OPPORTUNITIES AND CONSTRAINTS OF ELECTRICAL ENERGY STORAGE SYSTEMS IN SHIPS

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ABSTRACT

In recent years there has been a palpable shift towards the electrification of propulsion systems for commercial and naval ships, permitting improved design flexibility, operational efficiency and potential through-life fuel saving benefits. The drive for increased performance and emissions reduction, coupled with increasing load variability provides opportunities for energy storage systems (ESS).

Larger scale electrical ESS (beyond dedicated back up supplies) can introduce a number of key benefits to ships. With the quickly evolving landscape of ESS, driven by parallel industries, it would appear that the dominant forms of ESS will be batteries, flywheels and super-capacitors. Pertinent in using ESS, is to facilitate prime mover operation within its most efficient operating envelope with the ESS providing take-in take-out power to maintain constant loading of the prime-mover eliminating transients and thereby optimised to reduce fuel consumption.

This paper will consider the state of the art of ESS in ships and its future direction. The characteristics of the ESS devices and their applications for commercial and naval ships will be examined with a comparison of the challenges and implications of ESS, identifying common issues for the naval and commercial sectors by way of case studies. The paper concludes with the outlook for integrating ESS with future ships.

Keywords: Energy storage systems; fuel consumption; optimisation

1. INTRODUCTION

Commercial and naval ships have moved towards the use of full electric or hybridised power and propulsion systems over the last 20 years. This approach has provided a range of benefits, including the opportunity to reduce fuel consumption and consequently harmful environmental emissions. Increasingly challenging performance criteria, rules and legislative constraints such as those for emissions are coercing power and propulsion systems designers to adopt and adapt technologies to the marine industry.

Electrical energy storage in batteries, flywheels and capacitors has, until recently, been constrained to small scale dedicated Uninterruptable Power Supplies (UPS) (mainly batteries) for critical equipment. Kuseian (2015) and Tate and Rumney (2017) agree that in the naval sector, this has resulted in additional maintenance owing to the 10’s to 100’s of different small scale UPS. A centralised energy store could transfer a proportion of this burden, but also provide a number of other key benefits that will be explored in this paper.

Energy storage systems (ESS) have already been adopted for commercial ship applications, such as the Viking Lady offshore supply vessel and the Norled Ampere battery powered ferry (Stefanatos et al. 2015), the former vessel was predicted to save 15% of their annual fuel consumption because of integrating ESS. Commercial applications have the benefit of the ability to define the specific use case for ESS, whereas this is more difficult in naval applications because the use case can vary significantly (Stevens et al. 2017; Bellamy and Bray 2015). However, common to both sectors is the ambition to reduce fuel consumption and emissions.

The aim of this paper is firstly to compare and summarise the state-of-the-art pertinent ESS considered for commercial and naval application. Secondly to assess the opportunities and methods of integration for ESS. To achieve these aims the following was undertaken, a literature review on the current state-of-the-art of energy storage. Two candidate ships were then profiled for a case study to evaluate the reduction in fuel consumption and diesel-generator (DG) running hours over the respective operating profiles when lithium-ion based ESS is integrated with each of the ships baseline power and propulsion system. Each system was modelled under steady state conditions and the ESS was sized using a constrained optimisation method.

2. SHIPBOARD ENERGY STORAGE

According to Bellamy and Bray (2015) and Hebner et al. (2015) the primary shipboard ESS technologies will likely be batteries, capacitors or rotating machines. The characteristics in Table 1 show that Lithium-based batteries are more competitive in energy density and specific energy, which is often the critical parameters for commercial shipping. However when energy needs to be delivered or recovered in a short time period, for instance, for transient load demands, then power density is crucial, as such supercapacitors or flywheels are more suited. The attributes of each technology will now be discussed further.

Table 1: ESS state-of-the-art characteristics at cell level (Hadjipaschalis et al. 2009; GKN 2015; Chen et al. 2009; González et al. 2016; Luo et al. 2015)

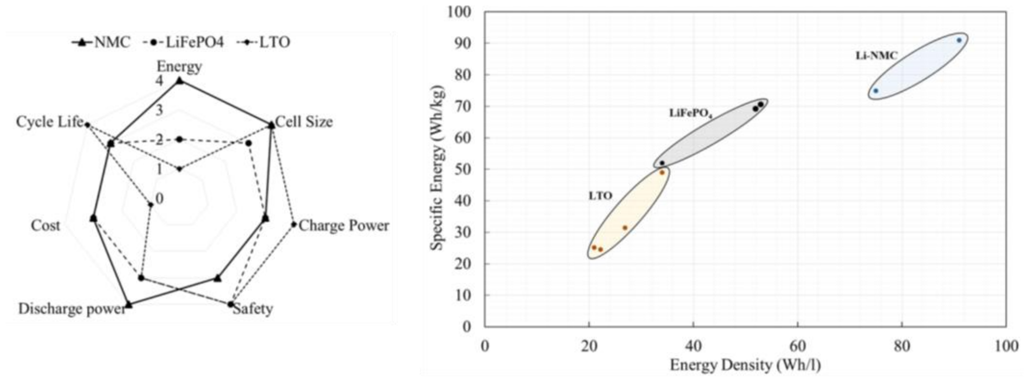
ESS	Energy density (Wh/l)	Power density (W/l)	Specific energy (Wh/kg)	Specific power (W/kg)	Daily self-discharge (% of energy)	Cycle life (cycles)	Lifetime (years)	System efficiency (%)
Lead-acid	60-110	10-400	20-40	75-300	~0.2	1,200-1,800	5-15	50-95
Nickel-Cd	150-300	80-600	50-80	150-300	~0.3	1,500-2,500	10-20	60-83
Lithium-ion	250-675	1,500-10,000	50-250	500-2,000	0.1-0.3	400-9,000	5+	90-99
Flywheel	20-80	1,000-2,000	10-30	400-1,500	≥20% per hour	>1,000,000	15-20	70-95
Super-capacitor	10-30	>100,000	1-10	500-10,000	10-20	>1,000,000	10-20	85-98

