (typically 55%) and it is not apparent how batteries can enhance their operation.

In contrast, there are around 14,000 small ships (22% of the global commercial fleet) most of which are coastal ships operating on short international or national routes (Clarksons, 2016). Many of these vessels tend to use relatively low powered two-stroke or four-stroke medium/high diesel engines to provide for propulsion and power but these tend to be less efficient, typically 45%, than the slow speed engines used in large ships and rarely is it possible to use EGWHRS. For these ships batteries may potentially offer opportunities for efficiency improvement.

In recent years, progress has been made with the development of battery powered ships (see Table 1). The Norwegian ferry *MF Ampere* shown in Figure 1 undertakes 56 journeys of 5.6 km per day, and is powered by 1.04 MWh Lithium-ion battery which is recharged by two 410 kWh shore charging stations located at each end of its journey (Corvus, 2015). Batteries have also been used in hybrid propulsion systems so allowing the diesel-engines to operate at an efficient load i.e. load levelling to improve efficiency e.g. Caledonian Ferries which has three hybrid vessels, each having two banks of 800 kWh of batteries. Batteries have also been used with solar energy e.g. several car carriers with extensive upper deck area have been equipped with photovoltaic panels which generate about 8% of ship's service load (Barnes, 2014). Experimental craft such as *Planet Solar* which has 8.5 tons of Lithium-ion batteries in its two hulls with solar cells to recharge them and the *ZEMSHIP* in which a 2.5 kWh Lithium battery working in a hydrogen fuel cell hybrid system (Zemships, 2010). These developments show there is increasing interest in battery power for small ships.

Table 1. Overview of existing merchant battery ships, data source: (Clarksons, 2016).

Purpose of battery	**Ship Number**	**Ship Type**
Store solar energy	7	Pure Car Carrier, Passenger/Car Ferry
Diesel-electric with battery	15	Passenger/Car Ferry, PSV, Diving Support
Full battery power	1	Passenger/Car Ferry
Mechanical-electric with battery	7	Tug

Figure 1. Battery ferry Ampere (NorledAS, 2015).

In most battery powered ships, improving energy efficiency to reduce atmospheric emissions seems to have been the key driver. However, considering batteries have technical limitations that include energy density, power density and lifetime, and their adoption potentially influences operational performance such speed and range of the vessel as well as impacting on ports such as the need to provide a recharging infrastructure, then the applicability of battery propulsion power for wider commercial shipping is not quite so obvious. Ships are normally designed to meet an economic transport need which dictates size, operating profiles, speeds, routes, etc. which in turn influences the power/propulsion plant design. The adoption of batteries to reduce emissions potentially disturbs that economic case e.g. specifying batteries will impact ship speed and range probably meaning longer transit times weakening the economic case for having the ship in the first place. Clearly, the power density advantage of diesels offers significant economic advantage over batteries hence the slow take up.

2. Batteries for ships

2.1 State of the art

The justification of using batteries over other Energy Storage Systems (ESSs) is clarified when considering Table 2. The ultra-capacitor has a high power density but offers a lower efficiency; ultra-capacitors and flywheels are better at delivering higher powers for short periods but this is not needed in most ships. Flywheels offer a superior lifecycle but their power density is lower. Currently, for shipboard propulsion, Li-ion batteries offer the highest energy density, a suitable power density, high efficiency and an acceptable lifetime. All ESSs have some safety concerns, flywheels have to be contained when they fail, the ultra-capacitor has potentially very high discharge currents, and Lithium batteries are subjected to thermal runaway if poorly managed. There have been some Lithium-ion battery accidents used on various kinds of transportation, including aeroplanes, electric vehicles, boats, etc., some of which lead to severe consequences (Rao et al., 2015).

Table 2. Comparison between principle ESSs (Zakeri and Syri, 2015).

