A review of energy efficient methods for all-electric ships

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Abstract. With stringent environmental regulations and growing concerns on energy consumption of the marine transport sector, there is a serious effort to make on board energy system more efficient. Improving fuel efficiency is conceived as a sustainable measure in terms of reducing greenhouse gas (GHG) emissions and overall marine energy use. As such, electrification of ship propulsion has been introduced as a solution for operating at higher efficiency and hence more saving fuel. However, energy efficiency in the context of marine transport is to be more stringent over time as required by International Maritime Organization (IMO). The energy performance indicators to evaluate such requirements include Energy Efficiency Design Index (EEDI) and Energy Efficiency Operational Indicator (EEOI). Several energy efficient methods are therefore proposed to further improve fuel efficiency on board electric vessels. These involve integration of energy storage system, implementation of DC distribution, optimal power distribution and scheduling as well as various operational practices that are currently applicable for existing conventional vessels. The paper summaries the concept of ship energy efficiency in terms of the standard indicators and provide a brief review on the energy efficiency improvement strategies published in literature. The aim of the review is to analyze the methods that are potential to incorporate into the autonomous system of all-electric vessels. The results show a significant variation in reported efficiency gain and thus a combination of various methods is suggested to achieve full potential for emissions reduction.

1. Introduction

For centuries, maritime transport has played a crucial role in the global economic system and lain at the heart of worldwide transportation networks. It is estimated that the world commercial fleet currently consists of over 93,000 vessels and has a combined tonnage of 1.86 billion dwt [1]. Consequently, there is an increase in public concerns regarding environmental impacts due to maritime traffic emissions. According to recent studies, CO₂ emissions produced by maritime sector account for approximately 3% of global anthropogenic greenhouse gas (GHG) emissions [2]. As indicated by the International Maritime Organization (IMO), if no further mitigating measures are enforced, the projection of emissions is expected to increase up to 250% by 2050 [3].

In this concern, the marine industry is forced to comply with stringent restrictions on the ship emissions imposed by IMO. The International Convention for the Prevention of Pollution from Ship (MARPOL) adopted by IMO has introduced a new chapter of MARPOL Annex VI to enforce shipping companies to further reduce GHG emissions through the use of mandatory efficiency standards [4]. The standards include Energy Efficiency Design Index (EEDI) and Ship Energy
Efficiency Management Plan (SEEMP) as well as Energy Efficiency Operational Indicator (EEOI) which are established with the main objective of ship emissions reduction by implementing technology advancements and employing practices for fuel efficient operations.

For the requirement of more efficient ships, extensive electrification of marine platform has become a topic of extensive research in the course of recent years. Electric propulsion implemented with integrated power system (IPS) appears as a very promising technology to comply with the environmental regulations through the contribution of higher fuel efficiency system. The concept of IPS is to enable ship propulsion system and all electrical loads to be powered from a single set of power generation units and thus eliminating the requirement of mechanical connections. A generic single line diagram of IPS is shown in figure 1.

In this paper, a brief review on efficiency improvement methods for all-electric ships through energy management and innovative concepts is presented. In details, ship energy efficiency concepts are introduced in Section 2. Potential energy efficiency improvement methods complying with the emissions framework are reviewed in Section 3. A brief discussion is given in Section 4, and finally conclusions are in Section 5.

2. Ship energy efficiency

Energy efficiency in the context of marine transport correlates with the amount of fuel energy required with respect to ship capacity and transport work [5]. Based on this definition, performance of overall on-board energy system is to be evaluated via energy efficiency indicators inaugurated by IMO. Such indicators are Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). Energy Efficiency Operational Indicator (EEOI) is also proposed as a monitoring tool for the SEEMP. These indicators are mandatory measures as energy efficiency standard for improved ship design and operation. The IMO has imposed requirements on the ship energy efficiency for existing and new ships with 400 gross tonnage and above to comply with the regulations by January of 2013 [4].

