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TECHNICAL NOTE

TECHNICAL FEASIBILITY OF HYBRID PROPULSION SYSTEMS TO REDUCE EXHAUST EMISSIONS OF BULK CARRIERS

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SUMMARY

The combination of a prime mover and an energy storage device for reduction of fuel consumption has successfully been used in the automotive industry. In the shipping industry, the potential use of a hybrid battery-diesel-electric propulsion system is investigated. The scope of this study is to suggest that in existing newly built vessels and in modern designs, such a combination can be achieved without significantly affecting the principal dimensions of the ship and the cargo capacity. This work considers structural arrangements of a bulk carrier fleet of all vessel types. Complete calculation of free, void and machinery spaces is performed. The energy requirements of each vessel size and the derived energy storage system are used to inform the installation and construction scenarios. Meanwhile, trim constraints are investigated and discussed. Installation and retrofitting issues affecting the housing compartments of the proposed system are investigated for the current ship designs. Results indicate that such an installation will fit in modern bulk carriers and that proper allocation of the weight may be used to improve the trim. Cargo capacity is affected by less than 1.0% and is dependent on the battery weight, the type of diesel generators and electric motor technology deployed.

NOMENCLATURE

Θ_u	Fuel Lower Calorific Value	[kJ/kg]
b_e	Specific fuel oil consumption	[g/kWh]
V_E	Engine Room Volume	[m^3]
bkW	Engine's break Power	[kW]
RPM	*Engine* Rotational Speed	[RPM]
$f_6 \ldots f_8$	Coefficients defined in text	[-]
MTC	moment to change trim	[tm]
LCB	Longitudinal Centre of Buoyancy	[m]
LCG	Longitudinal Centre of Gravity	[m]
Δ	Vessel displacement	[tonnes]

1. INTRODUCTION

Approximately 80% of world trade by volume is carried by sea [1]. In 2007 an estimate of CO_2 emissions from international shipping showed it was responsible for approximately 870 million tonnes of CO_2, or 2.7% of global anthropogenic CO_2 emissions [2]. Although this percentage is relatively low for the volume of cargo transported, shipping is responsible for a greater percentage share of NOx (~15%) and SOx (~4–9%) emissions [3] and there is increasing pressure to reduce all emissions from shipping. CO_2 emissions from shipping are directly related to the fuel consumption of the fleet. Three categories of ship account for almost two thirds of this consumption. The liquid bulk sector accounts for ~65 million tonnes fuel/year, container vessels for ~55 million tonnes fuel/year and the dry bulk sector for ~53 million tonnes fuel/year [2]. For all these vessel types there is typically an optimum calm water design speed, propeller, and engine operating rpm. The influence of sea state and to a lesser extent wind will increase fuel consumption and related emissions.

The concept of load levelling uses a hybrid technology that combines energy production and storage, where peaks in energy demand use stored energy to supplement the direct production. The energy storage device can be either mechanical or electrical. Its rated capacity will be dependent on the observed loading variance and duration. Hybrid technology and energy storage (NiMH NiCad and Li-Ion batteries) are already successfully used in the automotive industry and novel high temperature batteries and redox flow cells are under investigation [4]. Hybrid and energy storage and have been shown to contribute to reduced CO_2 emissions [5] [6], while energy storage systems in marine applications have been installed on-board conventional diesel-electric submarines since the Second World War.

The dry bulk sector was selected for this investigation since bulk carriers are slow speed vessels, without major fluctuations in the engine loading, and thus are commonly perceived to have less potential for emissions reduction by other means (e.g. slow steaming). A recent study of the performance of a fleet of 13 bulk carriers of all types, showed that the assumption of small engine loading fluctuations is not valid for Handysize, Handymax, Panamax and Post-Panamax bulk carriers, although is reasonable for Capesize types (>120000 tonnes DWT) [7]. The fluctuations in engine loading exceeded 5% and associated savings in fuel through use of an energy storage system could reach values of 15% during a single voyage. These fuel savings are dependent on the battery type selected, but do prove sufficient to justify the investment from an economic perspective. This concept combined the battery storage system with an All Electric Ship concept in order to obtain zero fluctuation in engine loading without reduction in the vessel's speed.

This paper takes the concept a stage further by investigating the technical feasibility of energy storage devices installed on bulk carriers through use of a systemic concept design spiral. Likely values of energy losses due to conversion are also considered. Through observation of engine variations and the operational curves of the engine the potential fuel savings of the hybrid system are compared to the conventional propulsion system. The hybrid system assumes a scenario of constant RPM operation. Any variance in loading and any peak requirements will be supplied from the storage system by applying load levelling to the system. Thus, diesel engines are either switched off to reduce the total fuel consumption or are operated at constant load and RPM in order to have the minimum Specific Fuel Oil Consumption (SFOC). In order to achieve significant fuel savings, the variance should exceed a specified percentage determined from the shape of the engine SFOC curve. The amount of fuel saving is dependent on the observed fluctuations as reported in [7] [8].

A system engineering approach is applied [9], which is holistic in its attempt to improve the Energy Efficiency Design Index (EEDI) in its initially proposed relationship of ships and the Energy Efficiency Operational Index (EEOI) for the actual vessel operation. This requires an understanding of the trade-off between system complexity and resultant new build cost against reductions in operational through-life cost and exhaust emissions. The adopted methodology is presented and through this the constructional and technical feasibility of the concept are demonstrated. The latter is examined for new builds based on a proposed and non-developed concept design. Furthermore, an investigation for retrofitting current designs for new-building projects is performed and examination to retrofit already built ships with short operational life, with the hybrid technology is made. In assessing the technical feasibility, the calculation of engine room volume is critical and is performed first, along with a record of all free spaces on board existing vessels. In addition the weight calculation and distribution are noted in order that any trim issues that arise can be inserted in the calculation of major loading conditions of the examined ship type. Finally, the energy storage devices and the electric components are introduced and their weights and volumes are inserted in calculations affecting the trim and filling the free spaces. The new components and the battery system have known volume and have to fit into the current compartments as well as maintaining the Ship's lightweight and with a minimal impact on cargo capacity and hence economic viability of the initial vessel.

