On the design of plug-in hybrid fuel cell and lithium battery propulsion systems for coastal ships

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ABSTRACT: A plug-in hybrid propulsion system comprising of a proton exchange membrane fuel cell (PEMFC) and lithium battery capable of being recharged in port offers a promising low carbon propulsion system for small coastal ships, e.g. small container ships, tankers and ferries, which typically sail over short routes at modest speeds. PEMFC operate at high efficiency and emit no harmful emissions, but their poor transient performance necessitates the need for an energy storage system such as a lithium battery. A shore-to-ship electrical connection is needed to recharge the lithium battery from the grid so as to improve the propulsion system performance both environmentally and economically. Production of both H_2 and grid electricity have a carbon footprint. In this paper a two-layer optimisation based methodology is used for the design of plug-in hybrid fuel cell and lithium battery propulsion systems for coastal ships. Results from a case study suggest that the design of hybrid PEMFC and battery propulsion systems should be influenced by the 'well-to-propeller' carbon footprint.

KEYWORDS: Plug-in hybrid fuel cell; energy storage system; hydrogen; ferry; propulsion system design.

1 INTRODUCTION

1.1 *Fuel cells*

Fuel cells offer the desirable combination of high efficiency and environmentally benign operation (Sharaf & Orhan 2014). Among the main fuel cell types, the low-temperature Proton Exchange Membrane Fuel Cell (PEMFC) and high-temperature fuel cells (e.g. solid oxide fuel cell and molten carbonate fuel cell) offer the most promising power sources for future marine propulsion applications (Luckose et al. 2009). However, the economic feasibility of fuel cells is currently compromised by their high cost, poor transient performance, poor reliability, availability of alternative fuel supplies e.g. H_2 and associated fuel bunkering facilities (de-Troya et al. 2016).

High-temperature fuel cells offer higher efficiency when compared to the PEMFC (van Biert et al. 2016). A higher operating temperature makes it possible to recover heat from the exhaust gas so as to improve overall thermal efficiency, e.g. a combined cycle plant. Importantly high-temperature fuel cells can use a range of fuel types including natural gas. However, the main challenges of high-temperature fuel cells in marine applications are their low overall power to volume density, long start-up times, limited cycling times and transient performance (Welaya et al. 2011).

PEMFC have been successfully applied to a range of propulsion applications, e.g. road vehicles, submarines and inland water boats (Sasank et al. 2016, Pei & Chen 2014, Han et al. 2012). PEMFC offer improved power to volume density but their efficiency is lower than high-temperature fuel cells and they can only operate on H_2 (van Biert et al. 2016). Unlike natural gas, H_2 does not exist naturally on earth so is produced using various means including electrolysis and reformation of hydrocarbon fuels. Therefore, H_2 through life Global Warming Potential (GWP), production cost, bunkering and onboard storage will all influence the feasibility of using PEMFC in ships.

For coastal ships operating on short routes at modest speeds then PEMFC with their better power to volume ratio appear to be more suitable. The PEMFC is well developed and its price is falling (DOE 2015). PEMFC with lithium batteries will provide acceptable transient performance. The low volumetric energy density of the hydrogen fuel suggests efficient operation is required to minimise onboard storage facilities. The production of H_2 has a carbon footprint as does grid electricity production. This paper explores these factors for a low carbon propulsion system.

NOMENCLATURE

Acronyms

AC	Alternating current
DC	Direct current
EMS	Energy management strategy
ESS	Energy storage system
GWP	Global warming potential
HHV	High heating value
MOO	Multi-objective optimisation
NGSR	Natural gas steam reforming
PEMFC	Proton exchange membrane fuel cell
PIHFCB	Plug-in hybrid fuel cell and battery
SOC	State of charge

Roman symbols

C	Lithium battery C-rate
c_{eq}	Equality constraint
F_1	Multi-objective optimisation 1st objective function
F_2	Multi-objective optimisation 2nd objective function
f	Single-objective optimisation objective function
g_{fc}	Fuel cell specific hydrogen consumption function
J	Time step number when the ship calls at the port
K	Total time step number
L_{fc}	Fuel cell lifetime, h
L_{ESS}	Lithium battery lifetime, h
M_1	Multi-objective optimisation 1st constraint function
M_2	Multi-objective optimisation 2nd constraint function
P_{ESS}	ESS power, kW
P_{shore}	Shore power, kW
P_l	Load power, kW
P_{fc}^R	Fuel cell rated power, kW
P_{fc}	Fuel cell power, kW
P_{ESS}^R	Lithium battery rated power, kW
p_h	H_2 price, \$/kg
p_{fc}	PEMFC price, \$/kW
p_{ESS}	Lithium battery ESS price, \$/kWh
p_e	Shore electricity price, \$/kWh
R_{fc}	Fuel cell power ramp up/down limit
SOC_i	Lithium battery state of charge at *i*-th time step
T	Voyage time, h
Δt	Time step length, h
V_D	Equivalent diesel system total volume, m^3
V_{df}	Diesel fuel tank volume, m^3
W_D	Equivalent diesel system total weight, t
w_h	H_2 specific GWP, kg CO_2/kg
w_e	Electricity specific GWP, kg CO_2/kWh
x	Decision vector
$x_{1,2,\ldots,K}$	PEMFC stack per unit power output
$x_{K+1,K+2,\ldots,2K}$	Lithium battery C-rate

Greek symbols

ρ_{fc}^v	PEMFC stack volumetric power density, kW/m^3
ρ_{ESS}^v	ESS stack volumetric energy density, kWh/m^3
ρ_t^v	H_2 tank volumetric energy density, m^3/kg H_2
ρ_{dg}^v	Diesel engine volumetric power density, kW/t
ρ_{fc}^g	PEMFC stack gravimetric power density, kW/t
ρ_{ESS}^g	ESS gravimetric energy density, kWh/t
ρ_t^g	H_2 tank gravimetric energy density, kg/kg H_2
η_1	Uni-directional converter efficiency
η_2	Bi-directional converter efficiency
η_b	Lithium battery efficiency

1.2 *Energy storage systems*

Energy Storage Systems (ESS) such as lithium batteries have already been adopted for use in commercial ship applications, often in a configuration of hybridisation with the diesel engine (Luo et al. 2015). When hybrid configurations are used, they can potentially achieve 15% annual fuel saving depending on operational profile, e.g. the Viking Lady offshore supply vessel (Stefanatos et al. 2015). When only a battery is used alone for propulsion, e.g. the Norled Ampere battery powered ferry, then the low volumetric energy density of the batteries restricts both speed and range.

