This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Ritari, Antti; Huotari, Janne; Halme, Jukka; Tammi, Kari

Hybrid electric topology for short sea ships with high auxiliary power availability requirement

Published in:
Energy

DOI:
[10.1016/j.energy.2019.116359](https://doi.org/10.1016/j.energy.2019.116359)

Published: 01/01/2020

Document Version
Peer reviewed version

Published under the following license:
CC BY-NC-ND

Please cite the original version:
Ritari, A., Huotari, J., Halme, J., & Tammi, K. (2020). Hybrid electric topology for short sea ships with high auxiliary power availability requirement. *Energy*, 190, [116359]. <https://doi.org/10.1016/j.energy.2019.116359>

Journal Pre-proof

Hybrid electric topology for short sea ships with high auxiliary power availability requirement

Antti Ritari, Janne Huotari, Jukka Halme, Kari Tammi

PII: S0360-5442(19)32054-7
DOI: <https://doi.org/10.1016/j.energy.2019.116359>
Reference: EGY 116359
To appear in: *Energy*
Received Date: 30 June 2019
Accepted Date: 13 October 2019

Please cite this article as: Antti Ritari, Janne Huotari, Jukka Halme, Kari Tammi, Hybrid electric topology for short sea ships with high auxiliary power availability requirement, *Energy* (2019), <https://doi.org/10.1016/j.energy.2019.116359>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2019 Published by Elsevier.

Hybrid electric topology for short sea ships with high auxiliary power availability requirement

Antti Ritari^{a*}, Janne Huotari^a, Jukka Halme^b, Kari Tammi^a

^a School of Engineering, Department of Mechanical Engineering, Aalto University, Espoo, Finland

^b School of Electrical Engineering, Department of Electrical Engineering and Automation, Aalto University, Espoo, Finland

*Corresponding author. E-mail address: antti.ritari@aalto.fi (A. Ritari).

Abstract

The inclusion of a battery system for a diesel mechanical short sea ship was investigated. The main benefits of the battery were assumed to emerge from shaving thruster generated power peaks, rather than starting additional generating sets to accommodate the power demand and additionally from replacing a diesel engine as a reserve power source. To support the analysis, an auxiliary engine power output dataset of a roll-on/roll-off passenger ferry operating in the Baltic Sea was acquired. Required capacity for the battery system was derived by considering power availability requirements and battery safety margins for performance deterioration. A multi-period mixed-integer linear programming model was constructed to derive a globally optimal power management strategy for the auxiliary engines and the battery, with the goal of minimizing the battery installation total cost. The battery system was found to reduce fuel oil consumption by 257.5 tons annually due to improved auxiliary engine efficiency alone. Furthermore, the battery system total cost advantage was found to vary from -€0.61 to €2.82 million during the ten-year investment period, depending on fuel oil and battery system costs applied in the modeling. For the studied case ship, the hybrid electric topology was concluded to be economically feasible.

Keywords: Hybrid ship, energy efficiency, energy storage, battery, mixed integer linear programming, optimization

Nomenclature

Symbols

A	Intercept of fuel flow rate function (kg/(kWh))
A'	Slope of fuel flow rate function (kg/(kWh))
c	Cost of fuel oil (€/kg)
c'	Cost of shore electricity (€/kWh)
C	Cost of the battery system (€/kWh)
D	Demand of electric power (kW)
E	Battery capacity (kWh)
I	Number of time steps
J	Number of auxiliary system operating modes
K	Number of engines
L	Number of engine operating regions
M	Maximum continuous rating of an engine (kW)
M'	Status of an engine
N	Number of operation cycles annually
N'	Investment period (year)
R	Auxiliary system reserve power requirement (kW)
S	Engine shutdown idling period fuel oil consumption (kg)
T	Size of time step (hours)
V	Battery state of charge dependent voltage drop (%)
x	Load of an engine (%)
$x_{\min}$	Minimum load of an engine (%)
$x_{\max}$	Maximum load of an engine (%)
x'	Battery state of charge (%)
x''	Initial battery state of charge (%)
X	Battery discharging power (kW)
$X_{\max}$	Maximum battery discharging power (kW)
X'	Battery charging power (kW)
$X'_{\max}$	Maximum battery charging power (kW)
X''	Shore power (kW)
$X''_{\max}$	Available shore power (kW)
y	Defines if operating mode is active
Y	Defines if an engine is shut down
z	Battery power output limit (kW)

Greek symbols

η	Battery discharging efficiency (%)
η'	Battery charging efficiency (%)

Subscripts

i	Index of a time step
j	Index of an auxiliary system operating mode
k	Index of an engine
l	Index of an engine operating region

Abbreviations

AE	Auxiliary engine
BT	Bow thruster
BAT	Battery
FFR	Fuel flow rate
HEL	Helsinki
HVSC	High voltage shore connection
IMO	International Maritime Organization
LFP	LiFePO ₄ battery chemistry
LMO	LiMn ₂ O ₄ battery chemistry
LS	Low sulfur
LTO	Li ₂ TiO ₃ battery chemistry
LVSC	Low voltage shore connection
MGO	Marine gas oil
MILP	Mixed integer linear programming
MIQP	Mixed integer quadratic programming
NCA	LiNiCoAlO ₂ battery chemistry
NMC	LiNiMnCoO ₂ battery chemistry
OCV	Open circuit voltage
RoPax	Roll-on/roll-off passenger ferry
SFOC	Specific fuel oil consumption
SoC	State of charge of a battery
ST	Stern thruster
STO	Stockholm

1 INTRODUCTION

The pressure to move towards greener shipping is constantly growing as the average temperature of the Earth's climate keeps increasing due to greenhouse gasses emitted by human activity. The global maritime regulation setting body, International Maritime Organization (IMO), has set a strategy for reducing emissions from the shipping sector. This includes a goal of reducing CO₂ emission by at least 50% by 2050 compared to 2008 levels [1]. Additionally, the IMO has set a target to limit sulfur in fuel oil to 0.5% from 2020 globally [2]. In emission control areas (ECA), such as the Baltic Sea, sulfur content is already limited to an even lower level of 0.1%.

In recent years, batteries have emerged as a feasible option for reducing emission and increasing the energy efficiency of ships. For instance, Bouman et al. [3] estimate 2-45% CO₂ emission reduction potential with hybrid propulsion systems. Bloomberg New Energy Finance [4] reports an 85% fall in weighted average lithium-ion battery pack price from 2010 to 2018. A similar positive trend is apparent in energy density, which increased by 150% from 2008 to 2014 [5]. As these trends are expected to continue, economically feasible applications of batteries for ships will emerge at an accelerating pace.