2. CONVENTIONAL DIESEL AND DIESEL ELECTRIC PROPULSION SYSTEM

Conventional diesel engine installations consist mainly of a large two-stroke engine in single screw vessels and in fast twin screw ships, one or multiple four stroke engines coupled with reduction gears as seen in Table 1. The engine - propeller coupling results in constraints in the rotational speed of the propeller, which leads to a significant drop in the system efficiency at off-design conditions [10]. The two-stroke diesel arrangement is found in the majority of ocean going vessels and requires independent generator sets to supply the auxiliary loads. The number of generators is defined by SOLAS and implemented to classification societies rules. For steam requirements, a waste heat boiler (economiser) and/or oil-fired boiler are used. On the other hand, different concepts involving electric generation for propulsion are also found in the marine industry. Full Electric Propulsion (FEP) uses electric motors that transform the electric energy produced by dedicated-to-propulsion generator sets and rotate propellers. Similar to the All Electric Ship (AES) and FEP concepts, the Integrated Full Electric Propulsion system is found, where the same electric generators cover the auxiliary loads too. However, the difference in an AES concept is that the latter feeds every single operation of the ship by the electric distribution network. Nevertheless, these systems have difficulties in coupling through differing component requirements for AC voltages/frequencies or DC, as well as transmission issues.

Table 1: Comparison of propulsion technologies

Arrangement Components	**Conventional 2-stroke Diesel**	**Hybrid Diesel-Electric System - All Electric Ship**
Prime Mover	2-stroke Marine Diesel Engine	4-stroke Marine Diesel Generator sets
Auxiliary Power	3 4-stroke generator sets, 1 emergency	Covered by the main propulsion unit (Fully electrified vessel)
Components	Shaft generator (if Applicable), Shafts and bearings	Marine type electric cables, Transformers, Converters/ inverters (motor speed control), Rectifiers (Storage system existence), Electric motors
Propulsor and manoeuvrability	Large diameter Fixed Pitch propeller, steering gear	FP propeller(s), CP propeller(s) with steering gear or Podded Propulsor (no steering gear)

In electric propulsion, a four stroke marine diesel engine is coupled with an alternator. Each engine occupies significantly less space and weighs less than a similar output two-stroke diesel, although the total mass of required engines and motors may be greater than a single two-stroke diesel engine. These generator sets can operate across a broad range of loadings, but it is extremely inefficient to run them at loads less than 50% of MCR, where the production of NOx, SOx and soot is high and the mechanical efficiency is low. The mechanical efficiency ranges from 88%- 96%, while the emission and consumption curves taken from the engine specifications can be found in Figure 1.

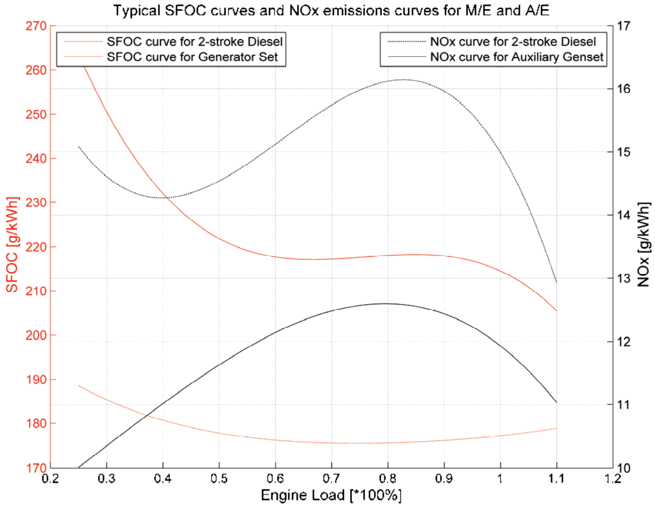

Figure 1: Consumption and NOx emission curves of 2-stroke Main Engine and 4-stroke Auxiliary generator sets.

As a result of the significant fuel consumption increase, an equivalent system has to run in near-optimum conditions and have multiple diesel electric sets to cover changes in demand by switching on and off.

In the proposal made in a previous study [8], the installation of an energy storage device has been considered. This applies load levelling to the demand and covers the fluctuating propulsion and hotel loads with the stored electric power, instead of alternating the output of the engines and causing an efficiency drop. The adopted technologies are batteries, and the installation requirement per vessel and type are presented in Table 2; hence the electrical output is a direct current (DC) flow. In order to couple batteries with the rest of the energy production system, converters which consist of inverters and rectifiers, are needed. A power electronic (is a fast and accurate controller for both speed and torque of electric motors. It is consisted from a transformer a rectifier from AC-DC and from an inverter to change the current from DC to AC. In the Hybrid system the inverter, apart from fulfilling the requirement of transforming the current of the storage medium to a form that can be coupled with the rest of the system (DC to AC), is used for controlling the electric motors, in order to achieve the requested rotational speed. Details about converter technology can be found in [11] [12]. DC to AC conversion of the power is an expensive solution for high power levels. For the storage system, this implies expensive components such as rectifiers to charge and inverters to discharge the storage medium in the AES concept which increases the total cost of the investment. Nonetheless, the primary technical concern is the efficiency drop due to the total number of installed components. The achieved efficiency values range from 95-97% for generator, 94-96% for frequency converter and up to 97% (load dependent) for electric motor efficiency with the potential to be increased in the future [12]. Thus, the overall system efficiency from the diesel engine’s shaft to the propeller varies from 84-92% dependent on the system load [11]. The Diesel engine efficiency can be determined by equation (1) using the information provided in Figure 1. Thus the total propulsive efficiency can be determined.

$$\eta_{eng} = \frac{P}{Q} = \frac{3,6\cdot10^{6}\cdot P}{\Theta_{u}\cdot m_{f}} \Rightarrow \frac{3,6\cdot10^{6}}{\Theta_{u}\cdot b_{e}} \qquad (1)$$

Where,

Θ_u is the lower calorific value of the fuel
b_e is the specific fuel oil consumption for this load

Transformers are used to change the voltage of the subsystem and sometimes to provide a phase shift. The latter application can be used to feed frequency converters for variable speed propulsion drives, in order to reduce distorted currents by cancelling the dominant harmonic currents that result in problems in the electric network [13] [14].

