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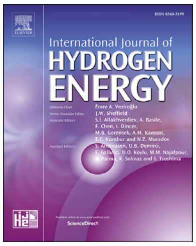

Energy management strategies for a zero-emission hybrid domestic ferry

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ABSTRACT

The paper presents three approaches for the sizing and control of a maritime hybrid power-plant equipped with proton exchange membrane fuel cells and batteries. The study focuses on three different power-plant configurations, including the energy management strategy and the power-plant component sizing. The components sizing is performed following the definition of the energy management strategy using the sequential optimization approach. These configurations are tested using a dynamic model developed in Simulink. The simulations are carried out to validate the technical feasibility of each configuration for maritime use. Each energy management strategy is developed to allow for the optimization of a chosen set of parameters, such as hydrogen consumption and fuel cell degradation. It is observed that in the hybrid power-plant optimization there are always trade-offs, and the optimization should be carried out by prioritizing primary factors the ship owner considers most important for day-to-day operations.

Introduction

Modern maritime transport is still heavily reliant on fossil fuels, including diesel and heavy oils, containing high levels of asphalt, carbon residues, sulfur (which may amount to as high as 5 wt%) and metallic compounds [1]. The absence of strict regulations combined with the low cost of fossil fuels makes shipping one of the main contributors to global emissions of greenhouse gases (GHG), accounting for 2.5% of global GHG emissions according to the third International Maritime Organization (IMO) GHG study. Maritime vessels are also a source for volatile organic compounds, particulate matter, and hazardous air pollutants (NO_x and SO_x) [2]. The United Nations, with UN Sustainability Development Goal n.14 and the IMO, want to change the current situation, introducing national and international regulations for vessels' emissions aimed at reducing the negative environmental impact of fossil fuels [3,4].

Zero-emission power systems have been in the last decade included in the design of new vessels or retrofitted to older vessels in order to comply with the new regulations [5,6]. These new hybrid or fully-electric systems aim at replacing old architectures based on the internal combustion engine (ICE) without having to compromise on operational flexibility, performance or safety. It is nontrivial to replace the ICE based architecture which has been developed for decades and has reached high peak efficiency values. Furthermore zero-emission systems have generally a lower technology readiness level, lower market adoption, and cannot yet rely on a fully developed supply chain. From a logistical perspective, marine vessels need to rely on the infrastructure of the departure ports and arrival ports for refueling and therefore

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need either large energy storage solutions or high density energy carriers to ensure that the range requirements are satisfied. With all these factors considered, no single zero-emission technology is suited for all applications, thus the power-plant configuration is decided as a function of the vessel operations (operational profile). In the 1–10 MW power range, battery propulsion is possible but best suited to short routes where frequent recharging is possible. Hydrogen fuel cells aim at bridging the gap between battery electric configuration with limited range, and the versatile, but polluting, diesel-electric configuration, by maintaining zero-emission output with no need for land-based charging. Proton exchange membrane fuel cells (PEMFC) have received certifications allowing them to be integrated into vessel power-grids [7,8], and can be used to provide baseline energy as prime movers' or backup power as range extenders' in hybrid configurations including energy storage solutions. To provide the same level of performance as ICEs' with respect to range and power production, PEMFC and battery hybrid systems need to be carefully optimized from a component sizing (CS) and energy management strategy (EMS) perspective.

In this paper, the optimization problem is studied considering the operations of a double-ended ferry with a length of 100 m and a beam of 18.2 m, with the capacity for 122 cars and 600 passengers [9]. Data relative to the operations of this ferry have been collected in a database over a period of six months for research and optimization purposes. This ferry is currently equipped with a 4 MW diesel electric power-plant. A previous publication from Balestra et al. proposes an alternative zero-emission hybrid power-plant along with its corresponding digital model representation. The digital model developed in Ref. [10] can be reconfigured and adapted to multiple CS and EMS solutions, and is used in this work to simulate the operations of three different power-plant configurations combined with three different EMSs. The EMSs selected for the study are inspired both by land-based grid applications and road transport applications. These EMSs are:

- Load leveling strategy
- Peak shaving strategy
- Charge depleting/charge replenishing strategy

Once the EMSs are selected, a sequential optimization to determine the number and rating of the PEMFCs and batteries is carried out for each EMS, taking into consideration power and performance requirements. The route considered in the simulations is the same in all of the three cases to facilitate the final comparison between the strategies and the simulation results.

The first objective of the paper is to show how sequential optimization can be used as one possible approach to component sizing, in a hybrid power-plant with PEMFC and batteries. The dependency between CS and EMS must be taken into consideration to achieve the best possible performances when using the system. The second objective of the paper is to demonstrate the dynamic behavior of the hybrid power-plant when operating with the three EMSs and verify that the performance level is satisfactory with respect to the diesel power-plant currently equipped, and does not sacrifice operational flexibility.

Using a dynamic model makes it possible to analyze the behavior of the PEMFCs, batteries and power electronics components. Particular focus is placed on hydrogen consumption, fuel cell degradation and other key operational factors. The final objective of the paper is to collect the data from the three configurations and compare the results and relative performances in order to evaluate which strategy would be best for the presented case study.

Brief system description

The vessel taken into consideration in this study is a double ended ferry with a length of 100 m and a beam of 18.2 m. The ferry can transport 600 passengers and 122 cars and operates a 45 min crossing in Danish national waters. The crossing is 7.7 nautical miles and is operated 18 times in a normal day. The vessel is equipped with 5 diesel generators powering 4 Azimuth thrusters and auxiliary loads [9].

A study previously carried out on this ferry in Ref. [10] was focused on a zero-emission alternative for the ferry's power-plant (Fig. 1). The alternative hybrid-electric power-plant was based on a combination of PEMFCs and Li-Ion batteries delivering the power defined by the operational profile through a DC-grid.

This paper expands upon how different EMSs require different power-plant configurations to operate at the best possible efficiency. Three EMSs are taken into consideration and the component sizing is performed using a sequential optimization approach.

The Matlab-Simulink model developed by the authors is used to simulate the three different hybrid power-plant configurations. This model includes a parametric model for the PEMFC, for the Lithium Ion battery, power electronics components and direct current (DC) load. The flexibility of the

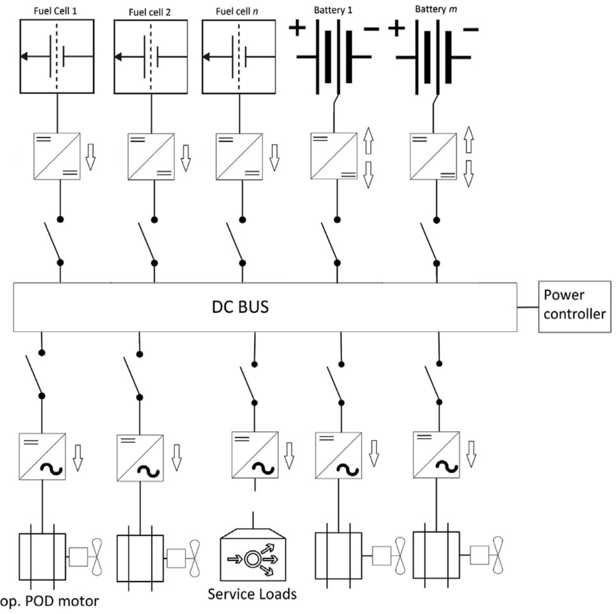

Fig. 1 – Simplified single line diagram of the proposed hybrid configuration.

model allows for a quick re-configuration of the power-plant, assigning *n* number of PEM fuel cells and *m* number of batteries, to test different components sizing approaches. The PEMFC model is based on [11] and configured using the datasheet of a commercial fuel cell rated for 100 kW of power. The characteristics of this unit are listed in Table 1.