Technology	Energy density [Wh/kg]	Power density [W/kg]	Life cycles [cycles]	Lifetime [years]	Overall Efficiency [%]	Safety
Li-ion	50-250	50-2,000	400-9,000	5-10	85-99	-
Ultra-capacitor	0.05-5	100,000	50,000	5-8	60-65	+/-
Flywheel	5-100	1,000	20,000-100,000	15-20	93-95	++

Table 3 compares the key battery performance parameters including energy density, power density, etc. of major battery types. The Lead-acid battery is a mature dependable technology but offers low specific energy and specific power, has an efficiency of around 70% and discharging below 80% will affect its lifetime significantly. Nickel-hydride batteries are superior to lead-acid batteries in terms of capacity and lifetime and have wide use in Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs), with their cost being similar to Lead-acid types. The Lithium battery technology has developed so that specific energies of 250 Wh/kg are available (Dsoke et al., 2015). The family of Lithium batteries is vast and the electro-chemistry can be tailored for specific need. Some types offer high energy density or high power density, some others like Lithium Titanium Oxide (LTO) have superior thermal stability for fast charging and discharging but offer lower capacity typically 50-70 Wh/kg. The recycling of Lead acid batteries is well established, less so for other types.

Research continues into electro-chemistry and new battery technologies, advanced Lithium-ion, Lithium-Sulphur and Lithium-air being types that seem to offer significant advantage and are having current focus. Essentially, the demand for higher energy density (driven by demand from the road vehicle industry) is spurring on development, potentially offering higher energy densities, fast recharge times, lower cost and enhanced lifecycle.

Table 3.Principle power battery comparison ((Thackeray et al., 2012), (Chen et al., 2009), (Díaz-González et al., 2012), (Luo et al., 2015),(Dunn et al., 2011), (Bruce et al., 2012), (Larcher and Tarascon, 2015), (Nykvist and Nilsson, 2015)), (Dsoke et al., 2015).

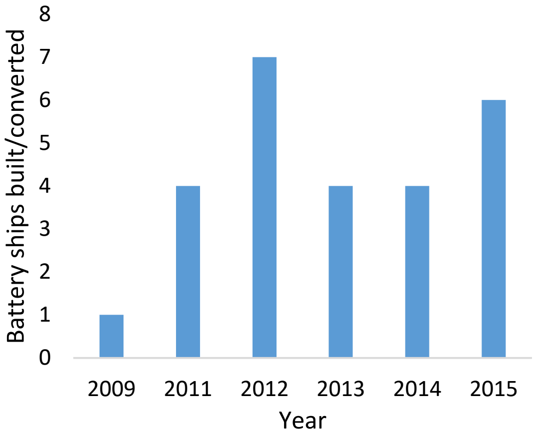
Battery type	Theoretical Specific Energy [Wh/kg]	Gravimetric Energy Density [Wh/kg]	Volumetric Energy Density [Wh/L]	Cost [$/kWh]	Lifecycle [cycle]	Efficiency [%]
Lead-acid	171	20-40	60-110	165	500-1,000	50-95
Ni-Cd	219	20-60	60-150	-	2,000-2,500	70-90
Ni-MH	240	50-70	140-300	146	500-2,000	89-92
Na-S (350°C)	754	~120	150-300	400	>1,500	86-92
Li-ion	398-843	50-250	250-675	200-600	400-9,000	85-99
Li-polymer	~884	~150	250-730	-	-	-
Li-S	2,567	400, Not commercialised	350	400-500	1,500	-
Li-O_2	~1,752-2,582	Not commercialised	-	-	-	-

2.2 Battery use in ships

Figure 2 shows the trend in the number of battery powered ships from 2009 to 2015 – a seemingly upward trend is obvious albeit the numbers remain small. Figure 3 is the shipboard installed battery capacity trend over the same period. In 2015, the maximum installed capacity reached 2.5 MWh. There is no reason to suggest that larger capacities cannot be used in the future.

Kyunghwa et al. (2016) summaries the major drawbacks of shipboard battery namely energy density which translates to volume needed in the ship to achieve reasonable speeds and range, the cost of the batteries (including replacement costs of expired batteries) and the need for recharging infrastructure ashore which is at the present time non-existent

Currently most coastal ships use Marine Diesel Oil (MDO) which typically has an energy density of 42,190 kJ/kg and volumetric density of 39,970 kJ/l and costs 42.3 $/MWh (MDO price 500 $/t) whereas the best available commercial battery has an energy density of 1,224 kJ/kg and a volumetric density of 2,434 kJ/l and costs 73.2 $/MWh (wholesale price of electricity 0.0732 $/kWh). It immediately appears that batteries are very uncompetitive and would never be preferred over diesel unless atmospheric emissions happens to be the key driver.