The distribution of electrical energy is achieved through switchboards. These receive control signals and distribute electrical energy. The most dominant technologies are the SF6 and vacuum breaker technologies. A ship has multiple switchboards. The main switchboards receive electric energy directly from the generator sets and, in cases where ‘cold iron’ facilities exist, from the shore power station. Another use of the switchboards is the prevention of short circuits. They also tolerate the consequences of one section failing. In stricter redundancy requirements, one switchboard should withstand failure due to fire or flooding.

The final, but most important, component of the electric propulsion is the electric motor. Typically, up to 90% of the load is fed to some type of electric motor. However, in the scope of this paper only the dominant electric motor technologies for propulsion will be mentioned.

Asynchronous (induction) motors are most frequently used in conventional applications. Their main attractive characteristic is low cost and the simple design which assures long lifespan, minimisation of breakdown risk and low maintenance [11]. Main structural and operational characteristics can be found in [15].

Although recent studies consider DC electric energy transportation though the ship electric network and DC motors, Currently the dominant category type of propulsion electric motors (PEM) are synchronous motors whose efficiency, depending on the excitation method, can reach up to 98.5%. The nominal voltage varies from 3.3 to 6.6kV and can reach the 11kV depending on the power output of the motor. Synchronous motors are not used for propulsion motors for power outputs less than 5MW, as asynchronous ones are more cost-effective.

Table 2: Added weight to the vessel due to propulsion system retrofitting and energy storage medium installation.

Ship Type	Handy Size	Handy Max	Pana-max	Post-Pana max	Cape-size
Required Energy [MWh]					
	8	8	15	5	4
Required Battery weight [tonnes]					
Sodium Nickel Chloride (SNC) 150Wh/kg					
tonnes	70	70	130	43	35
Vanadium Redox Flow (VRB) 50Wh/kg					
tonnes	160	160	300	100	80
Final Added weight to the vessel (propulsion system + storage)					
SNC	323	323	384	297	288
VRB	414	414	554	354	334
Increase in Lightweight [%]					
SNC	4.1%	3.4%	3.2%	2.0%	1.2%
VRB	5.2%	4.3%	4.7%	2.4%	1.4%

3. BULK CARRIER E/R CONSIDERATIONS

Whilst hybrid diesel electric propulsion may appear a promising means of emissions reduction, its technical viability needs to be assessed against the requirement of not increasing the size of the engine room or by reducing the areas reserved for cargo. Thus, it is crucial to estimate the available volume of the engine room. An estimate may be made of engine room volume using [16],

$$V_E = 21.6 \cdot f_6 \cdot f_7 \cdot f_8 \cdot \left(9.55 \cdot \frac{bkW}{RPM}\right)^{0.83} \qquad (2)$$

Where,

V_E = Engine Room Volume in m^3,
bkW= Engine's break Power in kW,
RPM = Rotational Speed of the Main Engine,
f_6 = 1.0 because of the fact that engine room is always located to the stern in the examined ship type,
f_7 = 1.0 due to the existence of a single propeller (single screw vessels),
f_8 = 1.0 as a consequence of the unrestricted Engine Room dimensions. The limits are set from the top tank, until the main deck and the side shell.

On account of the fact that equation (1) is not describing modern designs, a direct measurement was performed using vessel drawings (Vessel characteristics can be found in Table A3 of Appendix I). By this means, the actual volume of the engine room for a Panamax type bulk carrier is 88% of that estimated by equation (1). For a Post-Panamax type the corresponding figure is 90%. These figures reflect the more compact engines installed in modern designs. The volume used in subsequent calculations is thus 5150 m^3.

In table A1 of Appendix I the volume of each engine room component in a conventional two-stoke installation in a bulk carrier (Panamax and Post-Panamax types) is presented. Where available, the weights of the components are presented. It can be seen from this table that many items are not connected to the type of propulsion system used and are associated with the operation of the vessel. These items are thus accounted for in equivalent propulsion systems. Concerning the existence of pumps and other hydraulics, a separation was attempted with the intention of justifying those which can be replaced in an electric propulsion system, or even neglected.

Table A2 of Appendix I presents components representative of those installed in a modern cruise ship with integrated full electric propulsion (IFEP), equipped with conventional propulsion shafts instead of podded propulsion units. The power output for propulsion of such a vessel is four times the power required by a bulk carrier. The examined cruise vessel is equipped with two Lloyd Dynamoworks (LDW) Synchronous motors of 21MW rated power. Each one weighs approximately 150 tonnes. Using this information an approximation can be made for a bulk carrier installation. Recent technological improvements indicate that the weight for the same nominal output (20MW) could be reduced to only 89 tonnes and with more compact dimensions [17]. In subsequent calculations the weight of an electric motor rated at 10MW is taken as 75 tonnes. Although the extra volume for electric components is presented in Table A2, the dimensions of rectifiers, inverters, transformers and other parts of the circuits are relative to the number of generator sets. A general overview of the dimensions and weights is given for the equipment list of the fleet of cruise ships that were examined. The weight of the generator sets is lower that the weight of a conventional two-stroke diesel. However, for large power outputs and depending on the propulsion system design, more than two generator sets have to be installed. Hence the total weight of the engines including the appropriate electrical motor, can vary from -10% to +10% of the equivalent conventional engine weight. For the examined Post-Panamax type ship the increase in weight is 1.7% and is connected to the number of generator sets. The added weight for the propulsion system also has to account for the added mass of the storage medium. Using the preliminary sizing for the energy storage system from [7], the final added weight to the hybrid vessel is given as a percentage of lightweight in table 2. The weight values for Sodium nickel chloride refer to electrolyte weight which corresponds to the ~85% of the weight and volume of the battery system [18].

