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Modelling lithium-ion battery hybrid ship crane operation ☆

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HIGHLIGHTS

- We model hybrid and conventional ship fuel consumption for crane operation.
- Hybrid ship model based on data from ship owner.
- Battery, diesel generator and control systems modelled.
- A conventional and two hybrid control systems has been modelled.
- The novel hybrid system has lower capital costs and saves 30% fuel and emissions.

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ABSTRACT

We have investigated a hybrid power train for ship crane operations, using a lithium-ion battery in conjunction with diesel gensets for auxiliary power generation, as an alternative to a conventional power train using only gensets. We have simulated crane operations in port using both solutions, in order to quantify the potential economic gains of using hybrid power generation. This study is based on a real open-hatch dry bulk vessel of 50,000 dwt, which is compared with a corresponding newbuilding ship with hybrid auxiliary power generation. We have modelled the complete auxiliary power system, including diesel generators, lithium-ion batteries, cranes and ship hotel consumers. We have developed a novel hybrid control strategy that has the potential to reduce the minimal size and thereby cost of batteries for hybrid ships. Our results indicate that the hybrid solution will lead to about 30% reduced fuel consumption and CO_2 emissions while operating cranes, which amounts to annual savings of $110,000, with $450,000 savings over three years of operation, as well as reduced capital costs compared to the conventional power generation system.

1. Introduction

Battery hybrid power generation for ships has the potential to both reduce costs and reduce emission from shipping, as we will see in this paper. The shipping industry is under pressure to reduce emissions of CO_2, NO_x, SO_x and particulate matter, due to increasing awareness of anthropogenic climate change and the health effects of shipping [1]. New emissions control areas (ECA) are one example of legislation that forces ship owners to design ships with lower emissions. Presently, several hybrid and battery ships have been or are being built or retrofitted with batteries [2–4] while a hybrid tug started operations as early as 2009 [5]. Hybrid power trains can contribute to both significant cost and emission reductions in certain segments of shipping, as we show in this modelling case study of auxiliary power generation, based on a real 50,000 dwt open-hatch dry bulk vessel.

Today it is not clear in what segments of shipping that hybrids will be useful, as ships vary greatly in how they are operated and how their power generation systems are designed, this means that it is hard to assess the benefits and profitability of a hybrid ship without performing a detailed analysis. The primary goal of this paper was to develop a method, using detailed simulations of a ship's operation, in order to quantify the main economic and environmental impacts of installing a battery on a ship; namely finding the optimal battery size, the total system costs, and the reduction of fuel consumption compared to a conventional ship. In order to achieve this we have modelled the complete auxiliary power train including diesel generators, lithium-ion battery and power electronics; as well as the auxiliary power consumers. We have simulated one phase of the ship's operations, namely loading/unloading operations in port in which the auxiliary power

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Nomenclature

Hybrid	a ship with energy storage, e.g. battery
q, SOC	state of charge
C-rate	normalized measure of battery current
Genset	diesel engine with generator
SFOC	specific fuel oil consumption, g/kWh
B, Capacity	max. energy content of battery, kWh
P^b_{max}	maximum simulated (dis) charge power of the battery, kW
dwt	deadweight tonnage, used for ship sizes
PID	a proportional-integral-derivative controller
E	diesel genset engine size, kW
C_{max}	maximum C-rate
C_{min}	minimum C-rate
N_g	number of installed generators
$C^{\mathrm{h}}_{\mathrm{inst}}$	hybrid installation costs, $
$C^{\mathrm{c}}_{\mathrm{inst}}$	conventional installation costs, $
$C^{\mathrm{h}}_{\mathrm{op}}$	hybrid annual operational costs, $
$C^{\mathrm{c}}_{\mathrm{op}}$	conventional annual operational costs, $
c_{b}	battery price, $/kWh
c_{g}	diesel genset cost, $/kWh
c_{m}	maintenance and repair costs, $/h
c_{f}	fuel price, $/t
c_{p}	power electronics costs, $/kW
f_{h}	hybrid fuel consumption, t/ year
f_{c}	conventional fuel consumption, t/ year
t_{h}	genset running time hybrid system, h
t_{c}	genset running time conventional system, h
x	years before payback
y	years until operational savings equal battery cost

