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Fuel Cell Systems Applied in Expedition Cruise Ships – A Comparative Impact Analysis

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Abstract

Global endeavors to reduce emissions in the shipping industry are accelerating the interest in fuel cell system. This paper explores the application of different fuel cell types (LT-PEMFC, HT-PEMFC and SOFC) in combination with different fuels (LH_2, LNG, MeOH and NH_3) in expedition cruise ships. The goal of this paper is to evaluate the impact of the combination of fuel cell system implementation and operational profile on the design of expedition cruise vessels. Impact is expressed in ship size, capital cost, operational cost and emissions. The impact model takes into account: fuel storage, onboard fuel processing, fuel cell system characteristics, balance of plant components, fuel cost over operational lifetime and emissions of fuel cell & fuel processing. In the research, 7 different fuel cell systems and 3 different hybridization options are considered.

1. Introduction

Due to the severe possible consequences of climate change, IMO adopted several emission targets and regulations with the goal to reduce global warming, *IMO (2013,2018b)*. Fuel cells are considered as a promising solution to reduce hazardous emissions and to comply to these regulations, *Alkaner and Zhou (2006), Biert et al. (2016), Choi et al. (2016), Boudghene Stambouli and Traversa (2002), Evrin and Dincer (2019), Luckose et al. (2009), Tronstad and Langfeldt (2017)*. They have demonstrated lower heating value efficiencies of 60%, *Payne et al. (2019)*, (even 70% when used with combined generator cycles, *Patel et al. (2012)*) compared with internal combustion engine generators reaching up to 45%, *Biert et al. (2016)*. Cruise tourism is one of the most carbon emitting tourism segments, with an average of 160 kg CO_2 per passenger per day, *Baldi et al. (2018)*. Cruise lines are highly interested in the use of fuel cell systems on their ships. Besides complying to the IMO regulations, cruise lines have an additional interest in sustainable power generation:

i) Several cruise lines report the increasing demand of their customers to reduce their environmental footprint, *CLIA (2019), Alessandro (2019)*. This makes sustainability a competition aspect between cruise lines.
ii) Cruise lines state that continued access to ports is vital for future business operations, *Alessandro (2019)* and local legislators are restricting access for cruise ships with high emissions, for instance in Norwegian Fjords and Port of Amsterdam, *Claus (2019), Kerkhof (2019), WHC (2018).*

This research focuses on expedition cruise, which is a luxury segment of the cruise industry with a strong focus on (Ant)arctic areas. Fuel cells have several advantages for cruise ships compared to the conventional solution (internal combustion engine generators): reduction in emissions, high efficiency, good part load characteristics, high redundancy, low maintenance and no noise and vibrations, *Biert et al. (2016), Hristovski et al. (2009), Larminie and Dicks (2003), Minnehan and Pratt (2017), Siemens (2013)*. However, fuel cell implementation still struggles with: high capital expenses, size of fuel storage, lack of fuel infrastructure, short lifetime, slow transient behavior and low technological readiness, *Biert et al. (2016), Larminie and Dicks (2003), NN (2004), Tronstad and Langfeldt (2017), Volger (2019).*

1.1 Current literature

Current research of fuel cell implementation in (cruise) ships was reviewed. *Biert et al. (2016)* did a very extensive review of fuel cells for marine applications, covering fuel cell types, fuel processing, efficiency, power & energy density, dynamic behavior, environmental impact, safety & reliability and economics. It was concluded that LT-PEMFC fueled with liquefied hydrogen (LH_2) could be a solution for ships with mission requirements up to 12 hours. High temperature fuel cell systems in combination with hydrocarbon fuels can provide high efficiency and low emission solutions for ships with mission requirements of several days, *Biert et al. (2016)*. *Volger (2019)* researched alternative fuels for cruise vessels. He concluded that hydrogen as fuel for fuel cells has most impact on the design of a cruise ships. *Geertsma and Krijgsman (2019)* executed a case study for the application of fuel cells on board of navy support ships. They proposed a methodology to review alternative power system designs based on: mass & volume, capital & operational expenditure, technological readiness, fuel availability and emissions. They concluded that for fuel cells to be commercially used in ships, improvements in technological readiness, efficiency and cost of the fuel cell are necessary. *Minnehan and Pratt (2017)* studied the use of fuel cells on board of various ship types. They concluded that available volume of the vessel is the main technical constraint of the fuel cell system. The following was concluded from reviewing literature:

i) Performance differences for different fuel type and fuel cell type combinations are often not considered.
ii) Little research is performed in cost impact and often not considering fuel cost.
iii) The realized emission reduction is often not provided in the research.

1.2 Research objective

The problem is stated as follows: It is not known which fuel cell systems are most suitable for expedition cruise ships, how they should be applied and what their impact is on ship design, operability, cost and emissions. This information is necessary to successfully apply fuel cell systems. The research objective follows directly out of the problem statement: Evaluate the impact of the combination of different fuel cell systems and operational profiles on the design of expedition cruise vessels, in terms of ship size, ship building cost, fuel cost and emissions.

2. Preliminary selection of fuel cell systems

Based on literature, *Biert et al. (2016), Burel et al. (2013), Das and Gadde (2013), Ellis and Tanneberger (2016), Klerke et al. (2008), Larminie and Dicks (2003), Leites et al. (2012), Pan et al. (2005), Schneider and Dirk (2010), Tronstad and Langfeldt (2017), Semelsberger et al. (2006), Zamfirescu and Dincer (2008),* liquefied hydrogen (LH_2), liquefied natural gas (LNG), methanol (MeOH) and ammonia (NH_3) are selected as potential fuel types. LT-PEMFC, HT-PEMFC, MCFC and SOFC are selected as potential fuel cell types. Every combination of fuel type and fuel cell type represents a different fuel cell system, in terms of equipment and performance. A system decomposition is used to express the performance of these different fuel cell systems, Fig.1.

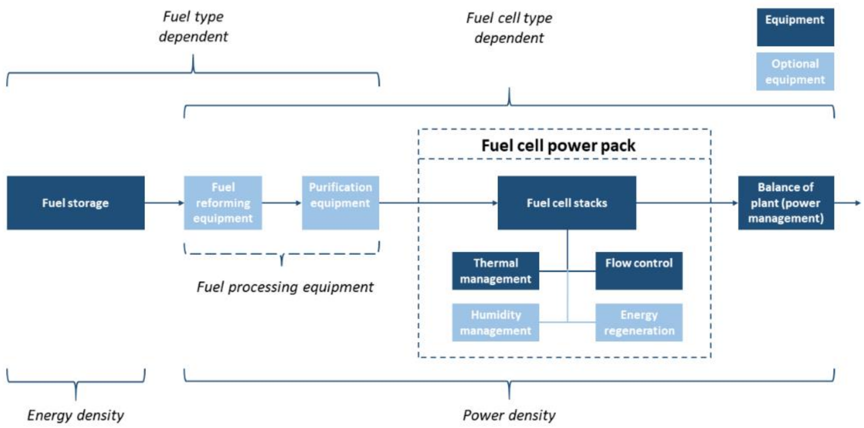


Fig.1: Generic overview of fuel cell system on board of a ship

The fuel cell systems are divided in fuel storage, fuel processing, fuel cell power pack and balance of plant. The performance is expressed by combining the performance of the different components. The performance is expressed in power density, energy density (gravimetric and volumetric) and specific cost of FC system, fuel storage system and generated electricity. Fuel cell lifetime and fuel cell efficiency are included in the performance. Table I quantifies the performance. The options that performed worse than other options on all stated criteria were discarded. E.g., MCFC performs badly on volumetric and gravimetric power density and does not perform better on any areas than all the other fuel cell types. The remaining seven different fuel cell systems are shown in Table II.

Table I: Performance of different fuel cell and fuel combinations on energy density, power density and costs. The performance is based on fuel storage equipment, fuel processing equipment, fuel purification equipment, the fuel cell power pack and electric balance of plant components. The presented data includes fuel cell system efficiency and lifetime of fuel cell stacks in order to compare different options fairly. Derived from *Biert et al. (2016), Chandan et al. (2013), Geertsma and Krijgsman (2019), Ellis and Tanneberger (2016), De-Troya et al. (2016), Fournier et al. (2006), Kee et al. (2005), Klerke et al. (2008), Larminie and Dicks (2003), Lan and Tao (2014), Law et al. (2013), Minnehan and Pratt (2017), Pan et al. (2005), Peters et al. (2016), Thounthong et al. (2009), NN (2004), Søndergaard et al. (2017), Kar Chung Tse et al. (2011), Volger (2019)* and supplier specifications.

