Technology and Science for the Ships of the Future
V. Crupi and V. Bucci (Eds.)

doi:10.3233/PMST250103

Optimized Energy Storage System Sizing for a Series Hybrid Waterbus to Minimize Pollutant Emissions

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Abstract. This study examines the optimal sizing of an energy storage system (ESS) to reduce hazardous pollutant emissions in a series hybrid powertrain designed to replace conventional waterbuses in Venice. The proposed system consists of three generator sets and two electric motors, offering a cleaner alternative for the city's public transportation network. A quasi-static simulation model was developed to assess powertrain performance using real-world operational data collected from waterbuses operating in the Venice Lagoon. Dynamic programming was employed to derive emissions-optimal control strategies, minimizing the trade-off between nitrogen oxides (NOx) and hydrocarbons (HC). By simulating different ESS configurations, the study assesses how energy storage capacity influences emissions reduction potential and system flexibility. At the same time, using the optimal energy management strategy when comparing different ESS sizes ensures that each configuration operates under the best possible conditions, eliminating biases introduced by suboptimal control strategies. This approach isolates the impact of ESS capacity on emissions and performance, allowing for a fair comparison between different storage sizes. The results indicate that even a relatively small ESS can significantly reduce NOx and HC emissions, while a larger ESS provides greater flexibility in selectively mitigating specific pollutants. Additionally, a larger ESS enables pure electric operation, allowing emissions to be spatially shifted when necessary. These findings emphasize the potential benefits of hybrid-electric ferries for coastal cities. Retrofitting existing fleets and integrating hybrid technologies into new vessels could play a critical role in improving urban air quality, ensuring compliance with emissions regulations, and advancing sustainable maritime transport.

Keywords. hybrid ship, EMS, dynamic programming, optimal control, emissions

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1. Introduction

Waterborne transport is a major source of local air pollution, emitting harmful substances such as sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), and hydrocarbons (HC). These pollutants pose serious health risks, particularly in densely populated coastal and port cities. In response to growing concerns over air quality and public health, stricter emissions regulations [1] have driven the development of cleaner technologies, including, among others, hybrid-electric powertrains

Hybrid propulsion systems, especially in short-sea passenger vessels, offer a promising solution for reducing urban air pollution. Traditional ship propulsion relies on internal combustion engines optimized for fuel efficiency at cruise speeds but suffers from inefficiencies during low-speed operations, leading to high emissions. Hybrid-electric systems on the other hand typically combine an internal combustion engine with an electric drivetrain, offering advantages such as load leveling, reduced fuel consumption, and improved responsiveness. More complex hybrid concepts exist which also take advantage of fuel cells [2] or [3].

Hybridization has been successfully implemented in cruise and naval ships for decades, primarily to enhance maneuverability in ports. However, recent advancements in battery technology and power electronics have expanded its application to ferries [4,2], including inland [5] and coastal [6] applications, ocean-going vessels [3], catamarans [7], utility vehicles [8], and tugs [9].

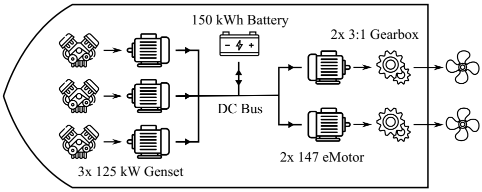
By lowering emissions during low-speed operations and in crowded waterways, these systems can significantly improve air quality and mitigate health risks for local communities. However, their effectiveness depends on a well-designed hybrid powertrain, which requires a comprehensive understanding of the operating scenario and energy management strategies. The energy management strategy (EMS) plays a crucial role in regulating power sources, such as diesel engines and batteries, to efficiently supply the vessel's instantaneous energy demands.

This study explores a new hybrid-electric powertrain architecture for a waterbus operating in Venice, one of the world's busiest coastal areas in terms of passenger traffic. In particular, we consider a series hybrid powertrain and focus on sizing the energy storage system (ESS) in order to minimize pollutant emissions.