For a marine Plug-in Hybrid Fuel Cell Battery (PIHFCB) propulsion system, the ESS provides transient capability and greater plant efficiency. Furthermore, when a shore charging facility is available, integration of ESS can further improve the overall energy efficiency through direct utilisation of clean grid electricity e.g. electrolysis of water generating H_2 rather than reformation of hydrocarbon fuels. For a PIHFCB propulsion system, lithium batteries are preferable over other main ESS types for better energy density (Hannan et al. 2017).

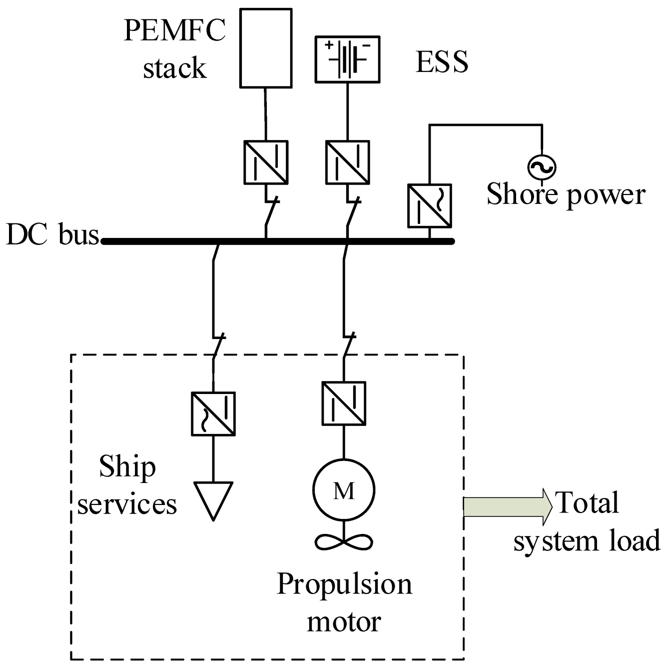

Figure 1. PIHFCB propulsion system layout.

1.3 *Design methodology*

Using fuel cells and batteries together the overall GWP can potentially be very low or even zero when renewable energy is utilised for electricity generation and hydrogen (Hansen & Wendt 2015). There are some research studies, e.g. Bassam et al. (2016) and Mashayekh et al. (2012) who have looked into the optimisation of hybrid ship propulsion systems. These works only focus on cost optimisation without considering the overall environmental performance of the propulsion plant i.e. well-to-propeller.

When multiple power sources are integrated into one propulsion system, two problems need to be resolved: 1) How to size the different energy and power sources to achieve an optimised well-to-propeller emission performance; 2) How to manage the different power sources to maintain high overall efficiency.

Since this paper is considering a PIHFCB propulsion system suitable for coastal ships which typically sail on short routes at modest speeds the analysis needs to consider GWP emissions and operating costs. The propulsion system design methodology consists two layers of optimisation:

1. An external layer applies a controlled elitist Multi-Objective Optimisation (MOO) scheme using evolutionary algorithms to optimise environmental and economic performance thereby overcoming the constraints on the propulsion plant design such as volumetric and gravimetric limits of the ESS and H_2 (Deb 2001).
2. The inner layer optimisation scheme utilises dynamic programming to generate most optimal Energy Management Strategy (EMS) for multiple power sources knowing the powering requirements and the operating profile.

2 PLUG-IN HYBRID PEMFC AND ESS PROPULSION SYSTEM

2.1 *Basic concept of operation*

There are different operating modes for coastal ships which need to be considered independently:

When the ship is at sea, both the PEMFC stack and lithium batteries work concurrently to power the ship propulsion and its service loads. The ESS has two functions: 1) Levelling the PEMFC stack loads to achieve the best overall efficiency; 2) Utilising the stored clean grid power to achieve the best overall environmental performance.

When the ship is manoeuvring, then the battery should supplement the fuel cell set at a lower output. The battery will charge or discharge as needed to reduce transients to the fuel cell but also to maintain high overall efficiency.

When the ship is in port, shore power is available to charge the ESS and to power the ship's services, i.e. cold ironing.

Due to the high volumetric demands of H_2 fuel it is assumed that the ship bunkers H_2 fuel for each voyage, i.e. every time it calls at the port.

2.2 *System layout*

Figure 1 presents the PIHFCB propulsion system layout. DC power distribution architecture is preferred since the power out from both PEMFC stack, and ESS is DC electrical power (Zahedi et al. 2014).

2.3 *Propulsion system dynamics*

According to energy conservation principle, the relationship between the PEMFC stack output power P_{fc}, battery power P_{ESS}, shore power P_{shore} and the lumped system power demand P_l can be determined as:

$$P_{fc}\eta_1 + P_{ESS}\eta_2\eta_b + P_{shore}\eta_1 - P_l = 0 \quad (1)$$

where η_1, η_2 and η_b are uni-directional, bi-directional converter efficiency and lithium battery ESS efficiency respectively; and $P_{shore} = 0$ when ship is sailing, $P_{shore} \geq 0$ when ship is at port. $P_{ESS} > 0$ when lithium battery ESS discharges, and $P_{ESS} < 0$ while ESS charges.

