Innovative Energy Systems: Motivations, Challenges and Possible Solutions in the Cruise Ship Arena

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Abstract. The worldwide effort on the environmental issue in the maritime field has led to always more stringent regulations on greenhouse gas emission (GHG). In this perspective, the International Maritime Organization has developed regulations intended to increase the ship's efficiency and reduce GHG emissions both in design phase, through the introduction of an Energy Efficiency Design Index (EEDI), either in management phase, adopting the Ship Energy Efficiency Management Plan (SEEMP). In this challenging perspective, several approaches and technologies adopted in land-based engineering can also be advantageous for marine applications. This is the case of the Distributed Energy Resources (DER) solution applied in land-based microgrids, which increases both the system's efficiency and reliability. This work is primarily focused on methodological aspects related to the adoption of a DER solution on-board cruise ships, with the integration of different energy sources in order to pursue a more flexible, reliable and sustainable management of the ship. In this context, another engineering best practice developed for land-based applications that is further investigated in the paper is related to the on board thermal energy recovery issue, revisited due to the implementation of the DER solution.

Keywords. Innovative Energy Generation, Shipboard Power Systems, Distributed Energy Resources, Energy Efficiency, Fuel Cells, Micro-turbines

1. Introduction

Cruise vessels are one of the most challenging and technologically advanced engineering systems. In fact, their design process involves a wide range of knowledge: from engineering and physics to interior design, logistics and economy. Moreover, it should be noted that, in a cruise ship, passengers are provided with a very high standard of accommodation and leisure facilities. This results in a large superstructure as a prominent feature of the vessel and a high level of power required by the on-board users and the propulsion system as well. Nowadays, these ships present an integrated electric power system, where all the main users and especially those related to the propulsion, are

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powered by the shipboard power system. In this perspective, in the near future it would be possible to talk about the well-known all electric ship (AES), where all the users are powered by electricity. This continuous electrification of the on board systems is also due to the recent worldwide increase of attention on the environmental issue. In fact, the International Maritime Organization (IMO) has introduced new normative aimed to reduce the pollutant emissions of greenhouse gasses (GHG) from the ships [1], [2]. This conversion to the electric power has already enhanced the ship's flexibility, and reliability; also allowing the integration on board of alternative energy sources.

In this perspective, aim of this paper is to present possible solutions in order to implement a distributed energy resource (DER) approach into the cruise ship design. This kind of approach has already been introduced for land-based applications such as the well-known microgrids, where both the electric and thermal energy sources are integrated in a more complex and efficient system [3], [4]. Modern ships are considered as marine microgrids [5]. Therefore, a cross fertilization between terrestrial applications and marine ones seems possible, which should result in more efficient, flexible and reliable ships [6]. Nevertheless, several challenges and restrictions may be faced in this process. These are mainly due to the limited spaces and volumes available on board, to the hostile environment in which ships operate, to environmental normative and to safety requirements [7].

Possible solutions to these challenges are proposed in the following paragraphs. In this perspective, the implementation of alternative fuels and innovative power sources are proposed for cruise ships together with an analysis on costs, volumes and efficiency of each solution, compared to the traditional design. Furthermore, the iteration between the electrical and thermal energy is studied and energy recovery solutions are proposed in order to enhance the whole efficiency of the ship.

2. Innovative solutions for shipboard energy systems

Due to the ever-increasing amount of electrical power installed on board the new cruise vessels and due to the ever stringent environmental and safety normative, in this paragraph, several innovative power generation systems will be introduced and described. The main characteristics of these solutions will be analysed depending on the fuel adopted, their integration with the possible power system configurations, their costs, volumes and weights. In this perspective, the main challenges on the integration of these solutions on board a cruise ship are introduced, discussed and solutions are presented.

