Hybrid powerplant configuration model for marine vessel equipped with hydrogen fuel-cells

Lorenzo Balestra*[1], Ingrid Schjølberg[1]
[1] Department of Marine Technology, Otto Nielsens Veg 10,
Norwegian University of Science and Technology, NO-7491, Trondheim, Norway
*lorenzo.balestra@ntnu.no, ingrid.schjolberg@ntnu.no

Abstract

The transport sector is investing in new technologies, shifting towards zero-emission propulsion systems. This shift can be observed in the automotive transport sector, but also in maritime transport, where shipowners are evaluating new powertrain configurations and less polluting energy carriers. The innovation in this field is aided by the development of software, based on simulation models representing the powertrain. In this paper, a quasi-static model for a hybrid powerplant is presented. The focus is on hybrid solutions utilizing proton exchange membrane hydrogen fuel cells and batteries. This model can aid the design of powerplants for new hybrid vehicles, or older ones waiting for a retrofit. The model is converted into a Matlab software application for ease of use. Results produced by the model define the powerplant composition and a series of factors, such as fuel cell degradation and hydrogen consumption, that have an influence on running costs. The functionalities of the Matlab software application based on the quasi-static model are demonstrated via one case study considering a harbor tugboat. The results obtained can also be used to measure the technical and economic feasibility of powertrain configurations. The presented model does not include effects related to components aging as all the hardware is considered at beginning of life.

Nomenclature

P_{op}: Vehicle's power demand [kW]

P_{fc}: Power output single fuel cell [kW]

$P_{\mathrm{fc\text{-}rated}}$: Rated power fuel cell [kW]

P_{b}: Power output single battery [kW]

P_{f}: Filtered power demand [kW]

P_{L}: Constant power demand [kW]

V_{fc}: Fuel cell voltage [V]

I_{fc}: Fuel cell current [A]

R_{t}: Fuel cell response time [s]

η_{fc}: Fuel cell efficiency

η_{bc}: Efficiency boost converter

$\eta_{\mathrm{bi\text{-}dir}}$: Efficiency bi-directional converter

n_{fc}: Number of fuel cells

n_{b}: Number of batteries

t_{tot}: Total simulation time [s]

t_{s}: Sample time operational profile [s]

Hpo: High power deg. rate [μVh^{-1}]

Lpo: Low power deg. rate [μVh^{-1}]

Tl: Trans. loading deg. rate [μV/ΔkW]

t_{hp}: Time at high-power operation [s]

t_{lp}: Time at low-power operation [s]

1 Introduction

The transport industry has always focused on innovation to improve the design of vehicles, efficiency of the powertrain, and reduce both production and running costs [1, 2]. In this paper the definition of a vehicle is considered to be the most broad interpretation, where a vehicle is any machine able to transport people or cargo, including road, rail and sea transport.

Regulations on pollutants and greenhouse gas emissions [3, 4, 5] have recently influenced different sectors to gradually find alternative solutions to the internal combustion engines (ICE) for power generation, and adopt hybrid or fully electric propulsion to improve the overall system efficiency and reduce the environmental impact [6].

Electric drivetrains prove to be a versatile solution, allowing for the elimination of the mechanical connection between the prime mover and the wheels, or propeller, removing the direct dependency between rotational speed of these elements and the engine crankshaft. This condition permits a more flexible load regulation, with the possibility to be as close as possible to the maximum efficiency operational point, with consequent fuel savings [7].

The transition to electric drivetrains paves the way for the adoption of components such as batteries, fuel cells and supercapacitors. These systems can be integrated into the vehicle's electric grid to replace ICEs for zero-emission operations. However, this transition presents many challenges as these components do not have the same technological maturity as ICEs and are still being developed at a fast pace. State of the art batteries still have relatively low energy density and are limited by the recharge time [8, 9, 10]. Zero-emission vehicles requiring long range capabilities and fast refuelling time need a more energy dense storage solution. For this use-case, hydrogen tanks and a series of proton exchange membrane fuel cells (PEMFC) can be installed on the vehicle to provide baseline energy or function as a complementary source of power when the batteries reach a low state of charge (SOC) [11, 12].

The optimization of a hybrid powerplant with PEMFCs and batteries for different types of vehicles is a non trivial task [13], as the choice of component sizing (CS) and energy management strategy (EMS) heavily influences the performance of the vehicle, its running costs, and maintanence intervals - among many other factors [14]. For this optimization it is important to consider the power demand and the use-case of the vehicle in order to define the operational profile (OP). The optimization also needs to comply with other design requirements such as footprint, weight limitations, or budget limitations.

The quasi-static model presented in this paper was developed as the foundation for an software application developed in Matlab. This software application aims to improve the design process by providing the possibility to study powerplant configurations based on user selected parameters. Different configurations can be saved and compared, verifying that they match with the requirements imposed for the powerplant, with the possibility to validate them in the dynamic model presented in [15, 16].

The developed software application currently includes two Energy Management Systems (EMS) both of the rule-based type, with 3 filters which are suitable for real-time control or hardware in the loop testing. The presented version of the software application is tested via one case study considering the operations of a harbor tugboat. The case study shows the capabilities of the model including validation with real-world data and testing. In the case study, both the peak-shaving strategy and the load-leveling strategy are tested. The model considers mostly ideal components and does not include effects related to components aging. However, this could be included in a later stage.

2 State-of-the-art for hydrogen powertrain models

The creation of models for the validation of a vehicle's powertrain design through simulation of the system is an area of strong interest in recent years. The access to cheap computational power allows both researchers in academia, and engineers in the industry, to create digital models that represent the system into consideration with different degrees of accuracy depending on the scope of the model. Such digital models, when focusing on the powertrain, allow the study of power generation, storage and distribution within the vessel's electrical grid, in addition to the definitions of factors that are impacted by the power flow.

