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A Multi-Criteria Approach For Comparing Alternative Fuels and Energy Systems for Marine Applications#

GN Montagna, S Piccardo, M Rivarolo, D Bellotti, L Magistri

Thermochemical Power Group, DIME, University of Genova, via Montallegro 1, 16145 Genova (Italy)

ABSTRACT

This paper presents an algorithm to compare traditional and innovative energy systems for maritime applications, adopting a multi-criteria method. The algorithm includes a large and updated database of market solutions. Two case studies are investigated: (i) a sailing yacht (ii) and a large-size cruise ship. For case (i), Fuel Cells represent a competitive solution, in particular considering navigation in emission control areas; the installation of electrical batteries is also evaluated. For case study (ii) Internal Combustion Engines are the best solution: the evaluation of alternative fuels (LNG, ammonia, methanol) is performed, also in dual-fuel configuration.

Keywords: alternative fuels, advanced energy technologies, maritime transportation, energy systems, energy storage, fuel cells.

NOMENCLATURE

Abbreviations	
CH2	Compressed Hydrogen
CO_2	Carbon Dioxide
ECAs	Emission Control Areas
FCS	Fuel Cell System
FO	Fuel Oil
GHG	Green House Gases
H_2	Hydrogen
HELM	Helper for Energy Layouts in Maritime applications
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LH2	Liquid Hydrogen
LNG	Liquid Natural Gas
MDO	Marine Diesel Oil
MeOH	Methanol
mGT	Micro Gas Turbine
MH	Metal Hydride Hydrogen
NH_3	Ammonia
NOx	Nitrogen Oxides
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
SOx	Sulfur Oxides

1. INTRODUCTION

It is a matter of fact that Green House Gases (GHG) emissions have dramatically increased in the last twenty years, up to the record value of 33.6 Gtons of CO_2 in 2019 **Errore. L'origine riferimento non è stata trovata.Errore. L'origine riferimento non è stata trovata.**. Electricity and heat production and transport are the most impacting sectors, with 14.1 and 8.2 Gtons respectively. Recent international energy policies have contributed to reducing CO_2 emissions, i.e., in EU-28 from 3.9 Gtons in 2007 to 3.0 Gtons in 2019. However, while the reduction in electricity and heat production has been significant (from 1.5 Gtons in 2007 to 0.9 Gtons in 2019), the transportation sector has remained constant (0.9 Gtons), making it the most impacting voice in terms of CO_2 emissions at EU-28 level today. Within the transportation sector, the impact of the maritime sector is significant, with an increase in terms of CO_2 from 962 Mtons to 1056 Mtons (+9.6%) from 2012 to 2018 **Errore. L'origine riferimento non è stata trovata.**.

Nowadays, nearly 99% of operating maritime vessels adopt the Internal Combustion Engine (ICE) technology for propulsion; considering the state-of-the-art technology, they are fed by Heavy Fuel Oil (HFO) or Marine Diesel Oil, (MDO), with a significant impact in terms of CO_2 and local pollutants, i.e., NOx, SOx and particulate matter [3]. The International Maritime Organization (IMO) set many regulations in recent years to limit emissions, with the creation of many Emission Control Areas (ECAs) for sulphur and nitrogen oxides limitation, in particular in coastal areas [4][5]. IMO also sets an initial strategy in 2018 (an updated version will be published in 2023), aiming at reducing CO_2 emissions per transport work by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008 [6].

To reach these targets, the introduction of low-carbon fuels and innovative technologies is mandatory. The replacement of HFO with LNG fueled engines is the first step but not sufficient [7][8][9]. Thus, other alternative fuels, i.e., ammonia and methanol, to be used in ICEs also in combination with other fuels, have been investigated recently [10-15]. In parallel, the use of Fuel Cell Systems (FCSs) onboard has been investigated; among FCSs, low-temperature PEMFC has been identified as the most promising, also integrated with batteries for hybrid propulsion [16-22]. FCSs are characterized by several interesting features for application in transports, namely: (i) high efficiency, also at partial loads; (ii) low emissions, noise, and vibrations. However, FCSs are currently available on the market for limited powers only (1 MW), thus they cannot provide propulsion onboard large-size ships.