Fuel cell system: *bunker fuel*	*fuel cell*	*Fuel cell plant* volumetric power density kW/m^3	*Fuel storage (inc. efficiency)* volumetric energy density kWh/m^3	*Fuel cell plant* gravimetric power density kW/ton	*Fuel storage (inc. efficiency)* gravimetric energy density kWh/ton	*for 15 years* FC plant €/kW	*inc. efficiency* Fuel storage €/kWh	*inc. efficiency* Fuel cost €/MWhe
LH2	LT-PEMFC	250	604	408	1250	€ 4,213	€ 10.00	€ 898
LH2	HT-PEMFC	99	543	74	1125	€ 6,256	€ 11.11	€ 998
LH2	MCFC	11	604	16	1250	€ 9,532	€ 10.00	€ 898
LH2	SOFC	32	604	119	1250	€ 13,043	€ 10.00	€ 898
LNG	LT-PEMFC	90	1254	272	2931	€ 5,393	€ 3.61	€ 51
LNG	HT-PEMFC	58	1098	74	2565	€ 7,681	€ 4.12	€ 58
LNG	MCFC	11	1411	16	3298	€ 10,735	€ 3.21	€ 45
LNG	SOFC	32	1882	119	4397	€ 14,658	€ 2.41	€ 34
MeOH	LT-PEMFC	41	1575	83	1755	€ 4,929	€ 0.09	€ 159
MeOH	HT-PEMFC	31	1400	74	1560	€ 7,000	€ 0.10	€ 179
MeOH	MCFC	8	1575	16	1755	€ 10,643	€ 0.09	€ 159
MeOH	SOFC	18	1925	119	2145	€ 14,534	€ 0.07	€ 130
NH3	LT-PEMFC	102	1130	155	1620	€ 4,466	€ 0.73	€ 365
NH3	HT-PEMFC	53	1004	74	1440	€ 6,628	€ 0.82	€ 410
NH3	MCFC	10	1256	16	1800	€ 10,087	€ 0.65	€ 328
NH3	SOFC	32	1507	119	2160	€ 13,167	€ 0.54	€ 274
MGO	DG	67	3985	79	3320	€ 425	€ 0.05	€ 121

Table II: Selected fuel cell systems out of performance

Fuel cell system							
LH_2	LT-PEMFC	LNG	LT-PEMFC	$MeOH$	LT-PEMFC	NH_3	LT-PEMFC
LH_2	HT-PEMFC	LNG	HT-PEMFC	$MeOH$	HT-PEMFC	NH_3	HT-PEMFC
LH_2	MCFC	LNG	MCFC	$MeOH$	MCFC	NH_3	MCFC
LH_2	SOFC	LNG	SOFC	$MeOH$	SOFC	NH_3	SOFC

3. Method

It was determined that an impact estimate of the seven selected fuel cell systems is most useful during the first design phase. Consequently, the design method is adjusted to the available information and required accuracy in this design stage. Fig.2 shows the workflow of the impact model, which will be explained in the following sections.

3.1 Input

In the first design phase, the cruise line delivers general requirements (passenger capacity and luxury level), a preliminary design (general arrangement) and the operational profile of the cruise ship. The main dimensions, number of passengers and operational profile are used as input, together with the desired fuel type, fuel cell type and hybridization strategy. Three hybridization strategies are defined:

- Full fuel cell powered ship - All energy is generated by fuel cells. Its main advantage is that no extra engine room is required for diesel generators. However, large fuel storage and an expensive power generation system are expected.
- Hybrid 1: Fuel cell power generation for auxiliaries - All power for auxiliary systems (including hotel) is provided by the fuel cell system. All power for propulsion is provided by the diesel generator set. The advantage of this option is that less balance of plant components are required to ensure the dynamic power capabilities of the power generation system. Fuel cells (especially HT FC) struggle with transient loads, *Biert et al. (2016), Larminie and Dicks (2003)*, and need to be combined with components with good transient behavior, *Choi et al. (2016), Minnehan and Pratt (2017), Welaya et al. (2011)*. From studying the on board power demand, it was concluded that the auxiliary load is much more constant (smaller changes in power demand per time step) than the propulsion load, resulting in lower balance of plant requirements. The disadvantage of this option is that the ship cannot operate solely on fuel cells.
- Hybrid 2: Diesel generators to support in transit - The transit operation, which requires the most stored energy and installed power, is supported with diesel generators. The transit operation is not part of a regular cruise, but executed a few times per year to get the ship to a different cruise location. Since fuel storage is critical for a fuel cell powered ship, this option provides a way to cope with long ranges and huge storage tanks, while still operating mostly on fuel cells. The extra advantage of hybrid option 2 is that the most harmful emissions are mainly emitted outside sensitive areas, which supports in complying to ECA regulations, *IMO (2020a,b)*.

In this paper, model results for different inputs (fuel type, fuel cell type, hybrid strategy) will be compared.

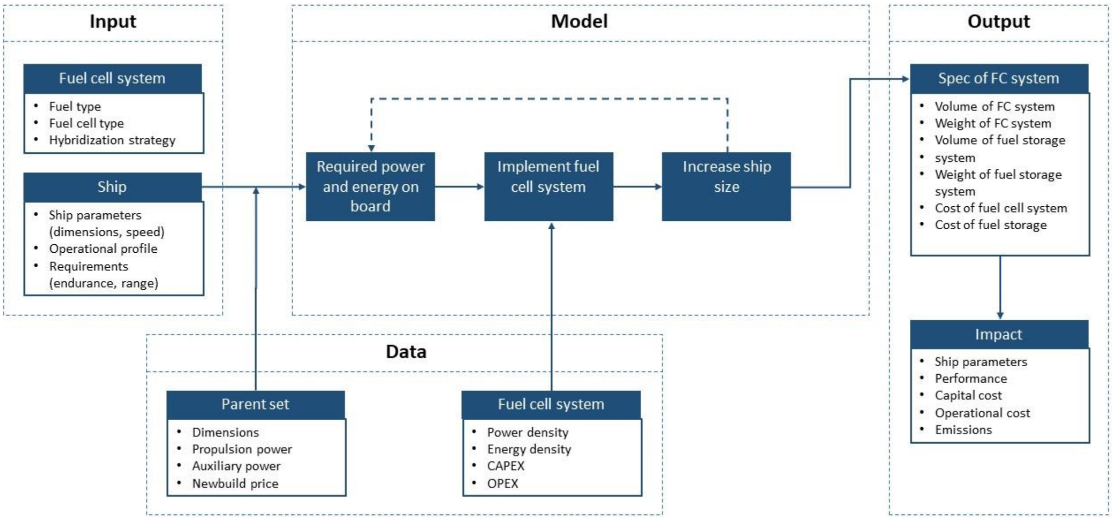


Fig.2: Schematic overview of workflow of impact model

3.2. Data

A parent set of ships is used to give a suitable suggestion for the main ship parameters. 36 expedition cruise reference ships are used which were defined as the luxury segment (>50GT/PAX) from a database of 291 cruise ships. The used reference ships range from 5000 to 70000 GT. The power density, energy density and specific cost for the different fuel cell systems, Table I, is used to determine the volume, weight and cost of the concerned fuel cell system.

3.3. Model

The ship requirements are combined with the parent set to estimate the required propulsion power and auxiliary power. Following, the volume, weight and cost of the fuel cell system can be calculated from the performance data. The propulsion power is combined with the operational profile and the propeller law to calculate required energy and energy usage. The first defining the weight, size and cost of the fuel storage system and the second defining fuel cost and emissions. This section shortly explains these different steps in the model. For a full understanding of the model refer to the report of *van Veldhuizen (2020)* where the model considerations and the used equations are explained.

3.3.1. Ship parameters

Regression relations retrieved from reference ships are used to suggest a suitable ship. The GT is estimated on the basis of the passenger capacity. The regression relation with GT is used to estimate the displacement. The other ship dimensions are also estimated with use of the GT. To make sure there is no mismatch with the block coefficient C_B and the desired speed, the CB is calculated and compared in the model with the CB of reference ships with a comparable speed.

3.3.2 Installed power estimation

The required power consists of the power required for propulsion and the power required for auxiliaries (including hotel). The required propulsion power is calculated with the admiralty formula and is thus based on the displacement and the ship speed. The admiralty constant is derived from the reference ships. Note that the admiralty constant is only constant for relatively small changes in displacement and ship speed, *Bertram (2012)*. The evaluated ship must not deviate much from the reference ship, so this developed method will not be suitable for evaluating an expedition cruise ship with unique design requirements, like a very high maximum speed.

The auxiliary power is defined in this research as all required power besides the propulsion. For expedition cruise ships, the auxiliary power is dominated by the hotel power. The auxiliary power is defined as function of the number of passengers (PAX). The amount of auxiliary power per passenger is also very dependent on the luxury level. For luxury ships the HVAC needs to cover more volume per passenger and luxury equipment also requires power. Table III shows how much auxiliary power is installed per passenger for different luxury levels on average. Dependent on the hybridization strategy, the required power is divided over the fuel cell plant and the diesel plant.

Table III: Average auxiliary power (including hotel power) per passenger for different luxury classes, based on reference ships (SD=standard deviation)

	Aux. power kW/PAX	SD kW/PAX	Aux. power % of installed
Budget	5.9	1.8	38%
Premium	8.3	2.9	39%
Luxury	16.2	5.7	41%

3.3.3. Energy estimation

Using the operational profile as input, it is possible to determine the required energy on board (defining the fuel storage size) and the energy usage (defining the fuel cost and emissions). The desired speed and propeller law are combined to estimate the required power for every sail mode in every defined operation. Harbour, manoeuvring, slow cruising and cruising are used as sail modes. The defined operations are Atlantic crossing, coastal cruise and (Ant)arctic cruise, which are distinctive itineraries. With the required power and the time for every sail mode, it is estimated how much energy is necessary for all operations.