In order to support this ESS design task, we develop energy management strategies using dynamic programming (DP), a computationally intensive yet globally optimal solution suitable for offline control. By leveraging DP in the design phase, it is possible to determine the best achievable fuel consumption and emissions reduction for a given hybrid architecture. This serves as a benchmark for evaluating different powertrain configurations (in this work, different ESS sizes) and developing real-time strategies that approximate optimal performance while maintaining feasibility for onboard implementation.

2. Case study

The hybrid waterbus under consideration is a series hybrid with three Diesel generators and two electric motors for propulsion, as depicted in Figure 1a. Each Diesel engine has a rated power of 125 kW, while the electric motors have a rated power of 147 kW



(a) Layout of the hybrid waterbus powertrain.

(b) The route covered by line 12 with selected stops.

Figure 1. Powertrain layout and operational mission.

each. The energy storage system is composed by a number of LFP battery modules, each having a rated voltage of 360 V and a nominal energy of 25 kWh.

The hybrid waterbus is meant to replace a conventional Diesel waterbus that is currently servicing line 12 in the Venice lagoon (Fig. 1b), which covers (in its longest variation) the trip from the city centre (*Fondamenta Nove*) to a peninsula (*Litorale del Cavallino*); a one-way trip lasts slightly over one hour.

3. Optimal energy management strategy

As previously mentioned, the energy management strategy for every ESS size was obtained with dynamic programmming, in order to obtain an unbiased comparison.

Specifically, a DP algorithm was implemented in MATLAB, using the open-source *DynaProg* [10] toolbox, to optimize control strategies for NOx and HC emissions.

To apply dynamic programming, the energy management strategy must be cast as an optimal control problem [11]. This includes defining a total cost to minimize over the mission, state and control variables, and a model for state dynamics [12].

Exogenous inputs are time-varying factors that affect state dynamics but cannot be controlled by the EMS, representing the operational mission (i.e. the propeller speed and torque). The chosen control variables include two for setting engine speed ω_{eng} and torque T_{eng} for active engines and a third variable, α, to set the number of gen-sets to activate. The state variables are the battery's state of charge σ and a second variable, α_{prev}, which tracks the number of gen-sets that are currently in operation.

The dynamic model for the battery's state of charge uses quasi-static models of the propulsion motors, DC bus, battery, electric generators, and the engines that drive them.

The speed ω_{mot} and torque T_{mot} of the electrical motor are obtained by applying the gearbox (fixed) transmission ratio and efficiency to the propeller's speed and torque. The motor electrical power $P_{\text{mot,el}}$ is obtained by adding the mechanical power and conversion losses, which are obtained by a loss map as a function of speed ω_{mot} and torque T_{mot}.

$$P_{\text{mot,el}} = \omega_{\text{mot}} T_{\text{mot}} + P_{\text{mot,loss}}(\omega_{\text{mot}}, T_{\text{mot}}). \tag{1}$$

The engine speed and torque, as well as the number of operating engines, are directly set by the control variables. The flow rates of HC and NOx emissions are obtained by using the appropriate engine maps, as a function of speed and torque:

$$\dot{m}_{\mathrm{NOx}} = \dot{m_{\mathrm{NOx}}}(\omega_{\mathrm{eng}}, T_{\mathrm{eng}}), \tag{2}$$

$$\dot{m}_{\mathrm{HC}} = \dot{m_{\mathrm{HC}}}(\omega_{\mathrm{eng}}, T_{\mathrm{eng}}). \tag{3}$$

Each engine operating point (ω_{eng}, T_{eng}) is equal to the corresponding generators' operating point (ω_{gen}, T_{gen}). The generators' electrical power $P_{\mathrm{gen,el}}$ can be whence obtained by adding electrical losses, which are again obtained from a loss map, similarly to the propulsion motors.

The power balance at the DC bus gives the battery power P_{b} as:

$$P_{\mathrm{b}} = \sum P_{\mathrm{mot,el}} + P_{\mathrm{aux}} - \sum P_{\mathrm{gen,el}}, \tag{4}$$

where P_{aux} models electrical auxiliaries.