With an energy storage, the total output power of the engines no longer needs to equal to the power demanded at each moment, and instantaneous energy production becomes decoupled from consumption. Most ships' electricity generation system consists of multiple diesel generators with different rated powers. The power demand can therefore be supplied by different combinations of engines and their loads as well as the battery. The challenge thus becomes, which specific charging/discharging cycle should be used to achieve goals set for the system, such as fuel oil consumption, CO₂ emission or operation cost minimization.

More specifically, the mechanisms by which batteries can increase energy efficiency and decrease harmful emission in ships include:

1. Shifting diesel engine operating points closer to their peak efficiency
2. Supplying electricity at port stay when shore connection is unavailable, eliminating emissions from diesel engines
3. Substituting a sub-optimally operated generator set as a reserve power source
4. Supplying thruster induced power demand peaks that would otherwise require starting up an additional engine
5. Decreasing engine installed capacity in newbuilds

The third use case from the list is likely to provide the greatest benefits for ships that visit ports frequently and operate in coastal areas and archipelagos. These ships operate auxiliary engines at low loads to ensure power availability for a rapid ramp-up of thruster electric motors. The cost of this safety feature is the low efficiency and high fuel oil consumption of the low loading operation. The peak efficiency of marine diesel engines is typically at 85% load, and the efficiency decreases when the load moves away from this point and begins to diminish exponentially below 50% load. For instance, specific fuel oil consumption is 14.4% higher at 25% load compared to 85% for a generating set reported in [6].

Figure 1 presents a histogram of auxiliary engine loads from a single operating cycle of a roll-on/roll-off passenger ferry (RoPax) studied in this paper. The distribution of the loads is bimodal, with the most frequent measurements appearing at the low load region between 30% and 40%. Similarly below 50% auxiliary engine loads were found to be the most frequent for cruise ferries [7]. Therefore, a potential for improving energy efficiency and reducing fuel oil consumption is apparent with a hybrid energy system that enables the engines to operate at higher efficiency, closer to the design point.

Figure 1. Histogram of auxiliary engine loads of a RoPax ship during a typical operating cycle.

Pyrhonen et al. [8] studied the feasibility of battery installation to a diesel-electric cruise ferry operating in an archipelago. Battery benefits were assumed to arise from power balancing, reserve power usage and faster response compared to a diesel engine. The ship energy system focused on capturing the dynamics of the system, while the power management strategy was rule based. The most attractive option economically was found to be a 1.5 MWh capacity battery with a 6 year payback period.

In the context of optimal power management for hybrid ships, Mohammadzadeh et al. [9] compared two machine learning algorithms to predict operational profiles of a diesel-electric ship with a battery. Mixed integer linear programming was then utilized to compute an optimal power management strategy for the operational profiles. Results suggested a significant 20 % fuel oil consumption reduction with the battery and optimal power management. Vu et al. [10] studied the optimal power split between diesel generators and a battery for an electric tugboat. The objective function to minimize contained fuel oil consumption and additionally penalty terms for changes in battery SoC (State of charge) and deviation between supplied power and demanded power. Recently, Jaurola et al. [11] presented an optimization tool for marine hybrid powertrain design, intended for use in the early stages of the ship design process. However, only a marginal fuel oil consumption advantage was found for a case study fishing boat with the hybrid system compared to a conventional diesel-mechanical propulsion.

Dedes [12] presents an extensive analysis on hybrid system feasibility for ocean-going ships, focusing on bulk carriers. The expected fuel oil saving benefits were assumed to emerge from the minimization of transient loads and load leveling. The work entailed the development of a ship voyage simulator, consisting of detailed component models. Fuel oil savings ranged from 0.30 to 7.23%.

None of the literature above dealt with the feasibility of including a battery to the auxiliary system of a ship with diesel mechanical propulsion, operating under continuous high power availability safety requirement. This study contributes to the literature by providing answers to the following questions:

- How to select the chemistry, capacity and power rating of the battery system?
- How to manage the distribution of power between the battery and the auxiliary engines?
- How economically feasible the battery system is?

The work utilizes measurement data acquired from an automation system of a case ship operating in the Baltic Sea. The dataset contains

power outputs and fuel oil consumption rates for each auxiliary engine with one-minute sampling rate. This provides an opportunity to compute the actual SFOC-curves of the engines for the energy system model of the ship.

2 METHODS

The problem formulation presented previously requires an optimization model for solving the complex battery and auxiliary engines network power management issue. This problem can be classified under the *operation* level in the three level energy system optimization framework [13]. The *design* level, on the other hand, covers the component sizing. While the auxiliary engine sizes are fixed, the battery capacity is a design level decision and can be represented by a decision variable in the optimization model. The *synthesis* level is out of scope in this work, which reduces the model complexity considerably.

The model types available for operation and design optimization range from fast and reliable linear models to complex nonconvex nonlinear models requiring advanced solver algorithms. In general, convex models, including linear models, have the advantage of fast solution times and convergence to the global optimum compared to nonlinear models. On the other hand, nonlinear relationships have to be approximated in linear models, which may reduce the usefulness of the results [14].

The load-sharing optimization problems in hybrid systems described previously require multi-period modeling. In this approach, the system is divided into a sequence of static models that each represent system power balance for a single point in the power demand input data. The time step duration for each static model is determined by dividing the time horizon by the number of time steps for which the static model is built. Subsequent static models are connected by dynamic constraints, which result from battery charge state changes and changes in the on/off states of the engines. Subsequently, the number of variables and constraints grow very large.

The relationship between marine diesel or gas engine SFOC and load is nonlinear. The relationship depends on the engine type, wear, tuning and other factors. Commonly the highest efficiency of marine diesel engines is achieved at 85% load. The efficiency curve is almost flat at loads above 50%, but it begins to deteriorate exponentially at lower loads.

The nonlinear engine efficiency in the objective function can be formulated as a convex quadratic model with continuous variables, which is straightforward to solve with state-of-the-art convex program algorithms [15]. However, the need to control engine on/off states with binary variables in the ship energy system would result in nonconvex mixed-integer quadratic program (MIQP). Performance of MIQP state-of-the-art solvers still lack MILP solver performance to such an extent that quadratic formulation is determined infeasible for the problem here [15].

The presented problem requires a multi-period model with binary decision variables for the on/off switching of individual engines. This suggests that mixed-integer linear program (MILP), which can be solved relatively fast and robustly for many thousands of decision variables, is the most feasible model type for the hybrid system optimization in this work [15]. Recent developments in state-of-the-art MILP-solvers, such as GUROBI and CPLEX make it possible to solve much more complex problems with a higher number of decision variables than what was possible only a few years ago.

2.1 Auxiliary engine network model

The auxiliary engines of the ship are diesel engines driving generators, which produce alternating current electric energy to the auxiliary system grid. The AC grid frequency is kept constant at 50 or

60 Hz, requiring that engine speed is maintained constant as well [16]. Two or more auxiliary engines that are connected to the same grid are synchronized. Engine loads are balanced equally in the parallel operation because this ensures that engine speed changes in load transients are equal for all connected engines regardless of their power rating.

