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Efficiency constraints of energy storage for on-board power systems

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ABSTRACT

Energy storage has the potential to reduce the fuel consumption of ships by loading the engine(s) more efficiently. The exact effect of on-board energy storage depends on the ship functions, the configuration of the on-board power system and the energy management strategy. Previous research in this area consists of detailed modelling, design, and comparisons of specific on-board power systems for explicitly defined operational profiles. The necessary inputs for these studies are rarely known initially however, since the effect of energy storage on the fuel consumption is not necessarily always positive, it is essential to know the limitations of fuel savings obtained by an on-board energy storage early in the design stage. To that effect, the paper proposes a set of algebraic formulas for the equivalent specific fuel consumption of on-board power systems equipped with electrical energy storage, which give a quick estimation of the maximum fuel savings obtainable. Depending on the specific fuel consumption of the prime mover, the loading point of the system and the use scenario of the battery, relative efficiency improvements can vary between −48% and 57%. A set of design guidelines is also proposed based on the obtained results.

1. Introduction

The use of large scale energy storage has been a popular research subject in recent years. This is not surprising, as energy storage is so far the only way of addressing the fluctuating nature of renewable resources and has therefore been a topic of great interest for the energy sector. While there is some overlap, the maritime industry poses specific challenges to the successful integration of energy storage into on-board power systems: size and weight are of greater importance, the power system is isolated for most of the time and the load characteristic of propellers favours mechanical propulsion. Nevertheless, energy storage is generally identified as an integral part of future marine solutions (Symington et al., 2014; Ahmed et al., 2016; Bolvashenkov et al., 2014; Haugom et al., 2015; Geertsma et al., 2017; Bouman et al., 2017).

In fact, the main reason for using on-board energy storage is to allow the internal combustion engines to run in more efficient operating conditions. In other words, any potential efficiency gains from energy storage are dependent on the functions of the ship, the configuration of the on-board power system, the operational profile and the energy management/control strategy used. The easiest way to understand the complex interrelation between these factors is to look at them from the perspective of ship design.

Chalfant (2015) identifies three distinct stages of ship design: concept design, engineering design and production design. The concept design phase consists of a functional analysis of the future ship, based on which an analysis of alternatives is performed. What the major equipment will be is decided in this phase. Engineering design consists of preliminary design (including the specifications of the main equipment) and contract design. Lastly the detailed design and the construction will take place during production design. Table 1 shows the occurrence of the previously identified relevant factors for determining the viability of on-board energy storage within the different design stages. The layout of the power system configuration (number of engines, electrical/mechanical propulsion, use of energy storage) is selected in the concept design stage and the components are subsequently sized in the engineering design stage. The level of detail regarding the operational profile of the ship may increase as design progresses (and even after the ship is in use) and therefore spans all design stages.

As the most impactful decisions regarding energy efficiency need to be made in the concept design stage, when very little information is available, it is beneficial to integrate it with engineering design (Armstrong and Banks, 2015). Considerable progress has been made in this regard, mainly through the use of evolutionary optimization algorithms (Skinner et al., 2009; Brown et al., 1998; Brown and Salcedo, 2003; Strock and Brown, 2008; Nelson et al., 2013; Sekulski, 2014). These studies are however focused on ship design as a whole and have very little options regarding the configuration of the on-board power system. Previous studies focused specifically on the design of ship power systems are intended for the engineering design stage (Skinner et al., 2009; Dimopoulos and Frangopoulos, 2008; Zahedi and Norum,

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Table 1
Occurrence of factors influencing the viability of on-board energy storage in the ship design process.

<table>
<tr><th>Concept Design</th><th>Engineering Design</th><th>Production Design</th></tr>
<tr><td>Ship functions</td><td></td><td></td></tr>
<tr><td colspan="2">Power system configuration</td><td></td></tr>
<tr><td colspan="2"></td><td>Control</td></tr>
<tr><td colspan="3">Operational profile</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

2013; Zahedi et al., 2014; Kim et al., 2015; Dedes et al., 2016; Roa, 2015; Ling-Chin and Roskilly, 2016). The complexity and level of detail of such models implies their development on a case-by-case basis. Significant effort has also been dedicated to the development of energy management and control strategies which can be employed once the configuration is selected (Geertsma et al., 2017; Cupelli et al., 2015; Trovão et al., 2016; Lashway et al., 2016; Vu et al., 2015; Chen et al., 2015; Bassam et al., 2016) and improved once operation profile data is available (Trodden et al., 2015). Until recently, the relatively small number of options meant that the selection of the power system configuration was reasonably straight forward. However, due to the emergence of alternative fuels and the versatility offered by all electric ships and energy storage this is no longer the case. Steps have been taken towards the integration of these new options into the concept design stage (Boveri et al., 2016; Solem et al., 2015). To the best of our knowledge, no strategy is available for evaluating the use of energy storage in the concept stage of ship design.