Different types of models have been developed, over the years, to study powertrains including proton exchange membrane fuel cells and batteries. Of particular interest are models developed for the maritime industry with large power requirements, as the model described in this paper has been developed to be used mainly for maritime vessels.

Several approaches consider a system with a predefined component sizing and mainly focus on the study of operation optimization with different energy management strategies [17, 18, 19]. Other approaches focus on the optimal sizing problem of the powertrain [20, 21] while neglecting the EMS optimization or providing basic strategies [22]. There are publications where the component sizing and energy management strategy were considered concurrently for the optimization of the entire system [23, 24].

The large majority of these powertrain models are dynamic models, but quasi-static models have also been developed as they offer faster computational time [25, 26].

The model described in this paper is a quasi-static model providing a platform for the quick-sizing of the power system to be tested using the dynamic model developed in [15]. This model also tries to fill the gap with respect to quasi-static models used for quick powertrain sizing before validation on a dynamic model that is more resource intensive. The software application of a simple quasi-static model can produce beneficial time saving effects when considering dynamic validation through models or in laboratories for hardware in the loop testing.

3 Framework description

The presented software application was developed using Matlab, and compiled to operate as a standalone software with graphic user interface (GUI). This software application is used to perform the component sizing of a vehicle's hybrid powerplant utilizing PEMFCs and batteries based on the energy management strategy selected. The component sizing is here defined as the number of powerplant components and relative rating or capacity. The focus is on the components that produce, release and store electrical power. The sizing is performed evaluating a series of inputs provided by the user (see Section 4). The sizing is also heavily dependent on the EMS adopted for the considered use-case (see Section 5).

The software application is based on a quasi-static simulation model of the powerplant, ensuring rapid execution time. The drawback of this approach is that the dynamic behavior of the components is not taken into consideration and the results obtained represent a first-attempt solution to the optimization problem that need to be validated in a dynamic simulation, before implementation. Quasi-static simulations adopting the backward method are best suited for a fast analysis and evaluation of the energy and power flow of the vehicle powerplant when computational resources are limited (see Fig. 1).

This model was created to dimension hybrid powerplants, utilizing PEMFCs and batteries, for different type of vehicles including cars, ships, transport trucks and locomotives. The possibility to dimension powertrains in such different power ranges it is given by the inherent scalability of hybrid systems. It is considered that to achieve the user-defined power level it is possible to connect multiple PEMFCs stacks in parallel to reach the desired output. The same approach with the parallel connection can be considered for commercial battery modules. This condition determines a scalability relation that can be considered linear with respect to the power output.

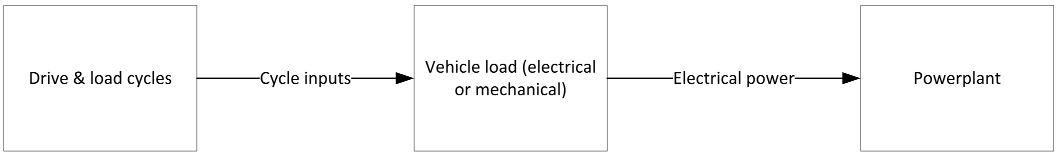

Figure 1: Flowchart representing the quasi-static energy based model (backward method) for vehicle simulation

4 Inputs and configuration

The software application requires a series of user inputs that are typed or uploaded using the GUI (see Fig. 5). The first input is the operational profile of the vehicle considered. The operational profile is an array of values defining the power demand during a considered time interval. In this paper, it is considered that the operational profile represents the power demand at the DC-Bus level, before the distribution to propulsion motors and auxiliary loads. For this reason the efficiency of the electrical grid is considered only up to the DC-Bus, including boost and bi-directional converters, but no inverters, variable speed drives or induction motors.

If the software application is used to configure a new powerplant for the zero-emission retrofit of a vehicle currently in active service, the operational profile can be sampled during operations by measuring the power output required over a specific transit route. The collection of the power data defining the OP sets a target power output for the hybrid zero-emission plant.

The second input needed is the sample rate of the operational profile. The sample rate influences the accuracy of the calculated results, and should be in the order of seconds to allow a correct calculation of the PEMFC transient response and degradation.

Further input is required to define the model of PEMFC selected for the specific system considered. As fuel cell stacks come in pre-packaged commercial units with pre-defined power outputs, the choice was made to have the user specify the fuel cells parameters for the model taken into consideration. The PEMFC characterization is carried out defining the voltage variation and the efficiency against the current in the operational range of the unit (see Fig. 2). The resulting power curve of the unit can be calculated from the obtained data. Such curves are available on datasheets or can be obtained experimentally with simple measuring equipment.

The definition of a specific PEMFC type provides some boundary conditions for the optimization of the powerplant, where the developed algorithm is tasked with the calculation of the number of PEMFC stacks needed to perform the imposed power demand.

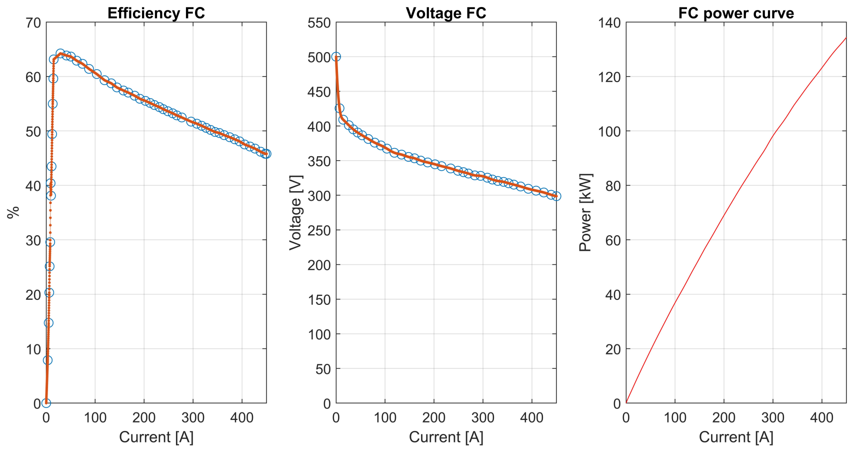

Figure 2: Efficiency (left) and Voltage (center) curve of the selected model of PEMFC. Allows the calculation of the PEMFC power curve (right)

The battery is not defined through user input and its capacity and C-rate is considered as a variable of the optimization problem. The battery characteristics are therefore determined indirectly once the PEMFC stacks output is calculated.