- Required energy on board - The required energy on board defines the weight, volume and cost for the storage of the different fuels. A fuel margin is defined to make sure delays in the operational profile are possible or to be able to sail a little faster when behind schedule, both increasing the fuel consumption. Consulting Damen engineers, a 10% fuel margin is used for the DG generators. For the FC system a 20% margin is needed, to make sure the range requirements can still be met at the end of the lifetime of the fuel cell stacks; the efficiency of the stacks decreases over their lifetime.

- Energy usage - The energy usage in every operation is used to determine the fuel cost and emissions. The energy required for an operation is combined with the relative frequency of occurrence of the operations to determine how much energy is used yearly for every operation. The usage rate of the different operations is defined as the percentage time the cruise line executes a certain operation yearly, for instance 10% transit, 50% coastal operation and 40% arctic operation. This especially matters for the yearly fuel consumption of hybrid option 2 where MGO is consumed in transit and alternative fuel is consumed in other operations. The yearly energy usage equals the sum for the different operations.

3.3.4. Fuel cell system implementation

At this point in the model the required power, required energy and energy consumption of the (hybrid) fuel cell system are known. This is combined with the fuel cell system performance, Table I, to calculate the volume, weight, capital cost and fuel cost of the fuel cell system. The required ship volume for the fuel cell system (and of the diesel generator system for a hybrid system) consists of the volume of the power plant (including space for maintenance and other systems) and the ship volume to store the concerning fuel. The power density and energy density data in Table I already include the efficiency of the fuel cell system. The weight of the fuel cell system is determined analogously.

The cost of the fuel cell system (and of the diesel generator system for a hybrid system) is also dependent on the power pack and the fuel storage. The cost of the power pack is equal to the required power times the cost per kW. The cost of the fuel storage is equal to the required energy on board times the cost per kWh for fuel storage.

The fuel cost of the (hybrid) fuel cell system depends on the yearly energy consumption, the operational lifetime and the cost of generated electrical energy, the latter depending on the fuel cost and the efficiency of the system. The efficiency of the fuel cell system decreases linearly with 10% over the lifetime of the fuel cell stacks. This implies a 10% increase of the required energy in the fuel storage and a 5% increase in fuel consumption over the lifetime.

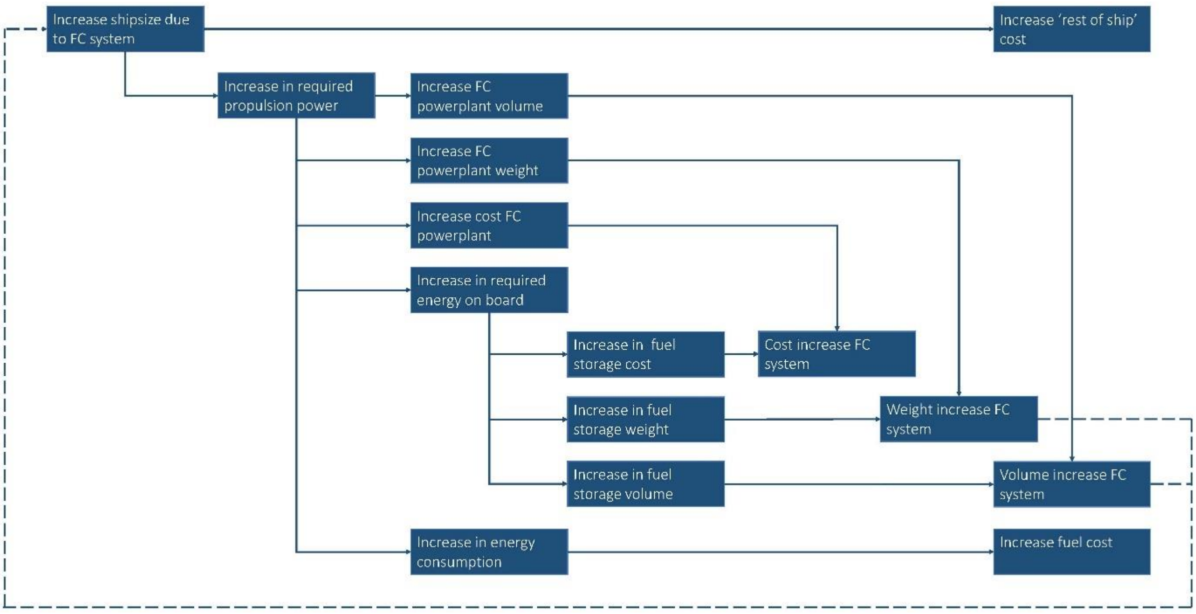


Fig.3: Consequences of increasing ship size to fit fuel cell system. Scheme shows 1 iteration in design

3.3.5. Fit the fuel cell system in the ship

To fit the fuel cell system the ship size is increased, consequently increasing many other ship parameters like installed power and energy consumption. Fig.3 shows on which parameters the increase in ship size has an impact. This impact is iterative: when the ship size increases, the required power increases, increasing the size of the power plant and fuel storage, further increasing the ship size.

- Increase in ship size - While increasing the ship size it is checked whether the increase in ship size is driven by the volume of the fuel cell system or the weight of the fuel cell system. Whether the increase in ship size is volume driven or weight driven was observed to be different per fuel cell system, per hybrid option and dependent on the operational requirements. Following, the actual increase in GT is determined out of the increase in displacement, using regression data. The increase in ship size is defined in GT because an extra cost per GT is defined to take into account extra cost for a larger ship, besides the increase in cost of the fuel cell system, such as cost of: steel weight, systems and cables.
- Increase of power plant - The increase in ship size results in a higher required propulsion power, due to an increase in ship resistance. The increase in propulsion power is again calculated with the admiralty constant of the reference ships via the increase in displacement.
- Increase in required energy - When the required propulsion power increases, the required energy on board increases (when range and speed remain constant). An increase in the required energy consequently increases the volume, weight and cost of the fuel storage system.
- Increase in energy consumption - When the required propulsion power increases, the energy consumption also increases (when operational profile remains constant). This has a direct impact on the fuel cost.
- Iteration process - At the end of one iteration the ship design does not converge: extra volume is calculated for the fuel cell system, but it is not yet fitted into the ship. When iterating infinitely the extra required space approaches zero and thus the increase in ship size approaches zero. This is the case because ΔGT becomes smaller every iteration. Several iterations were performed, and it was found that after one iteration ΔGT is smaller than 0.5% of the total GT for all combinations of fuel cell system and hybridization options. Consequently, one iteration is sufficient to exclude significant mutations from the end result.

Table IV: Specific emissions per generated MWhe for selected FC systems and conventional solution, including system efficiency, *Altmann et al. (2004), Biert et al. (2016), Bloom Energy (2019)*, http://convion.fi/products/, *Höhlein et al. (1996), Isaacs et al. (2013), Siemens (2013), Soltani et al. (2014)*. The emissions for MGO fueled diesel generator is derived with Damen mechanical engineers. As can be seen in the table, the NO_x, SO_x and PM emissions are not significant compared to those of a conventional system.

		CO kg/MWhe	CO_2 kg/MWhe	NO_x kg/MWhe	SO_x kg/MWhe	PM kg/MWhe
LH2	LT-PEMFC	-	-	-	-	-
LNG	LT-PEMFC	0.0225	514	-	-	-
LNG	SOFC	0.0150	343	0.0008	-	0.0001
MeOH	LT-PEMFC	0.0111	349	0.0005	-	-
MeOH	HT-PEMFC	0.0125	466	0.0006	-	-
MeOH	SOFC	0.0091	524	0.0008	-	0.0001
NH3	SOFC	-	-	0.0031	-	-
MGO	DG	1.56	661	11.99	2	1.60

3.3.6. Emissions

The main purpose of fuel cell implementation in shipping is to reduce emissions. So, it is relevant to indicate the fuel cell system emissions compared with a conventional solution. This shows the effectiveness of implementing such a system. Although fuel cell emissions are drastically lower than emissions of a conventional solution, *Biert et al. (2016), Larminie and Dicks (2003)*, it should be noted that for some fuel and fuel cell combinations significant emissions remain, *Bloom Energy (2019), Geertsma and Krijgsman (2019)*, http://convion.fi/products/, *Lee et al. (2015), Strazza et al. (2010)*. The emissions over the operational lifetime are calculated with use of Table IV, which shows the specific emissions for CO, CO_2, NO_x, SO_x and particulate matter (PM). This data includes the efficiency of the different fuel cell systems. Fuel cells have very low sulfide tolerance (ppm range), meaning sulfides (in H_2S form) are already extracted from the fuel before reforming, *Larminie and Dicks (2003)*. Zinc oxide is used to subtract the H_2S from the fuel. The absorbent is regenerated and H_2S is stored separately, *NN (2004)*. Consequently, for all considered fuel cell systems the SO_x emissions are zero.