The general consensus is that the fuel savings obtained by using energy storage need to be weighed against other costs in order to design a feasible system. However, because of the conversion losses in the system, using energy storage does not always lead to fuel savings. Indeed, emerging technologies are implemented to various degrees for different ship types (Rehmatulla et al., 2017). Using intuitive guidelines in order to decide to investigate energy storage for a particular case (such as: significant operation at low loads, predictable load variation, high redundancy requirements) can result in significant research and development resources being misdirected. The present work identifies quantifiable parameters which determine the feasibility of on-board energy storage regarding energy efficiency. Thus, for the wide range of ships for which energy storage will not result in fuel savings, this option can be safely eliminated in the concept design stage, and for the ships which can benefit from it an initial estimate of this benefit can be made. Moreover, the proposed method offers valuable decision support both before and after an estimation of the operational profile is available.

The following section will describe the general modelling approach, while Section 3 provides detailed information on the modelling of specific components. The different scenarios for which the use of energy storage is modelled are presented in Section 4. Additionally, Section 5 includes other design criteria which can be considered in the early design stages and which can affect the presented results. Calculations for three sample engines, with very different part-load performance, show a large variety in the potential benefits of using energy storage. The results are then compared with more detailed analysis found in literature for specific cases (Section 6). As mentioned before, the model is intended specifically for the early design stages, it was therefore important to make its limitations and applicability clear (Section 7). Lastly, the main conclusions of the presented work are given in (Section 8).

2. Methodology

The present work is based on a comparison between the fuel savings achievable by running the engine under more efficient conditions and the fuel used to generate the power necessary for the conversion process.

There are three primary steps: calculating the equivalent specific fuel consumption (esfc) for the benchmark (no energy storage) case, taking into account transmission losses (Equation (1)), calculating the equivalent specific fuel consumption for the additional power generated, which will be used to charge the energy storage (Equation (2)), determining the equivalent specific fuel consumption for the power output of the battery (Equation (3)). Note that the conversion losses will be dependent on the configuration and power pathway being investigated. This will be explained in more detail in Section 4.

$$esfc_{benchmark} = \frac{sfc_{engine}}{\eta_{benchmark}} \tag{1}$$

$$esfc_{surplus} = \frac{esfc_{benchmark}(optimum\ engine\ load) \times optimum\ engine\ load - esfc_{in}(load) \times load}{optimum\ engine\ load - load} \tag{2}$$

$$esfc_{battery} = \frac{esfc_{surplus}}{\eta_{battery}} \tag{3}$$

Several guiding principles were used in the development of the approach for the present study. These are the following:

1. The efficiency models used for each component in the system were simplified as much as possible. The only variable input parameter for these models is the percentage of the nominal load of the component. Some components were assumed to have constant efficiency. All simplifications are based on a literature review.
2. The calculations are done for the best case scenario: all necessary simplifications are done in a way that is more likely to under-estimates losses rather than over-estimate them.
3. The study only investigates the cases where the stored energy is produced on-board. To that effect, the equivalent specific fuel consumption for running on batteries will be calculated. This allows a more intuitive comparison and highlights the link to CO_2 emissions, which in the absence of after-treatment are almost exclusively dependent on the amount of fuel used.

In agreement with the research approach presented, it is assumed that the battery is always charged by running the engine at its most efficient point. To that effect, an equivalent specific fuel consumption can be calculated by determining how many more grams of fuels needed were consumed in order to get the power generated for the battery and dividing this value by the surplus power generated (Equation (2)). Note however, that the same equation applies if, due to capacity constraints for example, the engine is run at a sub-optimal loading point (the new load replacing the optimum engine load in the formula).

3. System components

3.1. Energy storage

Reviews on the use of energy storage for high power applications suggest Li-ion batteries as the most promising candidate for maritime applications (Luo et al., 2015; Farhadi and Mohammed, 2016; Chen et al., 2009). Alternatively, super-capacitors can offer significant advantages in the area of transient operation and can be used successfully in combination with batteries (Ghiassi-Farrokhfal et al., 2016; Burke et al., 2014; Hemmati and Saboori, 2016). However, since they are still early in the research and development process, the core efficiency study will be performed exclusively for Li-ion batteries. Flywheels are also an option that should be investigated in the future (Faraji et al., 2017).