2.1 Energy Efficiency Design Index (EEDI)

A concept of EEDI is to quantify CO₂ emissions which are considered the most significant GHG released from ships and to define baselines for newly-built vessel design. The index is planned to be more stringent every five years [3]. In this direction, development of more efficient vessels would be
encouraged progressively. Accordingly, shipowners can exploit the latest technologies for specific ship requirements to satisfy the environmental regulations. A general representation of the EEDI with the respective emissions conditions can be estimated with the following equation:

\[
\text{EEDI} = \frac{E_{ME} + E_{AE} + E_{PTI-AE(\text{Reduction})} - E_{ME(\text{Reduction})}}{\text{Transport work}}
\]  

(1)

Where complete definition of variables can be referred to [6]. The EEDI equation is influenced from five primary terms which each emissions-related term is predominated by the product of specific fuel consumption (SFC) and power demand.

- \( E_{ME} \): Main engine emissions represent total energy demand for the main engines
- \( E_{AE} \): Auxiliary engine emissions represent total ship service loads and electrical power requirements for the propulsion system
- \( E_{PTI-AE(\text{Reduction})} \): Power take in emissions represent shaft motor/generator power which can be reduced by energy saving technologies eventually present on board for the auxiliary system
- \( E_{ME(\text{Reduction})} \): Main engine emissions reduction represents energy saving technologies for the propulsion power
- Transport work represents ship capacity and ship speed

It should be noted that this formula may not be applicable to a vessel comprising non-conventional propulsion system except for cruise passenger ships and LNG carriers due to undetermined key variables in the equation [6]. However, based on continued improvement on EEDI calculation guidelines, the IMO intends to expand the standard to cover more ships types and propulsion systems by modifying the formula in the future.

2.2 Energy efficiency operational indicator (EEOI)

EEOI is established to represents an operational measure tool for evaluating energy efficiency of ship operations. The voluntary guideline of this indicator is applicable for all existing ships to assist ship operators in assessment of operational performance and implementing efficiency improvement practices on board. The EEOI expresses in terms of \( \text{CO}_2 \) emissions per unit of transport work. However, as against the EEDI which considers only single operating condition, the EEOI measures the actual \( \text{CO}_2 \) emissions from combustion processes of all fuel types over a certain period [5]. A general representation of average EEOI for a number of voyages is calculated as [7]:

\[
\text{Average EEOI} = \frac{\sum_i \sum_j (FC_j \times C_F)}{\sum_i (m_{\text{cargo}} \times D_j)}
\]

(2)

Where \( j \) is the fuel type; \( i \) is the voyage number; \( FC \) is the mass of consumed fuel; \( C_F \) is the fuel mass to \( \text{CO}_2 \) mass conversion factor; \( m_{\text{cargo}} \) is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships; and \( D \) is the distance traveled by the vessel.

3. Energy efficiency improvement strategies

This section presents some technologies and energy management approaches for fuel efficient operations of all-electric ships. Based on the energy efficiency design and operational index calculation, \( \text{CO}_2 \) emissions emitted by a vessel are directly proportional to fuel consumption in which an emissions factor is applied to the formula [6,7]. An effort to reduce fuel consumption is hence roughly equivalent to a reduction in \( \text{CO}_2 \) emissions.

3.1 Energy storage system

An integration of energy storage greatly contributes to the optimal operation through enhanced load levelling and alleviation of power fluctuation. Like the automotive industry, batteries are primary used on-board vessels by reason of relatively high energy density and low-cost solution compared to other
storage media. The characteristic of remaining high efficiency at practical discharge currents is also attractive for applications that require sustained operations.

A study in [8] analyzes battery technology in the scale of global shipping focusing on bulk carrier sector. The use of batteries proves to be more effective in reducing emissions which the potential for 1.8% reduction in world shipping GHG could be achieved. A comparison of battery types is also made to examine an appropriate technology for installation on board. From an economic point of view, Sodium Nickel-Chloride battery is feasible for initial investment return, while other storage medium is still at high cost or not yet suitable for marine applications.

In [5], a power management strategy for integrated battery system is presented within the EEOI constraint. The proposed strategy manages the batteries to store energy during low load operations and distribute power when the load demand is high. Alternatively stated that the propulsion power is increased during low load and decreased for high load. This leads to optimal power adjustment for propulsion system while keeping emissions low.