In the optimization model, load can be represented with a single variable x that receives values from zero to one. The load, as a percentage of maximum, is the same for all connected engines. Subsequently, the power output of an engine is the load x times the power rating of that engine.

Linear representation of engine fuel oil consumption as a function of load is expressed as:

$$f_{ffr} = (Ay + A'x)M \quad (1)$$

$$x - y \leq 0 \quad (2)$$

where x is a continuous variable in the interval $[0,1]$ representing the load between 0 and 100% while y is a binary variable indicating whether the engine is on or off. When the engine load is zero, the fuel flow rate should also be zero. The constraint (2) handles this functionality, letting y to equal zero when x is zero while forcing y to equal one when x is greater than zero. The parameters A and A' are the intercept and slope of the straight line in equation (1) and M is the power rating.

The engine load interval can be divided into an arbitrary number of regions that each have their own linear equation for the fuel flow. This approach enables approximating the nonlinear relationship between fuel oil consumption and load. Given L regions, the fuel oil consumption is given by

$$f_{ffr, piecewise} = \sum_{l=1}^L (A_l y_l + A'_l x_l) M \quad (3)$$

$$\sum_{l=1}^L y_l = 1 \quad (4)$$

where the variables and parameters, other than M , are now indexed over the set $\{1,2,\dots,L\}$. This piecewise linear formulation requires the constraint (4) to prevent two or more regions from becoming active at once.

The combined fuel flow rate for K number of engines can be formulated straightforwardly, because the load x_l is the same for all the engines online, as discussed previously:

$$f_{ffr, network} = \sum_{k=1}^K \sum_{l=1}^L (A_l y_l + A'_l x_l) M_k \quad (5)$$

By expanding the formulation in equation (5) with summation terms for I time steps and J operating modes, the total fuel oil cost for a journey becomes

$$f_{tc} = \sum_{i=1}^I \sum_{j=1}^J \sum_{k=1}^K \sum_{l=1}^L (A_l y_{i,j,l} + A'_l x_{i,j,l}) c M_{j,k} T_i \quad (6)$$

where c is the fuel oil cost and T_i is step size. The operating mode is simply the combination of engines that are online, with j representing the index and J the total number of operating modes. The engine load variable $x_{i,j,l}$ is also indexed over j . The set of operating modes for a specific energy system are defined in parameter $M_{j,k}$.

2.2 Battery model

Lithium based chemistries currently commercially available for mobile machines are LiNiCoAlO₂ (NCA), LiNiMnCoO₂ (NMC), LiMn₂O₄ (LMO), Li₂TiO₃ (LTO), and LiFePO₄ (LFP) [17]. These chemistries offer different tradeoffs between cost, life span, specific energy, specific power, safety, and thermal performance. NCA

provides high performance in multiple dimensions, but it is prone to thermal runaway. Similarly, LMO is challenging from a safety perspective. LTO and LFP chemistries, on the other hand, have a low risk of thermal runaway, but high cost and weak specific energy. For hybrid ships, a reasonable balance between the six dimensions is available in NMC. Specifically, NMC offers high specific energy and energy density, which is important in ships with limited space, while the power output is sufficient for thruster induced peaks. NMC chemistry with C-rate of four is assumed in the optimization model.

Figure 2. Equivalent circuit model of a battery.

The key factors that characterize lithium-ion battery behavior are open circuit voltage (OCV), rate-dependent capacity, temperature effect, and aging effect [18]. Next, all these four factors are discussed. OCV is the voltage that builds up between the anode and cathode when charge or discharge is not applied. OCV varies significantly as a function of SoC. According to a simplified equivalent circuit model (Figure 2), battery power output is

$$P = IV_{OC} - I^2 R \quad (7)$$

where R is the internal resistance and V_{OC} (SoC) is the open circuit voltage. For a single NMC cell, V_{OC} range is from 3.44 V to 4.20 V [19], which corresponds to 18% decrease in maximum power output between 100% and 0% SoC assuming that maximum current stays constant [20]. To account for this drop, a linear constraint was included in the optimization model, limiting maximum charge and discharge rates based on the SoC.

Rate-dependent capacity means that increasing the discharging current reduces the total capacity. This is apparent even from the simplified circuit equivalent model, where the power loss from internal resistance grows as a function of the square of the discharging current. However, in this work modeling rate dependent capacity is considered out of scope, because in lithium-ion batteries, the relationship between capacity and discharging profile has been observed to be very small [19].

Temperature affects the maximum charging and discharging rates as well as the capacity [18]. In general, the internal resistance decreases when the temperature increases. Battery performance begins to deteriorate exponentially when temperature declines below -10 °C [19]. The proposed ship battery system installation is not exposed to the climate conditions outside the ship and is here assumed to be controlled by a sufficient thermal management system.

Battery aging as a function of loading profiles can be modeled by including a penalty term to the objective function, accounting for the aging process [10]. In the present work, aging was taken into account by applying a scaling factor of 1.25 to the battery cost per unit of installed capacity, which accounts for a 20% decrease in capacity over the lifetime of the battery while sustaining the performance implied in the model formulation [21].

2.3 Shore connection infrastructure

The port receives its electricity from the medium voltage distribution network, which in Finland operates on a voltage of 10 kV and frequency of 50 Hz [22]. High voltage shore connection (HVSC) enables transferring the electric power from shore to ship in a single cable, whereas low voltage shore connection (LVSC) requires complex cable management system for as many as 14 cables. Power

rating in the range of 2.5 to 6.5 MW is standard in ports that offer HVSC to RoPax ships [23]. A 2.5 MW 11 kV / 50 Hz HVSC system described in standard IEC/IEEE 80005 is assumed in this work in the scenarios where shore connection is available.

Taking advantage of the shore supply requires interface equipment, control and monitoring systems and a transformer onboard the ship for stepping down the 11 kV shore voltage to 660 V of the auxiliary network. Both 50 and 60 Hz frequency networks are used in ships, and a frequency converter is required in the case that the shore supply has a different frequency than the ship. However, the onboard shore connection component investment is not included in the optimization model due to its one-time nature compared to the fixed time investment horizon of the battery system.

The shore connection investment cost for the port operator is out of scope in this work. The shipowner faces this cost in the electricity price margin that the port operator charges on top of the retail price. Thus, the readers should apply the electricity cost in their specific case study.