Finally, the battery current i_{b} was evaluated as:

$$i_{\mathrm{b}} = \frac{v_{\mathrm{oc}} - \sqrt{v_{\mathrm{oc}}^2 - 4R_{\mathrm{eq}}P_{\mathrm{b}}}}{2R_{\mathrm{eq}}}, \tag{5}$$

where $v_{\mathrm{b}}(\sigma)$ is the open circuit voltage characteristic and $R_{\mathrm{eq}}(\sigma)$ is the equivalent resistance characteristic. The SOC dynamics is then simply given by Coulomb counting as

$$\dot{\sigma} = \frac{i_{\mathrm{b}}}{C_{\mathrm{b}}}, \tag{6}$$

where C_{b} is the battery's capacity.

The last ingredient of the energy management strategy optimization algorithm is a total cost to be minimized by choosing the control sequence $(u_0, \ldots, u_{N-1})$ appropriately. The total cost J was defined as a trade-off between NOx and HC emissions:

$$J(x_0, u_0, \ldots, u_{N-1}) = \sum_{k=0}^{N-1} \left(\mu \frac{\dot{m}_{\mathrm{NOx}}}{\dot{m}_{\mathrm{max,NOx}}} + (1-\mu) \frac{\dot{m}_{HC}}{\dot{m}_{\mathrm{max,HC}}} + \delta \right), \tag{7}$$

with μ acting as a trade-off factor, and $\dot{m}_{\mathrm{HC,\,max}}$, $\dot{m}_{\mathrm{NOx,\,max}}$ are the maximum possible flow rates of HC and NOx. $\dot{m}_{\mathrm{NOx}}$ and $\dot{m}_{\mathrm{HC}}$ depend on the controls through Eq. 2 and 3. In addition, a penalty term δ was added to prevent frequent engine switchings:

$$\begin{cases} \delta = 0.09 \quad \text{if} \quad \alpha_{\mathrm{prev}} > \alpha, \\ \delta = 0 \quad \text{if} \quad \alpha_{\mathrm{prev}} \leq \alpha. \end{cases} \tag{8}$$

Finally, a charge-sustaining constraint was formulated on the SOC trajectory, i.e. $\sigma(t_{\mathrm{f}}) = \sigma(t_0)$.

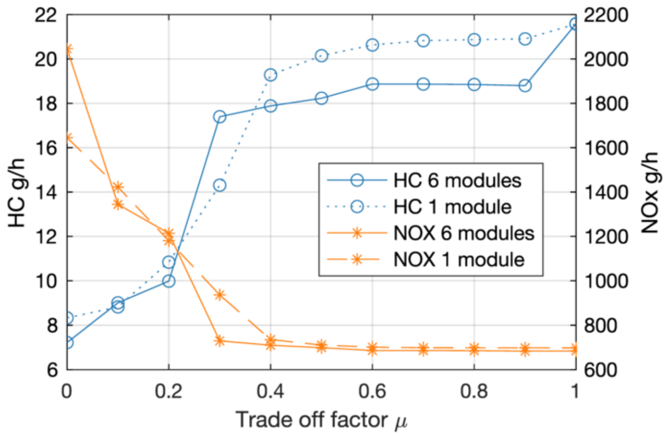


Figure 2. Average emissions with varying trade-off factors, with one or six battery modules.

4. Results and discussion

The simulation model of the hybrid waterbus was used in conjunction with the dynamic programming algorithm to run simulations and assess the average emissions of six powertrain configurations, which differ in the number of modules that make up the ESS. The smallest ESS has a single 25 kWh module, whereas the largest ESS has six such modules arranged in parallel for a total of 150 kWh. For each configurations, several simulations were run varying the trade-off factor μ, which defines the minimization objective of the dynamic programming algorithm. Values of $\mu = 0$ and $\mu = 1$ correspond to a purely HC-oriented or purely NOx-oriented strategy, respectively.

Focusing on the largest and smallest ESS designs considered (corresponding to the configuration with six battery modules and the configuration with a single module), Fig. 2 illustrates that a reduction in energy storage system size generally results in increased NOx and HC emissions. The difference is more marked in the simulations with a high (NOx-oriented) trade-off factor, where a noticeable increase in HC emissions can be noticed.