State of charge (SOC) is an important parameter for safety and control and much effort has been invested in the development of models that can estimate it (Zheng et al., 2016; Zhao and de Callafon, 2016; Zhang et al., 2016; Barré et al., 2013; Suresh et al., 2016). Nonetheless, its influence on the efficiency of the battery itself is negligible (as long as the battery is not over discharged). Instead, the most important factors influencing battery efficiency are the charge and discharge currents (Li and Tseng, 2015). For the purpose of the present work, the size of the energy storage is defined by its power output at $1C$ (a $1C$ rate means that the charge/discharge current will charge/discharge the entire battery in 1 h). The value is therefore inter-changeable with capacity, a $nkWh$ battery will provide nkW of power at $1C$. This approach offers an easy link between power demand and C-rates. The formulas used for the efficiency of the battery are those experimentally obtained by Li and Tseng (2015):

$$\eta_{charge} = 0.003 \times C^2 - 0.0297 \times C + 0{,}99814 \tag{4}$$

$$\eta_{discharge} = 0.002232 \times C^2 - 0.0246 \times C + 1 \tag{5}$$

The effect of self-discharge will also not be included, as in the case of Li-Ion batteries this is estimated at 0.1%–0.3% a day (Hemmati and Saboori, 2016). Note however that this can be higher if the SOC is high and is dependent on temperature (Schmidt et al., 2015; Wang et al., 2002; Pathiyil et al., 2016a,b) so self-discharge may be worth including at the detailed design stage.

3.2. Transmission elements

The efficiency of the relevant converters is generally high in the power range commonly found on board. Moreover the performance of these elements doesn't vary significantly over around 20% load (Aamir and Mekhilef, 2016; Vazquez et al., 2016; Davari et al., 2016; Wang et al., 2016; Sivakumar et al., 2016; Szcześniak et al., 2015). The highest values encountered in literature for the efficiency of these elements was considered in the present study, as dictated by the research approach. Table 2 shows the values used in the calculations.

3.3. Internal combustion engines

Three different variations of the diesel engine were considered: traditional diesel engine, dual-fuel engine in gas mode and diesel engine with sequential turbo-charging (STC). These are the main options for engine selection in early ship design. The choice is generally a trade-off between efficiency, low initial costs and technological maturity (traditional diesel engine), fuel costs and reduced green house gas emissions (dual-fuel engine) and dynamic response (STC engine). As Fig. 1 shows, these engines also exhibit different trends in their specific fuel consumption. The gas engine has significantly worse relative low-load performance than the diesel engine, while engines with STC have almost constant sfc over the entire loading range. The drop in efficiency at part-load characteristic of diesel engines is crucial to any potential benefits of using energy storage. To that effect a representative engine from each of the three categories was selected. Since there is very little difference in the relative part load performance of engines between different manufacturers, specific fuel consumption data given by MAN Diesel & Turbo was used as the basis of the calculations. The values extracted from the product guides of these engines can be seen in Table 3. The choice in manufacturer was made solely because of the availability of sfc data for the 10% loading point. The diesel mode of the DF engine was considered instead of another, more traditional, diesel engine because of the same reason (after ensuring that the values were comparable).

Table 2
Assumed efficiency of the transmission elements.

Component	Efficiency
Rectifier	98%
Inverter	98%
Gear Box	98%
Transformer	~100%

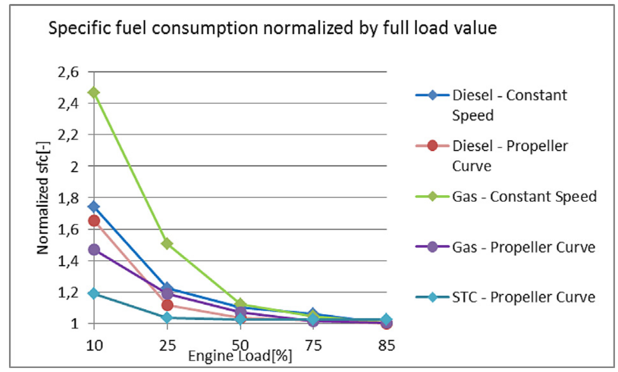

Fig. 1. Normalized specific fuel consumption for the engines and operating modes in Table 3.

3.4. Electrical machinery

For the present study, synchronous machines were used, as they are the most common in hybrid applications (El-Refaie, 2013) (Calfo et al., 2002). The efficiency of AC machines is heavily dependent on their rated power (Ferreira et al., 2015). Fortunately, as the sizes increases, the efficiency levels off at around 97%–98%. Motors/generators which can be used for on-board power systems are expected to fall within this range.