The PEMFC response time, considered as the time the unit needs to go back to stability after a period of transient loading, is an optional user-input that allows to filter out solutions that produce configurations where the required PEMFC response time is shorter than the one indicated by the manufacturer.

The number of PEMFC units or the size of the battery can be limited taking into account possible limitations in the available footprint of the vehicle or the relative cost of the powerplant. The limitation is introduced, for the PEMFCs, by specifying the maximum number of units that can be installed, and for the battery by specifying the maximum capacity.

5 Energy management strategy

The component sizing for the hybrid powerplant is dependent on the type of energy management strategy (EMS) selected. The EMS controls the energy production, distribution, and storage in a vehicle's electrical grid. This control is performed through the definition of a load-sharing strategy. The load-sharing strategy determines how the vehicle's total power demand (P_{op}), defined by the operational profile, is split between the PEMFCs and batteries. In this case the focus is on determining the load-share allocated to the PEMFCs utilized by the system. The battery is used to compensate the power deficit or surplus in the vehicles electrical grid during operations, ensuring that the power demand is always met.

The EMSs considered in this study are categorized as rule-based deterministic strategies, and are characterized through a series of pre-set rules that do not change during the simulation [27]. These rules determine the load-sharing strategy for each operational point.

The first EMS considered in this study is based on a load-leveling strategy. In this strategy the power produced by all the PEMFC stacks in the system ($P_{\text{fc-tot}}$) is constant throughout the simulation, fixed at a predetermined value (P_{L}). The value of P_{L} can be either calculated, using Equation 1, to determine a balanced solution in terms of powerplant footprint, or defined by the user, for sub-optimal solutions that comply with this condition.

$$P_{\text{fc-tot}} = P_{\text{fc}}\, n_{\text{fc}} = P_{\text{L}} = \frac{1}{t_{\text{tot}}} \sum_{t=0}^{n} (P_{\text{op}} t_{\text{s}}) \tag{1}$$

The second EMS considered is based on a peak-shaving strategy. In this strategy the power output produced by all the PEMFCs of the system ($P_{\text{fc-tot}}$) is calculated by applying a low pass filter onto the operational profile in order to smooth high frequency transients (see Equation 2). The resulting filtered PEMFC power output is defined as P_f.

$$P_\text{fc-tot} = P_\text{fc}\; n_\text{fc} = P_\text{f} = filter(P_\text{op}) \tag{2}$$

In the current version of the software application three filters are included: Butterworth, Gaussian or Chebyshev. Each filter has a different frequency response curve, providing different smoothing options for the OP. For example, the Butterworth filter rolls off more slowly around the cutoff frequency than the Chebyshev filter, but there is no ripple (see Fig. 3).

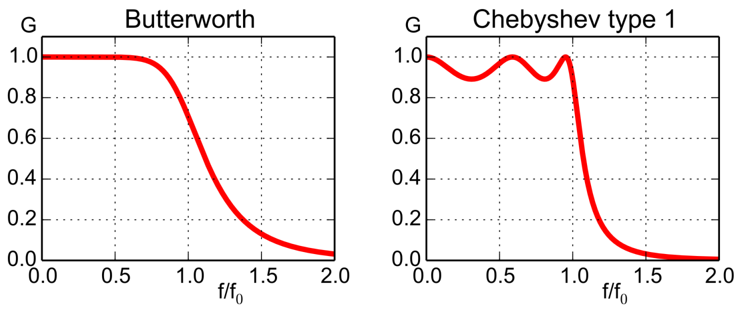

Figure 3: Frequency response curves of Butterworth filter and Chebyshev filter compared, each one as 5th order filter.

Each considered filter is defined by a two parameters that are considered as variables in the model, iterating among possible combinations. For the Butterworth filter the parameters are Order and Cut-Off frequency; for the Gaussian filter are Smoothing kernel and standard deviation (default is 0.5); and for the Chebyshev filter are Normalized pass-band edge frequency and decibels of peak-to-peak pass-band ripple. Each filter performs differently, with distinct responses to high frequency transient loading conditions. The amount of possible solutions obtained using each filter can be expanded or restricted by defining the range of variation for the filters parameters to be considered.

A specific EMSs is chosen considering the primary factors that need to be optimized in the powerplant configuration. A Load-Leveling EMS allows the fuel cell to operate at a constant output producing extremely low values of degradation but requiring more footprint for large batteries to compensate for the wider load range variations. The Peak Shaving EMSs, filtering out high frequency transients allows for a smaller footprint than load-leveling, while keeping the degradation values low.

6 Powerplant simulation model

In this section is described the set of equations upon which the model, and software application, are built. These equations are used to perform a simulation of the system, processing the input data provided by the user.

