PROCEEDINGS OF ECOS 2018 - THE 31ST INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
JUNE 17-22, 2018, GUIMARÃES, PORTUGAL

Integration of solid oxide fuel cells in cruise ship energy systems

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Abstract:

The growing trend of the cruise ship industry, together with increasing concerns over its impact on the environment, makes these ships a much relevant target for the efforts toward increasing ship energy efficiency, thus ultimately reducing fuel consumption and emissions of carbon dioxide and other air pollutants.

In a context of rising discussions concerning the use of cleaner fuels such as LNG and methanol in shipping, fuel cells are expected to become an increasingly viable solution for onboard power generation. In particular, solid oxide fuel cells (SOFC) can offer high electrical efficiency, power density and reliability with the possibility of combined heat, hydrogen and power production, which make them suitable for energy-intensive applications with a diverse demand (e.g., cruise ships) by integrating other complementary technologies.

In this paper, we investigate the potential for energy and emission savings in relation to the use of SOFCs on cruise ships. Given the limited ability of SOFCs to deal with fast load changes and start/stop cycles, the SOFCs are expected to tackle the baseload, while a combination of batteries and internal combustion engines are complementary for handling peak loads.

The proposed system is tested and optimized for a case study of a cruise ship operating in the Baltic Sea. Based on reference operational profiles for heat and electricity demand, the design of the system is optimized. The system proves particularly performant, with an overall efficiency close to 70% and a potential lifetime economic performance in line with conventional systems powered by Diesel engines.

Keywords:

Low carbon shipping; cruise ships; solid oxide fuel cells; combined heat, hydrogen and power production; hybrid propulsion

1. Introduction

The cruise industry, which has strong impacts on the maritime and global environment, is expected to grow in the coming years due to increasing passenger volumes. The use of fuel cells, given their high efficiency and low emissions, can be a solution for this issue.

1.1. The cruise industry and its impact on the environment

Shipping is one of the fastest growing industries in the world, given its strong ties with international trade. In addition, the cruise industry is blooming at even a further pace: the number of cruise ship passengers globally has increased from 17.8 million in 2009 to 24.7 million in 2015 [1], and volumes are expected to grow further in the coming years [1]. In terms of greenhouse gas (GHG) emissions, cruise travels are among the most carbon intensive in the tourism industry, estimated to an average of 160 kg_{CO2} per passenger and per day. As a consequence, the cruise industry was estimated to contribute 19.3 Mtons of CO_2 emissions in 2010 [2], compared to the total estimated emissions from shipping of around 972 Mtons [3].

In addition to their contribution to climate change, cruise ships are also under focus for other negative impacts on the environment, both in terms of air and water quality, and other wider impacts on the environment[4]. Cruise ships are highly energy intensive, they maintain relatively high energy demands even when stationing in port, and concentrate their operations in highly populated and environmentally sensitive areas.

1.2. Energy efficient cruise ships, a review

Cruise ships have a number of features that make them particularly interesting from a research perspective. Differently from most merchant vessels, cruise ships have a high demand of auxiliary energy, specifically electric energy for different types of on board system related to passenger comfort and entertainment, and thermal energy for HVAC, hot water, and other purposes. Marty et al. reported a 59% to 41% proportion for propulsion and auxiliary electric energy demand for a reference trip [5], with the heating demand in the same range [5]. Similar results were obtained in previous work by the authors for a smaller cruise ship, where the average yearly demand was estimated to be 41%/25%/34% for propulsion/electricity/heat demand share [6]. In addition, cruise ships have a highly variable demand, that depends on daily variations in the environmental conditions and in ship operations [5], [6]. Finally, cruise ships are completely independent from any resource network and need to be solely dependent on the onboard systems for fulfilling the energy demand.

Different authors have investigated the potential for reducing both fuel consumption and CO_2 emissions from cruise ships. From the perspective of the complete redesign of the ship systems, the use of gas turbines was shown particularly promising when used in conjunction with a steam turbine (up to 72% efficiency [7]), while their use in pure cogeneration mode did not show the potential to achieve similar efficiencies as Diesel engine-based systems (60% versus 67% [8]). From the perspective of system retrofit, organic Rankine cycles have been investigated, showing the potential to reduce the auxiliary power demand significantly [9]. Also more conventional steam cycles, particularly when four-stroke Diesel engines are used, proved a high potential of efficiency increase [10]. Previous work by the authors focused on improving the onboard heat recovery by means of process integration [11], [12] and on evaluating the potential benefits of retrofitting an existing cruise ship with a shaft generator on the main engines in order to improve the overall engine loading conditions [13].