The estimation of part-load efficiency is more elusive. Manufacturers generally give a very slight drop in efficiency from nominal to 75% load, however measurements done by Dedes et al. (2016) showed a drop of approximately 4 efficiency points in that load range. Moreover, simulations starting from the individual losses, suggested the opposite efficiency trend in the same load range (Zahedi and Norum, 2013) (Zahedi et al., 2014). Both cases were reported for optimal speed/frequency. Since the main focus of the present study is on the best case scenario, the most favourable efficiency will be used for the initial calculations (flat 97% efficiency).

4. Energy storage use scenarios

Four scenarios are investigated based on combinations of two different criteria: the type of propulsion and the intended use of the energy storage. There are three main types of transmission on board ships: mechanical, electrical and hybrid. From these, only the electrical and hybrid can be combined with electrical energy storage. The paths to and from the battery are the same in both transmission types: generator, rectifier, battery charging, battery discharging, inverter, motor. However, because of the original power flow (when no energy storage is involved), the relative benefits of using energy storage will differ significantly. The second criterion used to differentiate between different use scenarios is whether the battery replaces some of the existing installed power (downsizing), or adds to the existing installed power, providing an alternative power source at low loads.

4.1. Hybrid transmission

Hybrid transmission (PTO/PTI) uses a shaft motor/generator which can be used to link a traditional mechanical propulsion to an electric grid or a battery. In this case, the battery takes the power from the shaft and puts it back into the shaft. In other words, all the electric transmission losses are associated to the battery. The transmission loss associated to the original propulsion system is just the gear box. This is

Table 3
Specific Fuel consumption data used for energy efficiency calculations (MAN L35/44DF, 2017; MAN V28/33D, 2017; MAN V28/33D).

Engine	SFC [g/kWh]/[kJ/kWh]											
	100%		85%		75%		50%		25%		10%	
	n = ct.	prop.	n = ct.	prop.	n = ct.	prop.	n = ct.	prop.	n = ct.	prop.	n = ct.	prop.
MAN 35/44DF-D	175.5	175.5	175.5	175.5	186.5	179	193.5	182	214.5	196	306	290
MAN 35/44DF-G	7470	7470	7515	7515	7810	7595	8390	8020	11230	8870	18420	11000
M V28/33D STC	189	189	186.5	192	185.5	193.5	202	193.5	247	195.5	–	~225

reflected in the formulas used to calculate the equivalent specific fuel consumption (esfc) of the system.

$$\eta_{benchmark} = \eta_{gear\ box} \tag{6}$$

$$\eta_{battery} = \eta_{generator} \times \eta_{rectifier} \times \eta_{charge} \times \eta_{discharge} \times \eta_{inverter} \times \eta_{motor} \tag{7}$$

4.2. Electric transmission

With electric transmission most of the electrical losses occur regardless of the presence of energy storage. To that effect, the power from the battery will be taken from and returned to the grid. The losses of the generator, rectifier, inverter and motor are associated to the original system and only the charging and discharging losses are associated to the use of energy storage.

$$\eta_{benchmark} = \eta_{generator} \times \eta_{rectifier} \times \eta_{inverter} \times \eta_{motor} \tag{8}$$

$$\eta_{battery} = \eta_{charge} \times \eta_{discharge} \tag{9}$$

4.3. Energy storage replaces part of the installed power (downsizing)

In the case of downsizing, the esfc presented is composed of the esfc of the original system offset by the necessary amount for low loads, and an averaged mean between the esfc of the engine and that of the battery at high loads (Equation (10)). This is mainly representative of situations where energy storage is used to provide a boost to the engine at high speeds, making it possible for the same maximum speed to be achieved with a smaller engine. Consequently, the engine would run more efficiently over most of the operating range of the ship.

In the case of electric propulsion, this is also representative of using energy storage to achieve redundancy requirements (spinning reserve). For example, if two generator sets running at 25%load each to ensure the necessary spinning reserve one can be switched off if the energy storage can provide sufficient back-up power. This would lead to one generator set running at 50% load. From the perspective of the equivalent specific fuel consumption, this case is the same as the one above.