4. ESTIMATION OF HYDROSTATICS AND CARGO LOSS

The construction of the engine room greatly affects the ship design from hydrodynamic, aerodynamic, trim and stability points of view. It is fundamental to allocate the weight of the lightship such that when the ship is loaded, the trim of the vessel is as close as possible to zero. According to research performed in [2], achieving optimal trim of the vessel can result in fuel savings of up to 2%.

Table 3 presents the most probable loading scenarios of this ship type in operation and the trim is presented. The latter is given by,

$$Trim = \frac{(LCB - LCG) \cdot \Delta}{MTC \cdot 100} \quad (3)$$

Where,
MTC is the required moment to change by 1cm the trim of the vessel,
Δ is the displacement of the vessel,
LCB is the Longitudinal Centre of Buoyancy from AP,
LCG is the Longitudinal Centre of Gravity for AP.

The trim is positive (+) when LCG is closer to frame zero (After perpendicular) than the LCB in non-damaged waterline.

Due to changes in the total machinery weight, the proposed retrofitting of the machinery arrangement and the installation of energy storage devices and electric components for electrified propulsion should be performed in respect of the trim values. Design issues arise if the vessel is designed to have zero trim while no cargo is present. The case of zero ballast water and zero trim has to be further investigated. However, the design is mainly performed for the full load departure and full load arrival conditions, where cargo is present. The current form of bulk carriers, where the LCB is located forward of the amidships section, is directed at achieving this aim. Fore and aft asymmetry to the cargo holds does not permit any drastic change of weight distribution. Table 3 represents a set of loading conditions for the examined vessel. It can be observed from the table that the full load departure condition has no trim. On the contrary, every other condition has trim and most of the time, ballast water. Any future weight distribution of the current design requires a compromise between the full load departure condition and the remainder of conditions in order to optimise trim and reduce the amount of required ballast water.

Table 3: Loading Conditions of examined Post-Panamax bulk carrier[1], the worst case scenario is depicted in bold letters and considered to be the minimum cargo capacity, with zero ballast, 100% filled fuel and fresh water tanks, full provisions and minimum trim. Cargo loss is expressed as a percentage of the initial loaded cargo.

Condition	**Cargo [tonnes]**	**Cargo Loss %**	**Ballast [tonnes]**	**LCB [m]**	**LCG [m]**	**MTC [tm]**	**Trim [m]**
Normal Ballast Departure	0	0.00	23414.3	117.126	117.189	1040.2	2.08
Normal Ballast Arrival	0	0.00	26061.1	114.757	114.855	1068.1	3.045
Heavy Ballast Departure	16487.1	0.00	23411.7	115.991	116.059	1226.5	2.667
Heavy Ballast Arrival	16487.1	0.00	24476.8	116.88	116.682	1191.4	2.265
Grain Departure SF65	60188.4	0.00	2250.7	116.664	116.702	1346.4	1.674
Grain Arrival SF65	60188.4	0.00	2250.7	118.866	118.879	1298.4	0.514
69990 tonnes DWT cargo Departure	65152.1	0.54	0	115.448	115.501	1364.5	2.323
69990 tonnes DWT cargo Arrival	65152.1	0.54	0	117.517	117.548	1331.3	1.205
Homogenous Design Departure	67858.4	0.52	0	115.656	115.702	1364.6	2.09
Homogenous Design Arrival	67858.4	0.52	0	117.668	117.693	1336.3	0.983
Grain Departure SF42	87866.1	0.40	0	116.837	116.841	1392	0.335
Grain Arrival SF42	87866.1	0.00	939.4	117.483	117.482	1384.9	0

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[1] Values taken from ship's loading manual, data available at Fluid Structure Interactions research group at University of Southampton

Table 3 highlights the minimal cargo loss associated with the additional weight and volume of the necessary equipment for the proposed hybrid propulsion installation expressed as a percentage of the cargo carried. For the worst case scenario it is assumed that lightweight was increased according to Table 2, the DWT is now reduced but the reduction is affecting only the payload as the rest DWT elements remain the same as they are described by operational parameters and regulations. For the rest cases, the extra weight may be subtracted from the ballast water, as added lightweight reduces this amount instead of the cargo capacity.

It can be determined from Table 3 that cargo loss is related to the cargo transported and to the presence of ballast water. The lower the cargo capacity of the vessel, the higher the percentage cargo loss and vice versa (e.g. in Post-Panamax the cargo loss is 0.54% and reaches 0.78% for Panamax in Homogenous Loading).

5. DESIGN ISSUES AND CONSTRUCTION PARAMETERS FOR HYBRID PROPULSION SYSTEMS

Given that the allocation of the weight can be performed in an optimum way, a selection of proposed compartments for housing the systems has to be performed. However, before discussing these potential arrangements in detail, the following design constraints have to be observed.

The location and type of propulsor have to be selected, as does the location of the superstructure. The superstructure and its associated air drag contribute to the overall resistance of the vessel. Meanwhile, an optimum location of the bridge deck can allow better navigation if it is located near the bow. In the case of a propeller, a shaft system is required. The weight and the length of the shaft system are associated with the volume and compartment arrangement at the stern. It is not optimum to have large shafts and this is one of the reasons why a conventional two stroke diesel engine is located as close as possible to the stern. In that case, the engine room compartment has to be located at the stern to house the main engine and the exhaust piping, which usually requires the superstructure to be located on top of the engine room and astern. Therefore, there is no capability to alter the design and reallocate the weights.

The potential of electric propulsion allows a different approach in the design of the stern and overall layout of the ship. Electrified propulsion uses electric cables as the medium for power transfer instead of mechanical connections and this allows alternative locations of the prime movers to be considered, with subsequent optimisation of the hull form at the stern. However, the location of one or multiple engine rooms must be combined with the constraints of available space for cargo holds. As a result, the bow and stern are the most suitable spaces for machinery allocation. For a conventional electric propulsion system, electric motors and a shaft system are required. Due to the small dimensions of electric motors (see Table A2) the housing compartment can have limited dimensions in length.