2.4 *Proton exchange membrane fuel cell*

The PEMFC stack model is developed and calibrated using the methodology and data from (Larminie et al. 2003), (Tremblay & Dessaint 2009) and (Li et al. 2009). The PEMFC model is simplified to represent per unit power versus specific H_2 consumption based on the 141.8 MJ/kg H_2 High Heating Value (HHV) as presented in Figure 2 (Koroneos et al. 2004). The PEMFC stack specific H_2 consumption is given by:

$$SHC = g_{fc}(x) \quad (2)$$

where SHC is the specific H_2 consumption and is a function g_{fc} of the PEMFC stack per unit power x, $0 \leq x \leq 1$. For the rated PEMFC stack power of P_{fc}^R, the power output from the PEMFC stack is:

$$P_{fc} = P_{fc}^R x \quad (3)$$

2.5 *Energy storage system*

As lithium battery features high efficiency for charging and discharging, the round-trip efficiency of ESS charging/discharging is assumed as $\eta_b = 0.98$ within allowed State of Charge (SOC) range, e.g. $0.2 \leq SOC \leq 1$ (Ovrum & Bergh 2015). The SOC range is set to avoid excessive degradation due to over-discharge. Note that, the initial SOC is one. At time step t, SOC is calculated by:

$$SOC = 1 - \int_0^t C(t)dt \quad (4)$$

where $C(t)$ is ESS chrage/discharge C-rate at time step t. And $P_{ESS} = C(t)P_{ESS}^R$, where P_{ESS}^R is ESS power when C-rate is 1.

2.6 *Power converters*

Figure 3 shows the power converter efficiency characteristics used in this study (Martel et al. 2015). The uni-directional efficiency is slightly higher than that of a bi-directional one.

3 HYBRID SYSTEM DESIGN METHODOLOGY

Ship power and propulsion systems are customised for individual ships to provide efficient and reliable operation. The design of hybrid propulsion systems comprising multiple power sources should be optimised for the specific operational requirements and scenarios to exploit merits and avoid drawbacks of each type of power sources effectively. The electricity and alternative fuels (e.g. H_2) characteristics can vary from place to place. Also, novel power technologies such as fuel cells and batteries are typically limited by high production costs, limited lifetime and power/energy density for marine propulsion systems. These factors need to be considered for propulsion system designs.

3.1 *Methodology overview*

The proposed design methodology includes two layers of optimisation schemes as presented in Figure 4. The external MOO scheme searches predefined ranges to find optimum PEMFC stack rated power, ESS capacity and shore charging power. The power and propulsion solutions need to meet both volumetric and gravimetric constraints on the propulsion plant. The inner optimisation scheme based on dynamic programming determines the EMS for each combination of power sources generated by the external layer. The EMS minimises the voyage fuel costs satisfying the powering demands and power sources constraints.

3.2 *Multi-objective genetic algorithm – sizing optimisation*

The MOO solutions, in the form of Pareto fronts, allow the decision makers to make informed decisions by seeing a set of acceptable trade-off optimal solutions (Ngatchou et al. 2005). In this case, the trade-offs are between equivalent voyage GWP and average voyage cost. The former includes the equivalent CO_2 emission throughout the lifecycle of H_2 and electricity. The average voyage cost consists of H_2 cost, electricity cost and PEMFC and ESS degradation costs.

3.2.1 *Decision variables*

The decision variables of the external optimisation layer are rated PEMFC stack power P_{fc}^R, ESS capacity C_{ESS}^R and shore charing power P_{shore}^R. The searching range of the three variables are set considering the maximum power and total energy demands in operating profile as following:

$$P_{fc}^{min} \le P_{fc}^R \le P_{fc}^{max} \quad (5)$$

$$C_{ESS}^{min} \le C_{ESS}^R \le C_{ESS}^{max} \quad (6)$$

$$P_{shore}^{min} \le P_{shore}^R \le P_{shore}^{max} \quad (7)$$

3.2.2 *Objective functions*

The first objective function of MOO is the average voyage cost, which includes H_2 fuel and electricity cost for one voyage, battery and PEMFC stack degradation costs for one voyage:

$$F_1 = \sum_{i=1}^{K} g_{fc}(x_i)x_i P_{fc}^R \Delta t\, p_h + \sum_{i=J}^{K} P_{shore}^R \Delta t\,(K-J)p_e + \left(\frac{p_{fc}P_{fc}^R}{L_{fc}} + \frac{p_{ESS}C_{ESS}^R}{L_{ESS}}\right) \quad (8)$$

where p_h is the H_2 price in \$/kg, p_{fc} is the PEMFC stack price in \$/kW, p_{ESS} is the battery price in \$/kWh, K is the total time step number, i is i-th time step, J is the time step number when the ship calls at the port, T is the voyage time, $\Delta t = T/K$ is time step length, L_{fc} and L_{ESS} are fuel cell and battery lifetime respectively.

The second objective function of MOO is the GWP emission for one voyage, which is the sum of H_2 fuel GWP and shore electricity GWP in equivalent kg CO_2:

$$F_2 = \sum_{i=1}^{K} g_{fc}(x_i)x_i P_{fc}^R \Delta t\, w_h + P_{shore}^R \Delta t (K - J) w_e \quad (9)$$

where w_h and w_e are H_2 and electricity specific GWP respectively.