The last application reflected by these calculations is load levelling (or peak shaving). While this is mainly used to reduce severe transient loading of the engine (and thus reduce maintenance costs), it can also improve efficiency in some cases. For example, if the load is split between two engines, and the load requirements fluctuate between 40% and 60%, one of the engine can be turned off if energy storage is used for load levelling This case is also represented by the same esfc as the two above.

$$esfc_{in} = \begin{cases} esfc_{in}\left(\frac{load \times 100}{100 - P_{bat}}\right) & \text{if } load \le 100 - P_{bat} \\ esfc_{in}(optimum\ engine\ load) \times \frac{load}{100 - P_{bat}} & \text{if } load > 100 - P_{bat} \\ \quad + esfc_{bat} \times \left(load - \frac{load}{100 - P_{bat}}\right) & \end{cases} \tag{10}$$

4.4. Energy storage increases the installed power

If the battery is used as an alternative power source, the calculations were made under the assumption that the engine will be turned off and the battery will be used as an exclusive power source instead. The amount of the installed power replaced by the battery was calculating assuming 1 C rate discharge. This is in accordance with the ”best case scenario” principle. The equivalent specific fuel consumptions for the battery calculated in Equation (7) and Equation (9) are used to calculate the specific fuel consumption of the main engine, adjusted for losses.

$$esfc_{in\ (adjusted\ for\ losses)} = \frac{esfc_{bat} \times (optimum\ engine\ load - load) + esfc_{in}(load) \times load}{optimum\ engine\ load} \tag{11}$$

5. Additional design criteria

The focus in early design stages is very often placed on costs and finding cost-effective solutions. Unfortunately, cost models require significant input data which is dependent on local markets. It is, therefore, not feasible to create a generic cost model, however, several criteria will have a direct and predictable impact on the total life-cycle costs of the ship. This section presents the three design criteria which will have the biggest influence on different costs: the size of the battery will influence both initial costs and maintenance costs (through the profile of the battery state of charge and, consequently, battery ageing (Barré et al., 2013)); the engine running hours is the most important criterion influencing maintenance costs and the operational profile, together with the energy efficiency, will determine the overall fuel costs.

5.1. Battery size

For all types of engines the results will show only a slight benefit to the increase of battery power (or capacity, see section 3.1), in the case of battery only operation. This happens because the only effect of size in the current model is in the dependency of the battery penalty factor efficiency on charge and discharge rates.

In reality however, the capacity of the battery plays a much more important role, as a small capacity would result in the engine needing to be turned on and off at a very high frequency. The capacity required to obtain the presented results can be calculated by setting a minimum value for uninterrupted engine running time (Equation (12)). If necessary the *optimum load* parameter can be replaced with another load in order to obtain a lower battery capacity. A subsequent replacement in Equations (2), (10) and (11) will show the efficiency penalty resulting from the decrease in battery capacity. The battery capacity is also a predictor of size, weight and initial costs.

$$battery\ capacity = (optimum\ load - load) \times (minimum\ uninterupted\ engine\ running\ time) \quad (12)$$

In the case of downsizing, there is also a limit to the amount of power which can be replaced by energy storage. An initial estimation of this value can be deduced from the basic operational profile of the ship (Equation (13)). The load here was considered to be given as a percentage of the benchmark installed power.

$$\sum_{load=1}^{100} percentage\ of\ time\ spent \times (100 - P_{bat\ max} - load) \geq 0 \quad (13)$$

5.2. Engine running hours

A common reason of using energy storage is to reduce the running hours of the engines on-board. Since engine maintenance is generally performed after a certain number of running hours, this can have a significant impact on maintenance costs. The potential reduction in engine running hours is also dependent on the loading of the system. The greatest reductions will be achieved if the engine is run at nominal load when charging the batteries. Equation (14) can be used to determine the reduction in engine running hours obtainable at different loading points. The value represents the fraction of time the engines will be running if energy storage is present compared to the benchmark scenario.

$$running\ hours\ ratio = \frac{1}{\frac{optimum\ engine\ load - load}{load} + 1} \quad (14)$$

5.3. Operational profiles

In the concept design stage data regarding the operational profile is generally estimated by identifying different operating modes, the characteristic load for each mode and the percentage of time the ship will spend in each mode. As Equations (1) to (3), (10) and (11) are all a function of load, they can be used to determine the sfc corresponding to each operating mode. Equation (15) determines the average relative efficiency gain for an operational profile given in this format.

$$\eta_{gain} = \sum_{n=1}^{no_{modes}} \frac{\min(esfc_{in}(cload_n), esfc_{benchmark}(cload_n)) - esfc_{benchmark}(cload_n)}{esfc_{benchmark}(cload_n)} \times p_n \quad (15)$$

Where:

η_{gain} = average relative efficiency gain;
no_{modes} = number of operating modes;
$cload_n$ = characteristic load of operating mode n;
p_n = percentage of time spent in operating mode n;