The combination of diesel electric and energy storage devices permits the use of the void space above the electric motors for the installation of a part of the storage system, while housing the steering gear system in the adjacent room. Prime movers can be vertically installed in a bow compartment while a boiler room and/or turbine generators can exploit the rest of the space. Concerning the electric equipment (summarised in Table A2), it is recommended that it be located in different rooms, preferably in separate watertight compartments. For example, electric motors and control inverters should be in the same watertight compartment. The converters, located in a dedicated room, have to be situated as close as possible to the motors to reduce the length of the cables. On the other hand, generators can be placed wherever the ship design allows it. Concerning the superstructure decks, they can have the same use as before, while the construction and the design should bear in mind the aerodynamic drag and the wave spraying in case of slamming events.

An alternative approach with electric propulsion is the use of podded drives that combine steering and propulsion capabilities and do not require any space for electric motors inside the hull. However a dedicated compartment for steering the pods is essential. Any free space can be covered by a set of batteries, if an energy storage device is applicable. On top of this compartment, mooring equipment and bosun store can be constructed. The rest of the machinery, along with the rest of the battery storage system, can be installed in the bow section. The energy losses in cabling are estimated to be up to 6%, which is the maximum voltage allowed by the classification rules of Lloyd’s Register. The voltage

For the bulk carrier sector addressed in this study, two types are considered in more detail. These are the Panamax and Post- Panamax types, which are reported to either have significant fluctuations in their engine loading (e.g. Post-Panamax) or their number is significant in the overall ocean going fleet (e.g. Panamax) [18].

5.1 EXISTING SHIP DESIGN MODIFICATIONS

In order to install batteries in existing ship designs, typical general arrangements and capacity plans have to be studied. The extra volume of the battery system and components of the fully electrified propulsion system are given in table 4. A proportion of this volume can be installed in the engine room (ER) if there is sufficient space. The major contributors to the required volume are the components for the electrified propulsion system. It is important these be installed inside the engine room. An approximation of the engine room volume following installation of the components is also presented. If the final available volume is insufficient, other free and void spaces have to be selected in order to install the energy storage system. For the Vanadium redox flow batteries the battery volume can be a significant proportion of the total required volume. For example, in the case of a 15MWh installation (Panamax vessel) the required battery volume is almost 25% of the total volume required. However, due to the flow cell operation, the reactants can be stored in tanks away from the ER keeping the required ER volume low.

In assessing a potential hybrid propulsion installation more completely, details from the engine room plan and profile views, along with relevant photographs from the ship's void spaces have to be investigated and typical examples are shown in Figures 2 and 3.

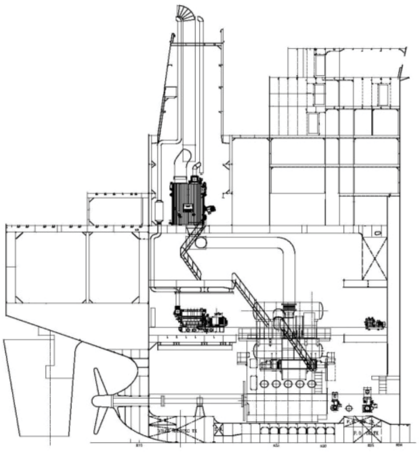

Figure 2: Longitudinal section of Engine room of a Panamax and Post-Panamax (same aft design) bulk carrier.

Figure 3: Void Space, between Bosun's store and Forepeak Ballast Tank for Panamax size bulk carrier. (Photos taken by Mr. P. Georgakis).

Figure 3 shows the void space located inside the forepeak compartment where limitations on storage apply according to classification societies' collision regulations. A void space is an enclosed space, with access and/or ventilation below the main bulkhead deck, astern and forward of the cargo length of bulk carriers excluding spaces for dedicated water ballast, carriage of cargo, storage of substances (e.g. HFO, provisions), installation of machinery and space used by crew. This compartment is suitable for energy storage devices since, being located at the fore peak, it improves the zero trim condition. The volume in certain designs approaches 1200m^3. The space is accessible through manholes from the Bosun's store and the height of the compartment is sufficient for easy handling and removal of components and inspection. However, the bow section of the vessel suffers from movement and slamming, hence the behaviour of batteries subject to such motions requires further investigation. Nevertheless, Common Structural Rules (CSR) and flooding scenarios set high standards for the longitudinal strength of the ship in specific damage conditions. This implies restrictions in weight allocation in forward and aft void or ballast compartments, as in certain scenarios the calculated bending moments exceed the maximum allowed value for the structural integrity

Another potential void space is the lower stool of bulkheads above the double bottom. The preferable selections have to be made as close to the forward perpendicular (between cargo holds 5, 6, 7) as possible in order to create a constant lever around the amidships point. This space is not accessible while cargo is present because the manhole openings are located inside the cargo hold. Nonetheless, a modification can be performed in specific bulkheads in order to be equipped with a housed vertical ladder that would allow access to the manhole of the lower stool. Unfortunately, the cargo volume will be reduced by this modification.

For safety reasons allocation of the batteries, in conjunction with the trim and stability issues, construction aspects such as maintainability, repair and regular visual control of the system, have to be well thought-out. Each compartment has to be easily inspected and maintained without any cargo removal. In case of failure, or flooding, a manual shut down of the electric system has to be implemented. Meanwhile, each array of batteries should have the capability of isolation in case of damage.

The Vanadium Redox flow batteries store the two reactants in different containers and their flow is performed using pumps [20]. When the reactants reach the membrane, the proton exchange occurs and electricity is produced. Consequently, the storage of reactants and the production of energy are two separate activities. Storage can be achieved in a similar manner as with Heavy Fuel Oil (HFO). Tanks allocated in the double bottoms can be used. However, these areas are mainly reserved for HFO storage in existing vessels. According to the new MARPOL regulations concerning the storage of heavy fuel oil, the top side tanks will be used instead of double bottom tanks. The regulation (Annex I regulation 12A) is applied to all new-buildings delivered after 1st August 2010, or for which their keel was laid after 1st February 2008, or their contract was signed after 1st August 2007 [21]. Thus, the double bottom space will be reserved for ballast water. As a result, the designs of new ships with minimum water ballast influence the storage of the reactants.