As many technologies for both propulsion and energy storage onboard are commercially available and the interest in low-carbon innovative technologies is growing fast, it is important to compare all the possible solutions to find the most interesting ones, also taking into proper account the vessel type and the application.

In this paper, a method for a preliminary evaluation of the solutions currently available on the market is described. The presented approach calculates the values of many relevant parameters for the main available technologies, thanks to a large database implemented inside the software, based on updated market data for each technology for energy production and storage. The algorithm is based on a multi-criteria decision method [23-26].

2. ALGORITHM DESCRIPTION

HELM software is based on a wide database including power generators and suitable storage systems. Fig.1 shows the software flow chart which describes the algorithm. Initially, HELM needs some principal inputs to identify the case study: vessel type, vessel dimensions, energy demand (required power and operational hours), navigation type, and ECA's navigation. Also, there are other inputs related to the different energy solutions, such as energy convertor's efficiency, batteries support power demand, as well as substitution ratio for dual-fuel ICE. Once the inputs are defined, for both power generation and storage systems, HELM creates a set of maps with different information, expressed as a power function. These maps, that have been defined on a wide available market data analysis, are the core of the HELM tool. The obtainable information is related to some main key-parameters: volume, weight, and costs for different sizes, and emissions evaluated case by case and related only to the power generator system.

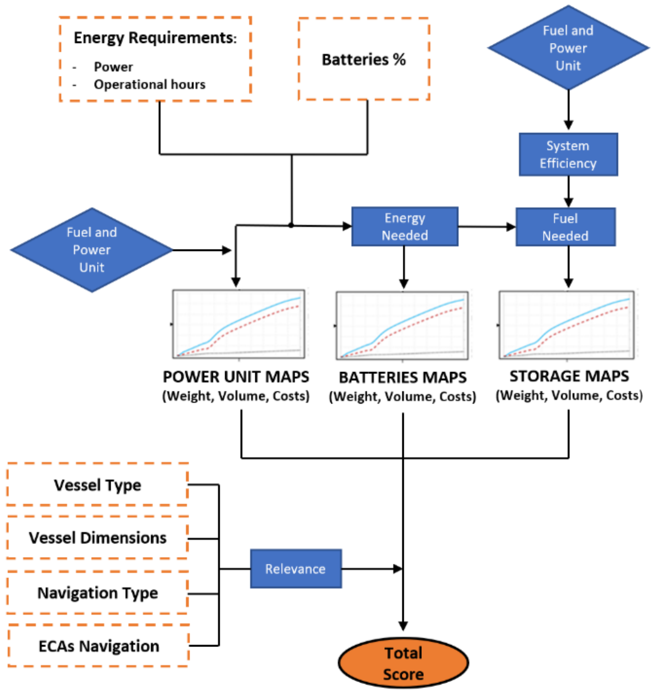

Fig. 1 Algorithm flow chart

After the key-parameters definition, HELM carries out a comparison process through the score evaluation for each key-parameter (represented by i-index in the following formula) and technology solution (represented by j-index in the same following formula). As shown in Tab.1, scores are defined on X_{ij} value basis. This variable correlates a generic key-parameter related with generic technology (v_{ij}) with the same parameter related to the best solution $(v_{best})_i$, according to the following relation [26]:

$$X_{ij} = \frac{v_{ij}}{(v_{best})_i}$$

Value (X_{ij})	Score (S_{ij})	Value (X_{ij})	Score (S_{ij})
$1 < X_{ij} \leq 1.1$	10	$3 < X_{ij} \leq 4$	5
$1.1 < X_{ij} \leq 1.3$	9	$4 < X_{ij} \leq 5$	4
$1.3 < X_{ij} \leq 1.6$	8	$5 < X_{ij} \leq 6$	3
$1.6 < X_{ij} \leq 2$	7	$6 < X_{ij} \leq 8$	2
$2 < X_{ij} \leq 3$	6	$X_{ij} > 8$	1

Tab. 1 Scores in function of the X_{ij} range of certain output variable

Based on the user inputs, HELM assigns a relevance for each key-parameter (R_i) (with the exception of the cost relevance, defined by the user). The relevance is a sort of weight that gives different importance to the different parameters. Their value ranges from 1 to 5 and multiplies the corresponding score. In conclusion, a total score for every technology is calculated and displayed on HELM interface as final output through the following formula:

$$(Tot.Score)_j = \sum_i (S_{ij} \cdot R_i)$$

One of the greatest advantages of HELM, besides its ease of use, is that its database is constantly updated to provide reliable data and solutions able to consider even the most recent technologies in the maritime sector, with also the possibility of analysing hybrid solutions. It is possible to include a new technology simply by inserting the maps in the program code. Technology solutions currently deployed are reported in Tab. 2.

