Power system sizing for zero-emission shipping

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Introduction

- In the light of increased effort imposed by IMO to reduce the environmental footprint caused by shipping, as well as the new global limit on sulfur content in marine fuels to take effect from January 2020, shipowners are facing challenges in complying with regulations and expectations to lower their emissions in a cost-efficient way.
- Several technological measures exist, some of them are switching fuels, installing exhaust gas after-treatment systems, and switching power generation systems - all of them increasing cost and complexity.
- Hybrid fuel cell - battery systems have been getting increased attention recently, and may be a part of the solution.

Objective

- In a hybrid fuel cell - battery system, the fuel cells are assumed to provide the base load, and batteries are assumed to be supplying both excess power for peak loads and storage capacity for load shedding - when instantaneous power demand fluctuates.
- The objective of the thesis is to develop a model to serve as a decision support tool for deciding on the cost-optimal combination of fuel cells and battery system for zero-emission shipping.
- The total cost of a power system over the vessel's life time will be dependent on system investment costs, fuel costs, maintenance cost and replacement costs, where the influence on each of them is correlated with each other, due to degradation mechanisms of the fuel cells and batteries with respect to their relative usage to their total capacity.
- As fuel cell technology and hydrogen fuel currently are of high costs, the model also need to compare the hybrid fuel cell - battery system to a conventional set-up, to investigate in which scenarios switching propulsion systems are favorable to the other options mentioned.

Method

- A typical round trip can be divided into specific operational modes, each with its power requirements and duration, see figure 1. From this, an aggregated yearly distribution of operational modes can be created, see figure 2. Each operational mode will have its characteristics in terms of power demand fluctuation.
- One approach is to assume a constant load for fuel cells, positioned at the load level where the sum of peak shaving energy equals the sum of load shedding energy. The batteries will serve as the buffer, providing peak shaving power and absorbing load shedding power. This approach finds the optimal trade-off between fuel cell degradation on a constant load and battery cycling due to required power supply and absorption - which affects the replacement costs as well as initial investment costs.
- Another approach is to include degradation mechanisms in transient behavior of fuel cells, and allow fuel cells to operate within a range.
- The difference between the two approaches are illustrated by the ranges and arrows in figure 3.

Implementation

- The model is implemented as a mixed integer non-linear problem (MINLP), with a non-linear objective function and linear constraints in Matlab, using a Genetic algorithm.

$$
\begin{aligned}
\min z = \ & \textbf{Fuel costs:} \\
& \sum_{t\in T}\sum_{o\in O_t}\sum_{e\in E^{FC}}\sum_{f\in F^{FC}} R_{ot} D_t y_f C_{ft}^{FC} \varphi_{eot} G_e \\
&+ \sum_{t\in T}\sum_{o\in O_t}\sum_{e\in E^{B}} R_{ot} D_t C_t^{el} \rho_{eot} \\
&+ \sum_{t\in T}\sum_{o\in O_t} W_{ot} \tau_{ot}^{El} C_t^{el} \\
&+ \sum_{t\in T}\sum_{o\in O_t}\sum_{d\in D}\sum_{f\in F^{DE}} R_{ot} D_t y_{fot} C_{ft}^{DE} P_d^R x_{dot} G_d(x_{dot}) \\
&+ \ \textbf{Emissions costs (NOx):} \\
& \sum_{t\in T}\sum_{o\in O_t}\sum_{d\in D} R_{ot} H^Y D_t C_{ot}^N P_d^R x_{dot} E_d^N \\
&+ \ \textbf{Investment costs, machinery + h2-storage:} \\
&+ \sum_{e\in E^{FC}} C_{FC}^I P_e^R \omega_e + \sum_{f\in F^{FC}}\sum_{s\in S_{sf}} C_{sf}^{SFC} z_{sf} \\
&+ \sum_{e\in E^{B}} (C_B^{IkWh} K_e + C_B^{Iinv} P_e^R)\mu_e \\
&+ \sum_{d\in D} C_{DE}^I P_d^R \alpha_d \\
&+ \ \textbf{Maintenance costs - fuel cells, batteries and diesel engines:} \\
& \sum_{e\in E^{FC}}\sum_{t\in T} C_{FC}^M P_e^R D_t \omega_e + \sum_{e\in E^{B}}\sum_{t\in T} C_B^M P_e^R D_t \mu_e + \sum_{d\in D}\sum_{t\in T} C_{DE}^M P_d^R D_t \alpha_e \\
&+ \ \textbf{Replacement costs - Fuel cells and batteries:} \\
&+ \sum_{e\in E^{FC}} C_{FC}^R \left[\sum_{t\in T}\sum_{o\in O_t} \frac{H^Y R_{ot} D_t \theta_{eot} \delta_e^{FC} \left(1 + 0.25\left\lceil \frac{\varphi_{eot}}{P_e^R \omega_e} - 0.8 \right\rceil + 0.25 \left\lceil 0.2 - \frac{\varphi_{eot}}{P_e^R \omega_e} \right\rceil\right)}{EL_e} \right] \\
&+ \sum_{e\in E^{B}} C_e^R K_e \mu_e \sum_{t\in T}\sum_{o\in O_t}\sum_{i=1}^{n_{ps}} 0.2\left(\frac{E_{iot}^{ps}\pi_e}{K_e \mu_e}\right)^{1.1} \left(1 - \left(\left\lceil 0.01 - \frac{E_{iot}^{ps}\pi_e}{K_e\mu_e}\right\rceil\right)\right) + 0.2 \frac{E_{iot}^{ps}\pi_e}{K_e\mu_e} \left\lceil 0.01 - \frac{E_{iot}^{ps}\pi_e}{K_e\mu_e} \right\rceil
\end{aligned}
$$