Nonetheless, judging from the outcome of previous studies [7] [8], a reduction in fuel oil consumption is possible. Thus, the double bottom space will be reserved for ballast water. As a result, the designs of new ships with minimum water ballast influence the storage of the reactants because these designs with V shape hull under the design waterline minimise the void spaces and limit the potential storage areas. Though a reduction in fuel oil consumption was demonstrated with the Hybrid system, hence, the requirement to carry more HFO in tanks is altered and space reserved for HFO can now be used for the electrolyte reactants allowing a flexible determination of storage areas. The largest environmental impact of Redox flow batteries is the polypropylene tanks, the flow frames and the steel stacks [18]. Thus, additional tank retrofitting should be made, in order to accommodate the reactants.

Sodium Nickel Chloride batteries are high temperature batteries that operate at near 300^{o}C [22]. In order to exploit the full energy and power density of these batteries, it is required that this temperature be kept constant and in the range 280 – 360 degrees Celsius to keep the electrodes in a liquid state [23]. As a result, a location near the main cooling system of the engine room is a potential solution. On the other hand, a cooling/ heating installation at the forepeak void space could be investigated. Unfortunately, such a heat exchange installation can increase the cost and the total weight of the system and above all, limit the space reserved for battery equipment. It should be mentioned though that additional space is required for the battery secondary circuit and control. Moreover, for protection purposes, it is advisable to have a switchboard panel installed in every compartment that stores a significant amount of energy, for minimisation of the short circuit risk and the possibility of overall storage system failure.

A schematic approach of the examined All Electric Ship and Hybrid is presented in Figure 4. This electric diagram depicts the consumers, the generators and the storage system. Furthermore, it contains a controller, were the control signals are shown in dashed line. Moreover, the propulsion system is included for clarity purposes. Figure 4 represents two different potential configurations for a hybrid propulsion system to maximise the propulsive efficiency. The final selection of the system depends on the output of the simulated system after runs of optimisation algorithms and engineering risk analysis.

Table 4: Hybrid energy requirements according to ship type [7] and required volume for the installation of selected battery types. Battery characteristics obtained from [21] and from Rolls Royce. Case study for Post-Panamax with Wartsila generators, type 8L32 and 8L26 Tier II. *denotes measured values.

Ship Type	**HandySize**	**HandyMax**	Panamax	Post - Panamax	Capesize
Required Energy [MWh]	8	8	15	5	4
Required Battery Volume m^3 for:					
1) Sodium Nickel Chloride 190Wh/L	42	42	79	26	21
2) Vanadium Redox Flow 30Wh/L	267	267	500	167	133
Engine Room Volume[m^3]	3800	4530	4900	5150	9600
Free volume in current engine room: 35% of total volume	1300	1580	1650*	1760*	3350
Added Volume due to electric components: 1040m^3 Additional Engine Volume: 2x100.4m^3 + 4x59.30m^3 = 438m^3 Deduction for two-stroke engine removal: ~436m^3 Deduction for auxiliary generators removal: ~96m^3					
Suitable for installation only in ER for 1):	no	yes	partially	yes	yes
Suitable for installation only in ER for 2):	no	no	no	partially	yes

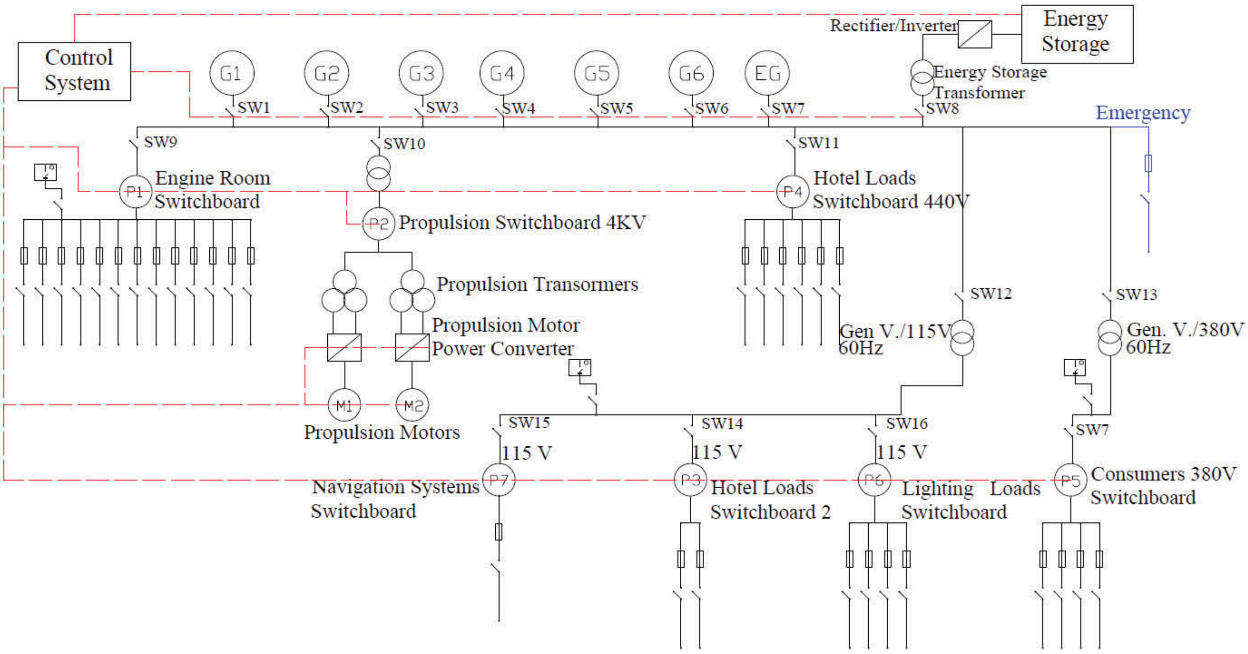

Figure 4: Line Diagram of the proposed AES concept with Energy Storage Device and Advanced Control System. The dashed line represents the controller signal flow, while the connections of the electric consumers and electric propulsion are depicted, including the necessary transformation of voltage.