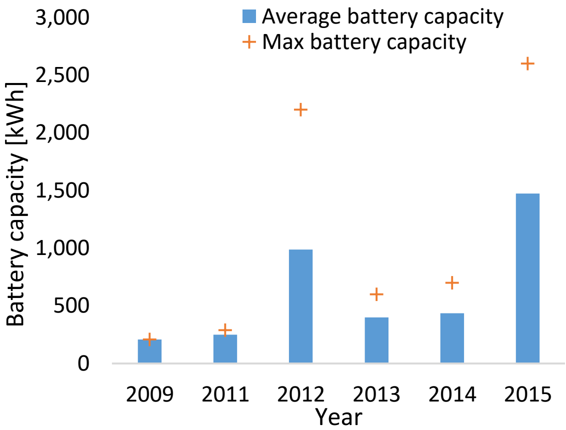


Figure 2. Battery ship number trend.

Figure 3. Battery capacity trend.

2.3 System configurations

Figure 4 shows the propulsion chain of a typical diesel-mechanical propulsion plant with typical efficiency values for each component, whilst Figure 5 presents typical shipboard diesel-electric propulsion system. Figure 6 assumes a cutting edge battery power prolusion system.

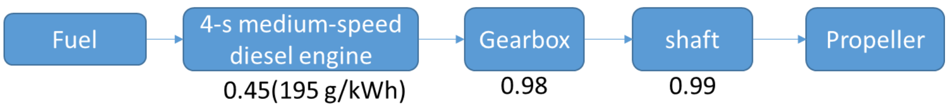


Figure 4. Typical diesel-mechanical propulsion chain.

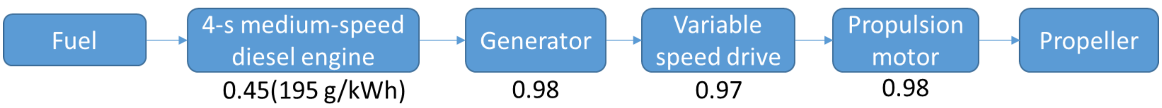


Figure 5. Typical electric propulsion chain.

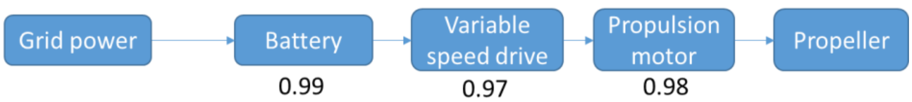


Figure 6. Typical battery prolusion chain.

Considering the three propulsion systems and assuming the efficiency of the propeller is the same in all designs (72%), then the overall efficiency (energy source to thrust) of the battery system is 67.8% against the diesel-mechanical solution is 31.4% compared to the diesel-electric 28.2%.

A battery powered ship would have no need for fuel tanks, fuel processing, exhaust and air trunking, the diesel engine and its gear box. In addition to the batteries though there would be need for power electronic modules and electric propulsion motors, equipment already widely used in diesel-electric ships. Auxiliary requirements would change to some extent since the higher efficiency reduces the cooling load requirement, there is no requirement for uptake exhaust trunking, air intakes, etc. Nevertheless, it remains that the relatively poor volumetric density and mass density of the batteries raises the greatest challenges for the ship designer hence performance will need to comprise to a lower design speed and/or reduced range.

Current batteries are limited in lifecycle (maximum is 10 years but typically 5 years) which means they may have to be replaced several times throughout the ship lifetime. The battery replacement cost together with the cost of electricity consumed from the local grid are the major operating cost of the propulsion plant but this is offset by the fact that there is no longer any need for bunkering diesel fuel and regular maintenance of diesel engines. Electric systems tend to be reliable and easily reconfigurable so a reduction in seagoing engineering staff may be possible.