2.4 Model formulation

The general optimization problem can now be formulated as follows:

$$\begin{aligned} & \text{minimize} \\ & x_{i,j,l}, x'_{i,j,l}, x''_{i,j,l}, X_i, X'_i, X''_i, y_{i,j,l}, Y_{i,j,l} \\ & EC + \sum_{i=1}^J \sum_{j=1}^K \sum_{l=1}^L c' X''_{i,j,l} T_i + \sum_{k=1}^K \sum_{j=1}^J \sum_{l=1}^L a_{i,j,l} Y_{i,j,l} + \\ & \sum_{j=1}^J \sum_{l=1}^L (A_j y_{i,j,l} + A'_j x'_{i,j,l}) M_{j,k} T_i \quad (8) \end{aligned}$$

subject to

$$-\sum_{j=1}^J \sum_{k=1}^K \sum_{l=1}^L M_{j,k} x_{i,j,l} + \frac{X'_i}{\eta'} - \eta X_i - X'' + D_i \leq 0, \forall i \quad (9)$$

$$\sum_{j=1}^J \sum_{l=1}^L y_{i,j,l} - 1 \leq 0, \forall i \quad (10)$$

$$x_{i,j,l} - x_{i,\max,j,l} y_{i,j,l} \leq 0, \forall i, \forall j, \forall l \quad (11)$$

$$-x_{i,j,l} + x_{i,\min,j,l} y_{i,j,l} \leq 0, \forall i, \forall j, \forall l \quad (12)$$

$$-Y_{i,k} + \sum_{j=1}^J \sum_{l=1}^L (y_{i,j,l} - y_{i+1,j,l}) M'_{i,k} \leq 0, \forall i, \forall k \quad (13)$$

$$-\sum_{j=1}^J \sum_{k=1}^K \sum_{l=1}^L (y_{i,j,l} - x_{i,j,l}) M_{j,k} - X_{\max} + X_i + R_i \leq 0, \forall i \quad (14)$$

$$W_i + x'_{i,j,l} - \frac{(X'_i - X_i)}{E} T_i \leq 0, W_i = \begin{cases} x'' & i=1 \\ x'_{i-1} & i>1 \end{cases}, \forall i \quad (15)$$

$$x'' - x'_{i=1} = 0 \quad (16)$$

$$z_i - V + x'_{i,j,l} (1 - V) = 0, \forall i \quad (17)$$

$$X'_i - z_i X'_{i,\max} \leq 0, \forall i \quad (18)$$

$$X_i - z_i X_{i,\max} \leq 0, \forall i \quad (19)$$

$$X''_i - X''_{i,\max} \leq 0, \forall i \quad (20)$$

$$i \in \{1, 2, \dots, I\}$$

$$j \in \{1, 2, \dots, J\}$$

$$k \in \{1, 2, \dots, K\}$$

$$l \in \{1, 2, \dots, L\}$$

$$x_{i,j,l}, x'_i, x''_i, z_i \in [0, 1]$$

$$X_i, X'_i, X''_i \in \mathbb{R}_{\geq 0}$$

$$y_{i,j,l}, Y_{i,j} \in \{0, 1\}$$

The objective function (8) to be minimized is the combined cost of the battery installation capital expenditure and the operation costs, which include fuel oil and shore electricity costs. The objective is to minimize the costs over the battery investment period N' .

The linear inequality constraint (9) specifies the energy system power balance. At each time step i , the sum of power outputs of the auxiliary engines, the battery (X'_i and X_i) and the shore power X''_i must equal or exceed the power demanded for the hotel load and thruster use (D_i). The term accounting for the engine powers first sums engine load variable $x_{i,j,l}$ over the sets $\{1, \dots, J\}$ and $\{1, \dots, L\}$ that correspond to the auxiliary system operating modes and regions, and then sums over all the engines that are online in that operating mode, represented by $\{1, \dots, K\}$. It follows from the power balance formulation that the battery is charged when combined powers of the engines and shore connection exceed the demand.

Constraints (10) to (12) define the properties of the auxiliary engine network. These include minimum and maximum loads of each operating region and constraints for binary variables that specify operating mode on/off control. Inequality constraint (10) allows only a single value of $y_{i,j,l}$, indexed over the sets $\{1, \dots, J\}$ and $\{1, \dots, L\}$, to equal one at each time step i . The purpose of this is to limit operating modes and operating regions according to the physical limits of the engines. Constraint (13) forces the binary start-up variable $Y_{i,j}$ to equal one when the corresponding engine j is shut down, indicated by $y_{i,j,l}$ changing from one to zero between time step i and $i+1$. In the objective function, the variable $Y_{i,j}$ accounts for the engine shutdown cost.

Marine safety regulations require that a ship must produce a certain amount of power rapidly for emergency use. For instance, while cruising in an archipelago, a rapid requirement may arise for executing a tight turning maneuver, which requires electric power for the thrusters. The reserve power requirement parameter R_i is indexed over the time steps, which means that its value can vary for different phases or environments where the ship operates during a specific journey.

Constraint (14) implies the reserve power requirement, which has terms for both auxiliary engine network and battery. The battery reserve is the difference between instantaneous output power X_i and the maximum rate $X_{i,\max}$, whereas, for the diesel engine network, it is the sum of reserves of each engine that is online. Specifically, in (14) the difference $(y_{i,j,l} - x_{i,j,l})M_{j,k}$ is the load that is in reserve in engine k at a specific operating mode j .

The battery is described by constraints (15) through (18) which cover the time-integration element and the power output limits. Constraint (15) accounts for changes in the state of charge such that at each timestep, the state of charge is determined by the previous level

and a change in electrical energy during the period, which is the time integral of charging or discharging power. Cyclic battery constraint (16) sets the initial SoC to equal that at the end of the journey. Finally, constraints (17) through (19) limit the battery maximum charge and discharge rate based on the SoC, while constraint (20) limits the available shore power.

2.5 Data acquisition

The measurement data used in this work was acquired from the case ship's automation system. The time period spanned one typical operation cycle between 14th and 17th January 2019. The dataset contained power outputs of each auxiliary engine, their states (connected, ready, idling) and fuel consumptions with one minute sampling rate.

2.6 Case ship

The analyzed ship is a conventional direct drive RoPax ship that was built in 1990, is 203 meters long and has a deadweight of 3779 tons. The ship operates in a 48-hour cycle in the Baltic Sea (Figure 4). Speed profile of this cycle is composed of mostly open sea cruising at 18 knots (Figure 5). The topology of the energy system of the ship with the proposed retrofitted battery can be seen in Figure 3.

The propulsion system consists of four 8145 kW diesel engines that drive two main propellers through two gearboxes. The system is decoupled from the auxiliary power generating sets as shown. Auxiliary power is generated by four diesel engines that drive generators. The two larger engines are rated 3200 kW and the two smaller ones 2400 kW. The primary electricity consumers are the three thrusters and the hotel load.

Figure 3. Case ship mechanical and electrical system layouts. The engine symbols do not depict the actual cylinder count or configuration.

Figure 4. Case ship route in the Baltic Sea.

Figure 5. Reference operational profile (speed vs. time) of the case ship. The roman numerals indicate the main sailing parts and stops in port.