In order to compare the potential fuel savings obtainable by energy storage with those obtainable by increasing the number of engines, the loading point of the engine needs to be adjusted accordingly and any redundancy requirements need to be accounted for. Equation (16) shows the appropriate equations to use if two engines are considered and no operating mode has particular redundancy requirements. Note that the relative efficiency gain obtained through this formula will overestimate the benefits as the decrease in efficiency with engine size is not taken into account.

$$\eta_{gain} = \sum_{n=1}^{no_{modes}} \frac{esfc_{benchmark}(load) - esfc_{benchmark}(cload_n)}{esfc_{benchmark}(cload_n)} \times p_n;\ \text{Where}\ : load = \begin{cases} cload_n \times 2 & \text{if } cload_n \leq 50\% \\ cload_n & \text{if } cload_n > 50 \end{cases} \quad (16)$$

Lastly, if the focus is on comparing the overall fuel costs, then it is also important to keep in mind the relevance of the percentage of time the ship is in use.

6. Results

This section shows the relative efficiency of using energy storage for different loading points, scenarios and prime movers. Additionally, the obtained results are analysed from two very important aspects: the size of the battery and the sfc curve of the prime mover. Lastly, in the case of downsizing a distinction is made between the benefits of energy storage and that of the efficiency driven selection of prime movers.

6.1. Relative efficiency

The results obtained for configurations containing diesel engines are shown in Fig. 2 and Fig. 3. As expected, the highest efficiency improvements are obtained in the case of diesel-electric propulsion. In such configurations, the majority of transmission losses are present even if energy storage is not used. In the case of hybrid transmission, a significant amount of the energy saved by running the diesel engine at a more efficient loading point is lost by converting the mechanical energy into electrical energy and back. In fact, significant improvements in energy efficiency are observed only at the 10% loading point. The figures also show that, in most cases, downsizing provides fewer benefits than increasing the total installed power and allowing battery only operation.

The drop in efficiency at low loads is much more pronounced in the case of gas engines. Consequently, the efficiency improvements attainable through energy storage are more evident (Fig. 4 and Fig. 5).

In the case of engines equipped with sequential turbo chargers, the specific fuel consumption varies very little throughout their entire operating range. To that effect, almost no benefits can be claimed by adding energy storage to such systems (Fig. 6).

6.2. Benchmark sfc curve

As can be seen from the three cases presented above, the shape of the benchmark esfc curve is the main determining factor for the applicability of energy storage to a particular system. Moreover, this also holds true for a specific loading case. Indeed, because of the capacity constraint it might be more efficient to run the engine in a suboptimal loading point. From Equation (2) and Equation (3) it follows that the minimum requirement of the benchmark esfc, in order to obtain any efficiency benefits from using energy storage is given by Equation (17). Note that the units of measurement are irrelevant for this equation.

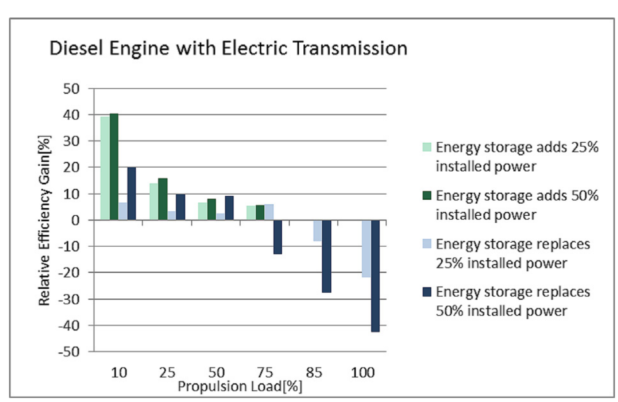

Fig. 2. Relative efficiency of using energy storage with a diesel-electric propulsion system.

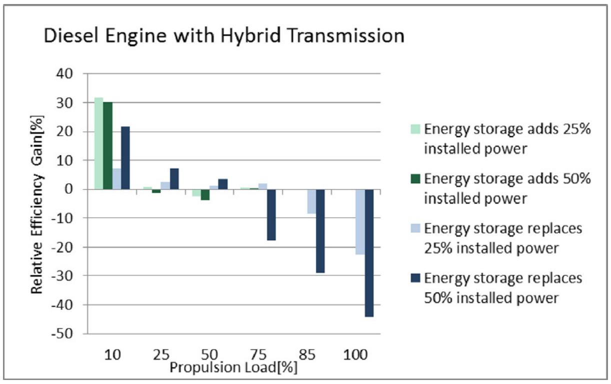

Fig. 3. Relative efficiency of using energy storage with a diesel-hybrid propulsion system.