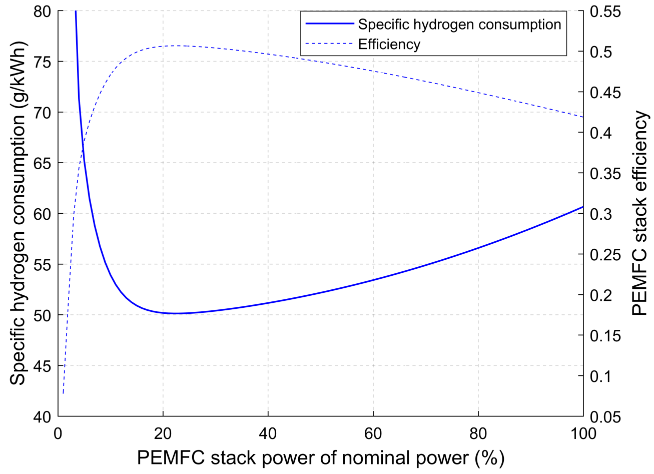

Figure 2. PEMFC stack specific H_2 consumption and efficiency.

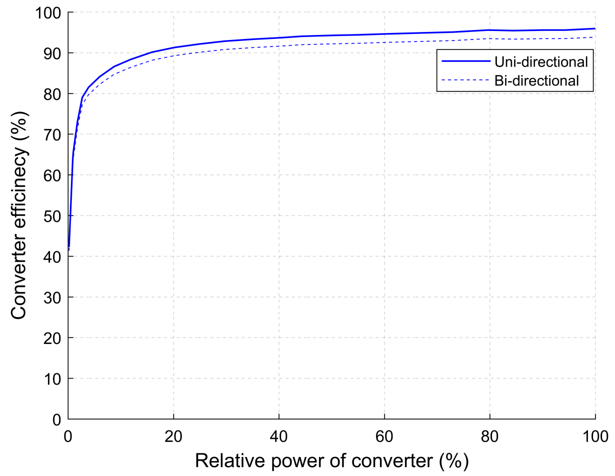

Figure 3. Power electronics characteristics.

3.2.3 *Constraints*

The first constraint function limits the hybrid propulsion system volume does not exceed the equivalent diesel-mechanical system volume. The difference between the hybrid propulsion system and the diesel-mechanical plant is:

$$M_1 = P_{fc}^R \rho_{fc}^v + C_{ESS}^R \rho_{ESS}^v + \sum_{i=1}^{K} g_{fc}(x_i) x_i P_{fc}^R \Delta t \rho_t^v - V_D \leq 0 \quad (10)$$

where ρ_{fc}^v, ρ_{ESS}^v and ρ_t^v are volumetric density of PEMFC stack, ESS and H_2 tank (contains H_2 for one voyage) respectively, V_D is the equivalent diesel system total volume and $V_D = P_{dg}\rho_{dg}^v + V_{df}$, ρ_{dg}^v is the diesel engine volumetric power density, and V_{df} is the diesel fuel tank volume. It is assumed the original case ship refuels diesel once a week in the subsequent analysis.

The second constraint function limits the hybrid propulsion system total weight does not exceed the equivalent diesel-mechanical system weight:

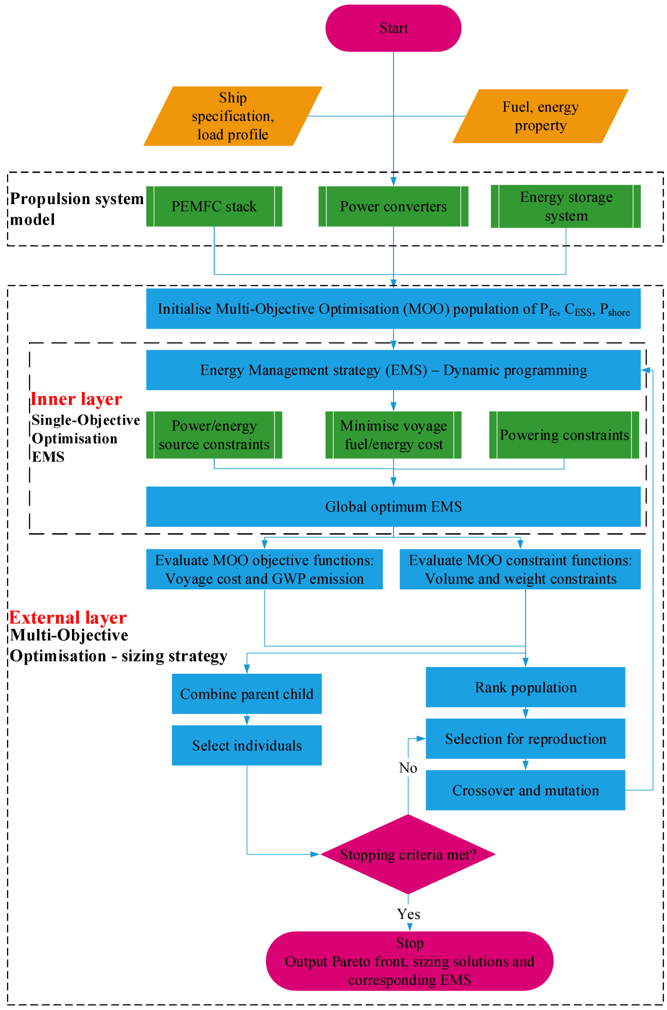

Figure 4. Hybrid system design methodology.

$$M_2 = P_{fc}^R \rho_{fc}^g + C_{ESS}^R \rho_{ESS}^g + \sum_{i=1}^{K} g_{fc}(x_i) x_i P_{fc}^R \Delta t (\rho_t^g + 1) - W_D \leq 0 \quad (11)$$

where ρ_{fc}^g, ρ_{ESS}^g, and ρ_t^g are the gravimetric density of PEMFC stack, battery and H_2 tank respectively, W_D is the diesel based system total weight including the diesel engine, gearbox and fuel weight.