Energy Generation system	Fuel Storage system
PEMFC	MH2
	LH2
	CH2
SOFC	LNG
mGT	
ICE	LNG + MDO
	MeOH + MDO
	NH3 + MDO
	MDO
	NH3 + H2

Tab. 2 Technologies implemented in HELM database

3. CASE STUDIES

3.1 Small size case study: sail yacht for leisure usage.

The first case study is based on a sailing yacht for cruise and race mainly designed for the Mediterranean sea, the Pelotari project launched in April 2019. It is long 20 meters, large about 5 meters and equipped with a diesel engine, but the same shipyard which build it, has just started with the design of a similar yacht fully carbon-free, powered by hybrid system PEM fuel cell and batteries.

To carry out the analysis, a study of the operative profile has been done. For this kind of vessel, generally used for coastal navigation, it has been considered a required power of 30 kW provided for 10 hours. For PEMFC solutions, it has been considered a batteries' percentage equal to 50%.

After the determination of the kind of vessel and the energy demand, the navigation characteristics have to be set. This yacht is a leisure boat and generally it operates near the coast, so the emission reductions are most important. Also, sometimes it may sail inside the ECAs, where the NOx emissions are limited. This led to CO_2 and NOx relevance equal to 5 and 3, respectively. In general for sail boats, in terms of propulsion system, the volume reduction is more important than the weight. Therefore, the relevance for weight is 3 while for volume is 4. In Tab.2 are shown the relevance values.

Cost Rel.	Volume Rel.	Weight Rel.	CO2 Rel.	NOx Rel.
2	4	3	5	3

Tab. 2. Relevance defined for small size case study (Pelotari).

3.1.1 Simulation Report

The first case study results are shown in Fig. 2. It can be seen that, up to now, the best solution remains the internal combustion engine fuelled by marine diesel oil. Due to the MDO high energy density, its storage simplicity and the ICE-MDO maturity, this technology allows to have a simple storage system having low volume, weight and cost, especially for this small vessel where there isn't a pre-treatment fuel system. Together with a high relevance on volume (set equal to 4), this solution obtains a high score mainly thanks to the volume score. Also weight and cost scores are higher than that of the other solutions. Despite these advantages, the CO_2 and NOx emissions are the ICE-MDO weakness. Having an high score on CO_2 emissions and a moderate score on NOx emissions, their contributes on total score are lower in comparison to other technologies. The others best solutions for this case study are PEMFCs fuelled by hydrogen which is stored in pressure (CH2 at 250 bar) or through metal hydrides (MH). Nevertheless this two solutions requires more space and they are heavier and more expensive than ICE-MDO. Also PEMFCs fuelled by liquefied hydrogen (LH2) have a good score but storage system, needed to keep hydrogen in liquid form, is too complex and too energy demanding for this case study. For this reason it has been excluded from the current analysis. Other technology solutions have lower scores, therefore they not been taken in account.