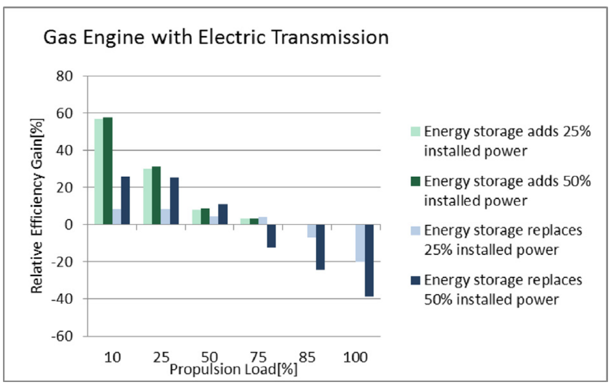

Fig. 4. Relative efficiency of using energy storage with a gas-electric propulsion system.

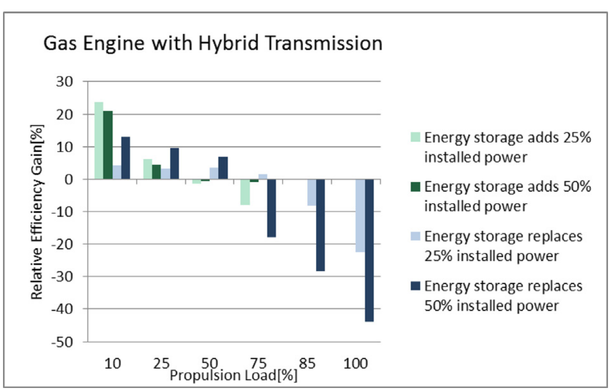

Fig. 5. Relative efficiency of using energy storage with a gas-hybrid propulsion system.

$$\frac{esfc_{benchmark}(load + surplus)}{esfc_{benchmark}(load)} < \frac{surplus \times battery\ penalty + load}{surplus + load} \tag{17}$$

6.3. Downsizing

While the three cases represented by downsizing (PTI, load levelling and spinning reserve) all result in the same equivalent specific fuel consumption, in the case of PTI the benefits obtained are not specific to the use of energy storage. In fact, better fuel efficiency can be achieved by using an additional engine. This is evidently not a good alternative if energy storage is used as spinning reserve, as it is the very option it replaces. To a certain extent this also holds true for load levelling, where dynamic loading would not allow for the additional engine to be turned on and off at the demanded rate. In other words, it depends on whether the energy storage is used to literally downsize the main engine, or if it is used to avoid turning on an additional engine.

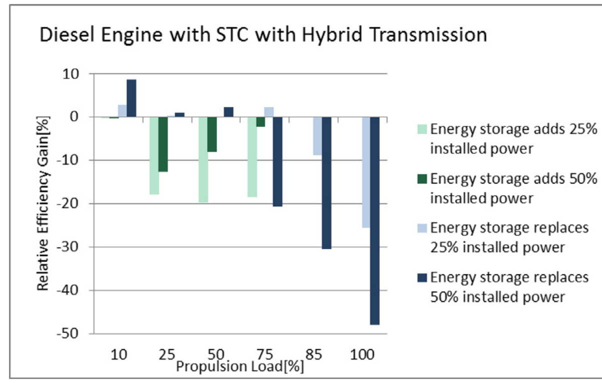

Fig. 6. Relative efficiency of using energy storage with a diesel-hybrid propulsion system and sequential turbo-charging.

6.4. Validation

State of the art in this area generally focuses on advanced techniques in control and energy management. To that effect, few studies have been done that isolate the benefits of energy storage. Nonetheless (Zahedi et al., 2014), offers a great opportunity for validation, as the results not only isolate the effect of energy storage, but are also broken down by operating modes. The operating modes are defined by a characteristic loading of the system and therefore are easily comparable with the obtained results.

As can be seen from Table 4, the obtained results are generally overly optimistic, in keeping with the ”best case scenario” strategy adopted. This discrepancy is further exacerbated by the fact that the DC system in the comparison study allows for variable speed operation at part load of the generator sets, which affects the shape of the sfc curve and diminishes the benefits of energy storage. The only unexplained result appears in the 33.5% loading point (which represents the transit supply operating mode). Unfortunately the level of detail provided in the comparison study does not allow for a more in-depth explanation of this error. Other studies also seem to support the present results. For example (Dedes et al., 2016) reports a 5.81% increase in efficiency at approximately 50% load, which is only slightly smaller than the obtained 7.87%. In (Godjevac et al., 2017) fuel savings of 15% are reported for the use of energy storage as spinning reserve in the case of dynamic positioning. This is similar to the 18.94% reduction obtained for the same case with the proposed method (downsizing scenario).