3.4. Model verification

A vast number of calculation steps is implemented in the model, making the chance on typing and programming errors significant. The following verification methods of *Sargent (2010)* are used:

i) Structured walk through.
ii) Balance checks of sums, averages and or combinations of parameters, Table V.
iii) Testing of extreme model conditions.

Table V: Verification of model: balance checks to verify output and intermediate values of the model

Balance check	Description	Max error	Verified
Ship design			
Displacement	Does displacement output match with $L_{wl} \cdot B \cdot T \cdot C_B$	0.0%	✓
GT-GV	Does GT output match with GV output	-0.1%	✓
Cb-speed	Does the block coefficient align with the desired speed	-	✓
Installed power	Is there enough power installed to reach maximum speed	0.0%	✓
Range check	Does total stored fuel satisfy range and endurance requirement	-0.3%	✓
Fuel cell system			
Density of fuel	Does weight and volume of stored fuel match with density	-0.3%	✓
Volumetric power density	Does installed FC power and FC volume match with used $\rho_{FC,vol}$	0.0%	✓
Gravimetric power density	Does installed FC power and FC weight match with used $\rho_{FC,grav}$	0.0%	✓
Cost			
Specific cost FC plant	Does cost of FC system and installed FC power match with c_{FC}	0.0%	✓
Cost of FC system	Does cost of FC system match with sum of cost components	0.0%	✓
Shipbuilding cost	Does shipbuilding cost match with sum of cost components	0.0%	✓

3.5. Model validation

After model verification confirmed that the presented model is correctly programmed, the reader should also get the confidence that the programmed model has sufficient accuracy for the model's intended purpose over the application range of the model, *Sargent (2010)*. Full scale validation by comparing the model results with similar models or real-life examples is not possible. Similar models are not found and there are no expedition cruise ships on which fuel cell systems are implemented on a large scale. The validation methods that were executed for this model are, *Sargent (2010)*:

- Data validation - The calculated performance data was presented to fuel cell experts and checked versus their knowledge of these systems.
- Benchmarks - Intermediate results of the model were benchmarked using research results and knowledge of suppliers and fuel cell experts. Examples of executed benchmark validations are:
  i) Size of LNG reforming plant is approximately 3 times the size of the power pack for LNG fueled LT-PEMFC.
  ii) Size of a 2 MW LTPEMFC plant.
- Logical interpretation of results - The results were interpreted and reasoned whether these

model outputs would match expectations from reality. Result interpretation is done in the next section where the results will also be presented.

- Sensitivity analysis - The input and/or internal parameters of the model were systematically changed to determine the impact on the model output. Input is varied in section 5 in terms of range, endurance and GT.

4. Results

This section compares the results of the impact model for different fuel cell systems and hybridization strategies. They are generated for an average ship (compared to the reference ships). The main particulars of this average ship are shown in Table VI. The main requirements and operational profile for the evaluated fuel cell powered ship are shown in Table VII and Fig.4. In all results, the model output is presented. This means for instance, when the volume of the fuel cell system is presented, it already includes the extra volume of the system that is necessary because the required power and required energy increased during the design iteration.

Table VI: Main particulars of average ship (average with respect to reference ships) for which the results are generated. The model uses PAX and luxury level as starting point, of which the other parameters are derived.

Dimension		Unit	Quantity		Unit
Length OA	191	m	Gross Tonnage	31321	GT
Length PP	168	m	Displacement	18858	ton
Beam	26	m	PAX	500	-
Draught	6.3	m	Crew	323	-
Depth	9.8	m	Lifetime	15	years

Table VII: Requirements of evaluated fuel cell powered ship. Derived from operational profiles and requirements of several expedition cruise ships.

Requirement		Unit	Requirement		Unit
Design speed	12	kn	Range	3600	nm
Max speed	14	kn	Endurance	17	days

Operational profile	Distance	Days	Time	Speed
	nm	-	%	kn
Transit			10%	
Harbour	-	4	23%	-
Manouvring	5	0.5	3%	0.4
Slow cruising	100	1	6%	4.2
Cruising	3500	12	69%	12.2
Total	3,605	18	100%	
Coastal operation			30%	
Harbour	-	2.5	18%	-
Manouvring	5	0.5	4%	0.4
Slow cruising	400	3	21%	5.6
Cruising	2000	8	57%	10.4
Total	2,405	14	100%	
Antarctic operation			60%	
Harbour	-	2	15%	-
Manouvring	5	0.6	4%	0.3
Slow cruising	100	0	0%	-
Cruising	2400	11	81%	9.1
Total	2,505	14	100%	

Fig.4: Used operational profiles for generated results

4.1. Fuel cell system

In this section, the characteristics of the fuel cell implementation are compared with the diesel generator system that would be necessary for a ship with the same requirements. Fuel cell implementation has an influence on the volume, weight and cost with respect to the conventional system.

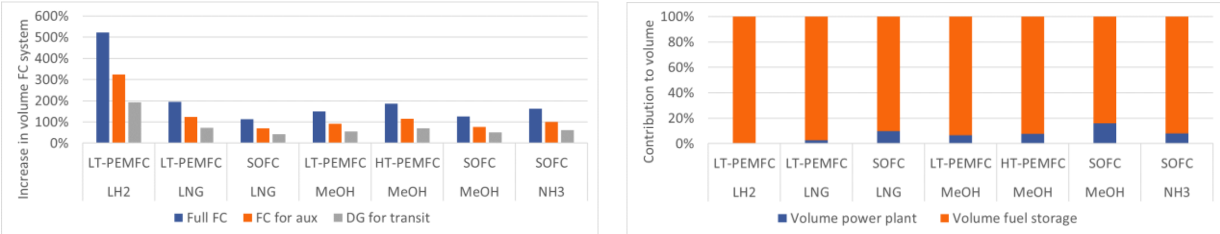


Fig.5: Increase in volume; left: Increase in volume of (hybrid) fuel cell system with respect to the volume of the DG system that would be necessary for a conventional ship. This graph includes power plant and fuel storage; right: Contribution of fuel storage system and power plant to volume increase of (left) for the full FC option (for the hybrid options the graph is similar).

Fig.5 (left) shows the increase in volume of the (hybrid) fuel cell system compared to the conventional system. The volumetric power density and volumetric energy density data of Table I were used to acquire these results. The volume increase is by far the largest for the LH_2 fueled LT-PEMFC system. LNG fueled SOFC offers the lowest increase in volume for all hybrid strategies of which hybrid option 2 (DG for transit) results in the smallest volume increase of all 21 options. The full fuel cell powered ship requires most volume for the fuel cell system; the diesel for transit option requires the lowest volume for all different fuel cell systems. Fig.5 (right) shows the contribution of the fuel storage and the fuel cell power plant to the volume of the FC system. The volume of all considered fuel cell systems is mainly driven by fuel storage.

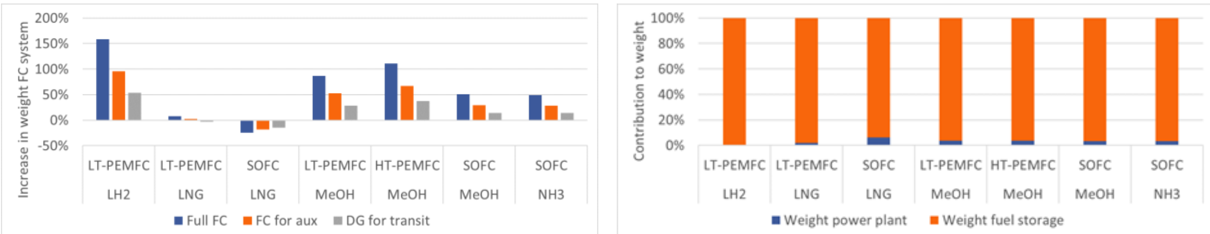


Fig.6: Increase in weight; (left) Increase in weight of (hybrid) fuel cell system with respect to the weight of the DG system for a conventional ship. This graph includes power plant and fuel storage; (right) Contribution of fuel storage system and power plant to weight increase of (right) for the full FC option (for the hybrid options the graph is similar).

Fig.6 (left) shows the increase in weight of the (hybrid) fuel cell system compared to the conventional system. The gravimetric power density and gravimetric energy density data of table 1 were used to acquire these results. The weight increase is the largest for the LH_2 fueled LT-PEMFC system. This can be explained by the high weight of the hydrogen storage tanks. For all considered fuel cell systems, the weight increase is mainly driven by the weight of the fuel storage, Fig.6 (right). For fuel cell systems fueled by LNG, there are options where the required fuel cell system is lighter than the conventional system, due to the low gravimetric energy density of LNG storage. This implies that for these options, the increase in ship size to fit the fuel cell system is purely volume driven.

Fig.7 (left) shows the increase in cost (from the perspective of the ship builder) of the whole fuel cell system compared to the conventional system. The capital cost data of Table I were used to acquire these results. Very large cost increases are found, especially for SOFC systems. Where volume and weight were mostly driven by the fuel storage system, the power generation system dominates in driving the cost (with exception of LH_2 fueled LTPEMFC), Fig.7 (right).