2.1. Distributed energy resources on board ship

Shipboard power systems can be properly identified as marine microgrids, where the loads and the generation units are geographically close. Moreover, these power systems usually operate in islanded mode, although these can be also connected to the shore grid. Therefore, it would be possible and useful to adopt some technologies and practice developed in the recent years for terrestrial microgrids. In this perspective, the distributed energy resources (DER) approach, which has been developed in land applications in order to integrate renewable sources into the grid, could be advantageously adopted also on board ships in order to increase both the efficiency and reliability of the whole system. In fact, a drastic improvement of the ship energy performances can be possible by adopting innovative configurations for the shipboard power systems combined with the integration of alternative power generation units such as fuel cells, micro gas turbines and energy storage systems. However, one of the most challenging task on adopting these innovative generation units is the proper storage of alternative fuels such as the natural gas (NG) or hydrogen (H_2). The working principle of the DER is the distributed installation of small generators in order to increase the availability of electric and thermal power sources close to the users; minimizing in this way the thermal losses, systems oversizing, and pollutant emissions [8], [9]. Therefore, this approach mainly consists in dividing and distributing on board the energy sources, which were previously concentrated in the engine room. Consequently, the traditional configuration of the power distribution system should be reviewed in order to maximize the benefits of the DER approach. In this context, a novel configuration of the grid can be selected instead of the traditional one.

The traditional radial configuration is characterized by a centralized generation system in medium voltage (MV), a MV primary distribution system from the main buses to the power transformers (e.g. which are installed in each accommodation and galley substation) and a secondary distribution s in low voltage (LV) to fed the distributed loads on board the ships. Each substation is a single branch of the network, which is powered by the primary distribution system through the substation transformer, as proposed in Figure 1. Being designed for a centralized power generation system, this configuration is well-suited for traditional applications.

In the perspective of introducing a DER approach, another configuration is shown in Figure 2, where a MV ring configuration is proposed. This can supply power to each single substation from two sides and, in case of failure, allows a complete reconfiguration of the network. Several power transformers have been eliminated and groups of substations connected to each other in LV (e.g. in red in Figure 2). The distributed generation units have been positioned in each substation in order to cover their normal operating load; the LV connection between substations increases the flexibility of the power system and its reliability in case of fault of one unit.