2.1 BATTERIES

Rechargeable battery cells store/deliver electric energy through an electrochemical system comprising two electrodes plugged in to an electrolyte. Electrons from the electrochemical reactions inside the cells transfer from one electrode to the other through external circuit during the charging/discharging processes (Hadjipaschalis et al. 2009). The ESS comprise cells that combine to form modules. Modules connect in series to form strings to achieve a desired voltage level, strings can then be paralleled to achieve a desired power output. Each string houses the necessary battery management system, cooling system, contactors and racking structure.

There are currently three types of electrochemistry used in commonly available batteries, i.e. Lead-acid, Nickel-based and Lithium-based. Lead-acid and Nickel-based battery cells are low voltage (~2 V) and low energy density compared to Lithium-based (typically over 3 V per cell) and therefore discounted from further investigation. The state-of-the-art Lithium-based batteries, mainly including Lithium-ion (Li-ion) and Lithium-polymer types have been widely used in portable devices and electric vehicles (EVs). The uptake in EVs has largely influenced the interest in ESS for marine vessels (Geertsma et al. 2017). The pertinent forms of Lithium-based chemistries for shipboard ESS are Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate ($LiFePO_4$) and Lithium Titanate Oxide (LTO). Li-NMC was commercially introduced in the EV market in the early 2010s (DNV GL 2016) and has been heavily adopted compared to other chemistries because of their strong power/energy performance (Chemali et al. 2016), this adoption has also transferred to the marine sector.

A comparison of the characteristics of pertinent lithium based ESS for marine applications is shown in Figure 1(a), alongside the energy density of certified ESS strings in Figure 1(b). Increased safety of the chemistries comes at the cost of energy density, as does the ability to have high charging power and cycle life. Total weight and volume of the integrated ESS solution are important factors regardless of type (Allen and Buckingham 2017). The contribution of hardware to the cells reduces energy and power density as shown in Figure 2.



(a) (b)

Figure 1: (a) Comparison of marine Li-ion battery strings and (b) corresponding energy density

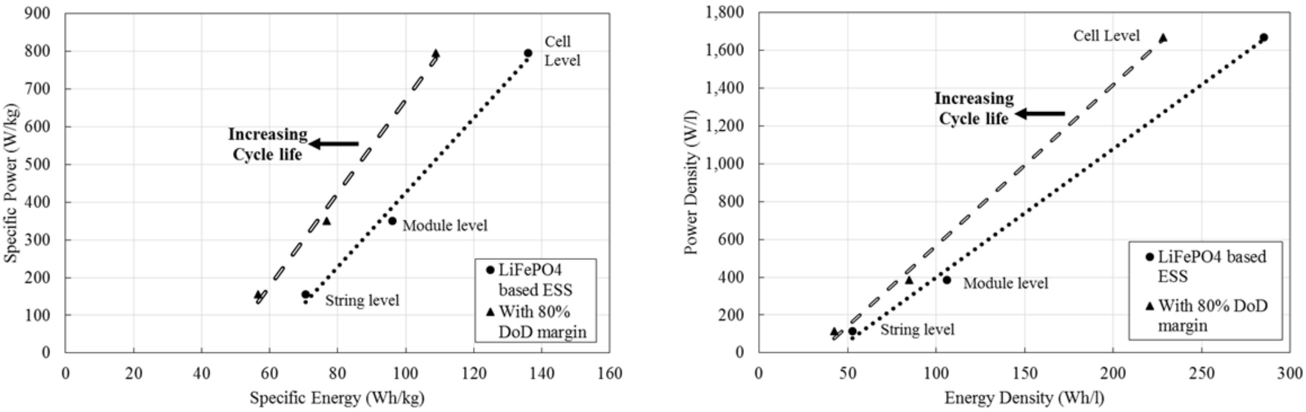


Figure 2: Energy and power density plots of a certified marine battery ESS at cell, module and string level (Poirier and D'Ussel 2009) (Saft 2017b; Saft 2017a)

The deviance in the trend line in Figure 2 is attributed to the additional hardware needed to form the strings when compared to the modules. To integrate the ESS, power electronics, control and cooling cabinets need to be considered. Commercial and naval battery ESS need to consider safety management, legislation is being enforced in the commercial sector to ensure manufacturers are tackling fire suppression, propagation of thermal runway to neighbouring cells and exhaust of off gas in their design solutions (DNV GL 2016). The naval sector further needs to consider penetration and shock events, therefore the energy density would further reduce to incorporate shock mounting and hardening of the housing structure.