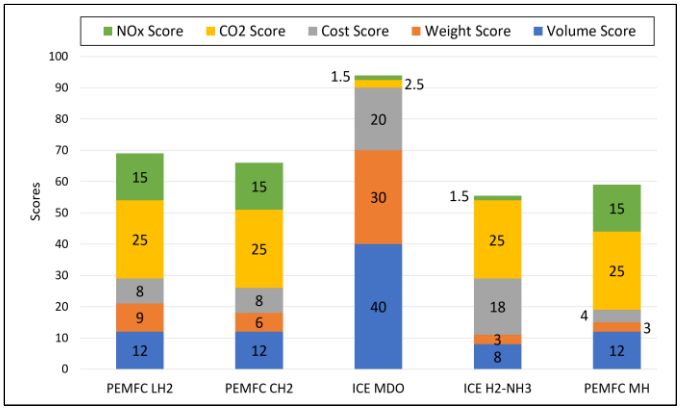

Fig. 2. Comparative HELM results for small case study

Fig. 3 shows the differences between the three best solutions in terms of volume, weight and cost. In terms of total volume, PEMFCs-CH2 and PEMFCs-MH are approximately equivalent and they have the same trend about volume distribution between storage system, generator and batteries. The main part of total volume is represented from batteries, which satisfy 50% of total required power for both cases. To store the same fuel amount, weight assumes higher values for PEMFCs-MH. This is mainly because metal hydrides are heavier than pressurized storage system. Indeed for PEMFCs-MH the most part of weight is represented by storage system, conversely to PEMFCs-CH2, for which generator system weight is the prevalent item. For both cases fuel weight isn't very relevant on total balance because of the low hydrogen density, even if compressed at 250 bar. Despite MH higher weight, it becomes one of the best solutions for this vessel type, because sailing yachts needs righting system as the dead weight. Cost is higher for PEMFCs-MH compared to PEMFCs-CH2 mostly because of high metal hydrides storage system price. For this solution storage system represents again the main item on total cost while for PEMFCs-CH2, batteries are the leading item. Fuel cells generator and batteries are the same for both previous cases but they weights in different manner on total volume, total weight and total cost beacause of different absolute values.

As total values show (Fig.3), ICE fuelled by MDO is confirmed as the best solution in terms of volume, weight and cost, even if pollutant emissions worsen. This solution doesn't use batteries foreseen for PEMFCs, involving a further advantage on previous key parameters. As shown in Fig.3, for this solution, generator represent the biggest part of total volume due both to the small amount of fuel needed and the ease of your storage system, which doesn't require any particular features: MDO is stored at ambient pressure and temperature. For small sizes the main part of total weight is represented by generator, followed by fuel contribute. MDO has a density aboundantely higher than hydrogen, therefore weight represent a fair part of the same total parameter. Due again to the storage system simplicity, total cost is mostly represented by generator.

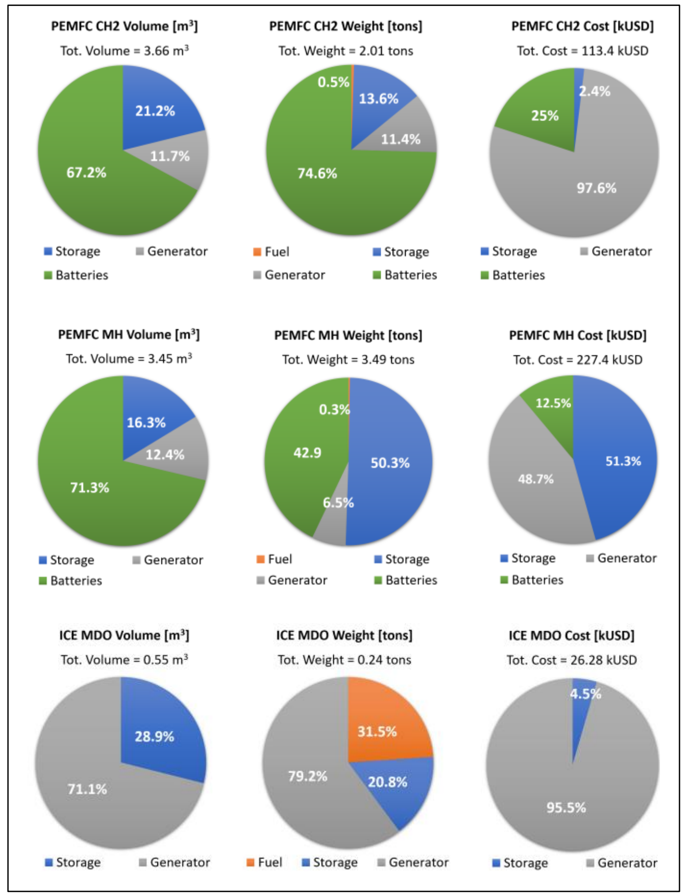

Fig. 3. Propulsion and storage systems comparison for the best technologies

3.2 Large size case study: cruise ship, Costa Smeralda.

The second case study is related to largest cruise ships currently in operation and belonging to the Italian company "Costa Crociere". It has an overall length of about 340 meters, a beam equal to 42 meters and it can accommodate more than 6500 passengers. This ship is currently powered by LNG through four Dual Fuel ICEs capable to provide a maximum power of 15440 kW each.