The Lithium Ion battery used in the simulation and connected to the system is not modelled upon any commercial model specifically, but is based on the 18,650 Li-Ion cell. The rated voltage for each battery is either 400 or 800 V depending on the power-plant configuration. The capacity of each battery module is considered as a variable and calculated for each EMS. This choice provides flexibility when it comes to selecting the appropriate battery capacity for the specific EMS. Flexibility in selecting the battery capacity allows to define a specific C-Rate at which a battery needs to operate. Choosing the appropriate C-Rate for the battery pack indirectly defines how much degradation the battery is going to experience during operations and also define how much footprint is required for battery storage in relation to the power demand allocated to the battery [12].

The vessel's grid is set to operate using DC current as both batteries and PEMFC output is DC. The voltage level selected for the DC-Bus is equal to 1000 V in all cases.

Methodology

State of the art for power management strategies and component sizing in hybrid vehicles

The power-plant optimization problem for all kinds hybrid energy systems is nontrivial. The optimization process does not have a unique solution as components sizing of the energy system heavily relies on how the components interact, which is defined by the EMS. At the same time, some types of EMS cannot efficiently operate without components in the correct number or rating. This problem is experienced in battery vehicles [13], but mainly in complex power-plant with both energy conversion (fuel cells) and energy storage (batteries) [14,15].

The majority of scientific studies and reviews focus on road transport and specifically on the design of energy management strategies [16–19]. Even if not directly aimed at maritime vessels, these studies provide important knowledge on existing strategies and define a framework that can be used when scaling up the total power installed in a marine multi-megawatt power-plant. Some studies have been recently carried out on a few vessels of small size (<1 MW) where there are multiple similarities with cars and road transport vehicles when considering the power requirements [20–22]. Components sizing methods are a key factor, but are only briefly mentioned in previously listed references. A review considering the dependencies between components sizing and EMS is carried out in Ref. [23], providing a base structure for the development of this paper. This structure is used, in this study, to identify and develop the three case studies presented. The goal is to apply the knowledge developed for road transport vehicles and apply it to large-marine power-plants, verifying the optimization process performances through simulations in the Matlab environment using a dynamic model.

Table 1 – Fuel cell data used for the model configuration.

Rated power (net)	100 kW
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%
Max waste heat	120 kW
Coolant outlet temperature	80C
Fuel inlet pressure	8–12 bar(g)
System pressure	1.6 bar(g)
Ambient temperature	−20 to +50C
Ambient relative humidity	5–95%, non-condensing
Weight	120–150 kg
Volume	300 l

Case study description

The study carried out in this paper focuses on the development of three different hybrid power-plant configurations including energy management strategy (EMS) and components sizing (CS). Each configuration is tested using the model from Ref. [10], with real world data to simulate realistic conditions. The results obtained from these simulations are analyzed and compared to identify advantages and disadvantages of each configuration and possible further improvements.

The power-plant configuration can be obtained using different approaches including sequential optimization, bi-level optimization or simultaneous optimization [23]. In this particular case the sequential optimization approach is selected, with the definition of the EMS in the first step, and the subsequent definition of the power demand for each component leading to the calculation of component number and rating.

An EMS can be defined as a series of rules and controls that allow to regulate the energy production, consumption, distribution and storage in a grid system. Each configuration uses a different EMS and therefore a different load sharing strategy, splitting the power between fuel cells and batteries. The EMS needs to ensure a satisfactory performance level in addition to ensuring a reliable power delivery. The selected EMSs are rule based, with deterministic or fuzzy-logic approaches. All the EMS considered in this study are online EMSs, defining the power distribution at each instant during the stationary, maneuvering and navigation phase of the ferry. Online EMSs can be used in real-time applications as they do not require knowledge of global informations, such as the complete operational profile, and can make dynamic decisions.

Equation (2) defines the ideal condition for every single operational point considered during the simulations. Ideally, the power generated by the PEMFCs and the power generated by the batteries is equal to the power demand (P_{op}) sampled from the diesel electric ferry. In reality, this condition is made more flexible to account for the dynamic behavior of the components during the simulation. The term δ is introduced to define the range of values that are considered acceptable for the power-output of the power-plant. A lower δ determines lower response time and higher performance, while a higher δ allows for smoother transitions with lower PEMFC and battery degradation. The value of δ is determined for each simulation to define the range of acceptable values.

$$P_{op} - \delta \le P_{op} \le P_{op} + \delta \tag{1}$$

$$P_{op} = (P_{fc}\ n / \eta_{bc} + P_b\ m / \eta_{bi-dir}) / \eta_{sys} \tag{2}$$

- P_{op}: power demand (operational profile)
- n: number of PEMFC
- m: number of batteries
- P_{fc}: power output single PEMFC
- P_b: power output single battery
- η_{sys}: On-board electric grid components efficiency.
- η_{bc}: Efficiency boost converter
- η_{bi-dir}: Efficiency bi-directional converter

In this particular case study, by considering a ferry with a scheduled route, it is possible to take advantage of the similarities in power demand between crossings. By analyzing multiple crossings sampled over a period of six months, only small variations in power demand, due to weather conditions and maritime traffic, were observed. For this reason it is possible to evaluate the model and obtain meaningful results on the performances of the power-plant configuration by considering just one typical crossing operational profile (OP). In this case a 1 h crossing carried out in mid November was selected (blue curve in Fig. 2 and Fig. 3). If computational resources are not limited or variability is observed between daily or weekly operations, it is suggested to extend the time interval considered.

System configuration

The Simulink model is configured for each one of the three power-plant configurations, including the code relative to the type of EMS selected and the correct number for PEMFCs and batteries defined in the component sizing calculations. The power-plant layout is based on the single line diagram presented in Fig. 1, with the EMS defining how the energy flows from energy storage/energy conversion to electrical load.

To define the number of PEMFCs required to satisfy the power demand for each case, it is necessary to analyze the load sharing strategy that the EMS implements during operations. For the PEMFC number there are limitations given by the fact that producers create modularized stacks with defined power levels. In this case the rated power of the considered unit is equal to 100 kW (Table 1). Each fuel cell installed in the system is identical and it is assumed that all have the same dynamic behavior when delivering the same electrical load. In each considered EMS the load share assigned to the fuel cells is equally distributed between all units. No unit, in this study, is controlled individually or switched on/off during operations.

The power output of the PEMFC can be expressed in equation (3). The voltage and efficiency curves of the fuel cell are obtained introducing the parameters found in Table 1 into the parametric model. The obtained curves match the ones reported in the PEMFC datasheet. These curves are obtained experimentally and take into account the real voltage (V_{fc}) and current (I_{fc}) output. If the voltage and current output is considered ideal, or the fuel cell consumption needs to be calculated, it is necessary to introduce the value η_{fc} representing the fuel cell efficiency.

$$P_{fc} = V_{fc}\ I_{fc} = V_{fc-ideal}\ I_{fc-ideal}\ \eta_{fc} \tag{3}$$

Unlike PEMFCs, Li-Ion batteries can be built to fit a specific use case, by combining multiple individual cells in series or parallel. The power delivery, determined by the load share of the battery, can be satisfied using a combination of factors such as number of units (m), battery capacity (Q_b) and C-Rating. The only factor that is fixed, in this case, is the rated voltage (V_b) set at either 400 or 800 V to reduce the number of variables. This flexibility allows to compensate for the fixed rated load of the fuel cell, and calculate the optimal battery size for each considered EMS.

As for the fuel cells case, if multiple batteries are installed in the system, each battery installed is identical and it is assumed that all have the same dynamic behavior when delivering the same electrical load. In every EMS the load share assigned to the batteries is equally distributed between all units. No battery, in this study, is controlled individually or switched on/off during operations.

In general, the term representing the power drawn from one battery can be expressed as Equation (4) where the term Q_{batt} is limited by the C-rate (factor of the cell internal resistance).

$$P_b\ t = E_b = V\ Q_b = V_b\ I_b\ t \tag{4}$$

Once the value of n, m, Q_b are defined for each EMS, it is possible to launch the model to simulate the amount of time selected by the user. Once the simulation is finished the results can be compared and analyzed.

In this paper, when calculating a power-plant configuration, specific safety class regulations regarding active and passive redundancy of components are not considered. The total power calculated in the configuration provides a conservative estimate but does not comply with any specific regulation from maritime certification societies.

