Ocean Engineering 162 (2018) 239–247

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Efficiency constraints of energy storage for on-board power systems

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ARTICLE INFO

Keywords:
Hybrid propulsion
Electric propulsion
Energy storage
Ship design

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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https://doi.org/10.1016/j.oceaneng.2018.05.004
Received 7 November 2017; Received in revised form 22 March 2018; Accepted 2 May 2018
Available online 29 May 2018
0029-8018/

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

Concept Design	Engineering Design	Production Design
Ship functions		
Power system configuration		
		Control
Operational profile		

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