1.3. State of the art on high-temperature fuel cell technology

The major types of fuel cells are low-temperature alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), and high-temperature molten carbonate fuel cell (MCFC) and solid-oxide fuel cell (SOFC). All three types of low-temperature fuel cell technologies are mature commercialized. However, their low operating temperatures (below 100 ºC) make them unattractive for combined heat and power generation. More importantly, they suffer from water management, low fuel flexibility (low CO_2 or CO tolerance and strict H_2-purity requirements), and a relatively fast degradation.

High-temperature fuel cells operate over 600 ºC, which allows combined heat and power production with high fuel flexibility and high tolerance to catalyst poisoning. CO_2 and CO molecules are no longer poisoning, and CO can even act as a potential fuel. SOFCs in particular offer a high fuel flexibility for various gases and liquids, e.g., methane, ethanol, methanol, propane, LPG, diesel, DME, ammonia, and more. More importantly, SOFCs have demonstrated their high efficiency, high availability and reliability, and good durability. State-of-the-art SOFC systems provide an electrical efficiency of around 60% and a CHP system efficiency up to 85-90% [14]. SOFC-GT hybrid system can even achieve electrical efficiencies of as high as 70% [15]. Although lifetime is also considered an issue for SOFCs, system duration of 40 000 hours are a reasonable objective for SOFC technology [16], and a runtime record of SOFC systems of 10-year continuous operation was recorded [17].

SOFCs can therefore be identified as the most potential fuel cell technology for ship applications. However, due to the slow start-up and load shifting, SOFCs are expected to handle base loads of heat and power. Complementary technologies, e.g., battery, PEMFC and internal combustion engines, can be integrated to handle peak loads. PEMFCs have been successfully used on submarines [18] and tested for long periods on a passenger ferry [19]. The potential for MCFCs as part of ship propulsion was also investigated by Dimopoulos et al., showing that efficiencies as high as 60% were achievable in a combined cycle configuration [20]. A more thorough review of previous experiences with fuel cells on board ships was published by van Biert et al. [21]

The possibility of flexible combined heat, hydrogen and power generation from a SOFC system allows the integration of SOFC with PEMFC and battery. The advantage of such a hybridization is that the hydrogen and power to fill PEMFC and battery are both produced from highly-efficient SOFC system. Becker et. al. have analysed a combined heat, hydrogen and power generation by combining SOFC with successive 1- or 2-stage water gas shift reactors and hydrogen upgrading via PSA or membrane technologies [22]. Such a system is now under design and demonstration in EU H2020 project CH2P for driving H_2 and electricity refilling stations [23].

1.4. Aim

The aim of this paper is to optimize the design of a marine power systems based on SOFCs as the main energy source of the ship. The main novelty of this work lies in the system design concept. We propose the use of a “hybrid” SOFC system for simultaneous heat, hydrogen and power production [22], [23]. The combined storage capacity of hydrogen tanks and batteries allows for operating the SOFC at close to constant load, hence ensuring the system efficiency and durability.

2. Method

The problem of optimizing the design and operation of a cruise-ship energy system powered by SOFCs as the main source for electric demand is addressed as a mixed integer linear programming (MILP) problem, aimed at minimizing the ship’s investment and operational costs. The details of physical models of all components are provided in Section 2.1; the assumptions for the cost functions are summarized in Section 2.2; finally, the optimization procedure is described in section 2.3.

2.1. Description of the proposed system

The proposed system is based on the use of SOFCs as the main energy source on board. As SOFC systems are not suitable to handle large load changes, we included in the design other, more respondent systems are used for load following. The proposed system is composed of (Fig. 1)

- A SOFC as the main energy source of the system
- A hydrogen storage system combined with a HT-PEMFC for medium-slow load transients
- A Gas Turbine (GT) for peak loads of electric power demand
- A Boiler for peak loads of heat demand
- Electrical energy storage (EES) for fast transients and peak shaving

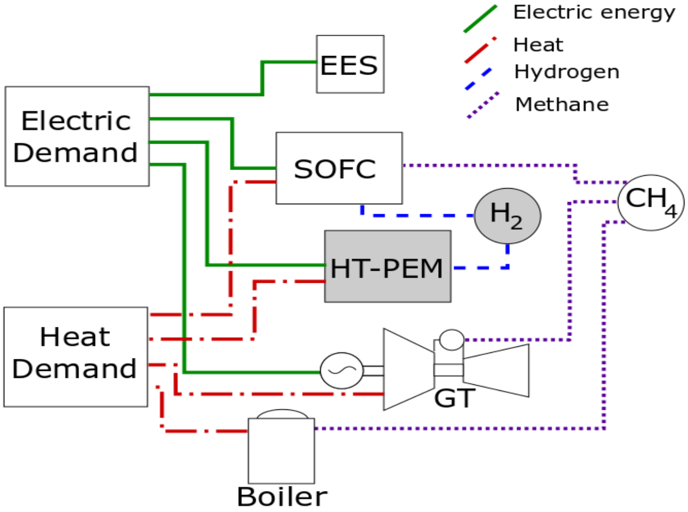


Fig. 1: Graphical representation of the proposed ship energy system. The hydrogen tanks (H_2) and the PEMFC are shown in gray as they are not included in the conventional system layout.