Load leveling EMS

Load leveling strategies are a common approach in large land-based electrical grids but can also be used in marine power-plants if the ICE generators are coupled with batteries for energy storage. In a diesel-electric configuration, this strategy is used to keep the diesel engine at the operational point where the break specific fuel consumption is minimum, compensating load transients with batteries. Maintaining the diesel engine at the point of peak efficiency reduces considerably the fuel consumption and the level of emissions.

A load leveling strategy can also be adopted for the control of a hybrid power-plant with PEMFC and batteries. In this case the power demand is split almost equally between the fuel cells and large battery packs, with the goal of maintaining the

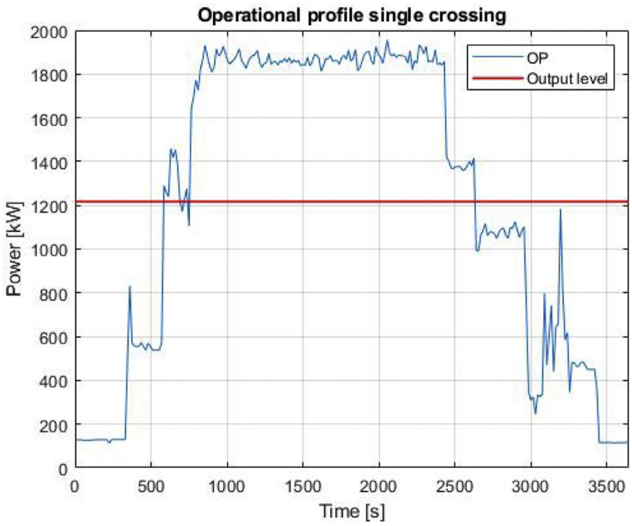

Fig. 2 – Operational profile and set output level with load leveling EMS.

fuel cell profile as flat as possible to limit the degradation given by load transients. The load leveling strategy is developed using an online deterministic rule-based approach.

The first step in the definition of the load leveling strategy is the definition of the rules that the EMS follows. In this case, the rules contained in Table 2 are formulated and implemented into the EMS code. These rules are formulated taking into consideration two variables: available power and the state of charge (SOC) of the battery. Based on these rules, both PEMFC and switchboard are controlled.

The second step in the definition of this strategy is the calculation of an output level (P_{OL}) defining the maximum power output for the PEMFC units during navigation. This P_{OL} value is key in defining the rules of the EMS. In this case the output value is calculated using Equation (5), integrating the operational profile over the amount of time considered for the study. The result is P_{OL} equal to 1217 kW.

$$\int_0^t OP\ dt = P_{OL}\ t \tag{5}$$

Considering the value obtained for P_{OL} it is possible to calculate the number of PEMFCs n. The choice is to install in the system enough PEMFCs to operate at P_{OL} with 80% of PEMFCs rated load. This choice was done based on the study of Fletcher et al. [14] and the values are listed in Table 3, keeping the PEMFC in low power operation and limiting degradation. In addition, the calculation of n takes into account a value for the efficiency of the boost converter (η_{bc}) equal to 0.97%.

$$n = \left(P_{OL}\ 0.8\ \eta_{bc}\eta_{sys}\right)/P_{fc-rated} \tag{6}$$

The result of equation (6) can be rounded to 18 PEMFCs. Setting the operational level to 80% of the rated load allows for a conservative estimate on the power installed.

The third step in the definition of the configuration for the load leveling strategy is the sizing of the battery. Because the load leveling strategy is applied not only during navigation, but also during the entire time interval considered, there are limitations with respect to maintaining the PEMFC at P_{OL} at all times. The main limitation is the amount of power that can be stored by the battery when the difference between P_{OL} and P_{op} is higher than the maximum value of P_b. A choice is made to limit the size of the battery to the capacity calculated during the discharge phase, represented by the area above the red line of Fig. 2. This ensures a trade-off between performances and battery size.

A first attempt at battery dimensioning is done by measuring the difference between P_{OL} and the peak power demand sampled during the entire period of ferry data collection (P_{max}, 2425 kW). Considering this peak value and the voltage level set to be constant at 400 V, it is possible to calculate I_b using Equation (7), derived from Equation (2).

$$P_{fc-max}\ n = \frac{P_{max}}{\eta_{sys}} - P_b\ m = \frac{P_{max}}{\eta_{sys}} - V - b\ I_b\ m \tag{7}$$

The value obtained for I_b represents the battery capacity for 1 battery considering a C-Rating of 1-C. With a battery rated for 400 V, the calculated capacity is equal to approximately 3020 Ah at 1C. In this scenario, in the effort to maintain the PEMFC output as close as possible to P_{OL} and to contain the C-rate at which the battery operates, the choice is to install 2 batteries rated at 400 V and 1750 Ah. Installing two batteries allows for a basic level of active redundancy and also for a small power reserve. The C-rate is limited at 2-C.

To check that the calculated capacity is adequate to the crossing it is possible to integrate the section of the

Table 3 – Degradation values from Fletcher et al. [14].

Operating Conditions	Degradation Rate
Low power operation (<80%)	10.17 μV/h
High power operation	11.74 μV/h
Transient loading	0.0441 μV/Δkw
Start/stop	23.91 μV/cycle

Table 2 – Rule based energy management system instructions.

Power Available	SOC Level	Action Battery	Action FC
$P_{vessel} + P_{rec} \le P_{fc\text{-}lim}$	SOC ≤ 80%	Recharge connected; P_{rec} = defined rec. I	$FC_{target} = P_{vessel} + P_{rec}$
$P_{vessel} + P_{rec} \le P_{fc\text{-}lim}$	SOC > 80%	No circuit connected; $P_{rec} = 0$	$FC_{target} = P_{vessel}$
$P_{vessel} + P_{rec} > P_{fc\text{-}lim}$; $P_{vessel} \le P_{fc\text{-}lim}$	SOC ≤ 80%	Recharge connected; $P_{rec} = P_{OL}$ - OP	$FC_{target} = P_{OL}$
$P_{vessel} + P_{rec} > P_{fc\text{-}lim}$; $P_{vessel} \le P_{fc\text{-}lim}$	SOC > 80%	No circuit connected; $P_{rec} = 0$	$FC_{target} = P_{vessel}$
$P_{vessel} > P_{fc\text{-}lim}$	SOC > 20%	Discharge connected; P_{dis} = OP - OOL	$FC_{target} = P_{OL}$
$P_{vessel} > P_{fc\text{-}lim}$	SOC ≤ 20%	No circuit connected; $P_{dis} = 0$	$FC_{target} = P_{vessel}$

operational profile above the value of P_{OL}. In this case the value calculated is lower than 3020 Ah and therefore the battery size is defined by Equation (7).

Once the load leveling EMS is defined through the equations in Table 2 and the component sizing is carried out it is possible to proceed with the simulation. With this particular configuration the focus is on maintaining the PEMFC output for as long as possible at the output level defined, producing an almost flat PEMFC output if the conditions allow it. Keeping the PEMFC flat is achieved by recharging the battery at constant current when the surplus of power allows it, and then switch to variable current until the output level is met. Values above the operational level are compensated by releasing the energy stored in the battery packs.

Peak shaving EMS

Peak shaving is the second EMS in this study and aims to eliminate the high frequency load variations experienced by the prime mover of the power-plant during operations. This type of EMS is effective in reducing emissions of diesel-electric power-plants as the high frequency transients are filtered out using a low pass filter, reducing the load variation on the diesel generators and therefore improving efficiency and reducing emissions [24].

The peak shaving EMS can be applied to power-plants with no energy storage solutions, but to achieve better response time and overall performances it is usually applied to hybrid power-plants where energy storage solutions can provide extra power while the prime mover output is capped.

In this study, the hybrid power-plant configuration does not have large individual prime movers, unlike a traditional configuration with an ICEs, but the baseline electric power is generated by the multiple PEMFCs that are connected in parallel. The PEMFCs all share the same load and provide power along the entire operational profile. The power requested during the ferry's operations is filtered through a low pass filter in real-time, smoothing the power demand allocated to the PEMFCs.