An application of battery system for low emissions operations is provided in [9]. The batteries are introduced to support single generator operation (SGO) which is an alternative practice to enhance fuel efficiency through maximizing the load factor of generators. During the SGO mode, both propulsion and service loads are only supplied by a power generation unit. However, this practice is unacceptable in terms of reliability and safety of ship operations. The batteries therefore provide emergency power to maintain operations in case of power outage. In this aspect, the battery system should be designed to cover the limited propulsion power and vital loads requirements.

3.2 DC distribution system
Advance in power electronic converters has made it possible to reinforce a tendency towards the use of DC distribution as a replacement of the conventional AC system. The incentive for this transition lies in the challenges of the AC system include the need for phase angle synchronization and imbalances of three-phase system. The DC grid concept, on the other hand, is conceived to enhance system efficiency by eliminating the need of all generator sets to be synchronized at a specific frequency (50/60 Hz) and allowing the engines to operate at optimal rotating speed.

A simulation of the variable speed diesel engines during dynamic positioning is performed in [10]. A test engine is used to measure specific fuel consumption based on various RPM and torque. The results indicate higher engine efficiency with up to 20% fuel saving can be achieved when operating with variable frequency at low power region. In [11], the variable speed capability is enhanced by energy storage to promote energy efficient operations of an offshore support vessel. Inherently, various operations of such a vessel require to continuously keep a redundant active generator set during large transient loads. The energy storage is therefore able to satisfy the redundancy requirement by playing a role of an active engine and thus no additional fuel consumption. The optimum fuel efficiency is hence obtained partly from reduced number of the active generators and partly from optimized rotating speed of the engines.

The DC electrical distribution is also conceived to enhance efficiency through weight saving and space arrangements. The high power-dense DC architecture makes it possible to reduce space requirements and weight of installed electrical equipment by up to 30% [12]. The significant saving is mainly due to facilitation of smaller high-speed generators and elimination of large low-frequency transformers. A case of transformation from AC to DC distribution in [13] shows the total weight of on board electrical equipment could be reduced from 115 tons to 85 tons.

3.3 Power distribution control
An optimal load allocation approach is encouraged to the minimum fuel consumption resulting from the optimal operating conditions of individual generators. As the engine conditions continuously change over the running time, the real-time monitoring for the fuel consumption and the load profile management are significant tools to assist the power distribution control process.
A real-time estimation algorithm for the specific fuel consumption (SFC) is proposed in [14]. The method involves using a recursive estimator to track the actual power based on recorded ship operation profiles. The optimal load dispatch therefore can be determined in reference to the real-time estimated SFC and by advising an appropriate operation mode (switch on/off and standby) for the individual generators.

A novel load prediction scheme for an electric harbor tugboat is introduced in [15]. The tugboat operation calls for a unique load characteristic and its optimal power split is based on a given load profile. However, in most practical applications, the operation load profile cannot be determined exactly. The proposed load prediction scheme can effectively respond such uncertainty by using only interval time information and general characteristics of operation modes. Nevertheless, the performance of this method largely depends on the accuracy of the load prediction. This limitation can be eradicated by equivalent consumption minimization strategy (ECMS) which is an alternative power management for improving fuel efficiency as studied in [16]. The ECMS is implemented as a real-time energy control and optimization of the fuel consumption by converting electrical power into the equivalent fuel consumption and thus the load profile is no longer required.

3.4 Power Generation Scheduling
An exceptional feature of integrated full electric propulsion is to supply all electrical loads through a set of power generation units. This centralized power system enables various optimization techniques to automatically select the active generators to respond the load changes in an optimal manner. On that account, the optimal power generation scheduling jointly with propulsion power adjustment can contribute to further reduced fuel consumption.

The study in [17] uses power generation scheduling and ship speed adjustment to minimize total variable operation cost which is expressed in terms of total fuel consumed by all generators. Dynamic programming is applied to decide which generators to be operated during examined time intervals. The EEOI is also used to monitor GHG emissions to ensure that resulting pollution from the optimization process is maintained below the threshold levels. More specifically, propulsion power and its corresponding programmed generators are optimized through the ship speed adjustment which the ship speed is significantly increased when approaching or departing ports and significantly decreased when cruising in open sea. In [18], the scheduling of power generation is further optimized through a coordination of energy storage and shore power supply by using fuzzy-based particle swarm optimization (FPSO) technique. The proposed optimal power management method demonstrates superiority in finding the optimal solution and higher performance than dynamic programming in terms of computation time.