Fig. 3 reports the variation in HC and NOx emissions with respect to the largest ESS (six modules). We can see that the five-modules, four-modules and three-modules configurations have comparable emissions to the six-modules configuration. On the other hand, the two-modules configuration shows a noticeable increase in either HC emissions, NOx emissions, or both. This increase is even more marked in the one-module configuration.

The reasons behind this increases in emissions can be investigated by inspecting additional details about the simulation results. Indeed, the variation in ESS size significantly affects the operation of the internal combustion engines, which operate under increasingly constrained conditions. This forces a progressive deviation from the optimal operating conditions and leads to a rise in pollutant emissions. This is clearly visible in Fig. 4 and 5, where the engine operating points are represented.

In the configuration with six battery modules (Fig. 4), the operating point is very stable and localized in a single area, which corresponds to the optimal region of the engine map with respect to the considered trade-off between NOx and HC emissions. This is clearly shown in Fig. 4a and 4b. As Fig. 4c and Fig. 4d show, each engine is either

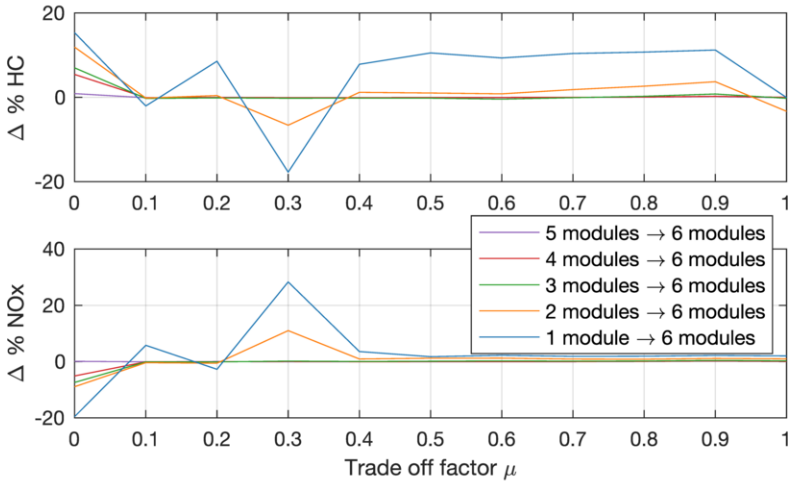


Figure 3. Variation in emissions with varying trade-off factors, with one to five battery modules, relative to the configuration with six modules.

turned off or providing the power corresponding to the previously mentioned operating point.

The scenario changes significantly when only one module is present Fig. 5. In this case, the power distribution (Fig. 5d) exhibits multiple additional levels, reflecting a more dispersed and less stable operating regime for all engines. This is also clearly visible in the time profiles shown in Fig. 5c. The engine operating points (Fig. 5a and 5b) are now far more dispersed, and include areas of the engine map that deviate from the previous concentrated area.

5. Conclusions

Hybrid electric powertrains are a promising technology to abate pollutant emissions from waterboren transport. However, proper sizing of the powertrain components is a crucial factor in maximizing the benefits of hybrid-electric powertrains. In particular, this case study has shown how the energy content of the ESS directly affects system efficiency, emissions, and overall performance. An optimally sized ESS allows for an effective balance between the internal combustion engine and the electric propulsion system, ensuring smooth operation and minimizing environmental impact. Conversely, improper sizing can lead to inefficiencies, increased pollutant emissions, and suboptimal energy management.

An excessive reduction of the ESS size in a series hybrid significantly constrains the behavior of the internal combustion engines and power management, causing their operation to deviate from the optimal point required for the specific mission. On the other hand, oversizing the battery creates a sufficient energy buffer to decouple the operation of the thermal and electric components, allowing the system to work in optimal conditions—but at the cost of a significant increase in weight and higher initial installation expenses.