3.3 *Dynamic programming – Energy Management Strategy solving*

The inner optimisation scheme applies dynamic programming based on Bellman's optimality principle to find the most optimal EMS with load profile is known before solving (Bellman 2013). The dynamic programming approach can be used to find the optimal EMS which can be used as a benchmark to evaluate the effectiveness of on-line real-time EMS (Song et al. 2014). The EMS solution for each power and energy source combination is passed to external MOO to evaluate the objective and constraint functions. The objective function values of MOO are infinite if no EMS solution exists.

3.3.1 *Decision variables*

The decision variables represent specific loading conditions for PEMFC stack and ESS. The shore connection delivers rated power whenever the ship is in port. The decision vector is:

$$x = [x_1, x_2, \dots, x_K | x_{K+1}, x_{K+2}, \dots, x_{2K}] \tag{12}$$

where $x_1, x_2, \dots, x_K$ are per unit power of the PEMFC stack, and $x_{K+1}, x_{K+2}, \dots, x_{2K}$ are the C-rate of the ESS from 1_{st} to K_{th} (final step of one voyage) time step.

3.3.2 *Objective functions*

The objective function of the inner optimisation scheme is the voyage total fuel and electricity cost:

$$f = \sum_{i=1}^{K} g_{fc}(x_i) x_i P_{fc}^R p_h + P_{shore}^R \Delta t (K - J) p_e \tag{13}$$

3.3.3 *Constraints*

3.3.3.1 *Powering*

For each time step, the power provided by all the power and energy sources should equal to the sum of load demand and system losses, therefore re-write Eq. (1) to discrete form:

$$c_{eq,i} = x_i P_{fc}^R \eta_1(x_i) + x_{i+K} P_{ESS}^R \eta_2(x_{i+K}) \eta_b + P_{shore} \eta_1(1) - P_{l,i} = 0 \tag{14}$$

3.3.3.2 *ESS state of charge*

The battery SOC needs to be within a range to avoid over-charge or over-discharge, therefore:

$$SOC_{min} \leq SOC_i \leq SOC_{max} \tag{15}$$

moreover:

$$SOC(i) = 1 - \sum_{1}^{i} x_{K+i} dt \tag{16}$$

3.3.3.3 *Fuel cell power ramp up/down rates*

Compared to diesel engines, PEMFC stack is weak in transient loads. Therefore, the fuel cell power change between two adjacent time steps should satisfy:

$$|x_i - x_{i-1}| \leq R_{fc} \tag{17}$$

where R_{fc} is the fuel cell power ramp up/down limit.

4 CASE STUDY

4.1 *Case ship specification*

In the case study, the proposed methodology is applied to design the PIHFCB propulsion system considering both environmental and economic performance for case ship which sails on short routes. The vessel specification is shown in Table 1 (Traffic 2015).

4.2 *Case ship operating profile*

For system level design and optimisation, the load profile of the case ship is modelled as a lumped power profile including both propulsion and service loads as shown in Figure 5 (Mashayekh et al. 2012). The load ramps up to a high value in the first 10 minutes and fluctuates to follow a sinusoidal wave to mock the power demand variations. Then the ship power ramps down (90-100 mins) to the port where shore connection charges the battery if necessary. Shore power is available to charge from 100 to 140 mins. This system load profile is converted into a discrete time series and repeats for each voyage.

Table 2 presents the price and specific GWP of H_2 generated via three typical approaches (Acar & Dincer 2014). The three types of H_2 were analysed to investigate the impacts from H_2 properties to the design of propulsion system. The electricity price is assumed to be \$0.12/kWh, and its GWP is 0.289 kg/kWh (Eurostat 2017).

4.3 *Case study parameters*

Table 3 describes the parameters applied in the case study. The PEMFC stack and battery properties, the prices are all for system level, i.e. including the ancillary devices. It worth mentioning that the results are sensitive to the parameters.

4.4 *Sizing results*

4.4.1 *Pareto fronts*

Table 1. Case ship specification (Traffic 2015).

Vessel type	Ro-ro/passenger ship
Gross tonnage	3,193 tons
Deadweight	572 tons
Length overall	87 m
Breadth extreme	17 m
Designed speed	12 knots
Installed engine power	2,148 kW

Table 2. H_2 characteristics (Acar & Dincer 2014).

H_2 generation method	Price (\$/kg)	GWP (kg CO_2/kg)
Nuclear Cu-Cl	1.7	1.6
Wind	7.2	1.3
Natural gas steam reforming (NGSR)	1.5	7.5

Table 3. Case study parameters.

Parameters	Value	Reference
Annual operating days	300 days	(Traffic 2015)
Daily voyage number	6	(Traffic 2015)
Fuel cell price	$1200/kWh	(Isa et al. 2016)
Fuel cell lifetime	3 years (or 10,800 h)	(Ballard 2017)
Battery price	$800/kWh	(Ovrum & Bergh 2015)
Battery lifetime	3 years	(Stroe et al. 2015)
Shore electricity price	$0.12/kWh	(Eurostat 2017)
Shore electricity GWP	0.289 kg CO_2/kWh	(Eurostat 2017)
PEMFC volumetric specific power	128.2 kW/m^3	(Ballard 2017)
PEMFC gravimetric specific power	200.0 kW/t	(Ballard 2017)
ESS volumetric specific energy	91.8 kWh/m^3	(Corvus 2017)
ESS gravimetric specific energy	80.6 kWh/t	(Corvus 2017)
Battery maximum C-rate	6.0	(Corvus 2017)
Diesel engine volumetric specific power	43.9 kW/m^3	(Wartsila 2016)
Diesel engine with gearbox specific power	54.8 kW/t	(Wartsila 2016)
Marine gas oil price	$0.64/kg	(BunkerIndex 2017)
H_2 tank volume	0.17 m^3/kg H_2	(Choi et al. 2016)
H_2 tank weight	28.5 kg/kg H_2	(Choi et al. 2016)

Figure 6 shows the Pareto fronts for H_2 produced from the three sources mentioned in Table 2. For the case of H_2 generated via Nuclear Cu-Cl, as both the H_2 specific GWP and price low, the Pareto front points only distribute in a small region of shore power. H_2 generated using wind power features for the lowest GWP, but the highest price can achieve best emission performance but leads to high voyage costs. The Pareto front of NGSR H_2 can contribute the lowest average cost, but also the highest GWP. In general, Nuclear Cu-Cl generated H_2 excels the other two.