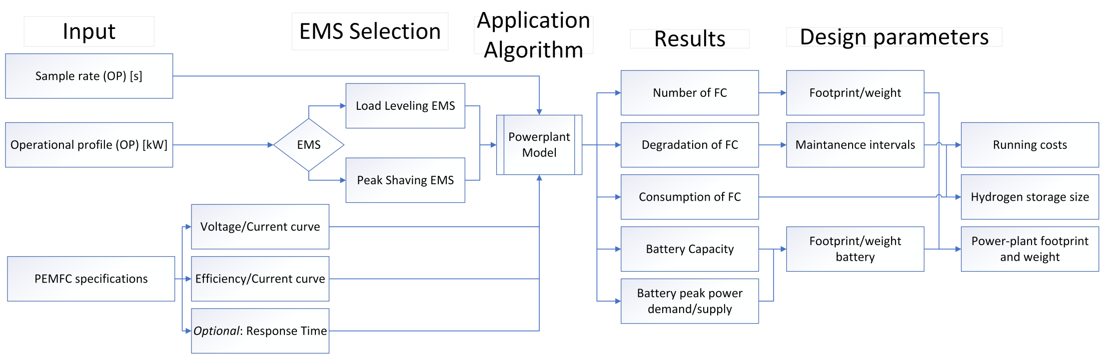

Figure 4: Flowchart describing the simulation process

The PEMFC is modelled as a serial circuit of an ideal voltage source, $V_{\text{fc-ideal}}$ and a total internal resistance R_{fc}. The PEMFC behavior is defined, during the simulation, using the voltage and efficiency data provided as input (see Fig. 2).

$$P_{\text{fc}}(t) = V_{\text{fc}}(t)\ I_{\text{fc}}(t) = V_{\text{fc-ideal}}(t)\ I_{\text{fc-ideal}}(t)\ \eta_{\text{fc}} \tag{3}$$

The model for the battery, similarly to the one of the fuel cells, is a simplified model. The battery is considered as an ideal energy storage, capable of storing and delivering power with an instant response time. No serial resistance is considered in this case determining an Ohmic efficiency of 100%. No thermal effects are considered. The choice of considering the battery as an ideal energy storage was determined by the intention to not tie the calculation to any specific battery technology, as each technology (e.g. Ni-Mh, Li-Ion, AGM) has different internal characteristics and efficiency values.

The model is based on the assumption, represented by the system of Equations 4, that in an isolated vehicle's grid the power demand imposed determined by the OP at each time-step ($P_{\text{op}}(t)$), is equal to the sum of the PEMFCs and batteries output, multiplied for the respective efficiency factors that reduce the power output.

$$\begin{cases} P_{\text{op}}(t) = P_{\text{fc-tot}}(t)\ \eta_{\text{bc}} + P_{\text{b-tot}}(t)\ \eta_{\text{bi-dir}} \\ P_{\text{fc-tot}} = P_{\text{fc}} n_{\text{fc}} = (P_{\text{fc-ideal}}\ \eta_{\text{fc}})\ n_{\text{fc}} \\ P_{\text{b-tot}} = P_{\text{b}} n_{\text{b}} = (P_{\text{b-ideal}}\ \eta_{\text{b}})\ n_{\text{b}} \\ 0 \leq P_{\text{fc}} \leq P_{\text{fc-rated}} \end{cases} \tag{4}$$

The EMS strategy, selected by the user, is used to calculate the value of $P_{\text{fc-tot}}$ at each instant using Equation 1 in the case of the load-leveling strategy, or Equation 2 in the case of the peak shaving strategy, after specifying the type of filter. The definition of $P_{\text{fc-tot}}$ allows the calculation of the number of PEMFCs required to satisfy the load demand. This value is calculated using Equation 5.

$$n_{\text{FC}} = max(P_{\text{fc-tot}})/P_{\text{fc-rated}} \tag{5}$$

The definition of the number of PEMFCs (n_{FC}) can be used to define the power output of the single PEMFC (P_{fc}). This allows the estimation of the degradation for the single PEMFC unit. The accurate calculation of the degradation is challenging as there is only a limited number of articles in the literature presenting degradation studies for PEMFC stacks. The articles utilized here for the estimation of the degradation are Fletcher et al. [28], considering a 4.8 kW PEMFC, and Chen et al. [29], considering a 10 kW PEMFC. Both articles consider stacks with a lower rated output than the one considered in the case studies presented (see Table 2). While the values do not have an influence on the formulation of the equation used to calculate the degradation, it is important to adapt these values to match the power output rating of the fuel cell stack considered in the case-studies to obtain meaningful results.

The values considered for the stack described in Table 2 for low and high power operations are the one obtained by Fletcher et al.; the value for transient loading degradation is recalculated using the article Chen et al. as a baseline. In [29] the transient loading degradation is identified using a value that defines the degradation produced at each cycle when passing from idling (10 < % Load) to high power load conditions ($\sim$ 100 % Load). Considering the nominal power of the stack (10 kW) and the load variation it is possible to obtain a value of 0.045 μV/Δkw in this case.

Table 1: Degradation values used in the developed model for the 100 kW PEM fuel cell

Operating Conditions	Degradation Rate
Low power op. (80 $\leq$ % Load)	10.17 μVh^{-1}
High power op. (> 80 % Load)	11.74 μVh^{-1}
Transient loading	0.0042 μV/ΔkW
Start/stop	23.91 μV/cycle

As it is possible to assume that the 100 kW stack considered in Table 2 is built combining multiple identical cells with the same current density as the one utilized for the stack with a 10 kW output, the value for transient loading degradation is recalculated. The new value has to take into consideration that the nominal power output is 10 times higher, modifying the ΔkW range. With this considered it is possible to determine a value over the new range that is equal to 0.0042 μV/Δkw (see Table 1).