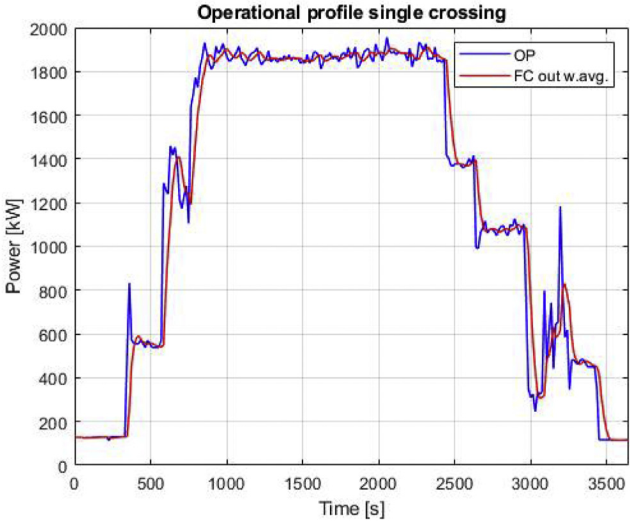

Fig. 3 – Operational profile and fuel cell expected output with peak shaving EMS.

The first step in the sequential optimization approach selected for this paper is the definition of the EMS. In the peak shaving strategy the power demand needs to be filtered in real time using the data collected in the present (*t*) and in the past (*t*-*n*) to define the power that is going to be delivered in the operational point at $t+1$. In this case the PEMFCs operational points are defined through a 5 point weighted average calculated using the 5 points sampled in the 5 time steps leading up to the present instant (Equation (8)) with each timestep being equal to 15 s. The first 75 s of operations are unfiltered as the buffer containing the power demand data fills up. This unfiltered interval does not impact the performances of the system as this time interval is taken during Ro-Ro operations where the power demand is low and practically constant.

This filtering approach is one of the simplest that can be adopted, limiting the computational complexity but still providing a smooth and relatively precise profile. It is possible to limit the response delay introduced by the use of an average modifying the weights in Equation (8). If the weights are modified it is important to consider that there is an inverse relation between suppressing high frequency transients and reducing the delay for the specific application.

$$FC_{out} = \frac{P_{t-5}w_1 + P_{t-4}w_2 + P_{t-3}w_3 + P_{t-2}w_4 + P_{t-1}w_5}{w_5 + w_4 + w_3 + w_2 + w_1} \tag{8}$$

Once the EMS approach is defined, it is possible to proceed with the component sizing. In this strategy, the share of power provided by the PEMFCs is always higher than the one provided by the batteries.

The PEMFC number is calculated using P_{max}, limiting the rated load to 80% according to Table 3, and considering η_{sys} e η_{bc}. With the peak shaving strategy the PEMFC output provides the baseline power to the ferry and the battery provides only temporary compensation during transients. The PEMFC number needs to be calculated taking into consideration that it should be possible to operate the ferry on PEMFCs alone without the battery pack. Similarly to the load leveling strategy, the PEMFC output is limited to 80% of the rated load to reduce degradation.

$$n = \frac{P_{max}}{0.8\ \eta_{sys}\ \eta_{bc}\ P_{fc-rated}} \tag{9}$$

The number of PEMFCs *n* can be rounded to 35 units. Setting the power limit to 80% of the rated load provides a large power reserve.

With the high frequency transients filtered out of the PEMFC output, the battery packs are tasked with compensating the high frequency oscillations to avoid power deficits. Similarly to the load leveling case, the first attempt at dimensioning the battery can be carried out by observing the maximum difference between P_{op} and FC_{out}. In this case there is no pre-set limitation to the maximum PEMFC output, so the difference between P_{op} and FC_{out} needs to be calculated by calculating FC_{out} for a series of profile, measuring the maximum value found. The maximum difference is equal to 740 kW. This value of 740 kW, considering a set voltage of

400 V, translates to a capacity of 1850 Ah if the C-Rate is limited to 1C. In this case, a large storage capacity is not required as the battery mostly provide short bursts of power before the fuel cell output catches up with the demand. For this reason, the battery C-rating in this case can be as high as 2C with a capacity set to 950 Ah. The excess capacity allows for the compensation of losses in the converters and grid.

This power-plant configuration maximizes the share of power allocated to the PEMFCs and reduces to a minimum the power allocated to the battery. The smoother profile also reduces overall degradation as the battery can compensate the fluctuation in load even below a defined output level.

Charge depleting/charge replenishing EMS

The charge depleting/charge replenishing (CDCR) strategy is an approach derived from the charge depleting/charge sustaining (CDCS) EMS used in road transport. CDCS is normally used in hybrid or plug-in hybrid vehicles as the trip length (driving cycle) is not know at the time of starting the car.

In CDCS one or more batteries are discharged during the charge depleting phase, where the vehicles uses only fully electric propulsion. Once the lower limit for the SOC is reached, a range extender turns on and supplies the power demand while the SOC of the battery is kept at a constant value in charge sustaining mode. The adoption of a charge sustaining mode in cars is to ensure the completion of longer trips, while keeping the possibility of running for shorter periods of time using batteries to save fuel or access city areas where ICEs are not allowed. The battery is recharged, once the trip is completed, at a charging station and the cycle can be repeated again.

In this case, this type of EMS is selected to evaluate a power-plant configuration relying primarily on battery power for propulsion and auxiliary loads, with PEMFCs acting as range extenders to include the capability for on-board power generation. The implementation of a CDCS EMS similar to the one applied for road transport would not be optimal for the ferry as, once the battery is depleted, the fuel cells would have to absorb all the high frequency transients defined by the power demand, increasing degradation. The use of CDCS would also mean that, once the battery is depleted, there is the need to recharge using land based infrastructure. For these reasons the CDCS strategy is modified to include a charge replenishing mode, becoming CDCR (charge depleting/charge replenishing). CDCR differs from CDCS as, with the ferry, the length of the crossing is known and the average power demand over time can be calculated. This allows to schedule a battery recharge phase (charge replenishing) onboard, without relying on expensive land based infrastructure that needs to be connected to the electrical grid. The recharging is carried out by the PEMFCs installed on-board.

CDCR uses a deterministic rule-based approach like the load leveling EMS, controlling the power delivery by operating the switchboard connections. The variables used for the control of the system are the power demand and the SOC of each individual battery.

The first step in the definition of the configuration is to specify how the EMS manages the power flow. In this case the choice is made to include 4 batteries in the system. Splitting the power draw between multiple batteries allows to limit the current flowing through the bi-directional converters to obtain better efficiencies. These batteries work alternatively to supply power, and a series of PEMFCs operating as a range extender and recharge energy source (Fig. 4). During normal operations only two batteries from a specific group (1 & 3 or 2 & 4) are in charge depleting mode ($m = 2$), delivering the power defined by the operational profile to the DC load. The other batteries are disconnected from the DC load using the switchboard and are connected to the PEMFCs for recharge (Fig. 4). Disconnecting the battery from the DC load allows a constant-current/constant-voltage (CC-CV) recharge of the battery, replicating the recharging conditions that would be encountered on land. This CC-CV recharging of the battery allows for an easier balancing of the battery pack individual cells therefore limiting degradation and maximizing capacity retention.

Sizing the power-plant for operations with the CDCR EMS starts from the battery packs. Batteries belonging to the same branch of the diagram of Fig. 4 are set to have same dynamic behavior during the simulations as they share the same power demand when in charge depleting mode and are recharged with the same amount of current when in charge replenishing mode. To improve the efficiency of the bi-directional converters that, in this case, need to stabilize the voltage on a much wider range of current outputs, the voltage of the battery is increase from 400 V to 800 V ($V_b = 800$). The capacity of the battery can be calculated using equation (10) and obtaining the capacity from I_b.

$$I_b = \frac{P_{max}}{\eta_{sys}\ \eta_{bi-dir}\ V_b\ m} \tag{10}$$

It is common to increase the capacity calculated in application where the battery is considered the primary source of power for the vessel. The increase in capacity needs to be measured as a trade of between footprint usage and battery depth of discharge (leading to degradation). In this case, a limit is imposed on the lower and upper level of the SOC, with 80% being the upper limit and 20% being the lower limit.