Figure 6. Electricity demand of the case ship on the 48-hour reference cycle.

A typical auxiliary power consumption profile for one cruise can be seen in Figure 6. The hotel load of the ship ranges between 2000 kW and 3000 kW. The use of thrusters when maneuvering in a harbor causes power peaks, whose magnitude depends on the load of the thrusters and how many are operated simultaneously.

2.7 Battery sizing

The power ratings of the auxiliary engines were chosen in the ship design phase to correspond to typical auxiliary loads. In the studied ship, this means the 2 – 3 MW power output at the engine design point. When approaching a harbor, however, additional auxiliary engines have to be started to supply the expected load transients produced by the thrusters. This upkeep of reserve power means that

the engines are operating at a suboptimal load level, reducing efficiency. If a battery system were sized adequately to ensure power supply for these transients, the issue would be resolved. Furthermore, the battery system can also respond to fast load transients, substituting the need for sustaining reserve power with the engines.

Minimum specifications for the battery are defined in safety regulations requiring a sufficient performance for substituting an auxiliary engine as a reserve power unit during archipelago or open sea cruising. Specifically, the battery power output must equal that of the smaller auxiliary engine output in all conditions to ensure sufficient power availability, hence setting an absolute minimum requirement for the capacity of the battery and C-rate. As the maximum power rating of the smaller auxiliary engine is 2400 kW, and the C-rate for the selected chemistry is four, the available battery system capacity must be at least 600 kWh in all conditions.

The battery may be specified according to the required power and energy for thrusters under port maneuvering scenarios represented in the data. Available capacity was determined to be a SoC range of 95% – 20% to achieve high cycle life for the battery. The highest energy consumed by the thrusters in port maneuvers is approximately 850 kWh, with 11% of events consuming this amount of energy. The lowest energy consumed in the analyzed events is approximately 300 kWh, with the rest of the values being quite evenly distributed between the maximum and minimum values. Based on the analyzed data, the 95% – 20% SoC range corresponds to a battery capacity of 850 kWh, determining that 1130 kWh should satisfy the energy demand of all the maneuvering events.

It must also be computed that the maximum power demand is in an acceptable range of C-rates for the specified chemistry. The data shows that the most frequent thruster power demand is in the range of 500 – 1000 kW, with a small number of occurrences where demand exceeds 2500 kW. The maximum thruster power demand was 3830 kW. With an 1130 kWh capacity battery, this would mean a discharge rate of 0.5-1 C during most of the operation, with a peak of approximately 3.5 C. These values are well in the acceptable range of current NMC chemistry battery systems [24].

In addition to peak-shaving, the battery system also provides redundancy for power production in case one of the active auxiliary engine fails. In such a scenario, the battery can be used as an emergency power supply until another engine is brought back online. The main question to answer is whether the 20% SoC reserve, which is always present in the battery, is enough to perform this task without the SoC falling below 5%. At such SoC levels, the open circuit voltage of the cells drops drastically, and the state of health of the batteries is altered significantly [25].

The maximum energy demand under the described emergency scenario equals the maximum power rating of the largest auxiliary engine aboard, multiplied by the time it takes to start another engine. According to manufacturers, it takes approximately 40 to 60 seconds to bring an auxiliary engine online in emergency conditions [6, 26]. The 60-second time period corresponds to a maximum emergency energy demand of 53.3 kWh for the ship under study or a 5% SoC decrease for the proposed battery system.

2.8 Space requirement of the battery system

The battery space consists of the battery cells and modules, which are organized in packs, and the necessary auxiliary systems, including thermal management, ventilation, fire protection, and air temperature regulation [27]. The inverter is located outside the battery space.

Table 1. Specifications of a 123.4 kWh NMC battery pack.

Attribute	Value	Unit
Capacity	123.4	kWh
Height	2.24	m
Width	0.87	m

Depth	0.74	m
Weight	1620	kg

Table 1 shows the specifications of an NMC chemistry battery pack offered by a maritime energy storage system provider [28]. In the case study, the smallest 940 kWh capacity battery is comprised of eight packs. The required floor space for the battery space is then 8.63 m² in a configuration of four packs in two rows and a one-meter wide maintenance corridor. Floor space of a 680 kW unit of a modular inverter system is 1.58 m² [29]. Thus, inverters dimensioned according to the full 4C output 3.76 MW require approximately 9.48 m² additional space, resulting in a total battery system installation area of 18.11 m².

The case ship vehicle cargo space is 2660 m². If the 940 kWh capacity battery system installation demanded space from the cargo area, it would claim only 0.68% of this space. Even the largest 3280 kWh capacity system would need less than 3%. The open sundeck on the case ship and other similar RoPax ships provides an alternative installation location if the machinery space is restricted.

2.9 Model parameter values for the case study

Engine efficiency as a function of load is approximated by L fuel flow rate linear equations, as shown in equation (6). Figure 7 shows 4093 case ship engine efficiency measurements, represented as SFOC points and utilized here to determine the parameter values of the engine model. Sufficient approximation is achieved by dividing the engine load into two regions at the 55% loading point, such that L receives a value of two. The values of the intercept A and slope A' for both regions are shown in Table 3 and also projected to the SFOC points in Figure 7. The projection is nonlinear because values of the linear fuel flow rates are divided by the corresponding power output.

Figure 7. SFOC measurements and FFR projections.

Table 2 shows the values of parameter $M_{j,k}$, which represent engines that are online at each auxiliary engine network operating mode and also the power ratings of the engines. If an engine k is disconnected at mode j , it receives a value of zero and otherwise its rated power. The operating mode set J contains only a subset of all possible combinations of a four-engine network because the engines are configured as two pairs of a small and large engine (Figure 3). Both engines of either pair must be started before an engine from the other pair can start.

Table 2. Values of the parameter $M_{j,k}$, which represents the power ratings (kW) of online engines in each engine network operating mode.

j	k			
	1	2	3	4
1	2400	0	0	0
2	0	0	3200	0
3	2400	0	3200	0
4	2400	2400	3200	0
5	2400	0	3200	3200
6	2400	2400	3200	3200

Reserve power requirement is 1200 kW when the ship is moored and 3000 kW otherwise. The value of the reserve power parameter R_i is set for each time step according to the navigation status that is active at the step.

The dataset contains individual auxiliary engine power outputs with one-minute sampling rate, as was described previously. However, setting the step size T_i to one minute for the entire round trip is not feasible, as CPU-time becomes very high. A solution for this problem was found by preserving the one-minute step size during port maneuvering, where power fluctuations are frequent and intense, and reducing the step size to ten minutes elsewhere.