Of importance for battery ESS is cycle life, this can impact energy and power density (Figure 2). As the number of cycles and Depth of Discharge (DoD) increases, the lifetime decreases owing to the increase in internal resistance of the cells in the battery system. To preserve the life of the battery, the working voltage window is limited within DoD limits, commonly to 80% (De Breucker et al. 2009). Despite a lower cell voltage, LTO can charge and discharge rapidly compared to NMC and $LiFePO_4$, this is attributed to lithium titanate used on the anode surface as they can release ions repeatedly for recharging and rapidly for high current (Stan et al. 2014).

2.2 SUPERCAPACITORS

Supercapacitors are electrochemical energy storage devices. The supercapacitors store energy by means of an electrolyte solution between two solid conductors which are typically made from high surface area materials. Large capacitance is achieved thanks to the high surface area and very small distance between the two electrodes, which further leads to higher energy storage capabilities compared to conventional capacitors (Chen et al. 2009). Supercapacitors are featured for their high power density which is a hundred to thousand times higher than batteries. Another advantage of supercapacitors is their cycle life, ranging upwards of millions of cycles. Supercapacitors have lower risk of fire than batteries for high power rate charging and discharging (Miller and Simon 2008), as they have low equivalent internal resistance and higher operating temperature range compared to batteries (Xiong et al. 2015). These characteristics make supercapacitors suitable for applications which have power bursts but are less sensitive to energy density (González et al. 2016).

2.3 FLYWHEELS

Flywheel ESS (FESS) store rotational kinetic energy and comprise a flywheel rotor which rotates inside a containment vacuum on a set of bearings, coupled to a motor/generator (MG) set that acts as the electromechanical interface. A bi-directional power electronic converter controls the power flow from the flywheel to the load and vice versa via the MG (Luo et al. 2015). Neglecting transmission losses from the generators to the FESS converter, the maximum roundtrip efficiency is approximately 90% at rated speed. High speed flywheels operating speeds range from 20,000 rpm up to 150,000 rpm (Bellamy and Bray 2015), but are typically high speed for transport applications that require energy and power density, as the energy stored is proportional to the square of the instantaneous speed. Owing to their high power, high cycle life and fast response characteristics, FESS are used to enhance power system stability, improve Quality of Power Supply (QPS), provide frequency regulation, compensate voltage sag in fault and pulse load conditions, act as a UPS (Luo et al. 2015) and energy recovery in high performance road vehicles and hybrid buses (GKN 2015).

3. OPPORTUNITIES AND CONSTRAINTS OF ENERGY STORAGE

Table 2 provides context to the foreseen opportunities of ESS for naval and commercial ships. The most common benefit to both is the potential to reduce fuel consumption and generator running hours. Naval ships are likely to combine energy store types to manage fluctuating, short duration loads and long period high power and energy demands (Tate and Rumney 2017; Hebner et al. 2015). Commercial ships are more likely to employ a single type of store to meet energy dominant demands such as a ferry with pre-defined routes, or dynamic positioning (DP) vessels with varying energy intensive loads like the Viking Lady (Stefanatos et al. 2015).

Table 2: Opportunities of ESS

ESS Opportunity	**Benefits**		**Characteristics contributing to define the appropriate energy store(s)**
	Naval	**Commercial**	
Fault ride through or power reserve	Single generator operation (SGO) and optimal engine loading. Reduces limits for spinning reserve and vulnerability to faults. Could reduce the number of generator start/stops, thus reducing maintenance.		Operating profile and operating philosophy, electrical load demands, etc. Further classification society and naval authority blackout recovery requirements.
Dynamic load levelling	Improves system stability, response rates and fuel consumption. Potential for reduced maintenance. Enhances manoeuvring and safety during DP or naval operations due to fast response rates of ESS and availability of power (presuming sufficient SOC).		Load ramp rates. Prime mover and ESS transient response characteristics.
Energy recovery	Reduce fuel consumption, as harnessed energy can be redistributed to other consumers when required. Could reduce the maintenance requirement for generator sets.		Maximum charge rate, power and cycling rate.
Emission free or quiet propulsion operation	Improved acoustic signature during operations e.g. Anti-Submarine Warfare. Emissions and fuel consumption reduction.	Emissions and fuel consumption reduction.	Energy required based on vessel operational profile/requirement to operate without additional generating capacity.
Supports combat system and pulsed loads	ESS acting as a buffer to protect the power distribution system and generator sets owing to combat system load profile.	Not applicable.	Weapon power and duty cycle of square wave pulse demand for pulsed loads. Combat system load profile.

3.1 INTEGRATION OF ESS

Architecturally, the key challenges are the characterisation of ESS in coordination with power generation units to match the loads, and secondly how distributed the ESS needs to be around a given platform (Tate and Rumney 2017). Matching the characteristics of the energy stores (such as charge rate and discharge rate) and power generation to the loads is an important consideration to maximise the capability of the system, therefore robust and flexible energy and power management is required. An example would be to meet QPS criteria under transient loads or minimise fuel consumption, which may suggest a bulk energy store on the main switchboard is suitable with sufficient response characteristics and energy capacity to meet the demand (Bellamy and Bray 2015).