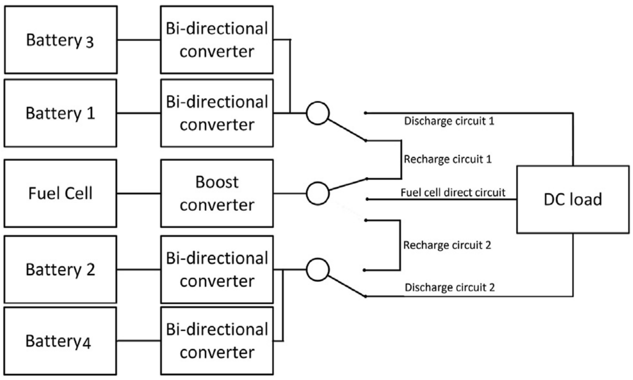

Fig. 4 – Layout configuration with CDCR EMS.

Considering a DC-bus voltage of 1000 V, C-rate of 2-C, a power electronic efficiency of 90% and the limit for the SOC, it is possible to provide a first attempt solution for the battery configuration. Each battery pack is configured for a capacity of 1500 Ah and a nominal voltage level of 800 V.

While the batteries in charge depleting mode are discharged at various rates according to the power demand of the vessel (blue line with different angular coefficients in Fig. 5), the batteries in charge replenishing mode are charged in constant current mode up until the maximum cell voltage is reached (orange line with constant angular coefficient in Fig. 5). It is necessary to specify that, in this case, due to the limitations on the SOC with an upper limit at 80%, the recharge of the battery is carried out only in constant current as the recharge is cut out at 80% SOC before reaching the maximum cell voltage.

The number of PEMFC *n* selected for this EMS is 18, the same amount defined in the load leveling strategy using equation (5). The calculation of the recharge current value, a function of P_{fc}, is nontrivial as each crossing depletes the SOC of the battery in a different way, not always consuming the whole SOC in one crossing. The recharge current value is therefore not unique and has to be recalculated by the EMS each time a group of battery changes its status from charge depleting to charge replenishing. The recharge current is increased or decreased considering the SOC value of the battery group that switches to discharge mode. If this SOC is lower than the maximum 80% it means that the recharge was not fast enough and the recharge current needs to be increased. This increase is calculated by the EMS using the percentage difference between the initial SOC and the upper limit. This approach is a simplified solution and can be expanded in the future using predictive algorithms to optimize the recharge current. The installation of 18 fuel cells allows to have a wide range of possible recharging currents considering the peak power of the fuel cell installation can reach 1800 kWh. The goal is to obtain a SOC curve as similar as possible to Fig. 5.

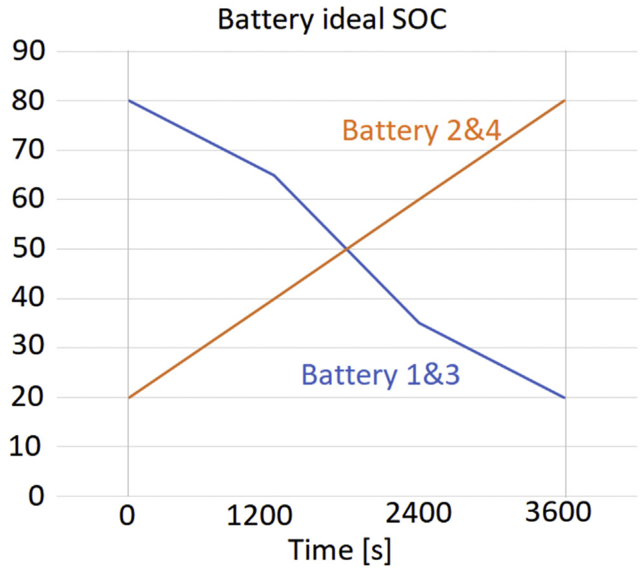

Fig. 5 – Ideal SOC curves with the CDCR EMS.

For this simulation the first attempt solution is to impose a recharge current of 550 A on each battery, that translates to a total of 1100 A that needs to be produced by the fuel cells, using 61% of the total PEMFC power installed.

Results

Results: load leveling strategy

The simulations for the load leveling EMS is carried out using the configuration presented in Table 4.

The first necessary step is to verify that the selected power-plant is capable of carrying out the crossing with no power shortages. This is done comparing the power produced by the modelled power-plant and the initial value of power demand specified (OP). For this comparison the power produced and the OP are considered overlapping if the two values are within ±1% in kW. To take into account transient loading and response time, the aim is to have more than 90% of points within ±20% of the value defined by OP.

The power demand (OP) represented in Fig. 6 is overlapping with the power delivered by the system to the DC bus (output FC + Batt Bus) for 65% of the operational points. The number of samples within the ±20% range is 98%, well within the threshold defined by the author to evaluate the performances of the power-plant configuration. The DC-Bus voltage is stable at the specified level of 1000 V and has slight variations only during the connection and disconnection of the recharge circuit. These variations are quickly compensated by the feedback loop in control of the bi-directional converter, with a fast response.

The difference between the power measured at the source (orange line Fig. 6) and at the bus (yellow line Fig. 6) is equal to the power lost in the converters simulated in the model. This value is influenced by the number of fuel cells and batteries, and therefore converters included in the system, and also by the range of operational values that the converter has to stabilize to 1000 V. In this case the efficiency of the boost converter is equal to 92%. The efficiency of the bi-directional converter is equal to 84%. The bi-directional converter has a lower efficiency compared to the boost converter as it has to stabilize a large battery pack with a wide range of current levels passing through it.

It is assumed that all 18 PEMFC have the same dynamic behavior as load is shared equally between all the units. The

Table 4 – Power-plant configuration for the load leveling simulation.

Total power installed	3200 kW
Bus voltage	1000 V
Battery units	2
Battery nom. voltage	400 V
Battery rated capacity	1750 Ah
Initial SOC	50%
Number of fuel cells	18
Rated power PEMFC	100 kW
Response time PEMFC	15s
Response time Battery	2s

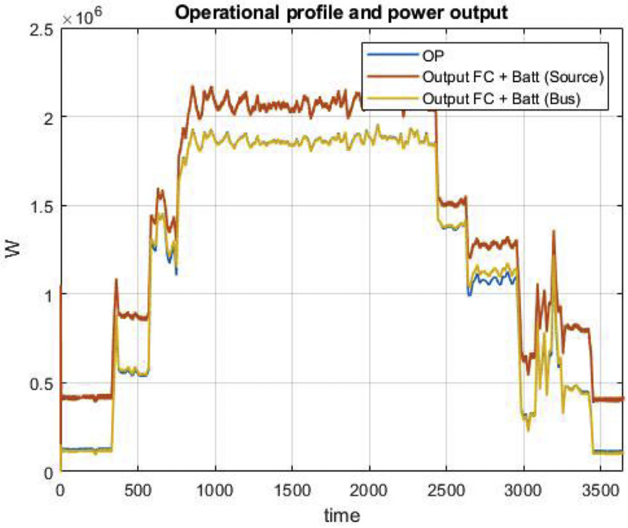

Fig. 6 – Operational profile and power-plant output with load leveling EMS.