The automation system of the ship controls engine startup and shutdown procedures such that excessive wear and load are avoided. The startup ramp cannot be observed from the one-minute data. This agrees with reported ramp-up times of about 30 seconds in engine product guides [6, 26]. However, a five minute cooling period is applied when a generating set is disconnected from the grid and shut down. During this period, the auxiliary engine is idling and consuming 62 l/h of fuel oil. In the model, binary variable $Y_{i,k}$ indicates this shutdown procedure and parameter S the cost, receiving a value of 4.39 (kg), which is the idling consumption for five minutes.

Table 3. Parameter values for the case study.

Symbol	Description	Value	Unit
$A_{f=1}$	Intercept of fuel flow rate function in engine operating region 1	0.01452	kg/kWh
$A_{f=2}$	Intercept of fuel flow rate function in engine operating region 2	0.006187	kg/kWh
$A'_{f=1}$	Slope of fuel flow rate function in engine operating region 1	0.1986	kg/kWh
$A'_{f=2}$	Slope of fuel flow rate function in engine operating region 2	0.2138	kg/kWh
I	Number of time steps	504	-
J	Number of operating modes	6	-
K	Number of installed engines	4	-
L	Number of operating regions	2	-
S	Shutdown period fuel oil consumption	4.39	kg
$x_{f=1,min}$	Minimum load in engine operating region 1	0.2	%/100
$x_{f=2,min}$	Minimum load in engine operating region 2	0.55	%/100
$x_{f=1,max}$	Maximum load in engine operating region 1	0.55	%/100
$x_{f=2,max}$	Maximum load in engine operating region 2	1	%/100
E	Battery capacity	940-3280	kWh
η	Battery discharging efficiency	0.95	%/100
η'	Battery charging efficiency	0.98	%/100
c	Fuel oil cost	0.35-0.9	€/kg
c'	Shore connection electricity cost	0.0825	€/kWh
C	Battery system cost	150-450	€/kWh
N'	Investment period	10	year
N	Number of cycles annually	180	-

Fuel oil cost and the battery system cost receive a range of values. Fuel cost range is based on five-year historical price data of low-sulfur marine gas oil (LSMGO) in Rotterdam [30]. Battery system cost ranges from the current lowest cost in the automotive industry to realized pilot project cost in a marine application [8, 31].

Shore connection availability is determined by the maximum charging power parameter $X''_{i,max}$. In the first studied scenario, shore connection is not available and $X''_{i,max}$ is set to zero for all i in $\{1,2,\dots,I\}$, which covers the operation cycle from start to finish. In the second scenario shore connection is available at both Helsinki and Stockholm ports. Subsequently, $X''_{i,max}$ receives a value of 2500 (kW) for the time steps i that correspond to the navigation status *moored*.

In the scenarios where shore connection is available, the case ship draws at most 4.34 GWh annually from the shore supply. Historical

retail electricity prices for Finnish industrial customers consuming between 2 and 19.9 GWh annually are reported in [32]. The reported prices consist of electric energy, distribution charge, and taxes. Although electric energy is traded on the spot market on an hourly basis with large price fluctuations, the historical monthly average price is highly consistent at around 80 €/MWh. Here, the shore connection electric energy cost parameter c' is given a value of 0.08246 (€/kWh), which was the average price in 2018.

Figure 8. Optimal engine scheduling with the conventional auxiliary system configuration on the reference 48-hour cycle. The sections with the grey background indicate that the ship is moored.

Figure 9. Optimal engine and battery scheduling (top) and battery state of charge (bottom) with the 3280 kWh hybrid auxiliary system configuration on the reference 48-hour cycle. The notation is same as in Figure 8.

Figure 10. Optimal engine and battery scheduling with the 3280 kWh hybrid auxiliary system configuration on the fifth port maneuvering event of the reference cycle.

Figure 11. Optimal engine and battery scheduling with the 940 kWh hybrid auxiliary system configuration on the fifth port maneuvering event of the reference cycle.

Table 4. Hybrid topology cost advantage (€, millions) in different shore connection availability, fuel oil cost, battery cost and battery capacity scenarios.

Fuel oil cost (€/ton)		Battery capacity (kWh)											
		940				1720				2500			
		Battery cost (€/kWh)				Battery cost (€/kWh)				Battery cost (€/kWh)			
	Shore connection	150	300	450	150	350	450	150	300	450	150	300	450
350	Not available	0.772	0.631	0.491	0.690	0.433	0.175	0.573	0.198	-0.178	0.455	-0.037	-0.523
	HEL and STO	0.694	0.554	0.413	0.613	0.355	0.097	0.495	0.120	-0.255	0.378	-0.114	-0.607
625	Not available	1.489	1.348	1.208	1.435	1.177	0.920	1.317	0.942	0.567	1.200	0.708	0.216
	HEL and STO	1.482	1.341	1.200	1.566	1.308	1.051	1.567	1.192	0.817	1.567	1.075	0.583
900	Not available	2.207	2.065	1.194	2.180	1.192	1.665	2.062	1.687	1.312	1.944	1.452	0.960
	HEL and STO	2.294	2.154	2.013	2.550	2.293	2.035	2.686	2.311	1.936	2.820	2.327	1.835

2.10 Solving the optimization model

The model constructed and presented in the previous section is limited to optimizing the power management of the engines and the battery, while the topology of the system and component sizes are fixed to keep the model linear. However, for each economic parameter combination, the optimal battery capacity was also investigated by solving the model with a set of capacity values. The selected capacities were 940, 1720, 2500, and 3280 kWh. The maximum power output was scaled with a C-rate of four. Other than the battery installation, the conventional and hybrid topologies were identical.

The cost minimization MILP problems have in this case been formulated with AMPL mathematical programming language and solved with GUROBI 8.1 solver package using default options.

3 RESULTS

In this section, the results of the ship operation optimization are first presented graphically for the conventional and two selected hybrid topologies to illustrate optimal auxiliary engine and battery power management strategies. The second graphical illustration is a histogram of engine operating points with the conventional and hybrid topologies in selected parameter values. Then, differences in battery system investment period total costs between the conventional and hybrid topologies are presented numerically in the latter part of the section.

In Figures 8 to 11, the results of two hybrid systems are presented and compared to the conventional auxiliary system layout. More specifically, Figure 8 shows the optimized output for the conventional auxiliary system that does not contain a battery, while in Figure 9, the

power and SoC are presented in the 3280 kWh battery capacity case. All scenarios have shore connection available, and fuel oil cost is 625 €/t. As expected, with the conventional topology the power demand is supplied by two engines operating at 30–40% load due to the reserve power requirement. With the larger battery installation, all of the six thruster demand peaks are primarily supplied from the battery, eliminating the need to start up an additional engine. On the contrary, all maneuvering operations require two online auxiliary engines with the small 940 kWh battery. This is illustrated in Figure 11, which focuses on the Mariehamn port visit starting at the 30.6 hour mark. The two online engines are operated at constant loads, and the battery supplies the transients, or when the engine power output exceeds the demand, the battery is charged. The same maneuvering event under the large 3280 kWh battery does not involve starting an additional engine (Figure 10).