4.4.2 *Optimal sizing*

Figure 7 presents the detailed Pareto front solutions including the information of PEMFC stack rated power, battery capacity and rated shore power. The optimal shore power distributed between a narrow region from 180 to 185 kW, which is because both the H_2 specific GWP and price are low amongst the three H_2 production methods. Furthermore, increasing the average voyage cost cannot further improve emission performance effectively. ESS mainly functions as an energy buffer to optimise PEMFC stack loading to achieve higher efficiency.

For the wind power generated H_2 case, as presented in Figure 8, the optimal solutions scatter in more substantial space. The combinations with high shore charging power and larger ESS capacity correspond to better emission performance (Figure 8b), but worse economic feasibility (Figure 8a). Such trends match the wind power generated H_2 property – high price, but low specific GWP.

In contrast, Figure 9 shows the trade-off between economic and environmental performances for the H_2 generated via NGSR (high specific GWP and low price). Higher PEMFC stack power leads to lower running cost (Figure 9a) but higher GWP (Figure 9b).

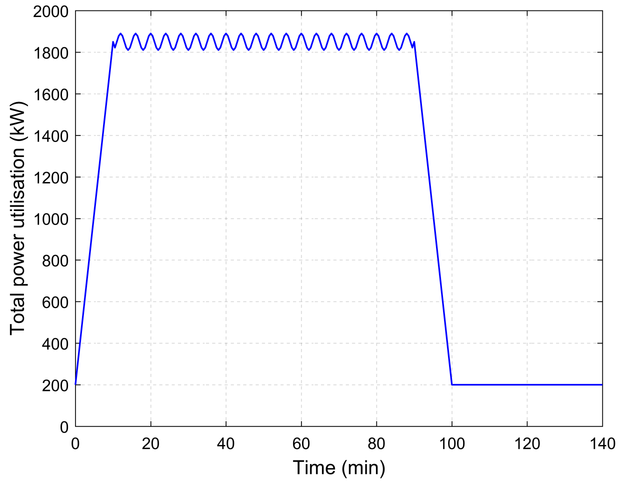

Figure 5. Case ship lumped load profile.

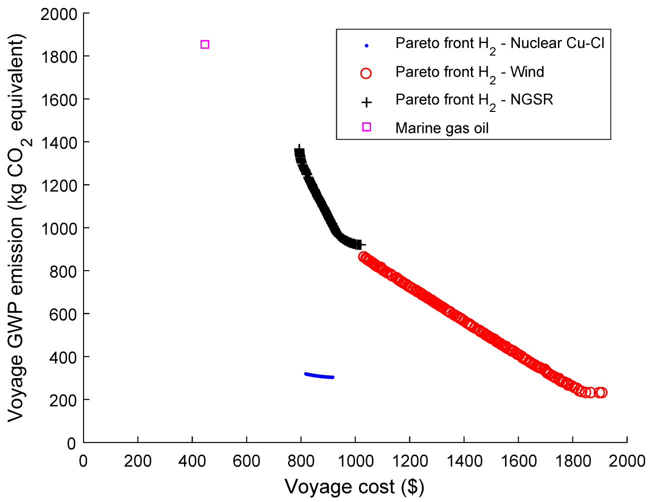

Figure 6. Pareto fronts.

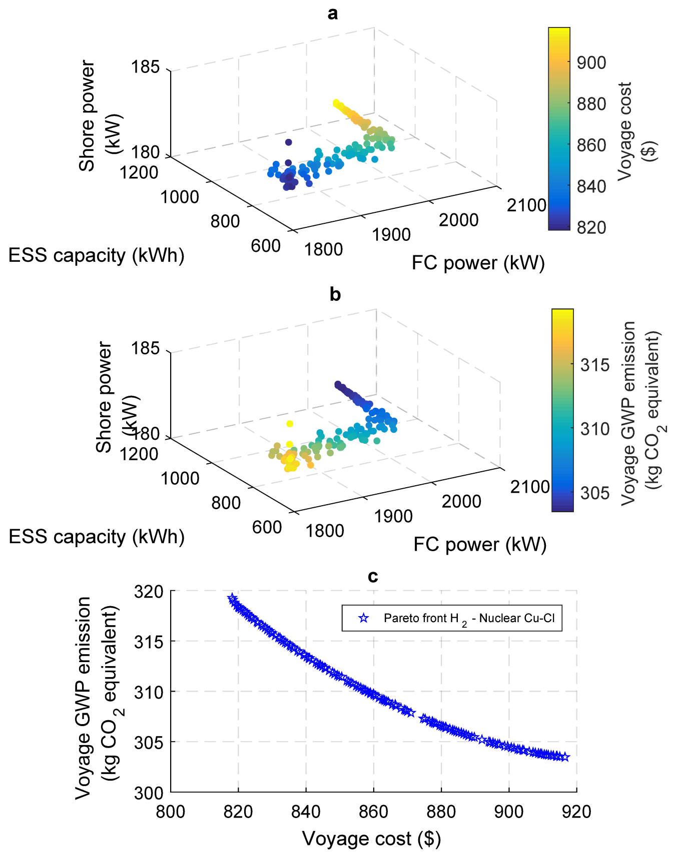

Figure 7. Power source sizing results of H_2 generated via Nuclear Cu-Cl method: (a) average voyage cost, (b) voyage GWP and (c) Pareto front.