To carry out the comparative analysis between different technologies, a required constant power equal to 21 MW, has been assumed. Autonomy has been estimated in 300 hours by knowing the fuel volume and the required power.

In addition to the type of vessel, the vessel dimensions and the energy demand, the navigation features need to be defined as input. This ship operates mainly in national water areas and often in zones where NOx emissions are limited. Regarding the cost cost relevance a value equal to 4 has been set, since cruise ships are intended to produce profit, considering the high construction costs. In this kind of ships the need of spaces saving is more important than onboard weight. For this reason, as shown in tab.3, volume and weight relevance have been set equal to 4 and 3, respectively. Due to the considered navigation type and ECAs navigation inputs, CO_2 and NOx relevance have been assumed equal to 5 and 4, respectively, in accordance with cruise ships environmental requirements [27]. All relevance values are shown in Tab.3.

Cost Rel.	*Volume Rel.*	*Weight Rel.*	*CO2 Rel.*	*NOx Rel.*
4	4	3	5	4

Tab. 3. Relevance defined for large size case study (Costa Smeralda).

3.2.1 Simulation Report

The analysis results for the cruise ship are reported in Fig 4.

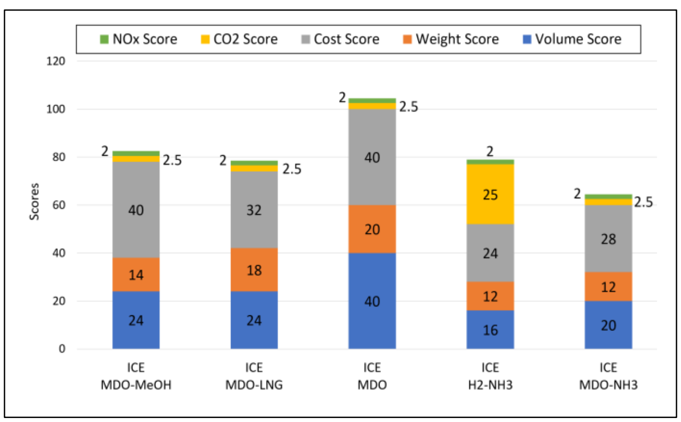

Fig. 4. Comparative HELM results for large case study (Costa Smeralda).

The best solution is represented by ICE fuelled by MDO. Large cruise ships require high power values which can be achieved using conventional fuel inside ICEs. This is because MDO has the highest energy density and, being liquid at ambient pressure and temperature, it doesn't need any particular storage systems. For these reasons, MDO storage system volume is lower than the one required by alternative fuel solutions, which need an additional smaller pilot fuel volume. A high value on this relevance (set equal to 4 for cruise ships) defines a good score for the same key-parameter, taking this solution at the first place. An equal score is obtained for the cost of this solution. This is mainly due to the ease to store this fuel which doesn't require any particular expensive system. Another competitive solution is represented by ICE fuelled by MeOH and MDO as pilot fuel with a MeOH-MDO substitution rate equal to 95% [28-32]. In this case Fig.4 shows a good result in terms of cost score. Methanol is liquid at ambient pressure and temperature and it can be stored in structural tanks which don't require expensive technologies. Volume and weight scores are lower than the MDO case because methanol has a low energy density and this involves the need of a larger fuel amount to achieve the same power. A similar total score is obtained for ICE fuelled by NH_3 blended with H_2. In this technology hydrogen is extracted from ammonia by a cracking process with a NH_3-H_2 substitution rate equal to 95% [33-36]. This solution appears the best one mainly due to the low CO_2 emissions (resulting in a high score). However, this technology presents a low TRL, and a regulatory framework is still missing . For this reason, it is likely that in the next future design guidelines will require further components for the fuel handling and treatment, currently not considered. This could negatively affect the volume score. Fig. 5 shows the percentage distribution of the storage and generator volume, weight and cost on total values for the three best solutions. For each solution the most part of the volume is occupied by the storage system in particular for the alternative fuel solutions which need more space due to the lower energy density. In accordance with volume, the most part of the total weight is rapresented by stored fuel, in particular for methanol case. This is due to its density, similar to that of MDO along with the need to store a bigger fuel amount. For ICE fuelled by NH_3 and H_2, storage weight represents a good contribute on total weight. This fuel is stored at low temperature (-33°C), therefore it is necessary to use particular tanks which increase weight. In this case both total volume and total weight are slightly increased by the cracker system installed onboard. Cost present the same trend for the first two solutions due to the similar storage systems and generators. A slight increase of the storage cost percentage is justified once again by a bigger amount of fuel which need a larger storage system. For the NH_3-H_2 technology cost increases as a result of both cracker system installed on board and storage tank capable to keep ammonia at liquid state.