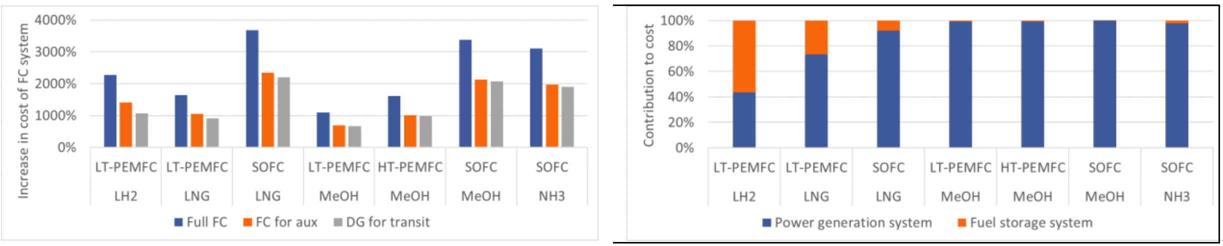


Fig.7: Increase in cost; (left) Increase in cost of (hybrid) fuel cell system with respect to the cost of the DG system for a conventional ship. This graph includes power plant and fuel storage; (right) Contribution of fuel storage system and power plant to increase in cost of (left) for the full FC option (for the hybrid options the graph is similar).

4.2. Increase in ship size

Since the (hybrid) fuel cell system is bigger than the conventional system, the ship size was increased to fit the fuel cell system. Fig.8 shows the increase in GT for the different fuel cell systems and hybrid options. The figure shows that the increase in ship size is very different per fuel cell system and hybrid option. Hybrid option 2 (DG for transit) consistently leads to the lowest increase in ship size. Overall, LNG fueled SOFC in combination with hybrid option 2 leads to the lowest increase in ship size. This was expected due to the high power-density of LNG and high efficiency of SOFC.

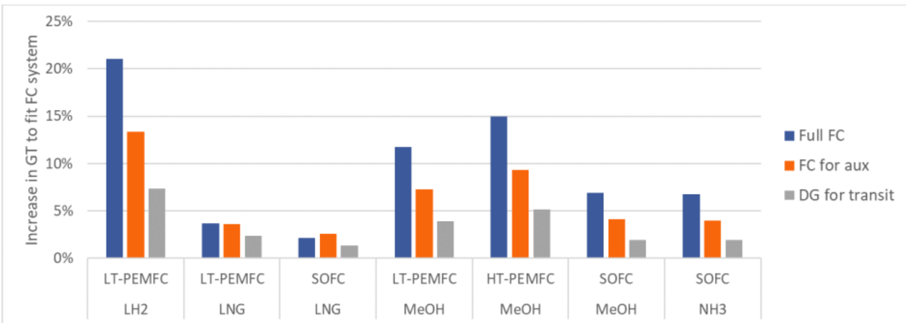
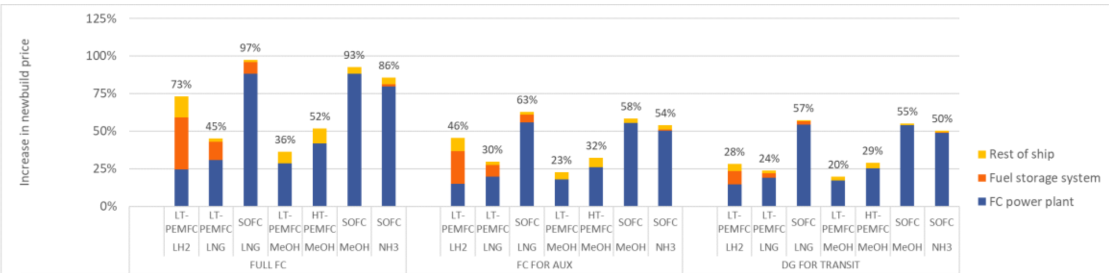


Fig.8: Increase in GT during the design iteration with respect to GT of conventional ship (in order to fit FC system in the ship).

4.3. Increase in cost

Fig.9 shows the increase in newbuild price for the different fuel cell systems and hybrid options compared to the same ship with conventional power generation. As was also reported for Fig. 7, the cost is still dominated by the cost of the power plant (expect for LH_2 fueled LT-PEMFC). The 'rest of ship cost' scales linearly with Fig.8, since a constant cost increase per GT was defined for the design iteration. Fuel cell systems that use SOFC cause the highest increase in newbuild price, due to the high cost of SOFC per kW.

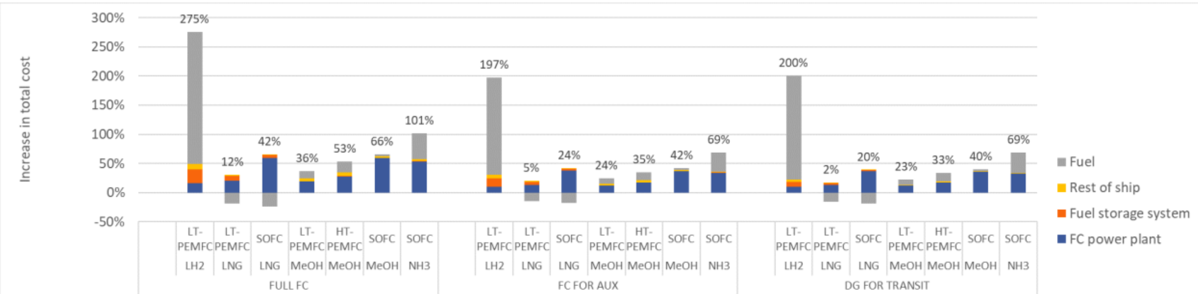


	FULL FC							FC FOR AUX							DG FOR TRANSIT						
	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3
Total increase	73%	45%	97%	36%	52%	93%	86%	46%	30%	63%	23%	32%	58%	54%	28%	24%	57%	20%	29%	55%	50%
Rest of ship	14%	2%	1%	8%	10%	5%	4%	9%	2%	2%	5%	6%	3%	3%	5%	2%	1%	3%	3%	1%	1%
Fuel storage system	35%	12%	8%	0%	0%	0%	2%	22%	8%	5%	0%	0%	0%	1%	9%	3%	2%	0%	0%	0%	0%
FC power plant	24%	31%	88%	28%	42%	88%	80%	15%	20%	56%	18%	26%	56%	50%	15%	19%	54%	17%	25%	54%	49%

Fig.9: Increase in newbuild price with respect to the newbuild price of a conventional ship with equal requirements. The data labels indicate the total increase in newbuild price.

For every hybridization strategy, the MeOH fueled LT-PEMFC results in the lowest increase in newbuild price. LNG fueled LT-PEMFC also offers a low increase in newbuild price for hybrid option 1 (FC for auxiliaries) and hybrid option 2 (DG for transit), followed by LH_2 fueled LT-PEMFC combined with hybrid option 2.

The increase in newbuild price is combined with the increase in fuel cost in order to give a well-founded recommendation on the financial impact of different fuel cell systems and hybrid options. Fig.10 shows the total increase in cost compared to the newbuild price plus the fuel cost of a conventional ship with equal requirements. The total cost is from the perspective of the cruise line. Time value of money and finance cost are not taken into account. As becomes clear from this figure, the fuel cost has a big impact on the economic viability of the option, especially for the LH_2 and NH_3 fueled fuel cell systems. It can be concluded that a ship equipped with LNG fueled LT-PEMFC is the best option for all hybridization strategies from a total cost perspective (perspective of the cruise line). This can be explained by the decrease in fuel cost by LNG. The next best performing options from this perspective are MeOH fueled LT-PEMFC and LNG fueled SOFC for hybrid option 1 and 2. Between the different hybridization strategies, the increase in total cost is slightly lower for hybrid option 2 for most considered fuel cell systems.



	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3
	FULL FC							FC FOR AUX							DG FOR TRANSIT						
Total increase	275%	12%	42%	36%	53%	66%	101%	197%	5%	24%	24%	35%	42%	69%	200%	2%	20%	23%	33%	40%	69%
Fuel	226%	-19%	-24%	12%	18%	4%	44%	167%	-14%	-18%	9%	13%	3%	33%	178%	-15%	-19%	9%	14%	3%	35%
Rest of ship	9%	2%	1%	5%	7%	3%	3%	6%	2%	1%	3%	4%	2%	2%	3%	1%	1%	2%	2%	1%	1%
Fuel storage system	23%	8%	5%	0%	0%	0%	1%	15%	5%	3%	0%	0%	0%	1%	9%	3%	2%	0%	0%	0%	0%
FC power plant	16%	21%	59%	19%	28%	59%	53%	10%	13%	37%	12%	17%	37%	34%	10%	13%	36%	12%	17%	36%	33%

Fig.10: Increase in total cost over ship lifetime (15 years) with respect to the newbuild price and fuel cost over ship lifetime for a conventional ship with equal requirements. Note that the data label (total increase in cost) does not correspond with the height of the bar, since the bars do not stack for negative values.