However, those two studies only consider the reduced fuel consumption as a single optimization objective and treat the emissions factor as a constraint. An effort in [19] hence applies both fuel economy and emissions constraint to a multi-objective optimization problem which can be solved by using non-dominated sorting genetic algorithm II (NSGA-II). It turns out from the results that these two conflicting objectives can be simultaneously achieved with the proposed technique.

3.5 Ship energy efficiency management plan (SEEMP)
SEEMP is an operational measure that establishes a mechanism to improve energy efficiency by monitoring ship performance based on EEOI and providing improvement practices on board [20]. Various operational approaches are suggested to cooperatively work with other technology-based methods to maximize fuel efficient operations. Suggested improvement practices according to IMO guidelines are summarized in table 1.
4. Discussion
Lowering fuel consumption has become a primary aim of energy efficient methods as it is a major contribution toward GHG emissions reduction. The efficiency gains from the proposed strategies are substantial with a potential in the range of 3 - 20% improvement. A significant emissions reduction is therefore achievable through a combination of various strategies both technology-based concepts and operational practices. However, several methods could meet technical and economic challenges such as immaturity of DC power equipment and economic incentives to invest the battery system on board. Accordingly, further research into the challenges as well as exploring innovative fuel-efficient technologies is required to further improve energy performance of the future electric vessels.

5. Conclusions
This paper has reviewed various energy efficient methods for all-electric ships. Energy efficiency can be analyzed within the scope of EEDI which proposes a long term technological development, while EEOI is an operational measure that uses existing technologies on board. The extensive electrification of ship power system proves as a promising solution for substantial fuel efficiency improvement. This is due to its capability to optimize overall shipboard components through power management strategies and innovative energy efficient concepts such as implementation of energy storage and DC distribution. These approaches should be eventually combined with operational practices suggested by SEEMP. Since the proposed strategies reveal significant variations in efficiency gain as reported on the literature, a coordination of various methods is recommended to achieve full potential for GHG emissions reduction.

Table 1. Overview of improvement practices and potential fuel efficiency gain [2,20,21].

| Improvement practices | Description                                                                 | Fuel efficiency gain |
|-----------------------|-----------------------------------------------------------------------------|----------------------|
| **Fuel efficient operation** | • Voyage planning: execution of voyages through voyage planning software | 0.1 – 48%           |
| | • Weather routing: implementation of real-time weather and sea-condition monitoring system combined with smart navigation software |                      |
| | • Optimized port operation: optimization of port operation activities enables berth availability and facilitate the use of ship optimum speed |                      |
| | • Speed optimization: operation at design speeds for minimized fuel consumption | 1 – 60%              |
| **Optimized ship handling** | • Optimum trim: adjustment of trim conditions allows minimum ship resistance | < 5%                 |
| | • Optimum ballast: adjustment of ballast conditions to meet the requirements of optimum trim and steering conditions through ballast water management plan | < 12%                |
| | • Optimum propeller and propeller inflow considerations: retrofit of propeller designs and improvement of propeller inflow by arrangement of fins and nozzles |                      |
| | • Hull maintenance: minimization of hull and propeller resistance by new technology-coating system and cleaning intervals | 1 – 10%              |
| | • Optimum use of rudder and heading control: implementation of automated steering control for better course control and minimized rudder resistance | < 4%                 |
| | • Propulsion system: enhancement of diesel engines by implementation of the latest electronic control engines technology |                      |
| | • Propulsion system maintenance: execution of planned maintenance schedule to maintain system efficiency | 1 – 25%              |
| **Improved fleet management** | Improvement in fleet planning might result in better fleet capacity and best practice of the fleet can be achieved by sharing efficiency, reliability and maintenance data | 5 - 50%              |
| **Energy monitoring** | Electrical service usage and machinery system should be reviewed for potential efficiency improvement such as thermal insulation approach | 0.1 - 5%            |
| **Fuel type** | The use of alternative fuels such as biofuels and liquefied natural gas | 5 - 84%              |
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