Table 4
Comparison of obtained results with results obtained with a more detailed modelling technique.

Loading point [%]	Improvement due to energy storage ((Zahedi et al., 2014)) [%]	Maximum improvement according to results [%]
33	12.2	13.23
53	3.2	7.6
50	4.7	7.87
17	14	29
66	0.5	6.45
72	0.2	5.9
33.5	15	13.08

7. Discussion

Due to the practical nature of the presented work, it is important to emphasize both its applicability and its limitations. The structure of this section reflects this fact.

7.1. Applicability

The fact that determining the right capacity for the on-board energy storage and designing a suitable control strategy are such complex tasks, is the main reason why it is important to have a preliminary assessment of the applicability of energy storage for a specific ship. Moreover, the simplicity of the equations allows for a large number of different configurations to be analysed, and thus facilitates a pre-selection of the configurations investigated by more complex simulations. The exclusive use of algebraic equations also makes the model suitable for integration into complex optimization algorithms.

The examples presented here were for arbitrarily selected sample engines representing the different operating principles which most affect the shape of the sfc curve,. Naturally, the equations can be used with any specific fuel consumption data available. Further more, as was shown in the test case, the formulas can be easily scaled for configurations containing multiple engines. Overall, this allows for preliminary estimations of potential fuel savings from energy storage for a specific operational profile to be calculated almost instantly. Additionally, an initial comparison of several competing configurations is easily accessible. The additional criteria included can be integrated into cost models for an initial estimation of total life cycle costs.

7.2. Limitations

The proposed method has seven main limitations:

1. The constant efficiency of the electric motor/generator can artificially inflate the estimated benefits in the case of hybrid transmission and underestimate them in the case of electric transmission. This enforces the already noted fact that energy storage offers more benefits when used together with electric propulsion.
2. When designing on-board power systems with energy storage, the capacity of the batteries is generally one of the key parameters. However, determining this parameter is not only the result of a complex trade-off (which also needs to take into account battery ageing), but it also requires a much more detailed operational profile, specifically, the order and duration of the different operating modes.
3. The control strategy of the power system also plays an important role. An advance strategy can lead to savings of around 9% (Vu et al., 2015).
4. Downsizing and battery operation have been presented here as two distinct scenarios. It was assumed that in the case of downsizing, battery only operation was not possible, as the batteries needed to maintain a minimum state of charge for redundancy purposes. In practice, for some operational profiles, advanced control algorithms can ensure the viability of combined systems, in which the energy storage can be used for both downsizing and as an alternative power source.
5. Several other, smaller factors are assumed to be investigated in a more detailed design stage. While the main costs considerations are related to the fuel consumption and the size (capacity) of the battery, maintenance costs of the engines are also affected by the use of energy storage: positively by avoiding operation at very low loads and negatively, by potentially turning them on and off more often. Another aspect that can influence the results, is local environmental restrictions. For example, reducing noise can be an incentive for battery only operation.
6. The availability and price of shore power plays an important role in estimating the benefits of energy storage for a particular case. While this was not explicitly included in the model, it can be added easily if fuel consumption is replaced with costs.
7. At the 10% loading point, the efficiency of the transmission elements may be significantly lower than the values used. If this loading point is of particular interest, the values should be adapted accordingly

The limitations presented above, reinforce the suitability of the method for the concept design stage.

8. Conclusions

Several general observations on the use of energy storage on-board ships can be made from the presented results:

1. Systems with electric transmission benefit more from the use of energy storage than systems with hybrid transmission, as there are less losses associated to the battery.
2. The size of the battery is mostly relevant through the limitations on its use imposed by capacity (in the case of battery only operation) or through how much of the installed engine power it can replace. By comparison, the effect on efficiency resulting from different C-rates are negligible.
3. Gas engines benefit significantly more from energy storage, as their efficiency decreases more drastically with load.
4. Engines with sequential turbo-charging are unsuitable for use with energy storage from the perspective of energy efficiency.
5. At most operating points, using the batteries as an additional power source (increasing the installed power) results in higher potential fuel savings than downsizing the engines.
6. Energy storage shows potential for fuel savings only for low load operation, using energy storage at high loads can actually lead to increased fuel consumption.

The conclusions listed above offer some very basic guidelines for the design of on-board power systems with energy storage. However, the strength of the present work lies in its easy adaptability to specific cases, providing insight at a very early stage in the design process.

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