During the open sea cruising periods, the battery functions mostly as a reserve power source without active use. Although the battery brings flexibility to the energy system, allowing the engines to operate continuously at the design point loading, this functionality is not taken advantage of in the larger battery installation. The SoC curve, in this case, is characterized by high power discharging events that correspond to the thruster peaks in port maneuvers. The Stockholm departure maneuver event alone depletes the battery from 95% to 51% SoC.

Figure 12 illustrates the impact of the battery on improving the engine operating points towards the high-efficiency loading region, comparing the conventional and the small battery topologies. The battery installation shifts the distribution to the right. The operating points at the low load region below the 50% load are removed entirely.

Figure 12. Auxiliary engine loads for the conventional and battery topologies.

Combined annual operating hours of the auxiliary engines were reduced significantly between the conventional and the hybrid system. With the small 940 kWh capacity battery alone, the reduction was from 15627 to 9072 hours (-41.9%) without shore connection and from 12957 to 6582 hours (-49.2%) with shore connection option and utilization. This contributes towards reduced maintenance costs, but this is not discussed further in this context.

Operation costs for the auxiliary system with the conventional topology depend on the fuel oil cost c , and shore connection availability values applied in the modeling. The cost ranges from €13.8 to €35.6 million within the economic parameter values and ranges presented in Table 3. Table 4 shows cost advantages, covering battery installation cost and operation costs, achieved with the hybrid system. The results are reported for three fuel oil and battery system costs and shore connection scenarios, and they represent the difference in total cost between optimization result for the conventional and hybrid topologies for the same parameter values. A positive value indicates a cost advantage in favor of the hybrid topology.

The greatest absolute cost advantage €2.82 million is achieved with the large 3280 kWh battery when shore connection is available, battery cost is the bottom end of the range, and fuel oil cost is at the top end of the range. A cost advantage is obtained independent of fuel oil or battery cost and shore connection availability, assuming that the optimal battery capacity is selected for each parameter value scenario. In the scenarios where shore connection was not available, the battery system cost advantage came solely from increased engine efficiency. The increased efficiency translated to 1.43 ton reduced fuel oil consumption on a single 48-hour cycle.

A general theme evident from the results in Table 4 is that the most economical battery capacity option varies according to the cost parameter values, such that higher fuel oil cost and lower battery capacity cost favor a higher capacity battery. Furthermore, fuel oil cost has a larger effect on the cost advantage with the ranges considered here whether or not shore connection is available.

When shore connection is available, charging the battery is economically attractive when shore electricity cost 82.5 €/MWh is lower than the cost of producing electricity with the generating sets, which ranges from 77 to 198 €/MWh, assuming loading at the design point.

4 DISCUSSION

The results suggest that the benefits of the battery are derived mostly from replacing the auxiliary engines for supplying the marine

safety regulation imposed power availability requirement, and not from active battery usage for improving engine operating points. The installation would be economically feasible even if the battery were not used at all, but only acting as a reserve power source enabling the reserve power demand supply from a battery and single diesel engine at high efficiency instead of two or more operating at a low-efficiency point. This is illustrated by the fact that the most economically attractive investment is found most often from the lower end of the battery capacity range considered in this study.

Pyrhonen et al. [8] studied cruise ferry battery installation feasibility with similar operational profile as the case ship in the present analysis. The battery was controlled with a rule-based strategy and enabled relaxed reserve power requirements for the generator sets. The results in the paper point to the same direction as the present work in the sense that a small capacity battery was found to be the most economically compelling.

While the hybrid system was found to reduce fuel oil consumption and make sense economically in most scenarios, the CO₂ emission reduction potential is partially canceled out by the emissions of the lithium-ion battery production. The CO₂ content of marine diesel engine exhaust gas burning MDO is 577 g/kWh [6]. SFOC at 75% load is 222 g/kWh for the auxiliary engines of the case ship, which translates to a conservative estimate of 2.66 g of CO₂ emitted for every one gram of fuel oil burned. The results showed that the hybrid system saved 257.5 tons of fuel oil annually due to the improved engine efficiency. During the ten-year battery investment period, the cumulative fuel oil saving is 2575 tons, which corresponds to 6850 tons of reduced CO₂ emissions. Lithium-ion battery production greenhouse gas burden is estimated to equal approximately 200 kg CO₂eq/kWh, but this varies according to the number of factors included in the calculation [33]. The production process of the smallest 940 kWh capacity battery in the case study would produce 188 tons of CO₂eq, which is only 2.7% of the 6850 ton CO₂ reduction potential attributed to the hybrid system.

Battery benefits may be underestimated in the present study for at least three reasons. First, the utilized power demand data does not have a sufficient sampling rate to accurately model power demand fluctuations in port operations and to capture the benefits of a battery's faster response to changes in electricity demand compared to a diesel engine. For instance, it would be profitable with brief power peaks that do not show up in the data to supply energy from the battery instead of starting an engine or having an engine idle as a power source. Second, the costs of starting and shutting down diesel engines might be higher than what was assumed in the present study. Requirements for idling the engine before shutdown and increased preheating, wear and maintenance cost caused by starting events were ignored. Third, the battery almost halved the total auxiliary engine running hours, which would translate directly to reduced maintenance costs. However, these costs were not evaluated or included in the economic feasibility analysis.

Usefulness of the developed optimization model increases as the complexity of the hybrid system operation grows. Generally, higher capacity battery, available shore connection, and larger operation cycle variation increase the challenge of determining a use schedule for the battery. On the other hand, modeling the battery feasibility strictly in reserve power source application does not necessarily require optimization, because in this case the battery does not have to be discharged at all in its intended normal use and a straightforward dynamic model is sufficient.

The MILP-optimization method and the model structure were found feasible for modeling the hybrid ship problem. The 48-hour reference cycle with variable one to ten minute step size resulted in 504 time steps, 15627 variables and 16127 constraints altogether, after solver algorithm presolve elimination processing. With default options, the GUROBI solver found a solution in less than a minute

with a standard desktop computer (3.2 GHz Intel Xeon processor and 32 GB RAM). This indicates that the model can be extended without a concern for intractability. However, the solution times achieved here might be strongly dependent on the parameter values. In addition, the solution time could be reduced by increasing time step duration in mostly steady state operation periods, such as when the ship is moored or cruises in an open sea with a constant speed.

5 CONCLUSION

A fast-computing model for optimizing hybrid ship operation was developed and applied with data from a RoPax ship operating in the Baltic Sea. The benefits of the lithium-ion battery in the numerical case study were primarily based on supplying reserve power for emergency maneuvering, thus enabling the auxiliary engines to operate at higher efficiency. The case study showed that retrofitting a battery to the case ship's auxiliary energy system is economically attractive except in a few edge cases, where battery cost is high and fuel oil cost is low. The battery was also found to reduce total auxiliary engine operating hours by almost half, which translates to reduced maintenance costs and increased lifespan.