Gas turbines are used in this study to handle peak demands. Gas turbines are not unseen in marine application, particularly for naval vessels. In this specific case, they are preferred over Diesel engines because of their higher power density, lower emissions, and better handling of methane as fuel.

In this work, we also consider the alternative layout using a standard SOFC concept, with no hydrogen production. According to this design, the fast power fluctuations can only be taken care of by the batteries and the gas turbine.

2.2 Optimization settings

The problem was setup as a mixed integer linear programming (MILP) problem and solved using the OSMOSE framework for the solution of MILP-based energy integration problems [24], with the total annualized cost (Equation 2) as the objective to minimize. The size of each component of the power plant (SOFC, PEMFC, GT, H_2 storage and batteries) are the decision variables of interest for the problem, while the energy and mass streams for each component at each time step also appear in the optimization as decision variables. The MILP approach was selected based on the high reliability and speed of available solvers.

$$f_{obj} = C_{inv} + C_{op} \tag{1}$$

Where:

$$C_{op} = \sum_{u}^{N_u} \sum_{t}^{N_t} \boldsymbol{x(u,t)}\ C_{fuel}(u,t)\ \dot{\mathrm{m}}_{\mathrm{fuel,max}}(\mathrm{u},\mathrm{t}) \Delta t_t \tag{2}$$

$$C_{inv} = \sum_{u}^{N_u} \frac{C_{inv,fix}(u) + \boldsymbol{x_{size}(u)}\ C_{inv,var}(u) P_{max}(u)}{\frac{(1+i)^{N_y}-1}{i(1+i)^{N_y}}} \tag{3}$$

The assumptions employed were 0.05 for the interest rate (i) and 0.5 USD/kg for the natural gas price (C_{fuel}) [25]. The expected lifetime and the investment cost factors of each component are shown in Table 1. Traditional components are assigned a lifetime of 20 years, while the SOFC systems are assigned a lifetime of 6 years, based on 50000 h of operations and on a use of roughly 8000 h/year, as the SOFC is responsible for the baseload of the ship and hence operated continuously. We assumed a 8-year lifetime for the PEMFC. Despite the general expected lower duration of PEMFCs compared to SOFCs, the PEMFC is not expected to be used continuously in the proposed system configuration. The assumption is based on an operational life of 30000 h and on 4000 h of operations per year. It should be noted that these assumptions can be considered as conservative, as in real applications only the fuel stacks, and not the full system, would be replaced.

*Table 1. Cost coefficients and expected lifetime for the investigated utilities. *The investment cost of a conventional SOFC unit is assumed as 10% lower of the cost of the hybrid SOFC. **The cost functions proposed in reference [26] were linearized in the vicinity of the optimal unit siye.*

Utility name	*Source*	*Fixed inv. Cost [kUSD]*	*Size-dependent inv cost. [kUSD/kW]*	*Expected lifetime [years]*
SOFC – CHP	[22]*	11300	1.62	6
SOFC – H2 gen	[22]	12560	1.80	6
HT-PEMFC	[27]	0	3.00	8
Gas turbine	[26]**	17280	1.23	20
Gas boiler	[26]**	71	0.08	20
Hydrogen storage [in kUSD/kWh]	[27]	0	0.045	20
Batteries [in kUSD/kWh]	[27]	0	1.08	5

The relationship between $\boldsymbol{x}$ (representing the component loading at each time step) and $\boldsymbol{x_{size}}$ (representing the component installed size) is provided by the inequality constraint in Equation 5:

$$\boldsymbol{x(u,t)} \le \boldsymbol{x_{size}(u)} \qquad \forall\, u, t \tag{4}$$

The problem is further defined by the equality constraints related to the energy demand of the system (see Section 3.2), as defined by Equation 5 for each stream type (i) and for each time step (t):

$$\sum_{u}^{N_u} \boldsymbol{x}(\boldsymbol{u},\boldsymbol{t})\,\dot{E}_i(u,t) + \sum_{p}^{N_p} \dot{E}_i(p,t) = 0 \qquad \forall\, i,t \tag{5}$$

2.3. Component modelling

According to the MILP approach, all components are defined by their energy and material streams, expressed as a linear function of the decision variable x, i.e. the component sizing:

$$\dot{E}_i(u,t) = \boldsymbol{x}(\boldsymbol{u},\boldsymbol{t})\dot{E}_{i,max} \tag{6}$$

2.3.1. Solid oxide fuel cell

The SOFC system proposed by Becker et al. [22] is used, where the composition of the unconverted gas out of the SOFC is adapted by water-gas shift reactors to enhance the hydrogen content, then the enriched hydrogen is upgraded by a pressure swing absorption (PSA) unit for high achieving high H_2 purity. The unreacted gas after the PSA is combusted and the generated heat is utilized within the system and for direct satisfaction of heat load. The system can operate in two modes: a baseline (B) operating mode and a hydrogen overproduction (HO) operating mode. In the latter case, the power and heat output are equal to the B case, but the fuel input is increased to enhance the hydrogen output. No flexible adjustment between hydrogen and power production is considered in this paper.