3. **Case Study**

Table 4 presents a coastal cargo ship specification. It takes about 10 hours for the ship to complete one voyage from port A to port B and 2 hours for loading and off-loading at port. For simplicity, it is assumed at designed ship speed, the main engine outputs 1,000 kW, i.e. about 80% of Maximum Continuous Rating (MCR), assuming the efficiencies of gearbox and transmission shaft are 0.98 and 0.99 respectively. For the 4-s medium-speed diesel main engine, specific mass and volume are assumed as 7.75 kg/kW, and 13.5 l/kW (Woud and Stapersma, 2002), (Wartsila, 2016), respectively, whilst the specific cost is 357.9 $/kW.

Table 4. Typical coastal cargo ship specification for the case study.

Designed ship speed	10 knots
Distance	185 km
Time at port per voyage	2 hours
Main engine type	4-s medium-speed
Main engine rated power	1,275 kW
MDO consumption per voyage	4.8 t

Table 5 compares the volume, mass and initial cost demands for the diesel and battery systems. Accounting for efficiencies of batteries, power electronics and propulsion motor which are 0.99, 0.97 and 0.98 respectively, the volumetric and gravimetric specific energy densities of battery are 300 Wh/l and 200 Wh/kg (Table 3). Also, assuming the volume and mass of battery cell are both 70% of the battery module, to provide the same speed, i.e. 10 knots, for the same voyage, the equivalent battery plant mass would be approximately 6.1 times of the diesel one (including engine, gear box and fuel), while the volume would be about 2.5 times, the initial investment of battery system could be approximately 7 times (however this does not account for economies of scaling so it is likely to be less) of equivalent diesel system.

Table 5. Volume and mass comparison between diesel and battery system.

	Mass [t]	**Volume [m3]**	**Cost [$]**
Diesel	15.3	25.0	458,618
Battery	93.8	62.5	3,283,170

To investigate the implications of battery improvements in specific energy (volumetric and gravimetric) to ship speeds, two future batteries (could possibly be future flow batteries), i.e. future battery 1 with specific energy of 1,000 Wh/kg and 1,500 Wh/l, and future battery 2 with specific energy of 2,000 Wh/kg and 3,000 Wh/l are included in the analysis together with the diesel and current battery systems. Applying equation (1), effective propulsion power demands for different ship speeds can be estimated, then the minimum battery capacity (further battery mass and volume) for one voyage can be calculated (with 20% reserved battery capacity and accounting the typical system efficiency values).

Figure 7 shows the relationships between required power plant mass and designed ship speed for the four systems. The mass gap between current battery and diesel system is significant, especially for high ship speeds. Nevertheless, future battery 2 with the gravimetric energy density of 2,000 Wh/kg could excel the diesel plant in terms of mass demand. In fact, when the specific energy reaches 1,950 Wh/kg, i.e. approximately 10 times of current value, the battery system mass demand would be the same as that of the diesel system. If the diesel plant is replaced by current batteries with same mass, (specific energy 200 Wh/kg), then the maximum achievable ship speed would be around 3 knots for the same voyage.

Figure 8 presents the volume demands of the four systems over ship speeds. The volume gap between current battery and diesel systems is not so significant compared to that of mass. Both the two future batteries require less volume over the diesel system. When the specific energy reaches 745 Wh/l, i.e. about 2.5 times of current value, the battery system volume demand would be the same as that of the diesel system. Constrained by diesel system, current batteries would be able to provide the speed of 6 knots if they are used to replace the diesel plant.

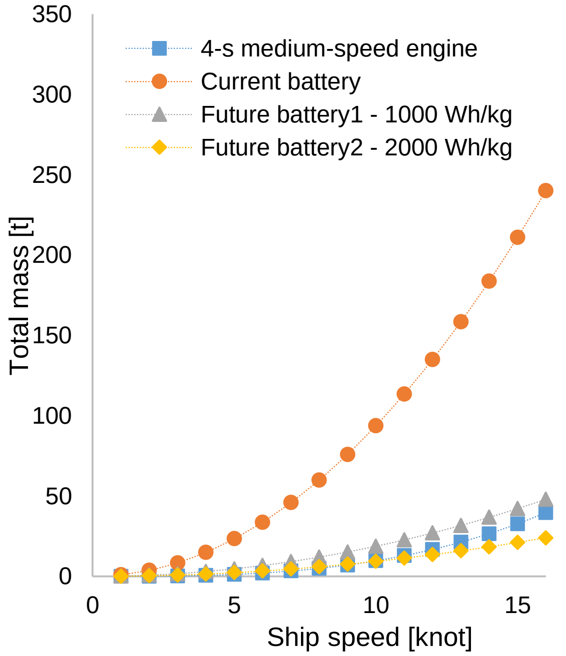


Figure 7. Battery mass vs speed.