The calculation of the degradation (d_{fc}) using Equation 6 is done considering the low power degradation interval, the high power degradation interval and transient loading degradation. The total degradation value at the end of the considered time interval is equal to the sum of the three components. No start/stop phase is considered.

$$d_{\text{fc}} = Hpo\ t_{\text{hp}} + Lpo\ t_{\text{lp}} + \sum_{t=0}^{n}(|P_{\text{fc}}(t) - P_{\text{fc}}(t-1)|\ Tl) \tag{6}$$

The hydrogen consumption ($Cons_{\text{H}_2}$) of the single PEMFC can be estimated using Equation 7. The efficiency data provided as input are interpolated and used to calculate the efficiency value at which the PEMFC operates at each time-step (η_{fc}) of the simulation. The value of the hydrogen energy density, equal to 120 MJ/kg or 33.6 kWh/kg, is used to estimate the consumption for each time-step.

$$Cons_{\text{H}_2} = \sum_{t=0}^{n} \frac{P_{\text{fc}}(t)}{H_2\ Energy\ Density}\ \frac{t_{\text{s}}}{\eta_{\text{fc}}(t)} \tag{7}$$

The battery capacity that needs to be installed in the powerplant to satisfy the power demand at each time-step is calculated as a function of $P_{\text{fc-tot}}$. The battery compensates for operational conditions where the PEMFC output determines a power deficit by releasing power, and for conditions where the PEMFC output determines a power surplus by storing power. The value for battery power P_{b} at each time-step, calculated using Equation 8 can be either positive or negative according to conditions of power surplus or deficit, determining a recharge state or a discharge state.

$$P_{\text{b}}(t) = \begin{cases} \frac{P_{\text{op}}(t) - P_{\text{fc-tot}}(t)\ \eta_{\text{bc}}}{n_{\text{b}}\ \eta_{\text{bi-dir}}} & \text{if } P_{\text{op}}(t) - P_{\text{fc-tot}}(t) > 0 \\ \frac{P_{\text{op}}(t) - P_{\text{fc-tot}}(t)\ \eta_{\text{bc}} \eta_{\text{bi-dir}}}{n_{\text{b}}} & \text{if } P_{\text{op}}(t) - P_{\text{fc-tot}}(t) <= 0 \end{cases} \tag{8}$$

The value representing the quantity of energy stored inside the battery at each time-stem during operations is calculated using Equation 9.

$$E(t) = \sum_{t=0}^{n}(P_{\text{b}}(t)\ t_{\text{s}}) \tag{9}$$

The minimum battery capacity C_{b} required to satisfy the power demand imposed by the operational profile is calculated using Equation 10.

$$C_{\text{b}} = max(E(t)) + |min(E(t))| \tag{10}$$

Knowing that the energy stored inside the battery cannot be negative, it is possible to calculate the amount of energy that has to be stored in the battery at the beginning of operations (E_{start}). This value determines the minimum initial state of charge (SOC) of the battery.

$$|min(E(t))| = E_{\text{start}} \tag{11}$$

An optional function is included in the model to verify that the load variation happening during a time-window that is equal to the PEMFC response time (R_{t}), is compatible with the technical limits of the unit imposed by the manufacturer, and specified by the user. This option is used with the peak-shaving strategy.

To perform this evaluation the condition represented in Equation 12 needs to be satisfied. This means that 2 or more power-data samples need to be available within the time-window considered to analyze the load variation ($U(n)$).

$$2 \leq \frac{R_{\text{t}}}{t_{\text{s}}} = y; y \in \mathbb{N} \tag{12}$$

If the calculation of y does not return an integer number, the result is rounded to the nearest integer greater than, or equal to that element. This produces a conservative evaluation with respect to the PEMFC response as the length of each time window where U is evaluated is longer than the actual PEMFC response time.

The load variation during the time-window defined by R_{t} is calculated using Equation 13.

$$U(n) = |P_{\text{fc}}(y + n) - P_{\text{fc}}(n)| \tag{13}$$

Every element of the $U(n)$ array has to be lower than the maximum acceptable U value specified by the user for the case study, between 0 and the rated $P_{\text{fc-rated}}$, for the solution to be considered valid.

Figure 5: GUI of the model based software application containing the simulation results

7 Case study

In this section is presented a case study where the software application is used to calculate two possible powerplant configuration for the conversion of an harbor tugboat from diesel-electric to a hybrid zero-emission system utilizing PEMFCs and batteries.

The PEMFC stack selected as the main power source for both cases has the characteristics listed in Table 2. The data required for the characterization of stack are obtained from the datasheet of the unit. The efficiency curve and the voltage curve are plotted and can be observed in Figure 2. The PEMFC response time for this type of unit is assumed, with a conservative estimate, to be around 8s.

The values used for the efficiency of the boost converter (η_{bc}), connecting the PEMFC to the grid, and relative to the bi-directional converter ($\eta_{\text{bi-dir}}$), connecting the battery to the grid are respectively 0.98 and 0.95. These values are considered constant during operations and are determined using the efficiency of components in the analyzed power range, as an average between conditions at low load, determining low efficiency, and conditions at high load, determining high efficiency.

Table 2: Parameters from a commercial PEMFC model used to define the operational capabilities of the unit in the quasi-static model

Rated power ($P_{\text{fc-rated}}$)	100kW
Gross output at rated power	320 V / 350 A
Peak power EOL,OCV @BOL	250,500 V
System efficiency (Peak, BOL)	62%
System efficiency (BOL)	50%
Response time (t_{fc})	8s

The considered tugboat is currently propelled by two diesel engines with a combined output of 2648 kW, ensuring a cruising speed of approximately 14 knots and a bollard pull of 48 tons. The operational profile considered in this case study is relative to 3 hours and 15 minutes of operations.

In this time interval the tugboat operates inside the harbor taking part in the procedure of pulling a crude oil carrier leaving port.

The first powerplant configuration is calculated using the peak shaving EMS, with the OP filtered using a Butterworth filter (see Fig. 7). The OP has a sample rate of 1 second.
The software application iterates through different combinations of filter's order and cut-off frequencies to find all the possible load-sharing solutions, defining $P_{\text{fc-tot}}(t)$. The values found are utilized in the model described in Section 6 to define the powerplant configuration. The solutions that comply with the conditions imposed in Equation 12, where the maximum value of U is set equal to $P_{\text{fc-rated}}$, are considered suitable for this case.

Figure 6: Tugboat of the same class of the one used in the study.

One solution that complies with the requirements set by the user, is a configuration using the Butterworth filter of order 5 and cut off-frequency of 0.01 Hz. The filtered operational profile can be observed in Figure 7.