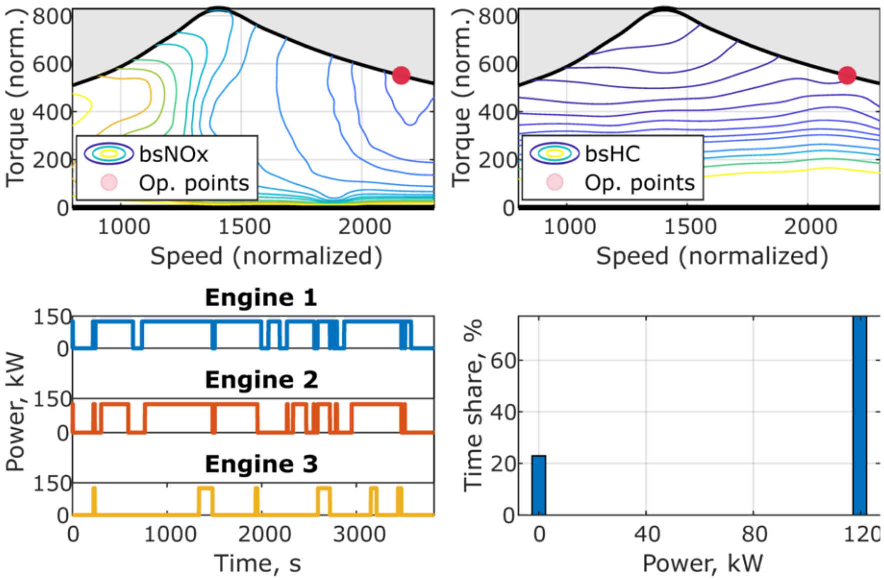


Figure 4. Simulation results of the configuration with six battery modules and a trade-off factor $\mu = 0.5$. Clockwise from top left: engine operating points with contour lines of specific NOx and HC emissions; distribution of engine power over time; time profiles of engine power.

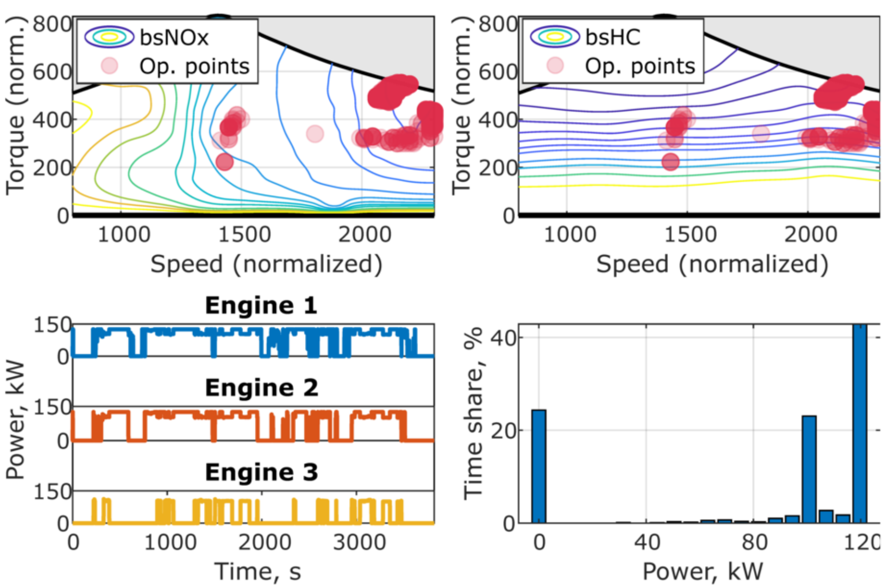


Figure 5. Simulation results of the configuration with a single battery module and a trade-off factor $\mu = 0.5$. Clockwise from top left: engine operating points with contour lines of specific NOx and HC emissions; distribution of engine power over time; time profiles of engine power.

In the case under examination, the optimal battery size corresponds to the case with three modules. In fact, despite the reduction in capacity, there is no noticeable variation in pollutant emissions. Nonetheless, it should be noted that the sizing procedure was conducted based on standard operating conditions on a specific service (line 12). A larger ESS might be recommended to ensure a significant safety margin in case of abnormal conditions or emergency situations. For example, given the C-rate limitation of the LFP batteries under consideration, the configuration with six modules is the only one that can guarantee maximum power to the propulsion motors if all gen-sets are turned off.

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