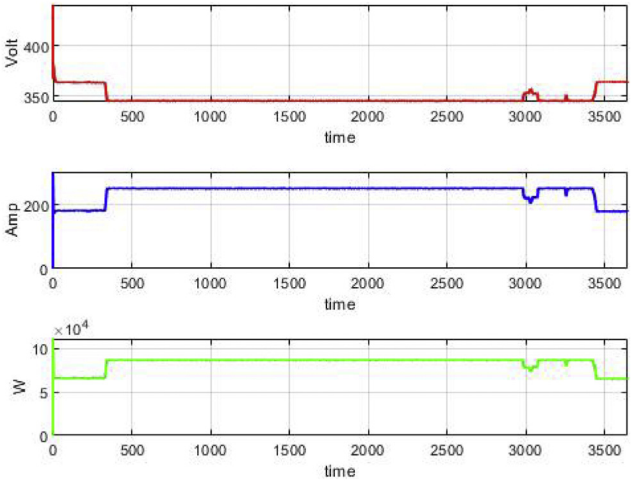

Fig. 7 – Single PEMFC output with load leveling EMS.

load of the single PEMFC can be observed in Fig. 7. In this case, it is possible to observe that for large part of the operational interval the fuel cell is operating at a constant value, defined by the value calculated in Equation (5) divided by the number of fuel cells. This value is on the limit of the low power operation threshold defined in the EMS description. While during this interval at constant power output the degradation of the PEMFC is low, the maneuvering phase has high frequency transients that are filtered out by the battery pack, that is charged with a variable current level.

Observing the state of charge (SOC) curve (see Fig. 8) it is possible to conclude that the batteries included in the system are capable or delivering the requested amount of power during the crossing. In this simulation the recharge of the battery was limited to a maximum value of 0.5C during recharge and 1C during discharge. The final SOC level is also slightly higher than the initial SOC level meaning that there is no need for on-shore recharging during Ro-Ro operations and this particular configuration can operate completely off-grid.

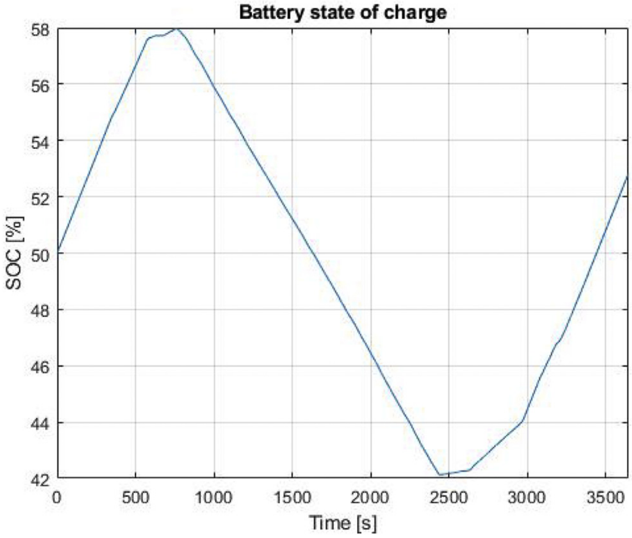

Fig. 8 – SOC of the battery with load leveling EMS.

The degradation for the single PEMFC is equal to 327 μV. The consumption per single FC is equal to 4.03 kg, meaning that the total consumption for the entire crossing is equal to 72.5 kg of hydrogen. By considering the 18 daily crossings that the ferry operates on a regular schedule and the hydrogen quantity that can be stored in fiberglass pressure vessels of commercial size, the ferry would need the equivalent volume of 3.5 20' containers to carry out daily operations. This calculation considers a storage pressure of 350 Bar, and the storage volume can be reduced even further by considering a storage pressure of 700 Bar or cryogenic storage.

Results: peak shaving strategy

The simulations for this EMS is carried out using the configuration presented in Table 5.

As for the load leveling strategy, the first necessary step is to verify that the selected power-plant is capable of carrying out the crossing with no power shortages. This is done comparing the power produced by the modelled power-plant and the initial value of power demand specified (OP). For this comparison the power produced and the OP are considered overlapping if the two values are within ±1% in kW. To take into account transient loading and response time, the aim is to have more than 90% of points within ±20% of the value defined by OP.

Table 5 – Power-plant configuration for the peak shaving simulation.

Total power installed	3502 kW
Bus voltage	1000 V
Battery units	1
Battery nom. voltage	400 V
Battery rated capacity	400 Ah
Initial SOC	50%
Number of fuel cells	35
Rated power PEMFC	100 kW
Response time PEMFC	15s
Response time Battery	2s

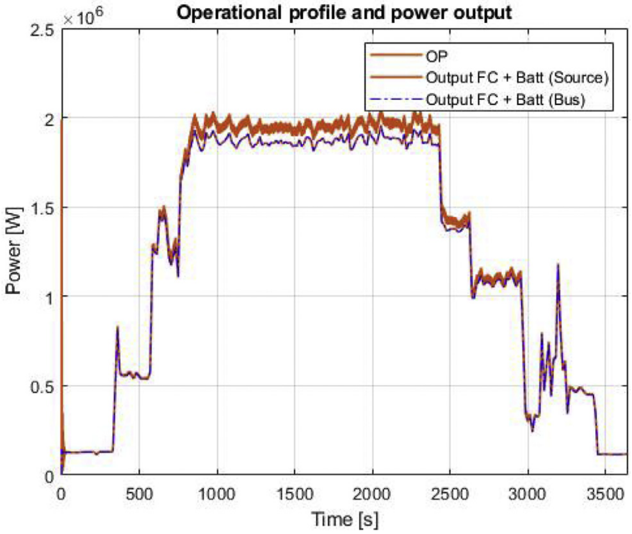

Fig. 9 – Operational profile and power-plant output with peak shaving EMS.

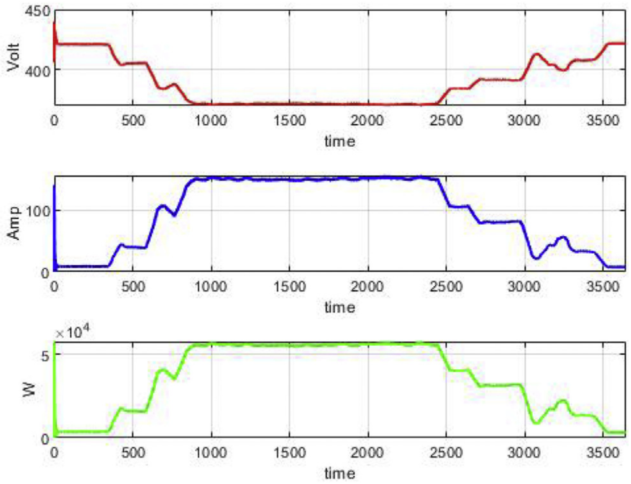

Fig. 10 – Single PEMFC output with peak shaving EMS.

The power demand (OP) represented in Fig. 9 is overlapping with the power delivered by the system to the DC bus (output FC + Batt (Bus)) for 74% of the operational points, and 90.5% of the points are within ±20%. This means that the power-plant is appropriately dimensioned in this case according to the defined criteria. Thanks to the smooth output of the fuel cell and the controlled battery output when charging or discharging, the DC-bus voltage is maintained constant throughout the entire operational interval, with no spikes.

With this EMS the measured efficiency for simulated single boost converters is equal to 95% and the efficiency of the bi-directional converter is close to 98%. These high values for the efficiency are obtained by re-tuning the bi-directional converter to operate in conjunction with the smaller battery capacity.

All 35 PEMFC included in the power-plant have the same dynamic behavior as the load is shared equally between all the units. The load profile of the single PEMFC can be observed in Fig. 10. In this profile it is possible to observe how the high frequency transients have been filtered out, in favor of smoother power output. With a peak power supplied below 60 kW each PEMFC is well within the limit established for low power operation. The degradation measured with this EMS for the single fuel cell is equal to 488.84 μV.

The battery SOC is analyzed to monitor that neither the upper or lower SOC limit, respectively 80% and 20%, are reached. The SOC level for this EMS at the beginning and at the end of the crossing should be equal to 50% as specified in the initial operational profile. This is verified by the results presented in Fig. 11.

Fig. 11 shows how a single battery of just 400 Ah of capacity is able to compensate the small high frequency oscillations during the interval considered.

The hydrogen consumption measured for the single PEMFC during the interval considered is equal to 1.608 kg. This means that, to complete the crossing, 56 kg of hydrogen are required. By considering the 18 daily crossings that the ferry operates on a regular schedule and the capacity of a 20 feet container equipped with fiberglass pressure vessel for storing hydrogen at 350 Bar, the ferry would need the equivalent volume of three containers to carry out operations. This storage volume can be reduced even further by considering a storage pressure of 700 Bar or cryogenic storage.