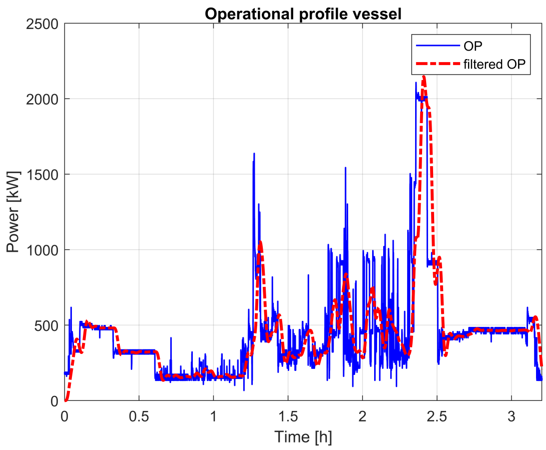

Figure 7: Operational profile of the harbor tugboat before and after filtering

The loading conditions that the single fuel cell stack experiences during the simulation can be observed in Figure 8. The number of fuel cell stacks needed to comply with the power demand calculated is equal to 22 PEMFC stacks, for a total rated power output of 2200 kW.

Based on the operational conditions on the fuel cell stack, the single fuel cell experiences a degradation that is equal to 83.74 μV. The hydrogen consumption of the single PEMFC stack is calculated to be equal to 3.11 kg, for a total hydrogen consumption of approximately 68 kg of hydrogen during the 3.2 hours of heavy operations considered.

With these filter parameters, the resulting minimum battery capacity calculated is equal to 81 kWh, with a peak power demand of 1303 kW. The power supply and demand can be observed in Figure 9. The estimated variation of energy content insider the battery of the tugboat can be observed in Figure 10. Considering the limitations in the depth of discharge it is recommended to increase the battery capacity to 130.5 kWh. This recommended capacity is calculated considering an interval for the state-of-charge between 20% and 80%, operating in the ohmic loss region of the battery's polarization curve, to reduce battery degradation.

Considering the peak power demand and the recommended battery capacity value, it is possible to calculate the C-Rate value that is approximately 10C. The recommended battery capacity calculated can be further increased by the user analyzing the results, to bring this value down and to match the technical specifications of the battery cells that are considered for this use-case.

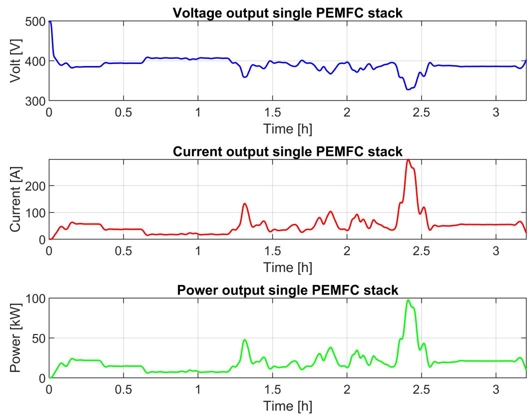

Figure 8: Single PEMFC stack load during the simulation

The presented solution is just one of possible configurations that can be obtained with the filtration of the OP using a Butterworth filter and comply with the user specifications. The execution time for the calculation is approximately 75 seconds, allowing the user to try multiple configurations in a relative short time span.

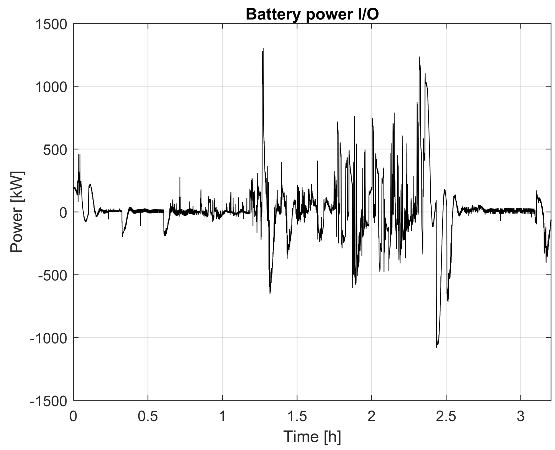

Figure 9: Power I/O for the battery of the tugboat with peak-shaving EMS

As a comparison, the configuration of a powerplant utilizing the load-leveling EMS is presented. In this configuration the 5 required PEMFC stacks operate at a constant 88.31kW at an efficiency of approximately 53%. The stack degradation calculated during operations is equal to 35.13 μV. The hydrogen consumption of the single PEMFC stack is calculated to be equal to 15.9 kg, for a total hydrogen consumption of approximately 79 kg of hydrogen during the 3.2 hours of heavy operations considered. The result is, in this case, higher in terms of total hydrogen consumption as the fuel cell operates for a longer period of time at a lower median efficiency rate compared to the one in the peak shaving strategy.

The resulting minimum battery capacity calculated is equal to 246.29 kWh, with a peak power demand of 1762.7 kW. The power supply and demand can be observed in Figure 11. The estimated variation of energy content insider the battery of the tugboat can be observed in Figure 12. Considering the limitations in the depth of discharge it is recommended to increase the battery capacity to 395 kWh. This recommended capacity is calculated considering an interval for the state-of-charge between 20% and 80%. Considering the peak power demand and the recommended battery capacity value, it is possible to calculate the C-Rate value that is approximately 4C.