is used for both hotel consumers (lighting etc.) and onboard cranes. The simulations rely on randomly generated auxiliary power demand profiles, based on data from the ship owner. The battery model is based on a real battery pack produced by Corvus [6] which has been installed on the Viking Lady [2]; and on Norway's first battery-only ferry [4], which will start operating in 2015. Propulsion power is provided by a main engine not connected to the auxiliary grid, and has not been included in the modelling.

By simulating the power generation versus a given power demand in time, we can test different hybrid power generation control strategies. By adding a battery to the power generation system, the control strategy shifts from being just a question of having the optimal number of gensets running, to a more complex issue. To illustrate, in a hybrid system one can run a different number of gensets, or none at all; one can run the gensets at chosen loads, letting the batteries take the responsibility for meeting the power demand; the batteries can be charged or discharged at given rates, and the gensets have to take responsibility for meeting the power demand; one can have rules stating the minimum or maximum capacity left in the battery; and more. We have developed two different hybrid ship power generation control strategies, both of which meet the power demand and result in a significant fuel consumption reduction compared to the conventional system. The first strategy, called the basic control strategy, slowly changes the genset loads to maintain the battery's SOC, this has been used by other groups simulating hybrid ships, e.g. [7]. Our second strategy, called the advanced control strategy, employs a novel mode where the genset will increase its load when the ship's power demand is high and vice versa, requiring a substantially smaller battery.

We have used the simulations to determine a minimal battery size for the conditions of our case study ship, and used this to estimate the costs, savings and payback time of a hybrid system compared with the conventional one.

In Section 2 we discuss the modelling of lithium-ion batteries; in Section 3 we discuss the modelling of the hybrid crane system; in Section 4 we discuss the case study; in Section 5 we discuss the results; in Section 6 we give our conclusions.

1.1. Hybrid ships

A hybrid ship in this context is a ship that has an energy storage device as part of its power generation system, e.g. flywheel, compressed air or electrochemical batteries. The energy storage unit accumulates energy from the ship's power generators or releases energy to the ship's power consumers in the same way the battery in the Toyota Prius hybrid car does. In shipping, the term hybrid ship can have several alternative meanings, but in our case we will use it in the same sense as in the automotive industry.

To estimate the total cost difference between a hybrid ship and a conventional ship, there are two main cost aspects that must be addressed:

- Capital costs – Installation costs of the battery and auxiliary engines.
- Operational costs – How can the battery contribute to reduced fuel consumption and maintenance during operation.

There are several compelling arguments to be made for hybrid power generation:

- *Optimal load* – The energy efficiency and emissions of diesel and gas engines depend on the engine load, being far worse for low loads than high loads (low load means low power output). In a hybrid ship, the battery can be used to handle deviations from average demand and allows the conventional engines to operate closer to the optimal load point.
- *Transients* – The energy efficiency of diesel and gas engines is lower when the engine is changing its load, while the emissions of SOx, NOx and particulate matter increase. In a hybrid system, the battery can handle the transient demand while the conventional engines deliver the average power.
- *Power redundancy* – In some cases, a battery pack can presumably count as a power source, allowing ship owners to install fewer engines while still satisfying class rules for redundancy.
- *Facilitate energy harvesting* – Energy storage is necessary for efficient onboard harvesting from renewable sources, such as solar cells.
- *Harbor mode* – If the battery installation is large enough (which is not the case in this study) the battery can provide all the power while in port, eliminating local emissions.

1.2. Hybrid cranes case study

To accurately quantify the benefits of hybrid auxiliary power generation we need detailed operational profiles. This is because the potential for savings lie mostly in time-varying power demands [8]. Vessel types that have mostly constant power demands, such as long-range freight vessels are expected to gain less from hybrid power trains, while a ship operating cranes or using dynamic positioning will have greatly varying power