It is assumed that, given the specific system, a DC distribution system is used. Hence, no inverter is included in the design, and both the electric generator of the gas turbine and the electric motors for ship propulsion are assumed to be DC electrical machines.

For the MILP problem, the SOFC subsystem is considered as a utility converting natural gas to electric power, low-temperature heat and hydrogen. The system is assumed to be linearly scaled without affecting its thermodynamic performance. The streams features are summarized in Table 2.

The operational data for a standard SOFC are taken from [28] and summarized in Table 3. The net electric efficiency reported at optimal load (67%) was lowered to 60% in order to account for the expected average performance over a wider load range.

Table 2. Operational data for the SOFC/reformer. From [22]

Stream	*Type*	$\dot{E}$ [kW]	T_{in} *[K]*	T_{out} *[K]*	$\dot{E}$ [kW]	T_{in} *[K]*	T_{out} *[K]*
		Baseline mode			*H_2 overproduction mode*		
Electric net power output	El	1019			1026		
Heat output	Flue gas	311	595	388	311	495	388
Heat output	Fuel mix	106	617	375	106	617	375
Hydrogen output	H_2	185			333		
Fuel input	CH_4	1941			2084		

Table 3. Operational data for the pure SOFC. From [28]

Stream	Type	$\dot{E}$ [kW]	T_{in} *[K]*	T_{out} *[K]*
Electric net power output	El	1.49		
Heat output	Flue gas	0.54	423	303
Fuel input	CH_4	2.48		

2.3.2. High temperature proton-exchange membrane fuel cell

PEMFCs operate at much lower temperatures compared to SOFCs and are, hence, more flexible in terms of load change [21], [29]. In this work, we propose the use of high temperature PEMFCs because of their better suitability to cogeneration purposes and of their higher tolerance of carbon monoxide impurities in the feed gas [21], [29]. The operational data for the HT-PEMFC are taken from [30] (see Table 4).

Table 4. Operational data for the HT-PEMFC. From [30]

Stream	*Type*	$\dot{E}$ [kW]	T_{in} *[K]*	T_{out} *[K]*
Electric power output	El	1.00		
Heat output	Flue gas	0.25	433	363
Fuel input	CH_4	1.92		

2.3.3. Energy storage units

The limitations on SOFC load that we imposed in this work make the use of energy storage units a requirement. In this work we consider the possibility of energy storage both in the form of hydrogen and electric energy.

For hydrogen storage, the charging and discharging efficiencies are assumed as 0.98 in order to compensate for all auxiliary power requirements [31]. Lithium-ion batteries are today the standard for marine installations [32] and are considered for electrical storage, The charging and discharging efficiencies are considered as 0.926 and 0.975, respectively, considering that no inverter losses are accounted for [31]. Finally, we assumed a depth of discharge (DoD) of 70% [32].

2.3.4. Other components

The gas turbine is modelled as a constant-efficiency utility, which is also capable of producing high-quality waste heat. In this paper, we assumed to use a stand-alone gas turbine with electrical and thermal efficiency of 0.33 and 0.6, respectively. The low value of the efficiency is justified by the fact that the turbine is rarely used at its most efficient load, and a conservative value taking into account the performance loss at part-load was selected. In addition, an efficiency of 0.95 for the associated electric generator was taken into account.

2.3.5 Load limitations

As previously mentioned, high temperature fuel cells can suffer from durability losses if asked to quickly follow load changes. To ensure high fuel cells durability, in this work the following constraint was used to limit the load change between two consecutive time steps:

$$x(SOFC,t) - x(SOFC,t-1) \leq \Delta P_{sofc,max} / P_{sofc,max} \quad (7)$$

The value of ΔP_{max} was assumed as equal to 500 kW for both SOFC types, corresponding to a limitation of changing the load by between 5-20% based on the installed size of the component.

In addition, it was also assumed that some components can only be operated within certain load boundaries. In the case of the SOFC/reformer, it was assumed that it can only be operated between 70% and 90% load to maintain the high overall efficiency of the optimal system design. In the case of the pure SOFC unit we assumed that operations are only allowed between 30% and 70% load, as SOFC efficiency deteriorates too strongly out of this load window [14]. Finally, a minimum load for the gas turbine of 10% was considered.