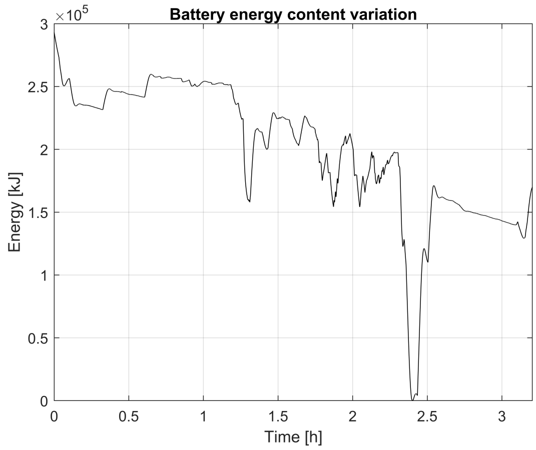

Figure 10: Energy variation in the battery of the tugboat with load-leveling EMS

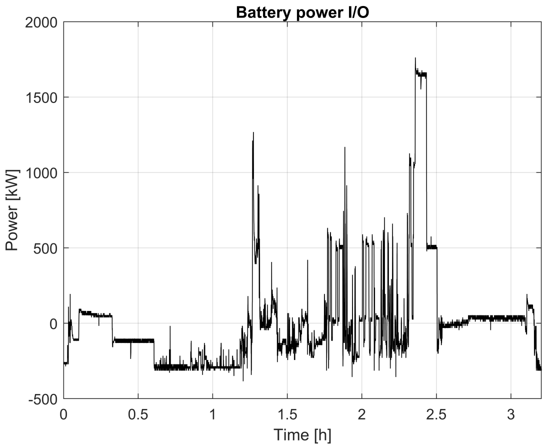

Figure 11: Power I/O for the battery of the tugboat with load-leveling EMS

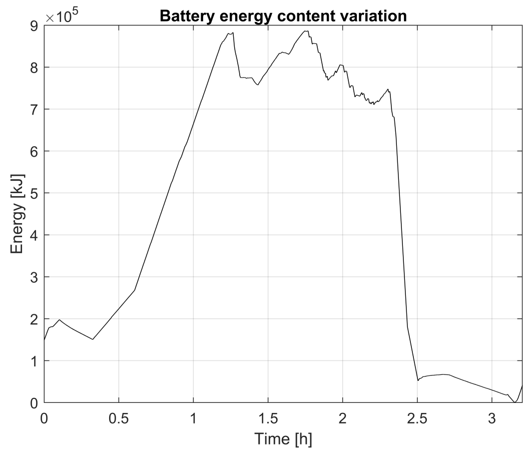

Figure 12: Energy variation in the battery of the tugboat with load-leveling EMS

8 Discussion

The presented case study shows how the developed software application, based on the presented model, allows the user to evaluate different hybrid powerplant solutions starting from the operational profile and the selection of a commercial PEMFC. The obtained results are necessary to make an evaluation on the technical and economic feasibility of a hybrid solution utilizing fuel cells and batteries for a specific use case. Technical feasibility can be evaluated, for example, considering the vehicles available space and weight for the engine compartment, and comparing it to the number of

PEMFCs and the battery size calculated. Another technical factor that can be evaluated using the results include the estimated size of the hydrogen storage based on the calculated consumption. Economic feasibility can be estimated using, for example, the consumption of hydrogen to calculate the cost of daily operations or the degradation values to estimate maintanence costs. The software application is successful in its task in the two analyzed use cases, producing results in line with pre-calculated estimates, and allowing the user to perform the aforementioned evaluations of the powerplant.

Multiple are the developments possible for this type of software application,including the implementation of additional types of EMS, the further development of the battery model to consider the response time, efficiency, and polarization curve for the different battery models. The main goal at the end of the software application development is to provide a tool with a comprehensive set of option for designers and engineers in charge of the design of hydrogen vehicles.

9 Conclusions

The development of a software application which defines powerplant configurations based on the operational profile is an important step towards simplifying the design process of zero-emission vehicles. This current version of the software application is targeted at vehicles equipped with proton exchange membrane fuel cells and batteries across different transport sectors.

Being able to quickly calculate the number of fuel cells and the size of the battery allows the user to assess the footprint needed on the vehicle for the power generation and storage components. This is important in the design of new vehicles, but particularly relevant for zero-emission retrofit projects where the usable footprint may be limited.

Calculating the number and type of components also plays an important role in the quantification of the initial investment needed for the installation of such components. Running costs can be estimated as a function of hydrogen consumption, and maintenance costs can be quantified by taking into consideration the degradation of the PEMFCs.

The developed software application provides results that are useful both in a research environment and in an industrial environment. Values calculated can be used by researchers working on topics influenced by the composition of the powertrain, such as those considering the vehicle weight distribution or aero/fluid dynamic performances. In an industrial environment the results can be used to evaluate the feasibility of an investment and the time needed to realize a return on investment.

Future work can be dedicated to improve the software application, introducing new features and functions to extend it's capabilities. The ultimate goal is to create a comprehensive tool that can aid in the transition to clean energy carriers or energy sources, thus reducing pollution and greenhouse gas emissions in cities and coastal areas and helping to preserve the environment and the health of the human population.

Acknowledgment

This work is supported by the Norwegian Research Council trough project number 90436501. The project is headed by IFE (Institute for Energy Technology) in Kjeller, Norway, and this work package is developed at the Department of Marine Technology of the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway.

Keywords

Hydrogen systems; Hybrid Powertrain; Marine propulsion; Fuel cells; Battery propulsion

References

[1] Tobias Wiesenthal, Ana Condeço-Melhorado, and Guillaume Leduc. Innovation in the european transport sector: A review. *Transport Policy*, 42:86–93, 2015.

[2] Laurent Franckx. Regulatory emission limits for cars and the porter hypothesis: A survey of the literature. *Transport Reviews*, 35(6):749–766, 2015.

[3] Bin Lin and Cherng-Yuan Lin. Compliance with international emission regulations: Reducing the air pollution from merchant vessels. *Marine Policy*, 30(3):220–225, 2006.

[4] A. Miola, B. Ciuffo, E. Giovine, and M. Marra. Regulating air emissions from ships. the state of the art on methodologies, technologies and policy options. *Regulating Air Emissions from Ships: The State of the Art on Methodologies, Technologies and Policy Options*, pages 978–992, 2010. Cited By :37.

[5] E. Martinot. Renewables. global status report. 2009 update, May 2009.