This paper will consider battery ESS integrated onto the main switchboard, this is a common method where the store is a primary source of power. Connecting the ESS to the main switchboard reduces the number of cabinets when compared to a distributed philosophy. ESS distributed on subsidiary switchboards or dedicated for a specific load provides more redundancy to consumers, important for naval applications. ESS could also be connected to the DC link of a propulsion converter in the case of a hybrid vessel with Power Take In, Power Take Off capability.

DC distribution systems are attractive for integrating energy storage because the number of conversion stages can decrease, therefore reducing losses and increasing efficiency. DC systems also permit variable speed prime mover generation allowing operation in the more efficient regions of their engine map and reduce the switchboard footprint within the vessel. System voltage level will also impact the ability to integrate energy storage, voltage limits of battery strings are 1000-1200 V_{DC}, this caters for a Low Voltage (LV) system if integrated with using one inversion stage, however if the system is Medium Voltage, the power density of the ESS would decrease because of the increased conversion stages and more complex control system requirements. The case study in this paper will focus on the use of a bulk battery energy store integrated with existing LV AC distribution systems.

4. CASE STUDY

The objective of this investigation was to characterise battery ESS to minimise fuel consumption over the operating profiles of a commercial PSV and naval frigate. The ratings of the baseline power systems were fixed, and the ESS characteristics varied to meet the objective within given constraints. Table 3 states the vessel parameters, based on the VS 485 PSV (Wartsila 2015) and a frigate as described by Gemmell et al. (2014).

Table 3: Case-study vessel characteristics

Ship	Top Speed(kts)	Length Overall (m)	Beam Overall (m)	Displacement (tonnes)	Propulsion System	Total Generating Capacity (MW)	Number of DGs	Engine speed
PSV	15	86.0	20.0	5,700	IFEP	6.3	4	Medium
Frigate	26	143.0	17.2	6,200	CODLOG	12.0	4	High

The baseline PSV architecture is described by Figure 3. The corresponding operational profile is presented in Figure 4. The minimum number of DGs run for DP operations was assumed as three in rough weather for safety. The frigate propulsion system is described by Table 4 and Figure 5, the operating profile is given in Figure 6.