Table 5. Assumptions about load limitations for different ship components

Stream	Load min	Load max	ΔP max [kW]
SOFC/reformer	0.7	0.9	500
pure SOFC	0.3	0.7	500
Gas Turbine	0.1	1	-

3. Case study

The proposed system is applied and optimized for the case of a small cruise ship sailing for daily cruises in the Baltic Sea.

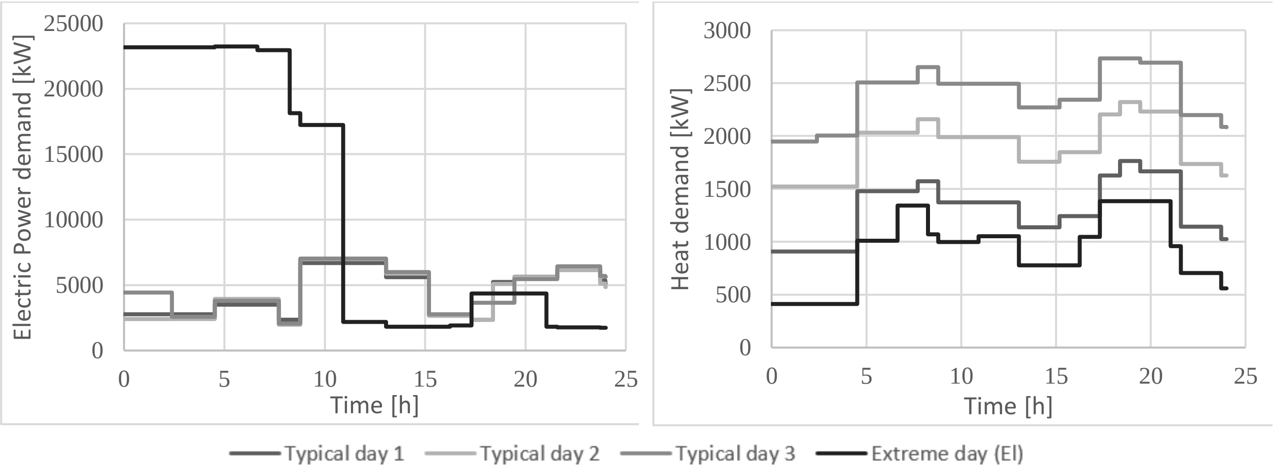
3.1. Ship description

The ship is 176.9 m long and has a beam of 28.6 m, has a design speed of 21 knots, and a capacity of 1800 passengers. It is equipped with several amenities and with a large HVAC system, making its auxiliary energy demand larger and more varied than that of a standard cargo vessel. The ship currently in operations is equipped with a total of eight Diesel engines, four main engines with a power of 5760 kW each, and four auxiliary engines for a power of 2780 kW each. The heating demand is fulfilled by a total of six exhaust gas boiler, a recovery system for the engine cooling waste heat, and on two oil-fired boilers. In this work, we consider a case of a newly built ship of similar size and operational profile.

3.2. Energy demand profiles

The energy demand is based on the work proposed in [6]. We consider for the ship a fully electric system (differently from the current ship, where propulsion and electrical demand are fulfilled by different systems, but similarly to the majority of cruise ships). The analysis of the demand, originally based on a full year of operations, was clustered as suggested by [33] into a total of four representative days one, of which being an "extreme day" for the electric power demand (see Figure 2). The three typical days represent normal ship operations in three different seasons (hence the difference in heat demand), while the extreme day represents high-speed sailing conditions.

The heat is assumed to be distributed on board using hot water with a temperature drop of 20°C and a maximum temperature of 90°C. This is similar to the current ship's system used by the HVAC systems and for hot water heating, which represent the largest share of the yearly heat demand. Compared to the results of [6], the demand for fuel tank heating and fuel pre-injection heating is disregarded, as methane does not need to be heated at high temperatures (150°C, as in the case of the heavy fuel oil typically used in shipping).



a) *Electric power demand* b) *Heat demand*

Fig. 2: Energy demand profiles used in the optimization

4. Results

The results of the optimization suggest that the proposed hybrid system performs better than the baseline case in terms of both energy efficiency and economic performance. In particular, the hybrid system reaches 72.9% energy efficiency and 56.3% exergy efficiency, compared to the baseline case of 70.0% and 54.0%, respectively. The higher efficiency also results in lower operating costs.