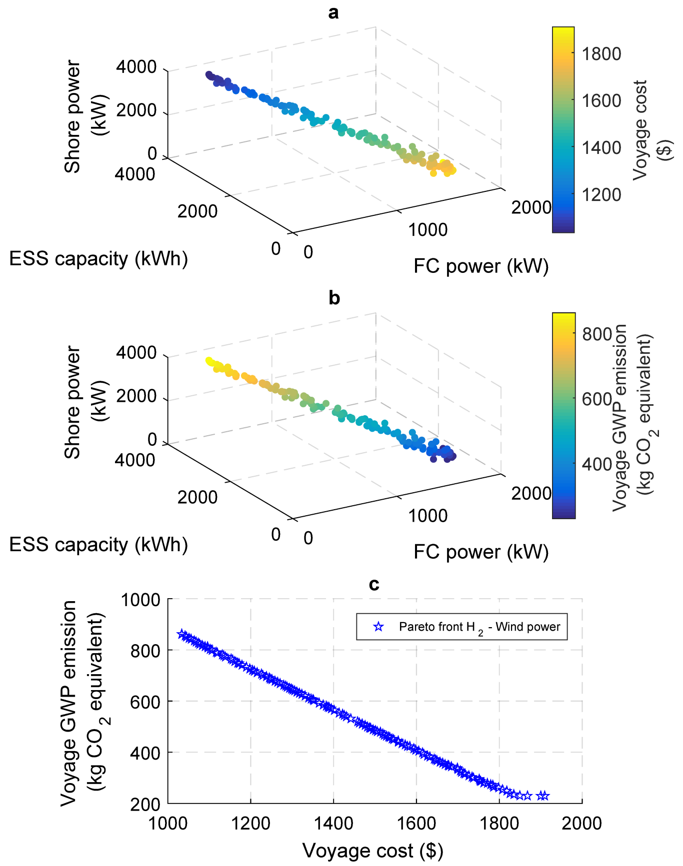

Figure 8. Power source sizing results of H_2 generated via wind power: (a) average voyage cost, (b) voyage GWP and (c) Pareto front.

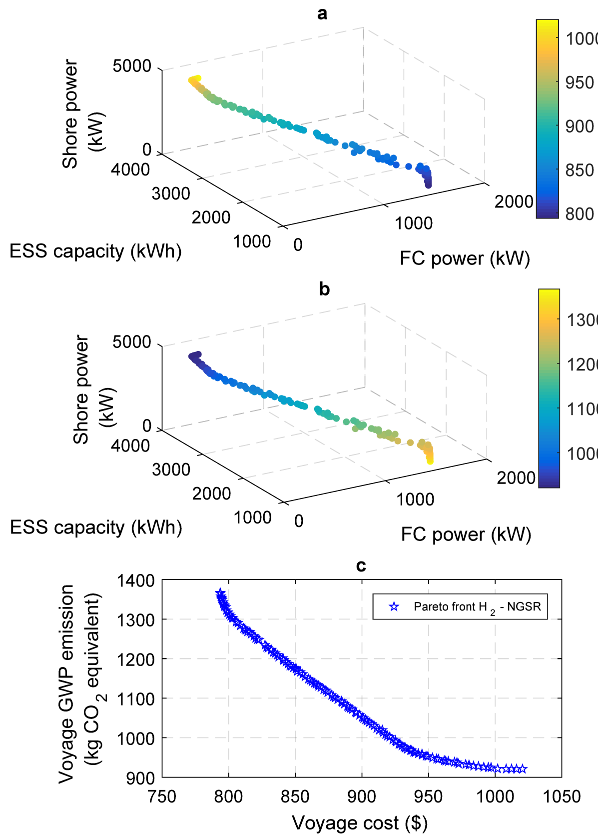

Figure 9. Power source sizing results of H_2 generated via NGSR: (a) average voyage cost, (b) voyage GWP and (c) Pareto front.

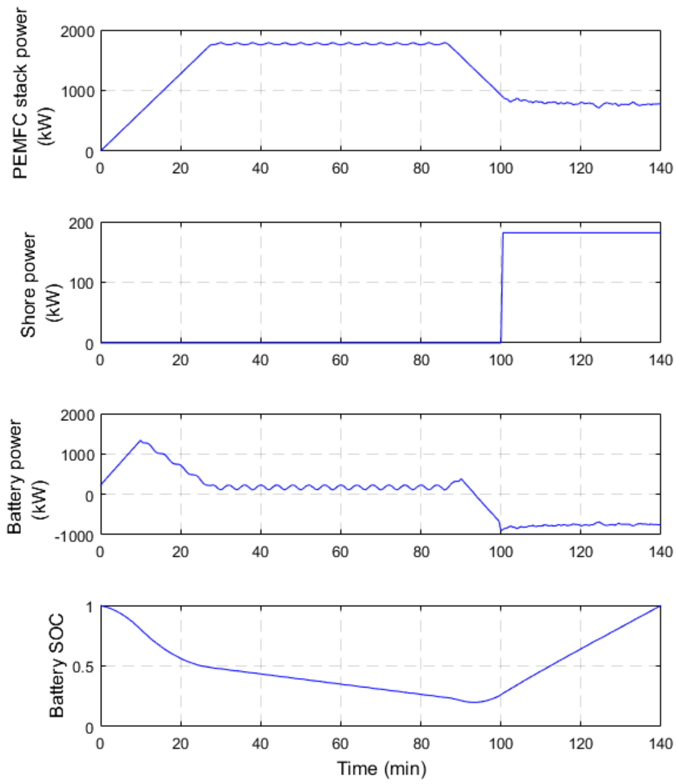

Figure 10. EMS of Nuclear Cu-Cl generated H_2 sample case: ESS capacity – 692 kWh, PEMFC stack power – 1823 kW and shore power – 182 kW.