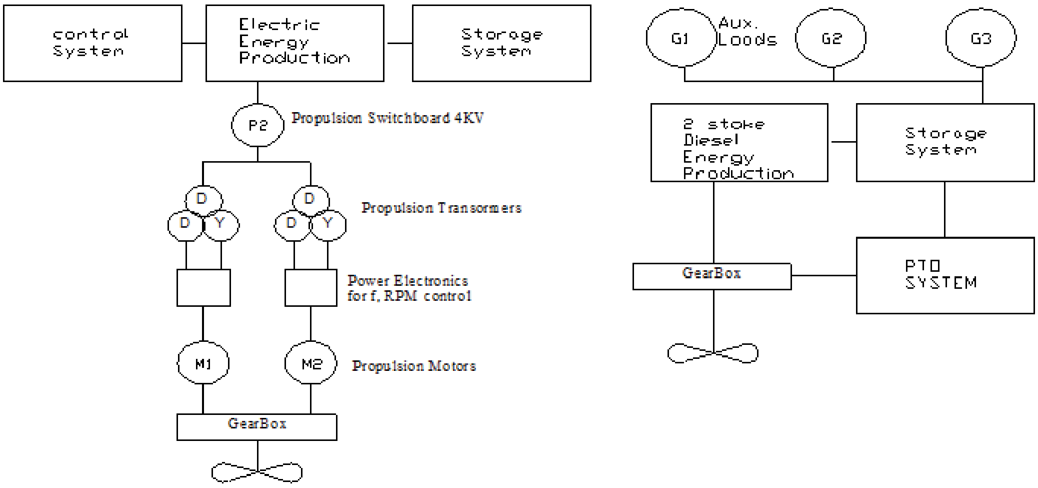

Figure 5: Concept layout and listing of major components of AES Hybrid system and two-stroke conventional hybrid for the propulsion loads.

6. CONCLUSIONS

The combination of energy storage devices for minimization of engine transient loads for emissions reduction appears promising to achieve fuel savings and lower exhaust emissions than conventional installations of machinery. The application of this technology, along with the all-electric ship concept, is feasible when the fluctuation of engine loading exceeds the percentage of the loading range covered by the 'flat' section of the fuel consumption curve of a conventional diesel engine. Although conversion losses from electrical to mechanical and vice versa are potentially significant, the progress of technology and proper sizing of the propulsion system can further reduce the losses in the power chain. The comparison of the fuel consumption of actual vessel operation minus the hybrid system consumption including the transformation losses, power loses for cooling and pumping the reactants can be found in [8]. The amount of savings was multiplied by the appropriate emission factors, as they are adopted by [2]. The likely amount of savings was projected to the world fleet, by multiplying the results of the sample with the category percentage of the world fleet as found in [19].

This study investigated the feasibility of constructing such a hybrid system in dry bulk ships by considering realistic loading conditions and the trim of the vessels, together with a description of factors to be considered in any change in weight distribution. This study showed that the equivalent propulsion system can be installed in current ships. Two feasibility scenarios were investigated; the first includes new-buildings using the current concept design and the second involves an innovative ship design suitable only for new-buildings.

Thus, concerning the first category, the proposed areas suitable for installation of energy storage devices proved to be part of the engine room and the steering gear room. In the cargo length, the lower stool compartments were considered. However, a construction retrofitting of some bulkheads is required, as the criteria of accessibility and monitoring during full load voyages were not met. In the bow section, the void space above the forepeak ballast tank and below the Bosun store was studied. Nonetheless, the ability of the battery system to operate in this location due to the high accelerations that are experienced by bow of the ship (e.g. slamming), requires further investigation.

The new concept design involves more radical change, moving the engine room and the superstructure decks to the bow section and providing the opportunity to also optimise the air drag. Meanwhile, the aft compartment is to be filled by the energy storage devices, the steering mechanism and the electric motors in the case of conventional propulsors.

The operational characteristics of the energy storage system were presented alongside a discussion of the appropriate compartments for their housing. It appears as though the operating temperature in Sodium Nickel Chloride batteries is a crucial criterion in the selection of compartments, however they are an attractive choice since the specific energy per m^3 and the energy density per kg is high. For the second selected battery type, namely Vanadium Redox Flow Batteries, large tanks are required to store the electrolytes (reactants) and their energy density per kg and per m^3 is significantly lower.

The overall design is strictly dependent on the number of generator sets and the installed energy storage devices. The overall feasibility is related to the operating profile of the vessel, the cargo loss, the ship constructional design, the age of the vessel and finally, the overall price of retrofitting, as any payback period of the system is directly related to the fuel savings that may be achieved due to the installation of the hybrid propulsion system.

It was demonstrated that the percentage of cargo loss is less than 1% for Panamax and Post-Panamax bulk carriers, dependent on the payload weight and the presence of ballast in the examined loading cases.