The hybrid system also shows lower equivalent annual costs, with both lower annualized investment cost and operating costs (Figure 3). This can be explained when looking at the installed sizes of the different utilities (Figure 4): the presence of the PEMFC and of the H_2 storage allows the installation of a smaller SOFC unit (4.7 MW versus 8.3 in the baseline case) and of lower electric energy storage capacity (7.2 MWh versus 9.3 MWh). The need for installing the PEMFC unit only partially compensate the savings in the initial investment, while the cost for the hydrogen tanks is marginal.

In both cases, the SOFC is the main contributor to the overall energy demand (76% of the power demand, 90% of the heat demand in the hybrid case, 87% and 60% in the baseline case. See Figure 6). In the hybrid case, the batteries and the PEMFC show a significant contribution to fulfilling the power demand (9.5% and 14.2%, respectively), while the heating demand is almost entirely fulfilled by the SOFC (97%). In both cases the gas turbine is operated only for marginal periods: in the hybrid case only, as expected, in high-speed sailing mode, while in the baseline case it is also sometimes used during fast transients. Finally, the baseline system relies much more heavily on the boiler for the heat demand (39.7%, resulting in an overall fuel-demand share of 8.6%), as a consequence of the base SOFC unit considered in this study being more focused on electricity production than on cogeneration. On the other hand, the boiler is only used in rare cases in the proposed hybrid system, leading to a marginal contribution to the overall fuel consumption (1.4%).

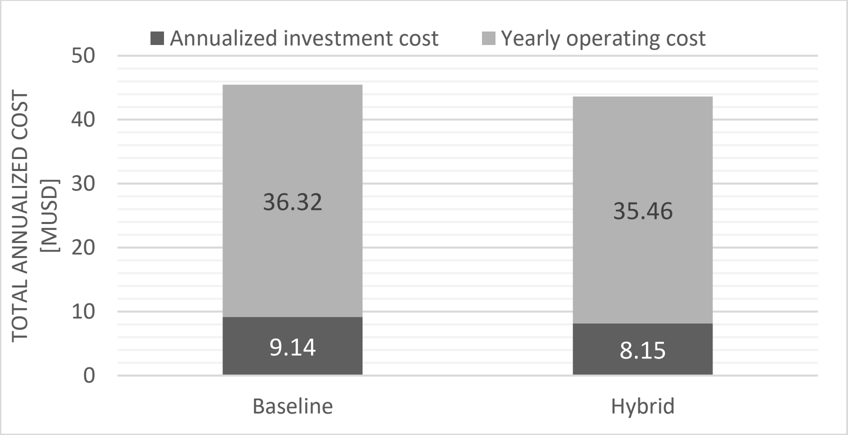
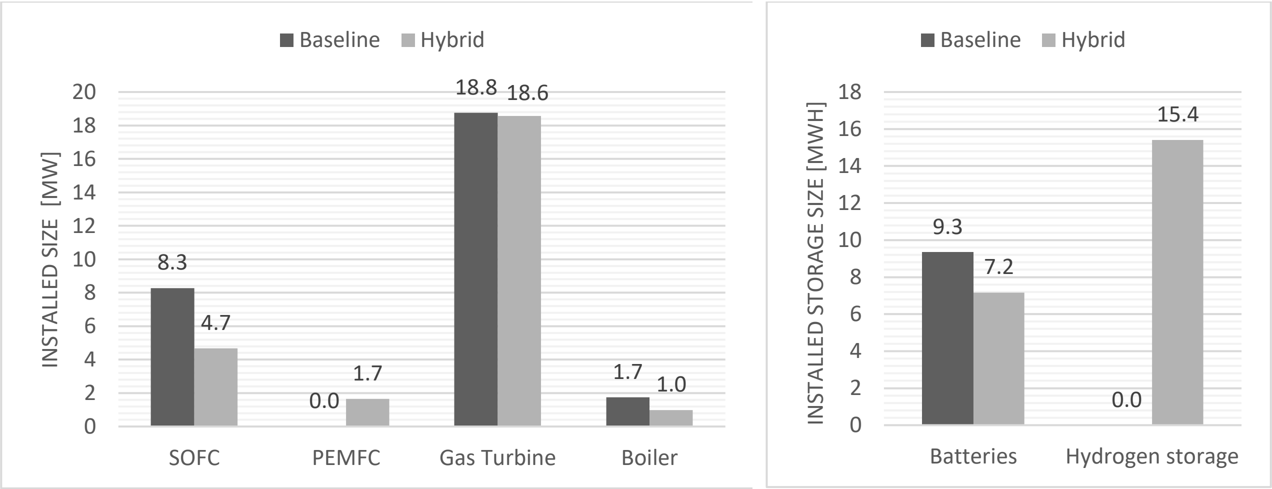


Fig. 3. Total annualized cost for the baseline and hybrid case.



a) Utilities *b) Energy storage*

Fig. 4: Installed capacity of different utilities and storage systems.