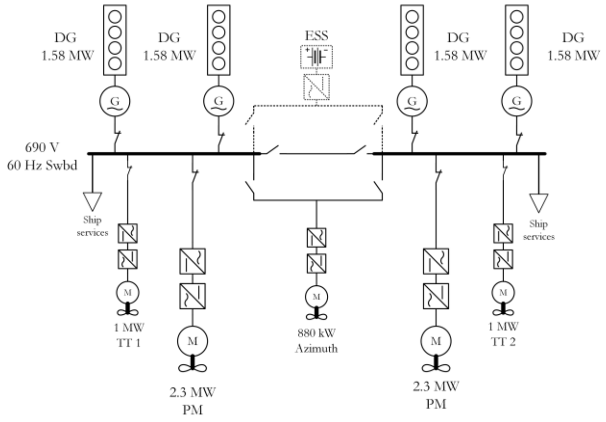


Figure 3: PSV propulsion baseline architecture

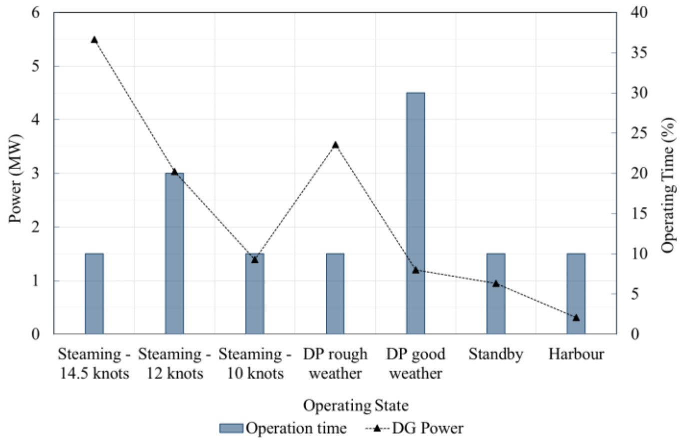


Figure 4: PSV operating profile

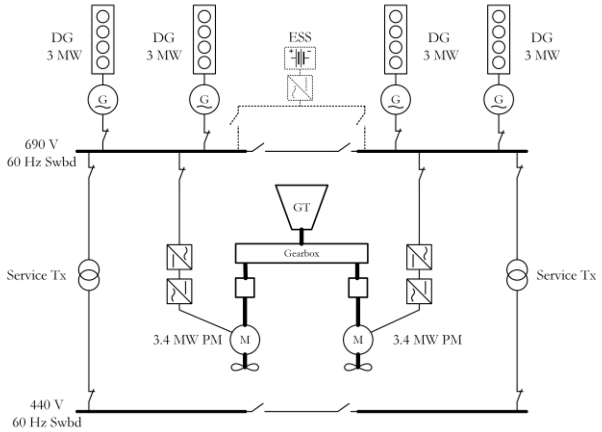


Figure 5: Generic frigate architecture

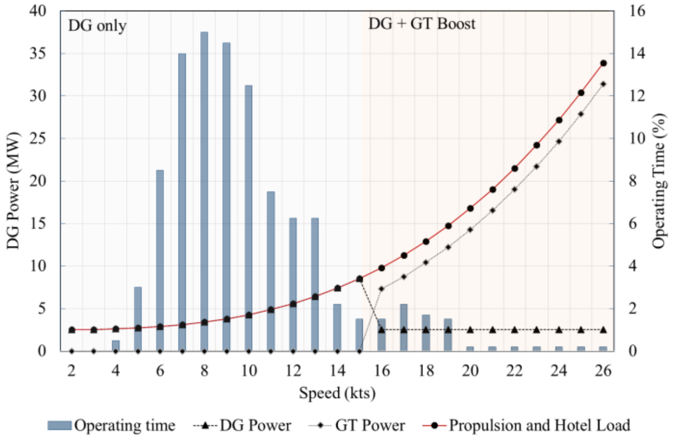


Figure 6: Frigate power-speed and operating profile

Table 4: Frigate reference values for loading

Propulsion power at 12 kts	Hotel Load	Shaft efficiency	Combined Motor and converter efficiency	Min number of DGs run	References
2.3 MW	2.5 MW	98%	80%	2	(Gemmell et al. 2014) (Allen and Buckingham 2017)

4.1 METHOD

A Matlab non-linear constrained optimisation code was developed to analyse the ships' operating profiles and generate optimal ESS sizing for the hybrid diesel/battery system and power management strategies. Figure 7 shows the schematic of the code. It is assumed that a battery string is added to the original propulsion systems. The optimisation iterates within pre-set battery capacity ranges and determines corresponding optimal loading strategies for the DGs and battery string to achieve minimum fuel consumption for one 24-hour voyage. This voyage emulates the operating profile of the ships as described in Figure 4 and Figure 6 above.

Expanding on Figure 7, the inputs to the solver are the ship operating profile including the powering information for one 24-hour voyage, DG Specific Fuel Oil Consumption Curve, minimum running DG number, DG ramp up and ramp down rates. For the battery the inputs were maximum C-rate of 6 C for charge and discharge, maximum 80% DoD and 100% initial State of Charge (SOC). It is assumed the difference between final SOC and initial SOC is always compensated by on-board DGs at the most optimal loading condition, 0.83 Maximum Continuous Rating (MCR) for the PSV medium-speed DGs and 0.8 MCR for the frigate high-speed DGs.

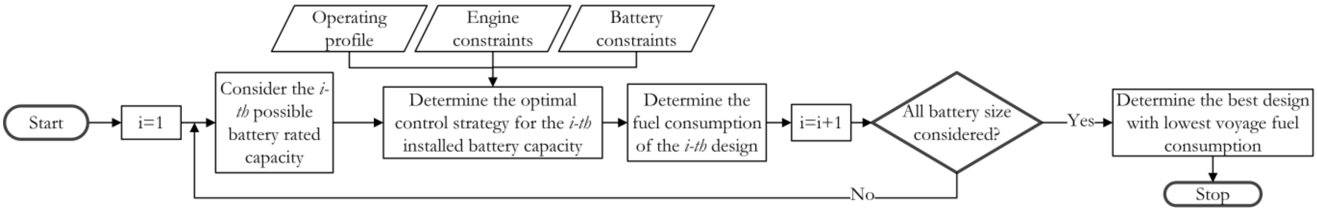
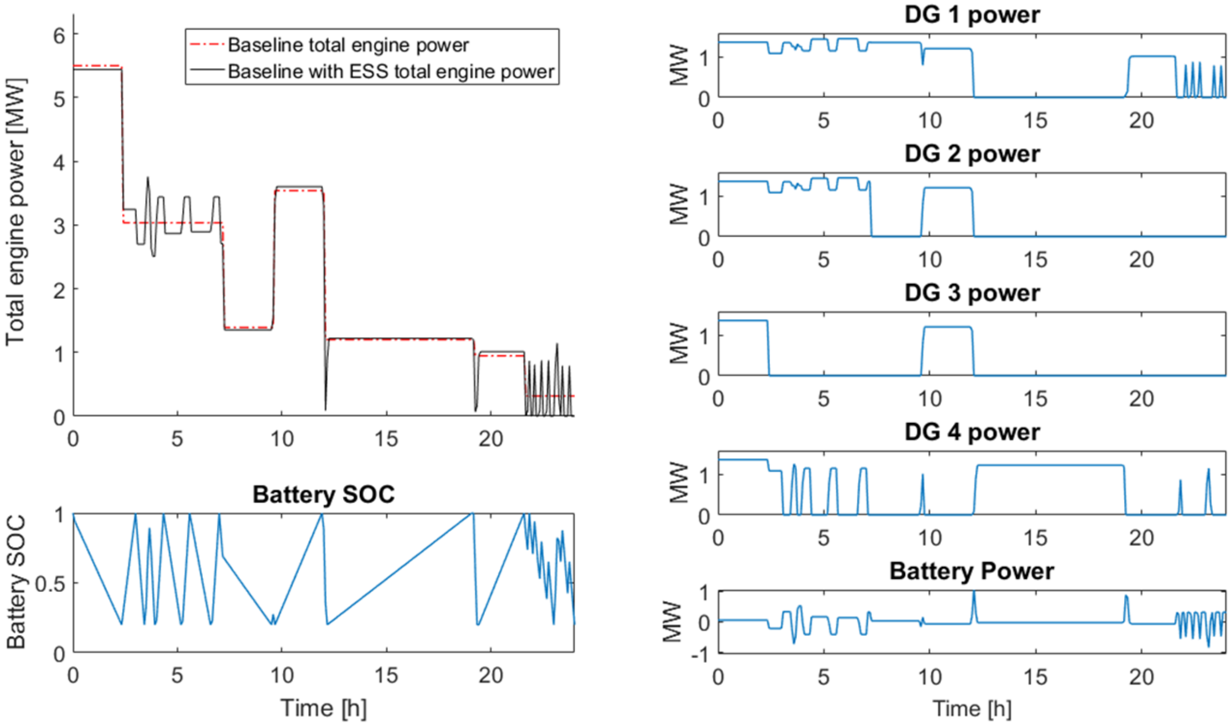