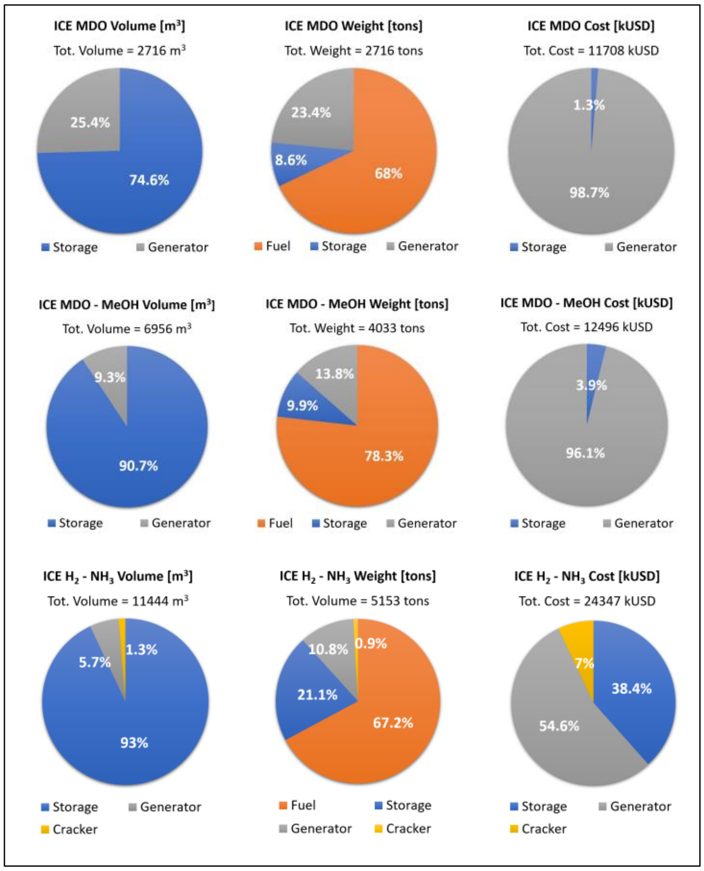

Fig. 5. Propulsion and storage systems comparison for the best technologies (Costa Smeralda).

4. CONCLUSIONS

This paper investigated the potentiality of the software HELM, which identifies the most suitable power system to be used in specific applications in the maritime field. Two applicative cases have been investigated.

In the first case study, a private yacht sailing in coastal areas generally, where the reduction of emissions has a high relevance, was considered. The simulation suggested the use of hydrogen-fueled PEMFCs as an excellent alternative to traditional FO engines. To investigate a different condition, the second case study is a large cruise ship operating in the National water, where the emissions control is still relevant, but the volume and weight reductions are more important. In this case, ICE is identified as the best technology due to the more stringent limits on volume and cost. However, a very good alternative to MDO is a different fuel as LNG, which allows for a reduction in CO_2, NOx, and SOx emissions.

The case studies analyzed are only two of all those considered during research activities conducted by the authors' research group. The decisional criterion has been tested in many cases, always returning likely results, proving the reliability of the algorithm. Furthermore, by inserting technologies with reduced environmental impact in the HELM database, the software shows unconventional options suitable for particular applications, in order to move towards decarbonization in the maritime field and a more sustainable future.

4.1 Ongoing upgrades

The software is going to be enhanced to have a more relevant result for the maritime applications.

The inputs are important as well as the formulas because they identify the case study, so they are the first to be upgraded. Currently , the studies are concentrated on the test of the multi-criteria method in order to avoid the ranking problems, but the most important improvements will be toward to define the characteristics of the energy demand and to include more parameters, in order to analyze all ship power system's impacts on vessel, people, and environment.

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