Results: CDCR strategy

The simulations for the charge depleting charge replenishing EMS is carried out using the configuration presented in Table 6.

Similarly to the two previous EMSs, the first necessary step is to verify that the selected power-plant is capable of carrying out the crossing with no power shortages. This is done comparing the power produced by the modelled power-plant and the initial value of power demand specified (OP). For this comparison the power produced and the OP are considered overlapping if the two values are within ±1% in kW. To take into account transient loading and response time, the aim is to have more than 90% of points within ±20% of the value defined by OP.

The power demand represented in Fig. 12 is overlapping with the power delivered by the system to the DC-bus for 99.6% of the samples obtained in the simulation. This high precision in following the power demand set by the OP is

Table 6 – Power-plant configuration for the CDCR simulation.

Total power installed	6600 kW
Bus voltage	1000 V
Battery units	4
Battery nom. voltage	800 V
Battery rated capacity	1500 Ah
Initial SOC 1	80%
Initial SOC 1	30%
Number of fuel cells	18
Rated power PEMFC	100 kW
Response time PEMFC	15s
Response time Battery	2s

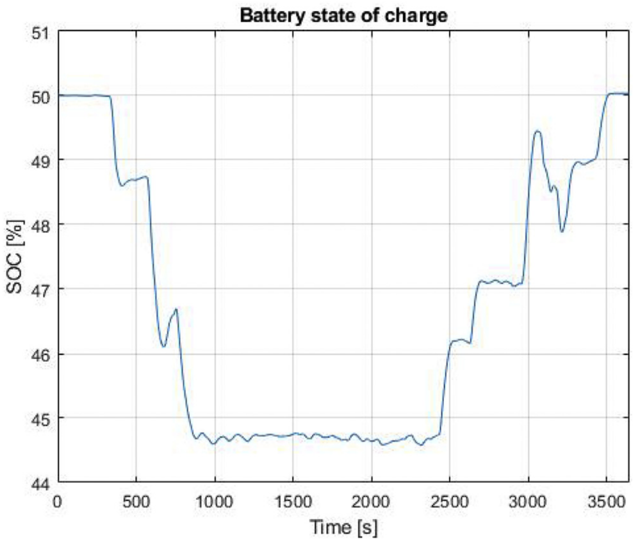

Fig. 11 – Battery SOC with peak shaving EMS.

thanks to the low battery response time, allowing to follow the power demand very accurately, even during load spikes.

The bi-directional converters inductance and capacitance value are recalculated for this specific case to take into consideration the higher current flowing through the sub-model. With the new values for inductance and capacitance it is observed that the feedback loop controlling the bi-directional converters allows an efficient voltage stabilization to the predetermined value of 1000 V during the entire simulation. The efficiency of the boost converter in this case is around 97%, befitting from a constant output on the bus side, while the bi-directional converter efficiency measured during navigation is equal to just 81%, having to stabilize the voltage for a quite wide range of current outputs.

All 18 PEMFC included in the power-plant have the same dynamic behavior as the load is shared equally between all the units. The load profile of the single PEMFC can be observed in Fig. 13. In this profile it is possible to observe that by disconnecting the PEMFC from the DC-bus and operating them only during recharge complitely eliminates transients, with benefits to the fuel cell degradation. The fuel cells supplies, during the simulation, 1100 kW to recharge the battery at the predetermined recharge current of 550 A, using 61% of the total power installed. The degradation measured with this EMS for the single fuel cell, excluding the initial stage at which the fuel cell reaches its operational point, is equal to 45 μV.

The power-plant selected for this EMS is comprised of two groups of batteries: group 1, comprised of battery 1 and 3, and group 2 comprised of battery 2 and 4. All the batteries belonging to a group have the same behavior in the simulation as they are supplying or receiving the same amount of current. This condition is also valid when considering the SOC, with all the batteries in group 1 having the same SOC during the simulation, and same for the batteries of group 2.

In Fig. 14 it is possible to analyze the performances of the two groups of batteries. Group 1, comprised of battery 1 and 3

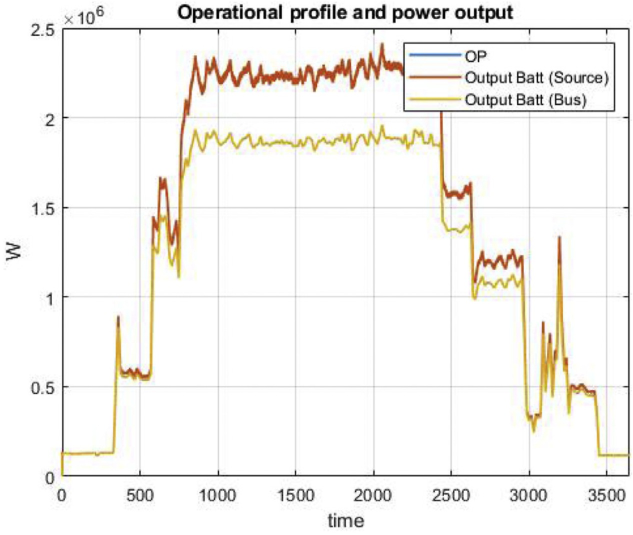

Fig. 12 – Operational profile and power-plant output with CDCR EMS.

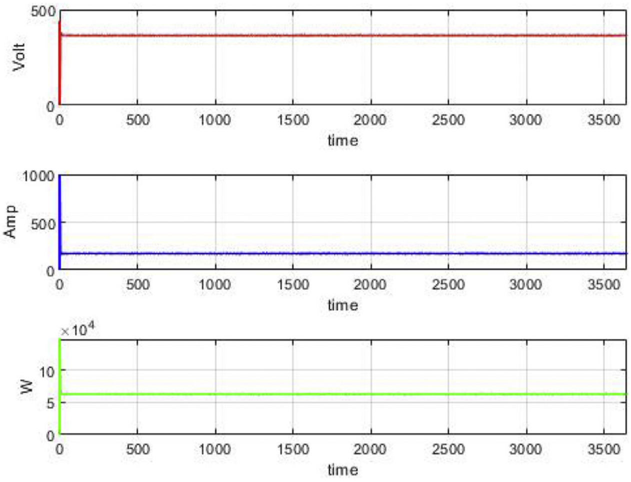

Fig. 13 – Single PEMFC output with CDCR EMS.

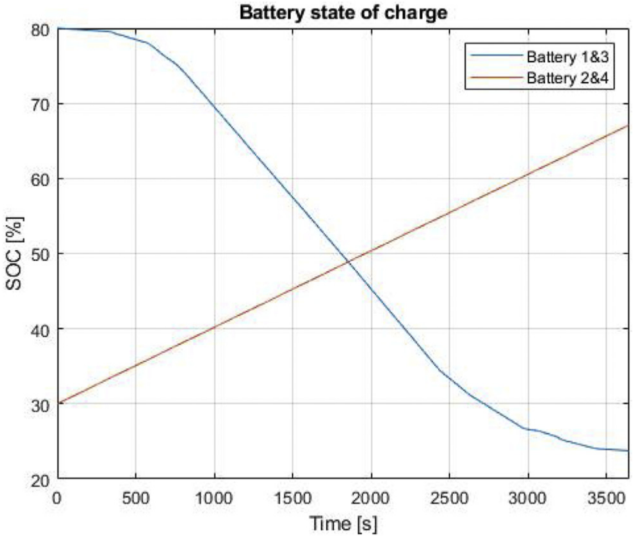

Fig. 14 – Battery SOC with CDCR EMS.

can deliver all the required power for the analyzed crossing. It also shows that at the end of the crossing not all the capacity is used, leaving a residual 5% capacity. Group 2, recharging each battery with a constant 550 A, manages to reach only 67% SOC at the end of the crossing. The fact that group 2 does not reach the upper limit of 80% means that once group 2 is switched to charge depleting mode, it will have a lower SOC than the upper limit. This is taken into consideration by the EMS and the recharge current is increased considering the difference in percentage between the SOC at the time of the connection of group 2 and the upper limit for the SOC.