4.4. Emissions

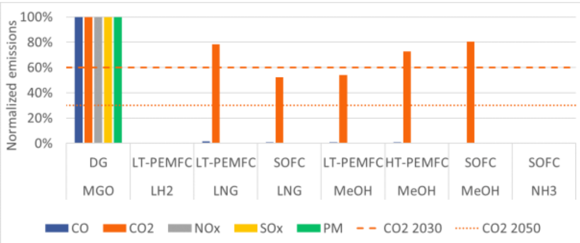
While interpreting results, keep in mind that the main driver for implementing fuel cell systems is the reduction of emissions. Fig.11 shows the normalized reduction in emissions compared with the CO_2 targets. The LNG fueled LT-PEMFC, MeOH fueled HT-PEMFC and MeOH fueled SOFC exceed the 2030 CO_2 target for all hybridization strategies. Only the LH_2 fueled LT-PEMFC and NH_3 fueled SOFC do not exceed the 2050 goals (for all hybridization strategies). Fig.12 shows the normalized reduction in emissions compared with NO_x, SO_x, and PM regulations. For the full fuel cell powered solutions, all upcoming regulations (inside and outside ECA zones) are easily met, since NO_x, SO_x, and PM emissions are not significant. For both hybrid options, only the SO_x and PM *S*emissions within ECA zones are not met. For hybrid option 2 this is easily solvable, since the ship can run solely on fuel cells in these zones (although with lower range and maximum speed). Hybrid option 1 cannot comply with the ECA regulations (without consideration of emission abatement).

4.5. Best performing options

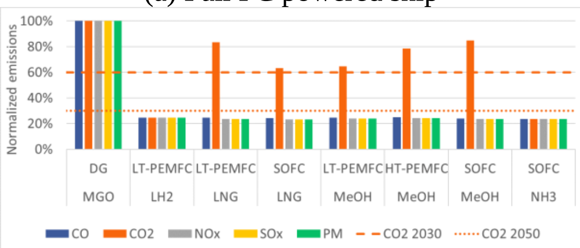
The results of the past sections are combined to make a recommendation for the best performing combinations of fuel cell system and hybridization option. The used criteria were the newbuild price, total cost and compliance to the 2030 CO_2 target and ECA regulations.

Table VIII: Recommendation for fuel cell powered ships

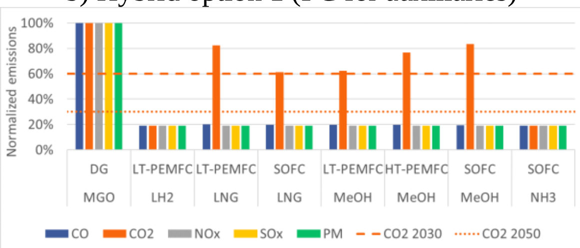
Rank	Fuel type	FC type	Hybridization	Ship price	Total cost	Compliance CO2 2030	Compliance CO2 2050	Compliance ECA
1	LNG	LT-PEMFC	Hybrid 2	++	++			✓
2	LNG	LT-PEMFC	Full FC	-	+			✓
3	MeOH	LT-PEMFC	Hybrid 2	++	+-	✓		✓
4	LNG	SOFC	Hybrid 2	- -	-	✓		✓
5	MeOH	LT-PEMFC	Full FC	+-	-	✓		✓
6	MeOH	HT-PEMFC	Hybrid 2	+-	- -			✓



(a) Full FC powered ship

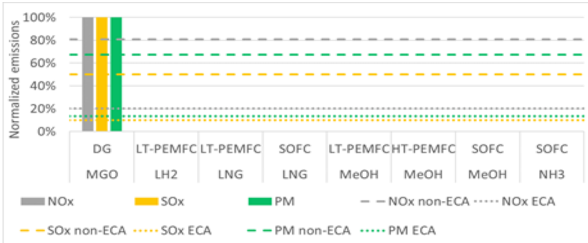


b) Hybrid option 1 (FC for auxiliaries)

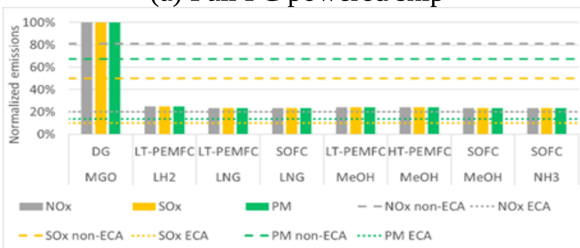


(c) Hybrid option 2 (DG for transit)

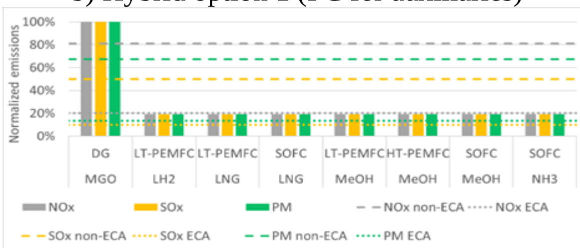
Fig.11: Normalized on-board emissions for CO, CO_2, NO_x, SO_x, and PM over lifetime of the average ship with a conventional system and with the selected fuel cell systems. The CO_2 ambition levels for 2030 and 2050 by IMO are also shown in the figures, *IMO (2018a)*.



(a) Full FC powered ship



b) Hybrid option 1 (FC for auxiliaries)



c) Hybrid option 2 (DG for transit)

Fig.12: Normalized on-board emissions for NO_x, SO_x and PM over lifetime of ship for conventional system and selected fuel cell systems. Compared with NO_x, SO_x and PM regulations inside and outside ECA zones, *IMO (2020a,b)*.

All options using hybrid option 1 are discarded since hybrid option 2 always performed slightly better than hybrid option 1. On top of that, hybrid option 2 has the additional advantage that it can operate solely on fuel cells. The six best performing options are selected and stated in Table VII. These will be used for a sensitivity analysis in the next section. Although a ranking is provided, the most recommended option is very case dependent. MeOH fueled LT-PEMFC combined with hybrid option 2 results in the lowest increase in newbuild price. LNG fueled LT-PEMFC in combination with hybrid option 2 results in the lowest increase in total cost (newbuild price and fuel cost.

5. Sensitivity analysis

For the 6 best performing options of Table VIII, a sensitivity analysis method of *Sargent (2010)* was used. The input values are systematically varied to determine the model's behavior.

5.1. Variation of operational requirements

The endurance of the transit operation is varied. It is important to determine the model's behavior for different endurances to see whether the selection of best performing options would be different for other operational requirements. Especially, since some fuel cell systems are more costly per kW installed power and others are more costly per kWh generated energy, which was clearly visible in Table I. The design speed is kept constant, meaning the variation influences the size of the fuel storage but not the size of the power plant, since the latter is related to the required power. The speed during the transit operation is also kept constant. Consequently, the transit range scales proportionally with the endurance.

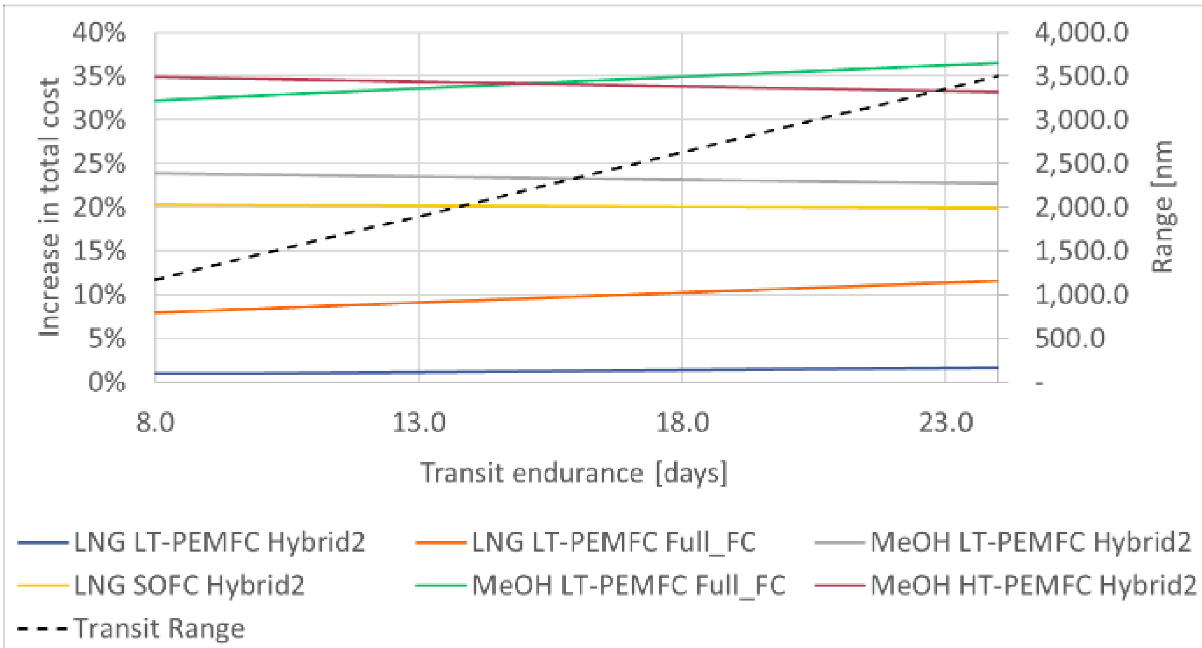


Fig.13: Increase in total cost (compared with a conventional ship with equal requirements) for different endurance requirements of the transit operation.