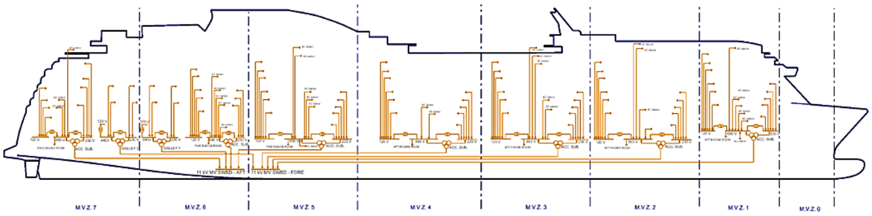

Figure 1. Traditional radial distribution system configuration

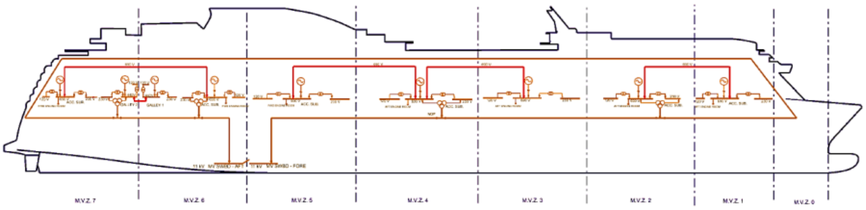

Figure 2. MV ring distribution system with substations connection in LV

The most interesting technologies for the distributed power generation are the micro-Gas Turbines (mGTs) and fuel cells, the firsts being characterized by a small size, reduced weight and very limited emissions [9] and the seconds by a very high efficiency, modularity and almost zero emissions in terms of noise, vibration and air pollutants[10], [11]. Fuel Cells can be fuelled with pure Hydrogen (H_2) or Natural Gas (NG) properly processed, while mGTs are fuelled with NG or liquid fuel. This study considers hydrogen and liquefied natural gas as the most suitable fuels to comply with the environmental limitations. Due to its very low volumetric energy density, hydrogen must be stored in high-pressure tanks, from 35 up to 70 MPa, or liquefied (e.g. also known as cryogenic hydrogen) that requires under atmospheric pressure a temperature equal to -253°C. The use of liquefied H_2 guarantees smaller volumes (e.g. energy density 2380 kWh/Nm^3) but requires almost the 30% of the stored energy for the cryogenic process and high-energy costs in order to reach very low temperature. The compressed H_2 is normally cheaper but the system is heavier and it occupies significantly volumes. On the other hand, NG is a petroleum subcategory and depending on the composition, its energy density is close to 47 MJ/kg. Natural gas can be stored as compressed gas up to 700 bar (e.g. energy density at 500 bar close to 3974 kWh/Nm^3) or liquid and it is currently one of the most important source of both hydrogen and methanol. Therefore, if coupled with a reformer, it can be considered an economic solution for H_2 production on board, with easier fuel management.

2.2. Electrical power load analysis for cruise ships

In order to properly select the distributed power generation units, the electrical power load analysis (EPLA) for the ship under exam must be performed and analysed. In this context, typical results of an EPLA performed for cruise ships are proposed [12]. The DER approach proposed in this paper is aimed to cover the electrical load of each accommodation and galley substations. Therefore, the EPLA will be analysed for these groups of loads under several operating conditions. It should be noted that these groups of loads account for a percentage of the total power installed between 10 and 20%. Considering, for example, a total power installed equal to 60 MW, their maximum load can be estimated between 6 and 12 MW, depending on the ship's characteristics [13]. However, it is to be highlighted that loads such as those related to the central compressors for the heat ventilation and air conditioning system are not considered in these groups. Traditionally, due to safety reasons (e.g. prevent from fire and flood) cruise vessels are divided in main vertical zones (MVZ). In each MVZ, power generation units can be distributed and installed in order to cover their operating load, which can be in the order of 500 – 650 kW, considering for example the case of a ship with seven MVZ. Usually, two galley substations are installed on board these ships, with an operating load of 600 kW each. In this context, for example, nine distributed generation units rated 800 kW can be installed in each LV substation [14].

2.3. Innovative energy generation units for cruise ship applications, fuel cells, micro-gas turbines and energy storage systems

Fuel cells are devices that convert chemical energy directly into electrical one, without combustion. They offer advantages such as high efficiency and environmental benefits when compared to conventional energy conversion technologies. A wide range of cells is currently available. Between the most interesting technologies for maritime applications can be higlighted the Proton Exchange Membrane (PEMFCs), the Molten Carbonate (MOFCs) and the Solid Oxide (SOFCs). Their operative temperature increases from 70°C (PEMFC) up to 800°C-1000°C (SOFC) [15]. This paper is focused on PEMFC and SOFC, since these are considered the most suitable for marine implementation [16]. The costs of both these technologies can be estimated around 4000 $/kW with a life cycle of 5 years and a peak efficiency between 35-52% and 60% for the PEMFC and the SOFC, respectively [15] - [17]. Considering the SOFC technology, if the heat from high temperature exhausts is used to supply energy for a mGT, the overall efficiency can reach over 65% [11], [18]. PEMFC, on the other hand, works at low temperatures allowing cold starts and fast load variation. However, it requires hydrogen with a high level of purity as fuel that can also be obtained by a LNG reformer, which cost can be estimated around 2500 $/kg of H_2 produced [19]. The SOFCs are highlighted for many advantages such as the fuel flexibility, high efficiency, high tolerance to impurities in the fuel and not requiring expensive noble metal catalysts [19].

Micro-Gas turbines owes their origins to the military and aerospace industry and often present single-stage radial compressors and centrifugal expander with a pressure ratio around 4, single-shaft and a high frequency alternate current generator. The micro gas turbine can either operates in a simple cycle configuration (e.g. where no heat is recovered from the exhaust for preheating of the combustion gases) or with a recuperated cycle. The system efficiency is around 33% (for recuperated cycle), and the whole costs are around 1200 € per kW installed with a lifetime of 10 years [20]. The volumes and weights of this technology are smaller than those of other technologies.