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APPENDIX I

Table A1: Weight and Volumes of machinery components, tanks and rooms located into an engine room of a conventional 2-stroke diesel propulsion system

No	Component	Installed No	Volume [m^3]	Weight [Kg]
1	Main Engine	1	436.48	255000
2	Auxiliary Engine	3	94.88	6030
3	A/C refrigeration Unit Acom.	1	3.31	N/A
4	Auxiliary air Reservoir	1	0.45	218
5	Bilge & Fire	1	5.20	N/A
6	Cabinet solenoid Valve	1	0.20	N/A
7	Central Cooler	1	13.13	1858
8	Compressors & Pumps General	20	27.30	3097
9	Control air Compressor	1	3.02	700
10	Deck Service air Compressor	2	6.05	700
11	Deck Service air Reservoir	1	1.34	446
12	DO Trans. P/P	1	0.11	N/A
13	Drain Cooler with Tank	1	7.20	N/A
14	Drink Hydrophore Unit	1	2.04	N/A
15	Emergency air Compressor	1	1.34	300
16	Fresh Water Generator	1	4.38	595
17	Fresh Water Hydrophore Unit	1	3.00	N/A
18	FWD Seal	1	0.44	N/A
19	HFO Trans. P/P	1	0.46	N/A
20	Hot water Calorifier	1	3.51	300
21	Hyd Power Pack	1	1.53	60
22	Jacket Water cooler D/G	3	0.79	N/A
23	LO Purifier	1	9.58	242
24	LO Purifier Feed Pump	2	0.19	N/A
25	LO Trans Pump	1	0.08	38
26	Local fire P/P	1	0.45	N/A
27	M/E & G/E FO Supply Unit	2	31.00	220
28	M/E J.W. Pre-heater	1	0.31	200
29	M/E Jacket F.W. Cooler	1	0.19	319
30	M/E Jacket Water Pump	1	0.94	115
31	M/E LO Cooler	1	4.70	3820
32	Main air Compressor	1	0.96	480
33	Main Air Reservoir	2	15.87	4530
34	Main Central CFW P/P	3	0.94	1764
35	Main CSW P/P	1	6.00	320
36	Oily Water Separator	1	8.75	650
37	Oily Water Separator P/P	1	0.06	65
38	Purifier	1	49.03	1410
39	Ref. Prov. Plant	1	1.57	N/A
40	Sewage System	1	10.00	N/A
41	Shaft & Bearings	1	21.68	29945
42	Composite Boiler		3.00	20000
COMPARTMENTS INSIDE E.R.				
42	Control Room	1	469.46	N/A
43	Engine Room Store	1	606.16	N/A
44	Engine Room Workshop	1	417.30	N/A
TANKS INSIDE E.R.*				
45	DO SERVICE	1	33.00	35.6
46	DO SETTLING	1	39.50	29.7
47	HFO SERVICE	1	42.30	38.7
48	HFO SETTLING	1	42.30	40.8
49	HFO STORAGE 4 P	1	254.80	245.9
50	HFO STORAGE 4 S	1	419.30	404.8
51	SLUDGE	1	12.30	Depended

52	L/S FO SERVICE	1	40.10	38.7
53	L/S FO SETTLING	1	40.10	38.7
54	CYLINDER OIL STORAGE	1	70.30	62
55	G/E LO STORAGE	1	29.60	26.1
56	M/E LO STORAGE	1	36.80	32.4
57	M/E LO SETTLING	1	29.60	26.1
58	GRAY WATER TANK	1	26.40	Depended
SUMMATION (items marked with * not accounted)			6301	334
Engine Room Free Volume:			2910m^3	

Table A2: Electric Components of an AES vessel inside engine room, found in a modern cruise ship.

No	Component	Installed No	Volume	Weight
1	Propulsion Transformers	4	**159.936**	47200
2	Component	1	**6.48**	-
3	Propulsion Converter SM			
4	Component 1	2	**18.304**	23600
5	Component 2	2	**41.472**	-
6	Component 3	2	**49.28**	23600
7	Component 4	2	33.28	-
8	Propulsion Converter BG			
9	Component 1	1	**27.664**	-
10	Component 2	2	**65.28**	23600
11	Component 3	1	**26.928**	-
12	Component 4	1	**16.64**	-
13	Engine Transformers SM	2	28.56	11600
14	Component 1	1	**3.6**	557
15	Engine Transformers BG	3	**69.12**	24000
16	Component 1	1	**3.6**	557
17	Main Switchboards	1	**104.4**	3300
18	Secondary Switchboard 1	1	35.28	684
19	Secondary Switchboard 2	1	56.88	275
20	Motor Load Control	2	12.672	-
21	Electric Motors	2	274.56	300000
	SUM:		**1033.94**	458.98

Table A3: Basic Characteristics of the examined vessels

	Handymax	Panamax	Post - Panamax	Capesize
FLAG / PORT OF REGISTRY	CYPRIOT / LIMASSOL	BAHAMAS / NASSAU	GREEK / PIRAEUS	GREEK / PIRAEUS
YEAR OF BUILT	2002	2005	2007	2004
CLASSIFICATION	A.B.S.	A.B.S.	L.R.S.	L.R.S
GRT / NRT	30,256 / 17,615	40,480 / 25,890	49,973 / 30,679	87,137 / 56,550
GRAIN (M3)/ BALE (M3)	66,731.2 / 64,729.3	91,720 / 91,510	109,037.9 / 103,586.0	188,916 / 179,470.2
DWT (MT) / DRAFT (M)	51,535.33 / 12,317	75,140 / 14.20	92451,85 / 14,7255	170,050 / 17,813
L (OA) / L (BP) / B (MLD) / D (MLD) / LIGHT WEIGHT	190 / 181 / 32.26 / 17.70 / 9,569.87	225 / 217 / 32.26 / 14.20 12860	229,50 /221,60 / 36,92 / 20,50 / 15515,85 MT	288.97 / 278 / 44.98 / 24.15 / 23,533
MAIN ENGINE TYPE BHP / RPM	MAN B&W 6S50MC-C 12,870 / 127	MAN B&W 5S60MC 12,215 / 92	MAN B&W 7S50MC-C 15,050 / 127	MAN B&W 6S70MC 22,920 / 91
D / GENS TYPE KW / RPM	YANMAR 6N21L-UV 3 X 660 / 720	DAIHATSU 5 DK-20 3 X 530 / 900	YANMAR 6N21L-UV 3 X 660 /720	HYUNDAI B&W 6L 23/30 3 X 780 KW / 720
PROP BLADES DIAM/ PITCH MATERIAL	4-BLADES 6.000 / 4.026 NI-AL-BRONZE	4-BLADES 7.250 / 5.0025 NI-AL-BRONZE	4 BLADES 6.600 / 3.9336 NI-AL-BRONZE	4-BLADES 8.100 / 5.654 NI-AL-BRONZE