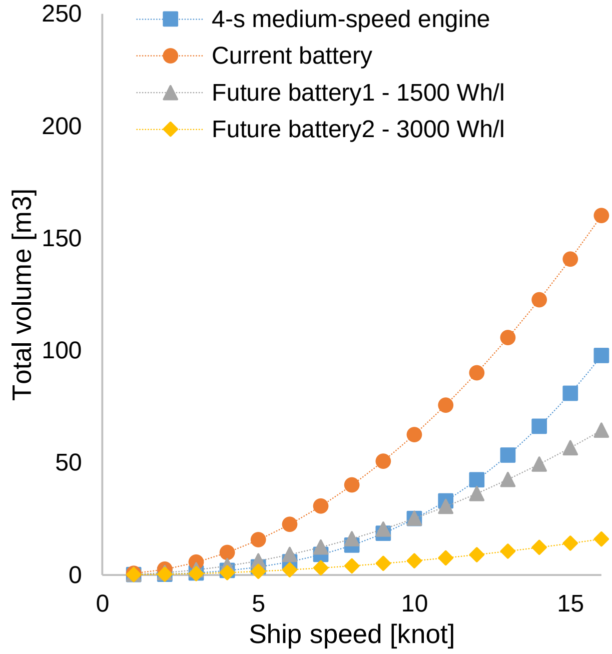


Figure 8. Battery volume vs speed.

Figure 9 presents 3 scenarios of through life cost under different battery developing patterns. Assuming ship's life is 30 years, annual running time is 300 days, ship speed is 10 knots, charge/discharge cycle limit is 2000 cycles, then batteries have to be replaced on the 5th year. The replacement interval could be extended if annual lifecycle increase is applied, e.g. 5% for one the scenarios. If the battery cost decreases 15% per year, then the implication of replacing batteries will be minor when the ship approaches its life limit. However, under a more conservative assumption of 6% annual cost decrease, with 5% annual lifecycle increase, the overall cost would be 14.5% higher than the scenario of 15% cost decrease. Nevertheless, for all the 3 scenarios, the cost of grid electricity, which is assumed 0.0732 $/kWh, is the majority of the overall cost.

Figure 10 shows the cumulative CO_2 emissions of the two systems, both at the speed of 10 knots. In 2009, according to European Environment Agency, the average CO_2 emission of electricity was 396.1 g/kWh, whilst in Norway, where renewable energy has been extensively used, it was only 4.5 g/kWh (EEA, 2011). As electricity grids decarbonise then it can be expected that there will be ongoing expansion of renewable power generation. For MDO, carbon is 86.68% of the fuel. Therefore, if the engine Specific Fuel Oil Consumption (SFOC) is 195 g/kWh, then 619.7 g/kWh CO_2 will be emitted. Assuming grid electricity carbon footprint decreases 2% per annum, compared to a traditional diesel propulsion plant – more than 50% CO_2 can be achieved over ship's life through full battery propulsion. The advantage of battery powered ships is evident from a CO_2 perspective but also for other harmful emissions such as NOx and SOx.

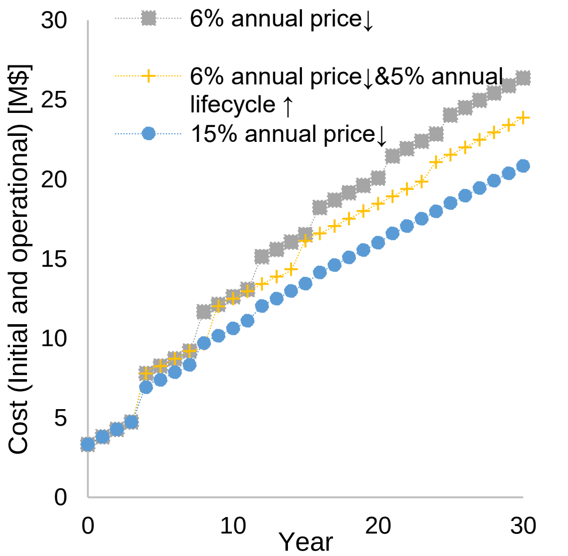


Figure 9. Through life cost under different battery developing scenarios.