Figure 7: ESS optimal sizing decision process

4.2 RESULTS

4.3 (a) Platform Supply Vessel diesel generator loadings

Figure 8 presents the optimal loadings for DGs and ESS when battery capacity is 175 kWh: (a) provides overall DG loading comparison between the baseline and baseline with ESS within the 24-hour voyage; more detailed individual DG and battery loading for system with ESS is shown in (b). The ESS functions as a buffer to level the DG loadings to achieve lowest fuel consumption. The batteries get charged when the hybrid total DG power is higher than the original total power. However, due to limited battery capacity, the battery cycles more frequently when steaming at 12 knots and harbour when baseline DG loadings deviate more from optimal loading point.



(a) (b)

Figure 8: (a) PSV baseline and baseline with ESS DG loadings and battery SOC (b) loading for DG and battery when battery capacity is 175 kWh

4.3 (b) Platform Supply Vessel fuel consumption and diesel generator running hours

Figure 9 shows the total DG running hours for one voyage for different ESS sizes. The time step was set at 5 minutes for all simulations to achieve reasonable error level and computation time. These errors are controlled within 0.2% and fitted curves are used to present the engine running hour and fuel consumption reduction trends. The total DG running hours reduced by 29% over the operating profile when 175 kWh of ESS is included. When the battery size is less than 25 kWh, the DG running hours are higher than the baseline system, due to the ESS capacity being too small causing the DGs to start/stop to charge the battery. When the battery capacity is over 125 kWh, the DG running hours were reduced by 12.5%; however, increasing battery capacity after 125 kWh did not reduce running hours because of the constraints applied, the code did not reduce the minimum number of DGs in DP operations.

Figure 10 shows the maximum fuel consumption saving that can be achieved for one voyage under optimal loading strategies for different battery capacities. When the battery size is 175 kWh, fuel consumption can be saved by 0.95%. The finding suggests that, for a hybrid diesel/battery propulsion system, a small battery ESS can potentially improve fuel economy considerably, provided that the power/energy are managed properly.