[6] M.A. Hannan, F.A. Azidin, and A. Mohamed. Hybrid electric vehicles and their challenges: A review. *Renewable and Sustainable Energy Reviews*, 29:135–150, 2014.

[7] Alf Kare Adnanes. Maritime electrical installations and diesel electric propulsion. In *ABB*, 2003.

[8] Ghassan Zubi, Rodolfo Dufo-López, Monica Carvalho, and Guzay Pasaoglu. The lithium-ion battery: State of the art and future perspectives. *Renewable and Sustainable Energy Reviews*, 89:292–308, 2018.

[9] Alireza Khaligh and Zhihao Li. Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art. *IEEE Transactions on Vehicular Technology*, 59(6):2806–2814, 2010.

[10] Tabbi Wilberforce, Zaki El-Hassan, F.N. Khatib, Ahmed Al Makky, Ahmad Baroutaji, James G. Carton, and Abdul G. Olabi. Developments of electric cars and fuel cell hydrogen electric cars. *International Journal of Hydrogen Energy*, 42(40):25695–25734, 2017.

[11] Mehmet Gurz, Ertugrul Baltacioglu, Yakup Hames, and Kemal Kaya. The meeting of hydrogen and automotive: A review. *International Journal of Hydrogen Energy*, 42(36):23334–23346, 2017.

[12] D.J. Durbin and C. Malardier-Jugroot. Review of hydrogen storage techniques for on board vehicle applications. *International Journal of Hydrogen Energy*, 38(34):14595–14617, 2013.

[13] L. Valverde, F. Rosa, C. Bordons, and J. Guerra. Energy management strategies in hydrogen smart-grids: A laboratory experience. *International Journal of Hydrogen Energy*, 41(31):13715–13725, 2016.

[14] Mauro G. Carignano, Ramon Costa-Castelló, Vicente Roda, Norberto M. Nigro, Sergio J. Junco, and Diego Feroldi. Energy management strategy for fuel cell-supercapacitor hybrid vehicles based on prediction of energy demand. *Journal of Power Sources*, 360:419–433, 2017.

[15] Lorenzo Balestra and Ingrid Schjølberg. Modelling and simulation of a zero-emission hybrid power plant for a domestic ferry. *International Journal of Hydrogen Energy*, 46(18):10924–10938, 2021.

[16] Lorenzo Balestra and Ingrid Schjølberg. Energy management strategies for a zero-emission hybrid domestic ferry. *International Journal of Hydrogen Energy*, 46(77):38490–38503, 2021.

[17] A. M. Bassam, A. B. Phillips, S. R. Turnock, and P. A. Wilson. Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship. *International Journal of Hydrogen Energy*, 42(1):623 – 635, 2017.

[18] Ameen M. Bassam, Alexander B. Phillips, Stephen R. Turnock, and Philip A. Wilson. An improved energy management strategy for a hybrid fuel cell/battery passenger vessel. *International Journal of Hydrogen Energy*, 41(47):22453–22464, 2016.

[19] Liangfei Xu, Fuyuan Yang, Jianqiu Li, Minggao Ouyang, and Jianfeng Hua. Real time optimal energy management strategy targeting at minimizing daily operation cost for a plug-in fuel cell city bus. *International Journal of Hydrogen Energy*, 37(20):15380–15392, 2012. The 2011 Asian Bio-Hydrogen and Biorefinery Symposium (2011ABBS).

[20] Diego Feroldi and Mauro Carignano. Sizing for fuel cell/supercapacitor hybrid vehicles based on stochastic driving cycles. *Applied Energy*, 183:645–658, 2016.

[21] Q. Cai, D.J.L. Brett, D. Browning, and N.P. Brandon. A sizing-design methodology for hybrid fuel cell power systems and its application to an unmanned underwater vehicle. *Journal of Power Sources*, 195(19):6559–6569, 2010.

[22] Marco Sorrentino, Cesare Pianese, and Mario Maiorino. An integrated mathematical tool aimed at developing highly performing and cost-effective fuel cell hybrid vehicles. *Journal of Power Sources*, 221:308–317, 2013.

[23] Davide Pivetta, Chiara Dall'Armi, and Rodolfo Taccani. Multi-objective optimization of hybrid pemfc/li-ion battery propulsion systems for small and medium size ferries. *International Journal of Hydrogen Energy*, 46(72):35949–35960, 2021. Special Issue on HYPOTHESIS XV.

[24] Nikolce Murgovski, Lars Johannesson, Jonas Sjöberg, and Bo Egardt. Component sizing of a plug-in hybrid electric powertrain via convex optimization. *Mechatronics*, 22(1):106–120, 2012.

[25] L. Guzzella and A. Amstutz. Cae tools for quasi-static modeling and optimization of hybrid powertrains. *IEEE Transactions on Vehicular Technology*, 48(6):1762–1769, 1999.

[26] Paul Rodatz, Lino Guzzella, and Leonardo Pellizzari. System design and supervisory controller development for a fuel-cell vehicle. *IFAC Proceedings Volumes*, 33(26):173–178, 2000. IFAC Conference on Mechatronic Systems, Darmstadt, Germany, 18-20 September 2000.

[27] Yanjun Huang, Hong Wang, Amir Khajepour, Bin Li, Jie Ji, Kegang Zhao, and Chuan Hu. A review of power management strategies and component sizing methods for hybrid vehicles. *Renewable and Sustainable Energy Reviews*, 96:132–144, 2018-11.

[28] T. Fletcher, R. Thring, and M. Watkinson. An energy management strategy to concurrently optimise fuel consumption & pem fuel cell lifetime in a hybrid vehicle. *International Journal of Hydrogen Energy*, 41(46):21503 – 21515, 2016.

[29] Huicui Chen, Pucheng Pei, and Mancun Song. Lifetime prediction and the economic lifetime of proton exchange membrane fuel cells. *Applied Energy*, 142:154–163, 2015.