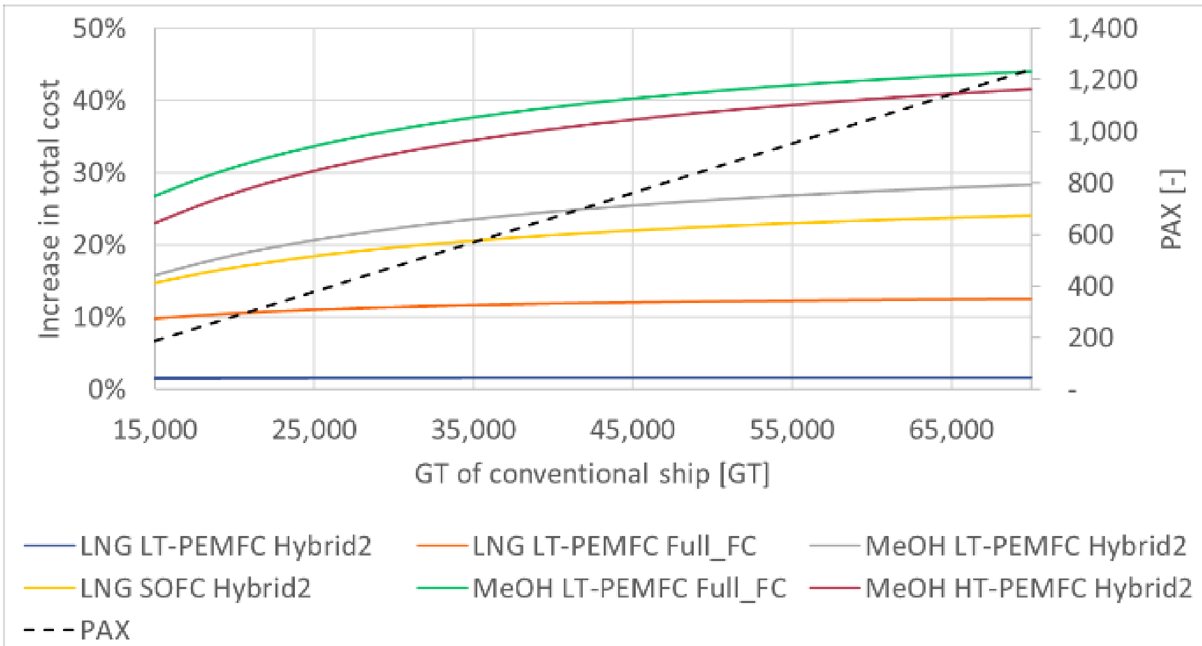


Fig.14: Increase in total cost (compared with a conventional ship with equal requirements) for different capacity requirements

In Fig.13, the total increase in cost is varied over the transit endurance requirement. The total increase in cost consists of the newbuild price of the ship and the fuel cost. Time value of money and finance cost are not taken into account. The green line and purple line cross, meaning between these options, the best performer on total increase in cost is dependent on the transit endurance. For the other options there is no interdependence for different endurance requirements. For all considered endurances, the same conclusion is found regarding the best performing option as was presented in section 4: hybrid option 2 with LNG fueled LT-PEMFC results in the lowest increase in total cost.

5.2. Variation of capacity requirements

In this section the size of the conventional ship (in GT) is varied in order to see whether some fuel cell systems and hybrid options perform differently for different ship sizes. The size of the ship (GT) is driven by the capacity of the ship (PAX) and they were linearly linked in the model since the luxury level is kept constant.

In Fig.14, the resulting total increase in cost is shown for varying GT. In general, the increase in total cost is higher for larger ships. For all considered GT the same order of performance was found as presented in Fig.10. None of the lines cross, meaning the best fuel cell and hybrid strategy for a certain ship in terms of total cost is not dependent on the ship size. For all considered GT, the same conclusion is found regarding the best performing option as was presented in section 4: hybrid option 2 with LNG fueled LT-PEMFC results in the lowest increase in total cost.

6. Conclusion & recommendations

Based on the results of this study it is concluded that:

- i) Depending on the fuel cell system and hybridization strategy, the increase in ship size (in GT) ranges from 2% to 21% for an average ship (with respect to the reference ships).
- ii) Depending on the fuel cell system, the increase in newbuild price compared to a conventional ship is 36% to 97% for a full fuel cell powered expedition cruise ship and 20% to 63% for the considered hybrid options. Depending on the fuel cell system, the increase in total cost compared to a conventional ship is 12% to 275% for a full fuel cell powered expedition cruise ship and 2% to 200% for the considered hybrid options.
- iii) iii) Hybrid option 1 (fuel cell for auxiliaries) is inferior to hybrid option 2 (DG to support in transit) in terms of cost, emissions and complying with ECA regulations.
- iv) iv) Hybrid option 2 with $MeOH$ fueled LT-PEMFC offers the lowest percentage increase in newbuild price for expedition cruise ships, which is under 25% for an average ship.
- v) Hybrid option 2 with LNG fueled LT-PEMFC offers the lowest percentage increase in total cost over ship the ship lifetime (including fuel cost) for expedition cruise ships, which is under 5% for an average ship. For the six best performing combinations, Table VIII, of fuel cell system and hybridization option, the range, endurance and capacity requirements are systematically varied to determine whether the choice of the best option depends on these requirements.

It was confirmed that conclusion v) still holds for a large range of endurances and ship sizes. Consequently, it was concluded that the choice of the fuel cell system from a total cost perspective should not depend on the range requirements and the size of the ship.

From a newbuild price perspective, hybrid option 2 with MeOH fueled LT-PEMFC is recommended. This does comply with NO_x, SO_x and PM regulations (including ECA zones) and CO_2 goals for 2030. From a total cost (new build price and fuel cost) perspective, hybrid option 2 with LNG fueled LT-PEMFC is recommended. This does comply with NO_x, SO_x and PM regulations (including ECA zones), but does not meet CO_2 goals for 2030. When it is desired to reach this CO_2 target, hybrid option 2 with MeOH fueled LT-PEMFC is also recommended from a total cost perspective.

Finally, it must be noted that no optimal fuel cell system or hybridization strategy can be pointed out. The fuel cell system and hybridization strategy selection are very dependent on the requirements of the customer (cruise line). The cruise line might prefer a ship with a lower newbuild price because it is easier to finance or the customer might even require a full fuel cell powered ship, because the cruise line needs full ship performance in ECA zones. For this reason, the proposed method is very useful, because it can be used to evaluate and compare the different options for different designs requirements.

References

ALESSANDRO, M. (2019), *Imagine - The Future of Cruise Ship Design*, Technical Report, RINA

ALKANER, S.; ZHOU, P. (2006), *A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application*, J. Power Sources 158, pp.188-199

ALTMANN, M.; WEINDORF, W.; WURSTER, R.; WEINBERGER, M.; FILIP, G. (2004), *FCSHIP: Environmental Impacts and Costs of Hydrogen, Natural Gas and Conventional Fuels for Fuel Cell Ships*, 15th World Hydrogen Energy Conference, Yokohama

BALDI, F.; AHLGREN, F.; NGUYEN, T.V.; THERN, M.; ANDERSSON, K. (2018), *Energy and Exergy Analysis of a Cruise Ship*, Energies 11/10, 2508

BERTRAM, V. (2012), *Practical Ship Hydrodynamics*, Elsevier

BIERT, L.V.; GODJEVAC, M.; VISSER, K.; ARAVIND, P.V. (2016), *A review of fuel cell systems for maritime applications*, J. Power Sources 327, pp.345-364

BLOOM ENERGY (2019), *Energy Server 5 Product Datasheet*, www.bloomenergy.com

BOUDGHENE STAMBOULI, A.; TRAVERSA, E. (2002), *Fuel Cells, An Alternative to Standard Sources of Energy*, Renewable and Sustainable Energy Reviews 6(3), pp.295-304

BUREL, F.; TACCANI, R.; ZULIANI, N. (2013), *Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion*, Energy 57, pp.412-420

CHANDAN, A.; HATTENBERGER, M.; EL-KHAROUF, A.; DU, S.; DHIR, A.; SELF, V.; POLLET, B.G.; INGRAM, A.; BUJALSKI, W. (2013), *High temperature (HT) polymer electrolyte membrane fuel cells (PEMFC) - A review*, J. Power Sources 231, pp.264-278

CHOI, C.H.; YU, S.; HAN, I.S.; KHO, B.K.; KANG, D.G.; LEE, H.Y.; SEO, M.S.; KONG, J.W.; KIM, G.; AHN, J.W.; PARK, S.K.; JANG, D.W.; LEE, J.H.; KIM, M. (2016), *Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat*, Int. J. Hydrogen Energy 41, pp.3591-3599