The hydrogen consumption measured for the single PEMFC during the interval considered is equal to 2.811 kg. This means that, to complete the crossing, 52 kg of hydrogen are required. By considering the 18 daily crossings that the ferry operates on a regular schedule and the capacity of a 20 feet container equipped with fiberglass pressure vessel for storing hydrogen at 350 Bar, the ferry would need the equivalent volume of 3 containers to carry out operations. This storage volume can be reduced even further by considering a storage pressure of 700 Bar or cryogenic storage.

Discussion

The discussion section focuses on the analysis of the results obtained for the three EMS strategies. The pros and cons of each power-plant configuration, including component sizing and energy management strategy are discussed. The results are compared and a score is assigned to different factors to evaluate the overall efficacy of each EMS strategy.

Result analysis

The results obtained with the load leveling EMS show that this strategy is effective in splitting the power demand equally between the PEMFCs and the batteries. The PEMFC output is flat for the majority of the operations, with no high frequency transients (Fig. 7) allowing for a reduction in degradation.

The first limitations with this EMS can be observed in the interval defined by the rule: $P_{vessel} + \setminus P_{rec} > P_{fc\text{-}lim}$; $P_{vessel} \leq P_{fc\text{-}lim}$. In this interval, the PEMFC output is kept constant at the value specified for $P_{fc\text{-}lim}$ by regulating the recharge current of the batteries. This means that the high frequency transients that are observed in Fig. 2, below the red line, are compensated by the batteries during recharge. The analysis of battery degradation phenomena is not considered in this paper, but it is important to specify that this strategy may lead to increased degradation on the battery pack as, by changing the recharge current frequently, it is difficult to perform a balanced recharge of all battery cells. Dead cells in the battery pack result in high maintanence costs that should be avoided if possible.

The results obtained with the peak shaving strategy show how this strategy is effective in delivering the majority of the power demand using the PEMFCs while keeping the degradation value low thanks to the filtering of the power demand. This strategy uses the power-plant with the highest possible power output per unit of volume by reducing to a minimum the size of the battery while still taking advantage of this type of energy storage during high frequency transients.

The power-plant configuration selected for the peak shaving strategy is, in this case, limited by a capped PEMFC output equal to 80% of the rated load to be within the limits of low power operations defined in Table 3. While performance results are satisfactory with the limit on the PEMFCs output, if this condition is eliminated at the expense of an increase in degradation, it is possible to obtain the most energy dense power-plant of all three cases, cutting the number of fuel cells from 35 to 28. This high energy density configuration may be the only viable solution if the footprint allocated for the retrofitting operation of the ferry, or other vessels adopting this EMS, is limited.

One drawback of the peak shaving strategy is that it relies on a high number of low power unit (PEMFC) working in parallel. This increases reliability thanks to active redundancy, but makes necessary to include a high number of boost converters connected to the fuel cells, reducing the overall efficiency of the system. Promising developments in the PEMFC sector, where units of increasing power output are presented regularly, is set to solve this problem when considering that the switch from 100 kWh PEMFC to 200 kWh PEMFC could cut in half the number of converters currently reducing the efficiency of the system.

The results obtained with the charge depleting/charge replenishing strategy highlight that this is the strategy with the lowest possible value for PEMFC degradation while obtaining the best performances when considering transient loading. This configuration still maintains the capability of operating independently from an on-shore recharging station. The low degradation is achieved at the expenses of a large portion of the vessel footprint dedicated to battery storage. This strategy aims at keeping the operating costs for the ship operators low by reducing the maintanence required by the power-plant through low degradation of both batteries and PEMFCs. One drawback of this strategy was evident during the simulations where, with only two large battery packs providing the entire power demand of the vessel, the overall efficiency was impacted, with this strategy having the worst efficiency value when considering the power delivery from power source to DC-Bus. This aspect can be anyway solved with a better re-design of the bi-directional converters or by using multiple smaller batteries.

Comparison between EMSs

To compare the three EMSs is it possible to compile a table that includes scores for each parameter considered. The parameters considered are: PEMFC degradation, single PEMFC consumption, power-plant performance and footprint used. For each parameter, a score ranging between *Low* to *High* is assigned, taking into consideration the values presented in the results section.

The PEMFC degradation parameter depends on the degradation measured during the simulation. The degradation considered is relative to the measurement for the single PEMFC unit. The power-plant performance is a parameter taking into consideration the difference between the power supplied and the power demand. In this case a high number of samples overlapping with the power demand determines the highest score. Footprint usage is a parameter that takes into

Table 7 – Table for the evaluation of key factors with different EMSs.

Parameter	Load Leveling	Peak Shaving	CDCR
PEMFC degradation	Medium	Medium	Low
PEMFC consumption (1 unit)	High	Medium	Medium
Power-plant performance	Low	Medium	High
Footprint usage	Medium	Low	High

consideration the space allocated to the power-plant. In the footprint usage parameter the space required for the storage of hydrogen is not taken into consideration as many different approaches are possible, with very different possible energy density values. The footprint usage is calculated using the approximate dimensions of the PEMFC unit used in this case (volume of 300 l per PEMFC) and the typical energy density of 18,650 battery cells (231.5 Wh/kg [25]). The PEMFC consumption parameter is a function of multiple factors, such as the reliance of the power delivery on the PEMFC output and the loading of the fuel cells in different EMSs. In this case the PEMFC consumption score is not simply a function of the amount of kg of hydrogen calculated in the simulation as this parameter is not directly representative of the efficient or inefficient usage of hydrogen in the power-plant.

The results of this comparison are listed in Table 7.

Conclusions

The simulations and the result analyses carried out in this paper demonstrates that there is no single solution to the optimization problem for a maritime hybrid power-plant equipped with PEMFCs and batteries. The different configurations tested allow for the optimization of primary selected parameters, while assigning a lower priority to other secondary parameters. There is always a trade-off when choosing which factors to optimize, with the resulting configurations always being a compromise due to the limitation of resources (e.g. budget, footprint).

In this paper, the limitations of the optimization process are considered, and three different power-plant configurations, including component sizing and energy management strategies, are presented. These configurations offer different approaches to the optimization of operations when considering the double-ended ferry service. Each configuration considers a different set of primary parameters. In the peak-shaving strategy, for example, the aim is to maximize the energy and power density of the system leading to a minimization of footprint usage, while with the CDCR strategy, the aim is to limit degradation of PEMFCs and batteries to a minimum to reduce the costs of system maintanence. The simulations carried out in these three cases have produced a number of results that can aid the further work on the optimization of the system both on the components sizing perspective and on the EMS perspective.

In this paper the focus is on deterministic or fuzzy-logic online rule-based EMSs, and it was observed that these approaches still have limitations when considering the overall behavior of the system. Online rule-based strategies offer a good trade-off between computational complexity, execution speed and implementation times allowing for real-time application, but still lack the precision of strategies based on dynamic programming. The adoption of online EMSs using optimization based approaches or multi-scheme EMSs turns out to be more complex as the definition of smart cost functions is non-trivial. Optimization based EMSs may increase the computational complexity, but will be the scope of future analysis to further reduce fuel consumption, PEMFC and battery degradation and improvement of performances. The focus of future work is on this type of online EMSs, such as equivalent consumption minimization strategy (ECMS) or model predictive control (MPC). The implementation of these new EMSs can be based on the version of the model that is used in this paper, as it shown that it is possible to be quickly re-configured the layout to follow both different component sizing solutions and energy management strategies.

In this particular case, the ferry company is presented with the required data to make a preliminary decision on which components configuration and EMSs bests fits their use case. This allows them to choose primary factors and secondary factors, defining priorities in the optimization process.

The ultimate goal of this work is to promote the use of clean energy carriers in the maritime industry, providing tools and software that can be used to measure economical and technical feasibility of clean hydrogen solutions to reduce both pollution and greenhouse gas emissions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ijhydene.2021.09.091.

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