Depending on the type of ship, the generation technology and the power system configuration, energy storage systems (ESS) can be adopted for several purposes, from spinning reserve to peak shaving or dynamic support. Considering FCs as generation units, ESS are required in order to supply a dynamic support in case of fast load variability, due to the slow dynamics of the FCs systems. On the other hand, in the case of mGT as source of power, an ESS can be useful for load shaving, allowing the mGT to work closest to its optimal working point (i.e. between 70 - 85% of its rated power). Therefore, for both these technology, an ESS may further enhance the whole efficiency of the power generation system. Typical ESS for marine application are lithium-ion batteries, which present good characteristics for energy and power density [21]**.**

2.4. Analysis of the power generation technologies

In order to analyse and compare the various technologies and the available fuels, it is provided a comparative study between 4 different possibilities. The first one considers the use of PEMFC coupled with a steam reformer for hydrogen production. The second one studies SOFC directly fuelled with LNG. Whereas the third and the fourth, on the other hand, account for PEMFC directly fuelled with Hydrogen stored in a cryogenic tank and mGT directly fuelled with LNG, respectively [22] - [26]. The comparison is developed in terms of efficiency, costs and volumes considering generation units rated at 800 kW and working from 100 to 200 hours per mission. From this analysis it can be highlighted that, although the PEM FC has an electrical efficiency of about 45%, the coupling with the reformer leads to a significant decrease of the overall performance up to a value of 28% (e.g. as proposed in Table 1). This fact would lead to prefer the solution with mGTs, since it couples a slightly higher system efficiency, with a considerable reduced footprint. In an “efficiency perspective”, it seems evident that the most interesting solution would be the direct use of H_2 with PEMFCs or the use of NG combined with SOFCs, since they do not require the use of fuel treatment and obviate the problem of the hydrogen storages on ships that has not yet been regulated by the IMO.

Moreover, in Table 1, a comparison in terms of costs between the various technologies is presented, where also the fuel storage costs are taken into account (e.g. 0.168$/kWh for LNG stored and around 3$/kWh for Liquid H_2 stored [27]).

Table 1. Systems comparison

Technology	**Consumption**	**Fuel**	**Eff.**	**CAPEX**	**Area**	**Vol.**	**Weight**
	kg		*%*	*K€*	m^2	m^3	*t*
PEMFC	9600	H2	28	5600	165	460	150
LNG Reformer	19200	LNG					
SOFC	5000	LNG	55	2800	120	290	145
PEMFC	9600	LH2	45	3600	130	380	180
mGT	33100	LNG	35	950	75	220	85

Despite the fact that mGTs have the lower capital costs, it should be noted that the SOFCs fuelled with LNG have the lower variable costs. On the other hand, considering the solutions with PEMFC and reformer, it can be noticed that the high cost due to low overall efficiencies and large volumes leads to discard this choice for a marine application. The direct use of H_2, stored in cryogenic tanks, on the other hand leads to sensible operational costs due to the high costs of liquid H_2. From a space and volumes point of view, the mGT appears to be the most promising technology in terms of volume and weight reduction. On the contrary, the PEMFC combined with liquefied H_2 is the weightiest solutions, also requiring the largest spaces and volumes [27] - [29].

3. Innovative shipboard thermal energy recovery with DER

When referring to energy production for modern diesel electric cruise ships, the focus is usually addressed to the electrical power generation. Nevertheless, thermal energy production is also essential for a cruise ship, due to the huge number of users on board. Thermal energy is recovered form endothermic sources on board, mainly from exhaust gases from diesel generators. However, until now, the energy recovered is not sufficient to cover the total thermal energy demand in each ship's operative condition. The distribution of energy sources in each MVZ could help the recovery of thermal power and the heat generation closer to users, which may increase the global efficiency.