CLAUS, S. (2019), *Steeds meer cruiseschepen mijden Amsterdam, de sector baalt*, https://www.trouw.nl/economie/steeds-meercruiseschepen-mijden-amsterdam-de-sector-baalt{~}b0fdb7f1/

CLIA (2019), *2019 Cruise Trends & Industry Outlook*, Cruise Line International Association

DAS, S.K.; GADDE, K.K. (2013), *Computational fluid dynamics modelling of a catalytic flat plate fuel reformer for on-board hydrogen generation*, J. Fuel Cell Science and Technology 10

DE-TROYA, J.J.; ÁLVAREZ, C.; FERNÁNDEZ-GARRIDO, C.; CARRAL, L. (2016), *Analysing the possibilities of using fuel cells in ships*, Int. J. Hydrogen Energy 41/4, pp.2853-2866

ELLIS, J.; TANNEBERGER, K. (2016), *Study on the use of ethyl and methyl alcohol as alternative fuels in shipping*, EMSA, http://www.emsa.europa.eu/news-a-press-centre/external-news/item/2726-study-on-the-use-of-ethyl-and-methyl-alcohol-as-alternativefuels-in-shipping.html

EVRIN, R.A.; DINCER, I. (2019), *Thermodynamic analysis and assessment of an integrated hydrogen fuel cell system for ships*, Int. J. Hydrogen Energy 44, pp.6919-6928

FOURNIER, G.G.; CUMMING, I.W.; HELLGARDT, K. (2006), *High performance direct ammonia solid oxide fuel cell*, J. Power Sources 162, pp.198-206

GEERTSMA, R.; KRIJGSMAN, M. (2019), *Alternative fuels and power systems to reduce environmental impact of support vessels*, Marine Electrical and Control Systems Safety Conf.

HÖHLEIN, B.; BOE, M.; BØGILD-HANSEN, J.; BRÖCKERHOFF, P.; COLSMAN, G.; EMONTS, B.; MENZER, R.; RIEDEL, E. (1996), *Hydrogen from methanol for fuel cells in mobile systems: Development of a compact reformer*, J. Power Sources 61, pp.143-147

HRISTOVSKI, K.D.; DHANASEKARAN, B.; TIBAQUIRÁ, J.E.; POSNER, J.D.; WESTERHOFF, P.K. (2009), *Producing drinking water from hydrogen fuel cells*, J. Water Supply: Research and Technology 58, pp.327-335

IMO (2013), *MARPOL Annex VI and NTC 2008 with Guidelines for Implementation*, Int. Mar. Org., London

IMO (2018a), *GHG Emissions*, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx

IMO (2018b), *UN body adopts climate change strategy for shipping*, http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

IMO (2020a), *Nitrogen oxides (NOx) - Regulation 13*, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-\T1\textendash-Regulation-13.aspx

IMO (2020b), Sulphur oxides (SOx) - Regulation 14, http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-\T1\textendash-Regulation-14.aspx

ISAACS, R.; PALFREEMAN, N.; ROBERT, R. (2013), *Achieving Ultra-Low NOx Emissions in Methanol Downfired Reformer Applications*, Int. Combustion Symposium, American Flam Research Committee, https://collections.lib.utah.edu/details?id=14363

KAR CHUNG TSE, L.; WILKINS, S.; McGLASHAN, N.; URBAN, B.; MARTINEZ-BOTAS, R. (2011), *Solid oxide fuel cell/gas turbine trigeneration system for marine applications*, J. Power Sources 196, pp.3149-3162

KEE, R.J.; ZHU, H.; GOODWIN, D.G. (2005), *Solid-oxide fuel cells with hydrocarbon fuels*, Proc. Combustion Institute 30 II, pp.2379-2404

KERKHOF, M. v.d. (2019), *Clean Shipping - Vision 2030 and Action Plan until 2021*, Port of Rotterdam

KLERKE, A.; CHRISTENSEN, C.H.; NØRSKOV, J.K.; VEGGE, T. (2008), *Ammonia for hydrogen storage: Challenges and opportunities*, J. Materials Chemistry 18, pp.2304-2310

LAN, R.; TAO, S. (2014), *Ammonia as a Suitable Fuel for Fuel Cells*, Frontiers in Energy Research 2

LARMINIE, J.; DICKS, A. (2003), Fuel Cell Systems Explained, Wiley

LAW, K.; ROSENFELD, J.; HAN, V.; CHAN, M.; CHIANG, H.; LEONARD, J. (2013), *U.S. Department of Energy Hydrogen Storage Cost Analysis*, U.S. Department of Energy, https://www.osti.gov/scitech/servlets/purl/1082754

LEE, Y.D.; AHN, K.Y.; MOROSUK, T.; TSATSARONIS, G. (2015), *Environmental impact assessment of a solid-oxide fuel-cell-based combined-heat-and-power-generation system*, Energy 79, pp.455-466

LEITES, K.; BAUSCHULTE, A.; DRAGON, M.; KRUMMRICH, S.; NEHTER, P. (2012), *Design of different diesel based fuel cell systems for seagoing vessels and their evaluation*, ECS Trans., pp.49-58

LUCKOSE, L.; HESS, H.L.; JOHNSON, B.K. (2009), *Fuel cell propulsion system for marine applications*, IEEE Electric Ship Technologies Symp., pp.574-580

MINNEHAN, J.J.; PRATT, J.W. (2017), *Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels*, Sandia National Laboratories, https://classic.ntis.gov/help/order-methods/

NN (2004), Fuel Cell Handbook, EG&G Technical Services

PAN, C.; HE, R.; LI, Q.; JENSEN, J.O.; BJERRUM, N.J.; HJULMAND, H.A.; JENSEN, A.B. (2005), *Integration of high temperature PEM fuel cells with a methanol reformer*, J. Power Sources

PATEL, H.C.; WOUDSTRA, T.; ARAVIND, P.V. (2012), *Thermodynamic analysis of solid oxide fuel cell gas turbine systems operating with various biofuels*, Fuel Cells 12, pp.1115-1128

PAYNE, R.; LOVE, J.; KAH, M. (2019), *Generating Electricity at 60% Electrical Efficiency from 1-2 kWe SOFC Products*, ECS Transactions, The Electrochemical Society, pp.231-239

PETERS, R.; DEJA, R.; ENGELBRACHT, M.; FRANK, M.; NGUYEN, V.N.; BLUM, L.; STOLTEN, D. (2016), *Efficiency analysis of a hydrogen-fueled solid oxide fuel cell system with anode off-gas recirculation*, J. Power Sources 328, pp.105-113

SARGENT, R.G. (2010), *Verification and validation of simulation models*, Winter Simulation Conf., pp.166-183

SCHNEIDER, J.; DIRK, S. (2010), *ZEMShip*, 18th World Hydrogen Energy Conf.

SEMELSBERGER, T.A.; BORUP, R.L.; GREENE, H.L. (2006), *Dimethyl ether (DME) as an alternative fuel*, J. Power Sources 156, pp.497-511

SIEMENS (2013), *SINAVY PEM Fuel Cell*, https://www.industry.siemens.com/verticals/global/de/marine/marineschiffe/energieverteilung/Documents/sinavy-pem-fuel-cellen.pdf

SOLTANI, R.; ROSEN, M.A.; DINCER, I. (2014), *Assessment of CO2 capture options from various points in steam methane reforming for hydrogen production*, Int. J. Hydrogen Energy 39, pp.20266-20275

SØNDERGAARD, T.; JENSEN, J.O.; AILI, D.; HU, Y.; CLEEMANN, L.N.; LI, Q. (2017), *High-Temperature Polymer Electrolyte Membrane Fuel Cells*, Ph.D. thesis, Technical Univ. of Denmark

STRAZZA, C.; DEL BORGHI, A.; COSTAMAGNA, P.; TRAVERSO, A.; SANTIN, M. (2010), *Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships*, Applied

Energy 87, pp.1670-1678

THOUNTHONG, P.; RAËL, S.; DAVAT, B. (2009), *Energy management of fuel cell/battery/ supercapacitor hybrid power source for vehicle applications*, J. Power Sources 193, pp.376-385

TRONSTAD, T.; LANGFELDT, L. (2017), *Study on the use of fuel cells in shipping*, EMSA European Maritime Safety

VAN VELDHUIZEN, B. (2020), *Fuel cell systems Applied in Expedition Cruise Ships - A Comparative Impact Analysis*, Delft University of Technology

VOLGER, C. (2019), *Alternative fuels on board of carbon-neutral cruise vessels*, Delft University of Technology

WELAYA, Y.M.; EL GOHARY, M.M.; AMMAR, N.R. (2011), *A comparison between fuel cells and other alternatives for marine electric power generation*, Int. J. Naval Architecture and Ocean Engineering 3, pp.141-149

WHC (2018), *Norwegian parliament adopts zero-emission regulations in World Heritage fjords*, World Heritage Centre, UNESCO, https://whc.unesco.org/en/news/1824

ZAMFIRESCU, C.; DINCER, I. (2008), *Using ammonia as a sustainable fuel*, J. Power Sources 185, pp.459-465