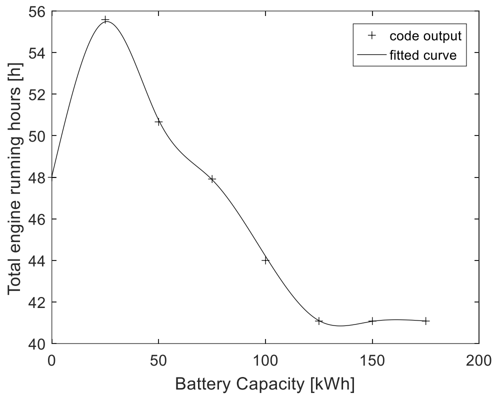


Figure 9: PSV DG running hours vs. battery capacity

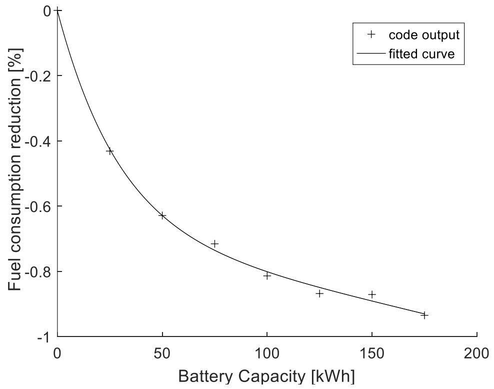
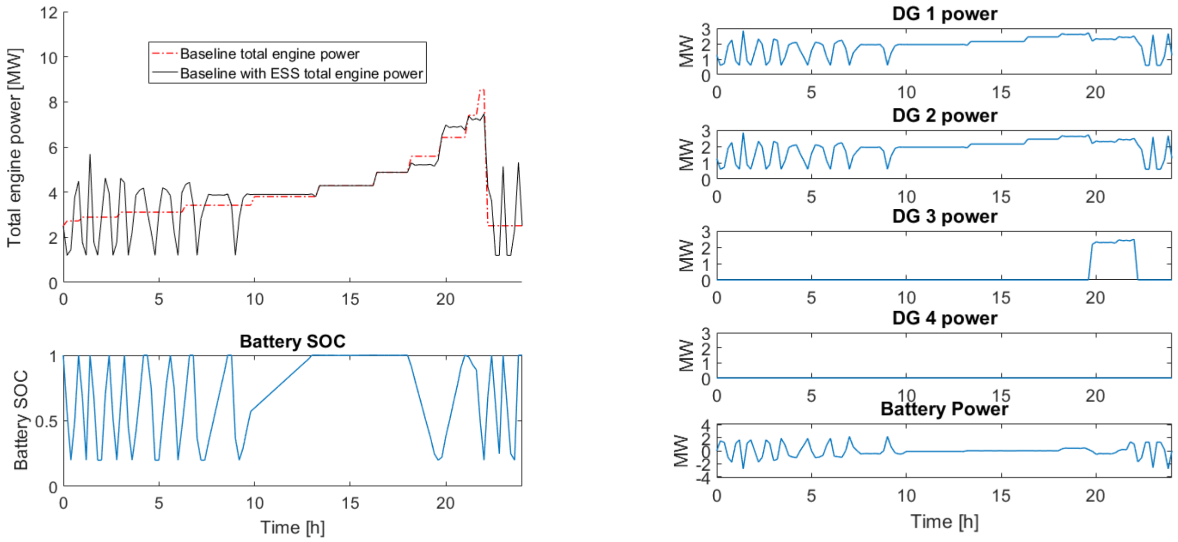


Figure 10: PSV fuel consumption reduction

4.3 (c) Frigate diesel generator loadings

Figure 11 presents the loadings for the DGs and ESS for the 700 kWh battery size: (a) shows overall DG loading comparison between the baseline and baseline with ESS over the 24-hour voyage and (b) shows more detailed individual DG and battery loading for the hybrid system. Because of the requirement to run two DGs, there is significant variation in the loading of DG 1 and DG 2 at lower speeds when the ESS is used to minimise the fuel consumption when compared to the baseline system shown by the dotted line in Figure 11 (a).



(a) (b)

Figure 11: (a) Frigate DG loadings of baseline and baseline with ESS and battery SOC (b) Frigate optimal loading for DGs and battery when battery capacity is 700 kWh

4.3 (d) Frigate fuel consumption and diesel generator running hours

The frigate optimisation was performed with a minimum of two DGs running and secondly permitting the power system to run in single generator operation (SGO) mode over the operating profile. This was considered a valid approach in this investigation because as the battery size increases the power reserve increases, therefore the minimum number of DGs running could be relaxed, therefore providing the opportunity to reduce fuel consumption further. The results for DG running hours and fuel consumption reduction are compared in Figure 12 and Figure 13 respectively for different ESS sizes. The running hours were not decreased when a minimum of two DGs are running because the load was always shared equally between the DGs and the ESS. However, when SGO is enabled and 700 kWh of ESS is installed, the DG running hours are decreased by 27% over the profile. When the battery capacity is lower than 200 kWh, the total engine running hours were higher than the original running hours, this is due to the DGs start/stopping frequently to optimise the loadings. Increasing battery capacity after 700 kWh did not reduce DG running hours significantly under the applied operating constraints, similarly the rate of change in fuel consumption savings was slower as the capacity increases after this point. Therefore 700 kWh was selected from the results as the optimum result in this case study. Under this condition the fuel consumption can be saved by approximately 0.95% over the operating profile when SGO is enabled, when two DGs running is mandated this decreases to 0.35% fuel saving.