3.1. Thermal energy recovery systems

The innovative electrical power generation units considered allow to a heat recovery in order to exploit the thermal energy still present in the exhaust flows. Considering the mGTs, the exhaust gas temperature is around 280 °C and the system can reach a thermal efficiency of 50% and an overall efficiency of around 80% [30]. Therefore, the exhaust heat can be used in the District Heating Network (DHN) reducing the fuel consumption. On the other hand, PEMFCs exhaust temperature is around 70°C therefore the thermal efficiency is around 30%. Finally, the exhaust temperature for the SOFC is around 800°C with a thermal efficiency similar to the PEMFC one (e.g. around 30%) [31]. The choice of the best Combined Heat and Power (CHP) technology depends on the loads profile, the energy costs and the system management.

3.2. Thermal energy balance for cruise ships

The on-board thermal energy balance provides a description of the energy required by all users on board in different operating conditions, which are different from those considered for the EPLA. Five standard conditions have been defined: manoeuvring, cruising at 15kn, cruising at 20kn, cruising at maximum speed and anchor. These are also divided considering the differences between winter and summer loads. Main users on board are:

- machinery users, which mainly refers to the treatment of the fuel before being injected in engines; depending on the type of fuel used (e.g. diesel oil or LNG), systems involved and power required change significantly.
- accommodation services, thermal energy for water heating is used in hotel services for different purposes, such as laundry, galleys, cabins, swimming pools and air conditioning system.
- evaporators, which are usually considered separately due to the high amount of heat required.

A comparison between electric and thermal power demands is proposed in Table 2 considering both winter and summer conditions.

Table 2. Ratio factors between electric and thermal load power

Season	Man.	Cruising 15 kn	Cruising 22 kn	Cruising Max.	Anchor
Winter	0.25	0.9	0.25	0.2	1.05
Summer	0.2	0.7	0.2	0.15	0.75

It is to be noted that the impact of thermal energy on the global energy demand of the ship is lower when the ship is cruising, due to the high power request from the propulsion systems. However, even in these cases, thermal power must be considered.

4. Limitations and future challenges

One of the challenges related to the introduction of DERs on board of a cruise ship is their integration within the shipboard power system and the on board available spaces. In particular, due to the high complexity of a cruise vessel and the high number of systems and services present on board, finding an adequate allocation for DERs is challenging. However, when introducing DER systems on board, additional volumes on board can also be obtained by [14]:

- introducing azipods for propulsion; in this way, the space dedicated for propulsion electric motor and bow thrusters can be almost entirely recovered, as well as space allocated to power shafts,
- modifying the grid configuration, as proposed in 2.1,
- reducing the DGs rated power, since part of electrical power is generated with DERs.

Nevertheless, even with these modifications, additional space shall be created in order to provide volumes required by DERs. This can be done with a smart integrated design of both the ship platform and the on-board systems, allowing the optimization of spaces and volumes since the early phases of the ship design. Otherwise, the only solution would be reducing the number of internal cabins and other areas dedicated to hotel services (e.g. estimated in the order of 2.0 - 4.5% of the total), depending on the technology adopted. It is important also to remind that the distribution of volumes and the normative dedicated to fuel storage and treatment changes whether the main fuel is LNG, diesel oil or H_2. Concerning the on board power system, the integration of DER should be analysed considering each technical aspect such as power quality, islanded analysis and power and energy management.

5. Conclusions

The main motivations to introduce innovative energy systems on board cruise vessels have been presented and discussed. These regard not only the reduction of the environmental footprint of these ships but more in general, the possibility to drastically enhance the energy performance adopting technologies and design approaches, which have already been developed for land-based applications. In this perspective, one of the most promising approach is to redesign the shipboard power system with a DER configuration and adopt power generation technologies such as FCs, mGT and ESS.

Some limitations and challenges have been highlighted for the proposed solutions, which cover topics from the spaces and volumes to costs and normative. These limitations can be overcomes with a smart design of the ship, which should consider the integration of these solutions already in the first phases of the ship's design.

Despite the challenges highlighted for the integration on board of these technological solutions, the benefits found by combining: new generation units, fuels alternative to those traditional used (e.g. diesel oil), revised configurations of the on-board electrical system and thermal energy recovery systems can justify future studies regarding their systematic use on board cruise vessels.

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