The storage capacity is used to allow the SOFC to operate at close to constant load (see Figure 7 for the Typical Day 1). It should be noted that in Figure 7 the fuel flow is represented, and hence the actual power delivered by the PEMFC is roughly half of what is represented in the figure. In addition, operating the SOFC at constant load prevents the lack of waste heat available during port stays, when the electric power demand is low and the engines are turned off, making it necessary to operate the boilers instead.

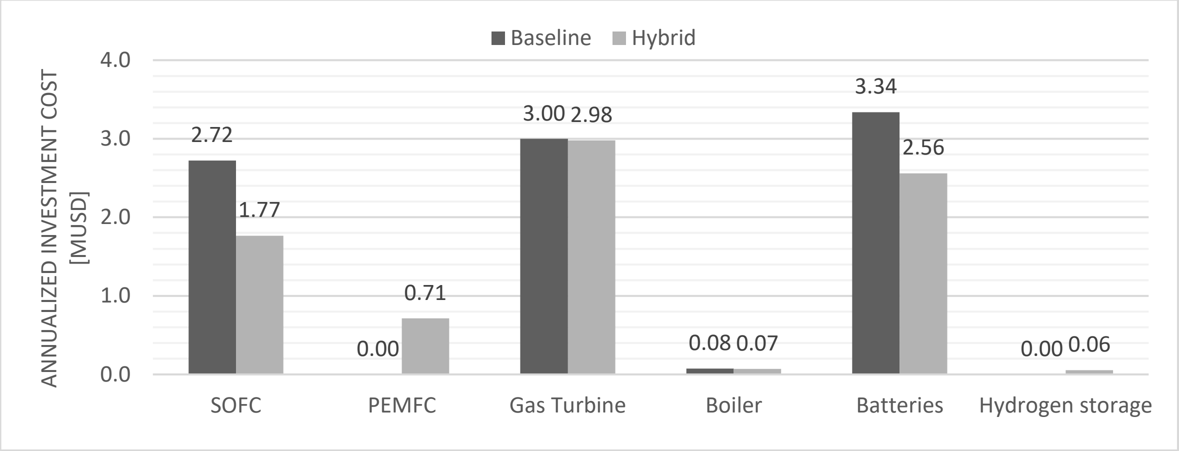
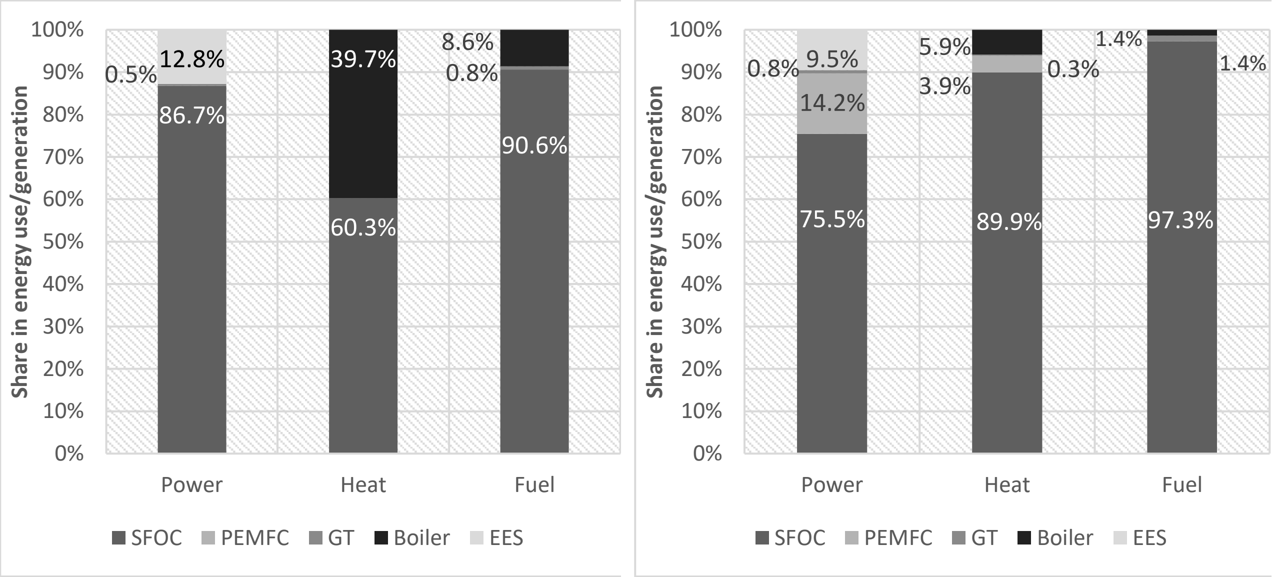


Fig. 5. Annualized investment cost for all considered components



a) Baseline system

b) Hybrid system

Fig. 6: Yearly energy generation share between different utilities, electric power and heat