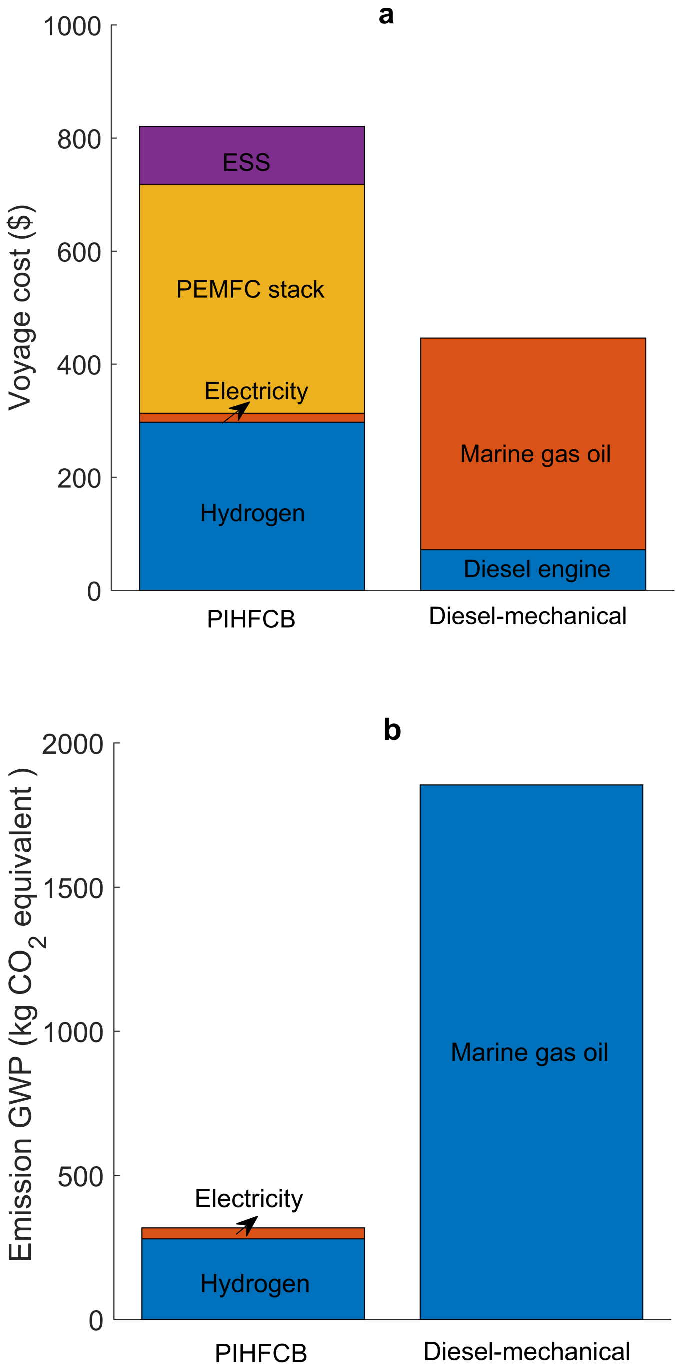

Figure 11. Voyage cost (a) and voyage GWP (b) breakdown comparison of Nuclear Cu-Cl generated H_2 sample case: ESS capacity – 692 kWh, PEMFC stack power – 1823 kW and shore power – 182 kW vs baseline diesel-mechanical system.

Figure 10 presents the most optimal EMS for H_2 generated by Nuclear Cu-Cl case: the ESS capacity is 692 kWh, PEMFC stack power is 1823 kW, and shore power is 182 kW. The battery starts to provide most of the power demands at the beginning while the PEMFC stack increases the power output gradually and takes over most of the load. The battery tackles most of the power transients during cursing. It is interesting that when the ship is at the port, the fuel cell stack still delivers power to the system, which is mainly due to the H_2 generated by Nuclear Cu-Cl is cheap.

Figure 11 compares the voyage cost and GWP emission breakdown between diesel-mechanical plant operating on marine gas oil and the alternative PIHFCB propulsion system (the scenario discussed in Figure 10). The average voyage cost of the hybrid system is approximately 70% higher than the diesel-mechanical system. Nevertheless, about 60% of the hybrid system voyage cost is from battery and PEMFC stack degradation. The fuel cell and battery technologies have been evolving rapidly in the past decade, which can potentially cut down the cost significantly (Sharaf & Orhan 2014, Nykvist & Nilsson 2015).

5 CONCLUSIONS

This paper presents a PIHFCB design methodology for coastal ships sail on short routes and have accessibility to H_2 bunkering and battery charging facilities. The two-layer optimisation methodology has been shown to generate optimal sizing solutions with an energy management strategy for each design point. Instead of providing a single design point, the solution space provides the decision makers with a better view of the trade-offs between overall emission reduction and commercial feasibility.

The case study results show that electricity and H_2 characteristics have a significant influence on the design of hybrid PEMFC and battery propulsion system. The volumetric and gravimetric impacts from H_2 fuel, PEMFC stack and battery can be mitigated for coastal ships sail on short routes with easy access to H_2 bunkering and battery charging facilities. Fuel cell and battery degradation can potentially contribute to more than 50% of the average voyage cost, while marine gas oil is the main portion for that of a diesel-mechanical plant. Fuel cell and battery lifetime and durability are expected to be improved to be commercially competitive with conventional diesel engine based propulsion plants. Nevertheless, the GWP emission reduction from the PIHFCB propulsion system can be more than 25%, even using H_2 produced from NGSR.

As the degradation of both PEMFC and battery could potentially impact the average voyage cost significantly, more detailed PEMFC and battery degradation models are expected to be included in future work.

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