When assessing battery installations, shipowners should pay attention primarily to fuel oil cost, which was shown to be the dominating uncertain parameter influencing the hybrid system cost advantage with the ranges considered. Larger capacity batteries provide the greatest absolute cost advantage in favorable economic conditions, but lead to economic losses in unfavorable conditions. In other words, the variance of the economic benefit increases with the battery capacity.

ACKNOWLEDGEMENT

The authors thank Tallink Silja Oy, Kim Hiort Af Ornäs and Aleksi Jerohin for providing support and data for this study.

FUNDING

The research was funded by Business Finland INTENS-project.

REFERENCES

- [1] IMO. MEPC.304(72) IMO Strategy on reduction of GHG emissions from ships. *Int Marit Organ* 2018;304:1–27.
- [2] International Maritime Organization. Sulphur 2020 - cutting sulphur oxide emissions. <http://www.imo.org/en/mediacentre/hottopics/pages/sulphur-2020.aspx> (accessed March 25, 2019).
- [3] Bouman EA, Lindstad E, Rialland AI, Strømman AH. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. *Transp Res Part D Transp Environ* 2017;52:408–21. doi:10.1016/j.trd.2017.03.022.
- [4] Goldie-Scot L. A Behind the Scenes Take on Lithium-ion Battery Prices. *Bloom New Energy Financ* 2019. <https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/> (accessed April 29, 2019).
- [5] Department of Energy (DOE). Solving Challenges in Energy Storage. 2018.
- [6] MAN. L27/38 Project Guide - Marine. 2018.
- [7] Baldi F, Ahlgren F, Nguyen T, Thern M, Andersson K. Energy and Exergy Analysis of a Cruise Ship 2018;11:1–41. doi:10.3390/en11102508.
- [8] Pyrhönen O, Pinomaa A, Lindh T, Peltoniemi P, Lana A, Montonen H, et al. Future Energy Storage Solutions in Marine Installations - FESSMI - Final Report. 2017.
- [9] Mohammadzadeh N, Baldi F, Boonen E. Application of Machine Learning and Mathematical Programming in the Optimization of the Energy Management System for Hybrid-Electric Vessels Having Cyclic Operations. *Int. Nav. Eng. Conf. Exhib.*, Glasgow, UK: 2018.
- [10] Long Vu T, Dhupia JS, Ayu AA, Kennedy L, Adnanes AK. Control Optimization for Electric Tugboats Powertrain with a Given Load Profile. *Int Symp Flex Autom* 2014:8.
- [11] Jaurola M, Hedin A, Tikkanen S, Huhtala K. TOpti: a flexible framework for optimising energy management for various ship machinery topologies. *J Mar Sci Technol* 2018. doi:10.1007/s00773-018-0617-4.
- [12] Dedes EK. Investigation of Hybrid Systems for Diesel Powered Ships. University of Southampton, 2013.
- [13] Frangopoulos CA. Recent developments and trends in optimization of energy systems. *Energy* 2018;164:1011–20. doi:10.1016/j.energy.2018.08.218.
- [14] Biegler LT, Grossmann IE. Retrospective on optimization. *Comput Chem Eng* 2004;28:1169–92. doi:10.1016/j.compchemeng.2003.11.003.
- [15] IBM. CPLEX User's manual. Version 12. 2015.
- [16] Borstlab R, ten Katen H. Ships' electrical systems. Enkhuizen: Dokmar; 2011.
- [17] Dinger A, Martin R, Mosquet X, Rabl M, Rizoulis D, Russo M, et al. Batteries for Electric Cars. 2010.
- [18] Zhang C, Li K, McLoone S, Yang Z. Battery modelling methods for electric vehicles - A review. 2014 *Eur Control Conf ECC* 2014 2014:2673–8. doi:10.1109/ECC.2014.6862541.
- [19] Doerffel D, Sharkh SA. A critical review of using the Peukert equation for determining the remaining capacity of lead-acid and lithium-ion batteries. *J Power Sources* 2006;155:395–400. doi:10.1016/j.jpowsour.2005.04.030.
- [20] Zhang R, Xia B, Li B, Cao L, Lai Y, Zheng W, et al. A study on the open circuit voltage and state of charge characterization of high capacity lithium-ion battery under different temperature. *Energies* 2018;11. doi:10.3390/en11092408.
- [21] Keil P, Schuster SF, Keil P, Schuster SF, Lüders C Von, Hesse H. Lifetime Analyses of Lithium-Ion EV Batteries. 3rd *Electromobility Challenging Issues Conf* 2015.
- [22] Finnish Energy. Structure of the electricity networks 2019. https://energia.fi/en/energy_sector_in_finland/energy_networks/electricity_networks (accessed September 22, 2019).
- [23] Ericsson P, Fazlagic I. Shore-Side Power Supply. Chalmers University of Technology, 2008.
- [24] Kokam. Li-ion/Polymers cell specifications 2019. kokam.com/data/Kokam_Cell_Brochure_V.3.pdf (accessed February 7, 2019).
- [25] Mishra PP, Garg M, Mendoza S, Liu J, Rahn CD, Fathy HK. How Does Model Reduction Affect Lithium-Ion Battery State of Charge Estimation Errors? Theory and Experiments. *J Electrochem Soc* 2017;164:A237–51. doi:10.1149/2.0751702jes.
- [26] Wärtsilä Finland Oy. Wärtsilä 32 Product Guide. 2018.
- [27] DNV. Guideline for Large Maritime Battery Systems (Rev. V1.0) 2014.
- [28] Corvus Orca Energy 2019. <https://corvusenergy.com/products/corvus-orca-energy/> (accessed September 20, 2019).
- [29] Schneider Electric. Conext Core XC ES 2019.
- [30] Rotterdam LSMGO price. Sh Bunker n.d. <https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#LSMGO> (accessed December 9, 2018).
- [31] McKinsey. Electrifying insights: How automakers can drive electrified vehicle sales and profitability. McKinsey Co

- 2017:28. doi:10.3748/wjg.v19.i46.8752.
- [32] Statistics Finland. Statistics: Energy prices.
http://www.stat.fi/til/ehi/index_en.html (accessed September 3, 2019)
- [33] Romare M, Dahllöf L. The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries. 2017. doi:978-91-88319-60-9.

Highlights

- Optimization model for designing and operating a hybrid ship
- Application in retrofitting of a lithium-ion battery to a passenger ferry
- Case ship operating profile and engine model based on measurements
- 257 tons of fuel oil savings attributed to the hybrid system
- Higher fuel oil costs increase the attractiveness of battery investment