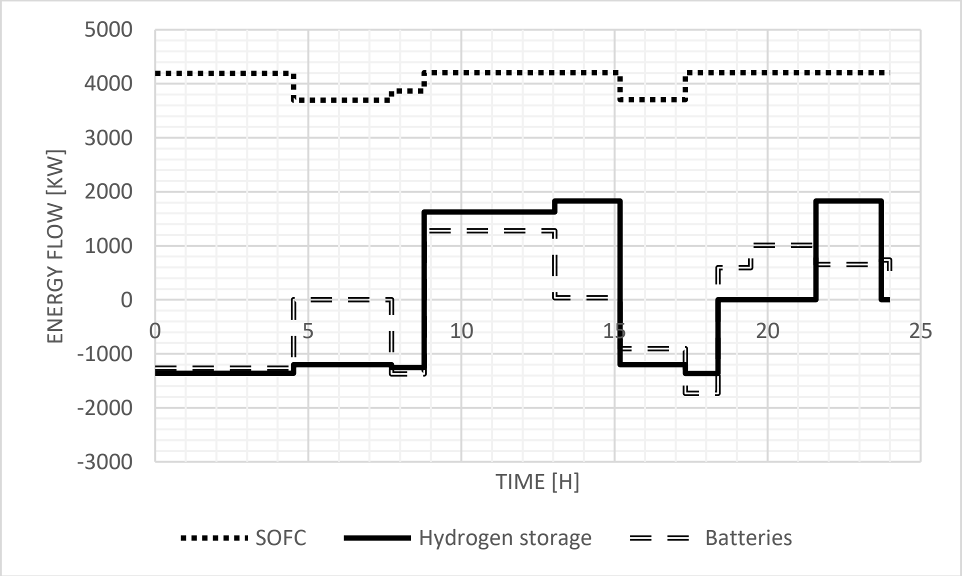


Fig. 7: Hourly generation profile of the different electric utilities for typical day 1.

5. Discussion

The results proposed in this work make a point in favor of SOFC-based marine power systems. However, a number of additional challenge should be tackled in order to further investigate the feasibility of these systems. As we approached the problem as an MILP, it was not possible to consider the off-design performance of the different utilities, which might affect the results and the optimal load-sharing strategy. Furthermore, the definition of the problem relied on the assumption that the SOFC can only be operated in a limited load window, and with restricted ability to adapt to the ship load. In a real system this would be treated as a trade-off rather than a hard constraint.

Similar to all optimization problems, the MILP solution that we propose relies on a number of thermodynamic and economic assumptions. Future investigations should include an analysis of the sensitivity of the solution to the uncertainty in the cost functions, the expected lifetime and the thermodynamic performance of the different utilities. In addition, the uncertainty on the price of natural gas as a marine fuel should also be taken into account.

Finally, this work only focuses on the economic and energetic performance of the system. The technical feasibility of the installation of SOFCs on ships, including the storage of hydrogen on board, should be investigated.

6. Conclusion

In this paper we presented the optimization of a ship propulsion plant using solid oxide fuel cells as the main energy conversion device for the generation of electric power and heat on board. In order to overcome the notorious limitations in rapid load changes of high-temperature fuel cells, we proposed a system were different means for energy storage (batteries and hydrogen tanks) were used. The resulting optimal system was compared to an alternative, more conventional option where the fuel cell is only integrated with batteries.

The results of this study showed that the proposed system can achieve substantially higher performance compared to the baseline, improving the overall efficiency from 70% to 73%. The use of a hybrid SOFC that can generate both electric power, hydrogen and heat allows not only for a high design efficiency of the system, but also for a relatively large degree of flexibility. The use of batteries and hydrogen storage, in combination with a PEMFC, allows operating the SOFC at constant load and close to its most optimal point, hence increasing the efficiency and the durability of the system.

The results of this paper suggest that an SOFC-based power plant for a cruise ship is not only possible, but also can be efficient and economically viable on the long term.

Acknowledgments

The main author’s work was financed under the MSCA-IF fellowship as part of the H2020 program.

Nomenclature

Symbols:

C_{fuel}	Fuel cost [USD]
$C_{inv,fix}$	Investment cost, size independent [USD]
$C_{inv,var}$	Investment cost, size dependent [USD/kW]
i	Interest rate
$\dot{m}_{fuel}$	Fuel mass flow [kg/s]
N_y	Unit lifetime [years]
P_{max}	Unit installed power
Δt	Time step duration

Acronyms

EES	Electric energy storage

GT	Gas turbine
HT-PEMFC	High temperature proton exchange membrane fuel cell
MILP	Mix integer linear programming
SOFC	Solid Oxide Fuel Cell

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