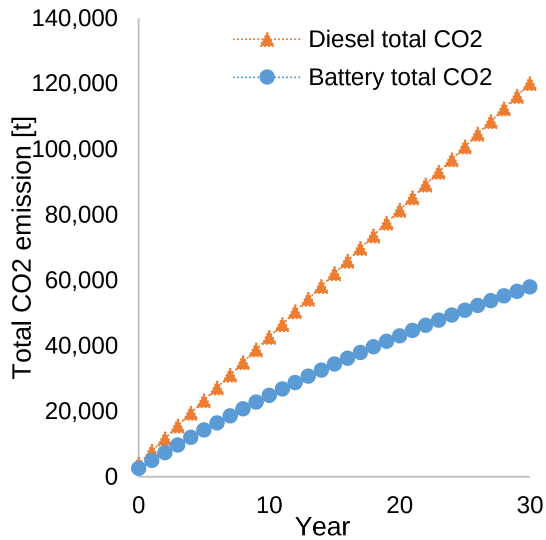


Figure 10. CO_2 emission comparison between battery and diesel propulsion power.

4. Discussion and Conclusion

This paper has considered the application of batteries in ships for the purposes of power and propulsion. The approach taken has been to consider the differences in the energy source diesel v electricity and their relative CO_2 footprints noting that the decarbonisation of the grid will lead to greener electricity. The change to battery ships would be a step change in reduction in CO_2 emissions.

Onboard the ship one of the greatest challenges is the relatively low energy density of the batteries both in volumetric and gravimetric terms. The removal of diesel fuel tanks, the diesel propulsion chain and the auxiliaries associated with it frees space but this insufficient for the amount of batteries needed to provide for reasonable speeds and ranges. However, electro-chemistry is developing rapidly so battery technology can be expected to improve and be more competitive in the future.

Costs of batteries are expected to decrease in terms of $/kWh and this will impact the economic viability of battery powered ships. However, the increasing reliance of the grid for the power supply may be feasible in some nations but not all. Additional capacity would be needed (competing with increased electric vehicles) at a time when the priority is to replace existing capacity with renewable sources.

The battery compartment would need to demonstrate safety in design building on recent experience so will likely need to be separated by structural and thermal boundaries with perhaps a heptafluoropropane fire extinguishing system installed in the battery space. Battery compartments could be decentralised throughout the ship, which could mitigate the ship design impact of the volumetric and gravimetric densities of batteries to some extent.

The case study has shown that it is necessary to optimise energy management strategies to achieve a long life of the battery modules. Shore based infrastructures for charging needs to be developed. When charging at port, fast charging will be necessary that would have impacts to the local grid or else energy storage available in ports 'ready to go' modules. It could be possible that the following battery powered ships would be practical in the future:

- Hybrid Internal Combustion Engine (ICE)/battery ships, with batteries charged by on board ICE, providing zero-emission operation in coastal waters/future ECAs.
- Hybrid battery/ultra-capacitor ships, e.g. naval ships with high pulse loads.
- Hybrid battery/FC ships, with battery for load levelling and low load operations.
- Larger full battery powered ships, and ship types could include Platform Supply Vessels (PSVs), tugs, coastal cargos ships, etc.

Finally, it is apparent that ships with a lower propulsion power requirement and shorter sailing distance are more suitable for battery power at the current time. Considering the high production cost and limited life cycle of current batteries, hybrid propulsion using ICEs and small scale batteries is likely to be feasible for some ships such as tugs and ferries. Nevertheless, based on the results of the case study, it can be anticipated that, full battery powered coastal ships will become practical in not to distant a future with the ongoing developing battery technologies driven by other industries.

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