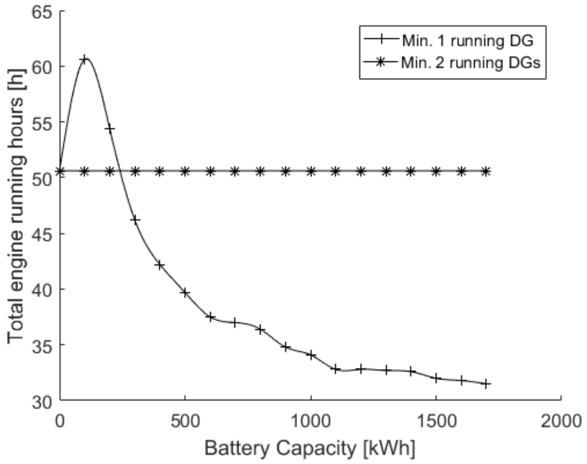


Figure 12: Total frigate DG running hours vs. battery capacity

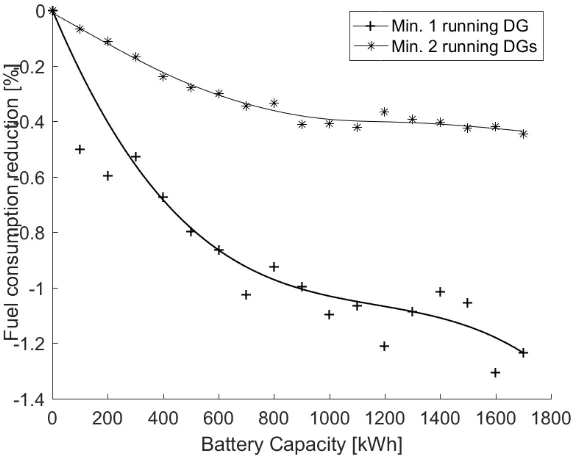


Figure 13: Frigate fuel consumption reduction

4.3 DISCUSSION

Both the commercial and naval cases have demonstrated the potential of ESS to reduce fuel consumption and DG running hours. Nevertheless, as the prolusion system of each ship is customised per its operating profile, the opportunities of applying ESS should be analysed based on a case by case basis, considering the constraints including operating philosophy, DG characteristics, ESS characteristics (e.g. maximum depth of discharge, maximum C rate). The PSV needs 175 kWh battery bank to reduce fuel consumption by 0.95%, whilst the required battery capacity is 700 kWh for the frigate case to reach similar reduction if SGO is enabled. The gradient of fuel consumption reduction rate reduces gradually as the increase of battery capacity for both cases. The frigate case demonstrated the operating philosophy can greatly impact the potential savings. SGO for example could be permitted in peacetime operations, DG availability could be increased and maintenance costs could potentially be reduced.

The simulations were done for steady states, focusing on analysing potential of ESS in shipboard propulsion systems. However, the steady state results could be a reference for more detailed analysis with dynamic modelling. The large ripple of the ESS and DG loadings observed in Figure 8 at 5 hours and 22 hours representing steaming at 12 knots and harbour operating states, indicate that energy and power management would need to be addressed further.

5. SCOPE OF ESS DIRECTION

Since Viking Lady was fitted with 450 kWh of Li-ion based ESS in 2012 the capacity of Lithium based ESS has increased. Corvus Energy recently announced 6 MWh of Li-ion ESS to be installed on European polar exploration cruise vessels to allow ‘silent’ propulsion and reduce the environmental impact in polar operating areas (Corvus Energy 2017). In contrast naval surface ships are yet to see a large battery ESS installation, largely owing to safety concerns, and volume and weight implications, instead the focus has been on the development of systems for high pulsed power and short duty cycles. The U.S. Navy's most recent aircraft carrier, the USS Gerald R. Ford, is the first with an electromagnetic (EM) catapult supported by rotating energy storage and integrated with the ships electric power system to provide aircraft launch capability (Hebner et al. 2015).

Significant investment to decarbonise the automotive sector, expounded by the inclusion of battery design and development for EVs in the UK industrial strategy (Department for Business Energy and Industrial Strategy 2017), will provide anticipation of improvements in electrochemistries, either incrementally by developing current commercially available options such as NMC or $LiFePO_4$, or via more optimistic alternatives such as Li-Air and Li-Sulphur as described by Chemali et al. (2016). The development in electrochemistries of batteries with increasing energy and power densities, higher charge/discharge rates, reducing cost and continual de-risking of battery technology will provide a pathway for large battery implementation on naval ships (Radan et al. 2016).

Hybrid ESS capable of supporting increasingly dynamic load profiles is anticipated for naval ships, owing to the advent of more electric combat systems that need high power and energy density (Hebner et al. 2015). This will support capability during operations and in reducing fuel consumption and maintenance, and improving QPS. Similarly, hybrid supercapacitor and battery combinations have been identified for EVs by coupling the advantages of power density and cycle life of the former energy store for the dynamic aspects of the load profile, with energy density of the latter for vehicle range, therefore prolonging battery life (Chemali et al. 2016).

6. CONCLUSIONS

This paper firstly aimed to summarise and compare the state-of-the-art of energy storage for naval and commercial ships. A review of the literature showed that the pertinent options for ESS were lithium based batteries, supercapacitors and rotating machines. The review found that the electric vehicle industry influenced the electrochemistries used in lithium-based ESS for ships, of which the most prominent are Li-NMC, $LiFePO_4$ and LTO. The review highlighted the trade-off between energy density, power density and cycle life is ongoing, and chemistries are developing to improve this.

The paper proceeded to capture the benefits and opportunities of ESS. Common to naval and commercial was the ability to improve fuel consumption and reduce generator running hours over the operating profile through power and energy management. This was built upon using a case study in section 4. The case study showed that under steady state analysis the operating philosophy of the power system can greatly influence the potential savings if ESS is installed, particularly if SGO is allowed. The volume and weight impact to the host platform for the PSV battery system (excl. power electronics) would equate to 2 tonnes and a footprint of 2 m^3 if Li-NMC is used, conversely the frigate battery would occupy approximately 8 m^3 and weigh 8 tonnes (excl. shock rating equipment) both at approximately 1% fuel savings over the operating profile.

The installed capacity of battery energy storage for commercial ships has been increasing and naval vessels have begun to implement solutions to support transient high power loads. The landscape of energy storage is continuing to move forward with new chemistries and solutions, increasing in power and energy capacity, which holds great potential for advancing ship power and propulsion systems to operate more efficiently in the future.

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