A Multi-Criteria Design Tool for Performance Comparison of Innovative Energy Systems for Maritime Sector

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A multi-criteria design tool for performance comparison of innovative energy systems for maritime sector

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Abstract. This paper describes a multi-criteria tool for the performances comparison of alternative and conventional on board energy systems for maritime sector, both for hotel and propulsion loads, depending on the mission taken into account. The tool, named HELM (Helper for Energy Layouts in Maritime applications), carries out this analysis based on an extended and up-to-date market database of many technologies in terms of power units and suitable fuel storage systems. A wide range of maps has been created, correlating costs, volumes, weights, emissions and fuel environmental hazards with the installed power and the operational hours, given by the user as input. In this work, different maritime vessels typologies are investigated and the choice of the best solution is performed for each one, considering the single evaluation parameters. It is worth noting that the multi-criteria analysis carried out has a general approach, allowing it to give preliminary information on the energy system, in order to respect new requirements (e.g. more and more stringent normative in terms of pollutant emissions in ports and restricted areas). HELM can be used for many design approaches, either for a new ship project or for already existing ships retrofit; furthermore, the database can be easily extended to other generation and storage technologies.

1 Introduction

As the importance of decarbonizing many energy sectors, including transport, is becoming a key target, the International Maritime Organization (IMO) set an official strategy for maritime sector in 2018 [1], targeting CO_2 significant reduction for 2050 (-50% compared to 2008). To fulfil the decarbonisation target, many strategies are possible, including use of alternative fuels and innovative technologies [2-4]. The replacement of commonly used, Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO) with liquefied natural gas (LNG) in internal combustion engines (ICE) is only the first step and many companies are pushing the study of other fuels, such as methanol [5] and ammonia [6]. Regarding energy production technologies, the investigation of fuel cells [7], both low-temperature PEM Fuel Cells (PEMFC) fed by pure hydrogen [8-10] and high temperature Solid Oxide Fuel Cells (SOFC) fed by LNG [11-12], is performed in many research projects.

As the interest in low-carbon innovative technologies is growing fast and many alternatives are possible, it is important to have tools and decision instruments to help comparing all the possible solutions [13-14], also taking considering the vessel type, the application and the constraints. In this paper, the authors present an in-house software tool, named HELM (Helper for Energy Layouts in Maritime applications), developed by Thermochemical Power Group at University of Genoa, for preliminary evaluation of the commercially available solutions [15]. The presented approach considers many evaluation parameters (weight, volume, cost, and environment) for the main available technologies, thanks to a large and updated database implemented in the software.

2 Algorithm Description

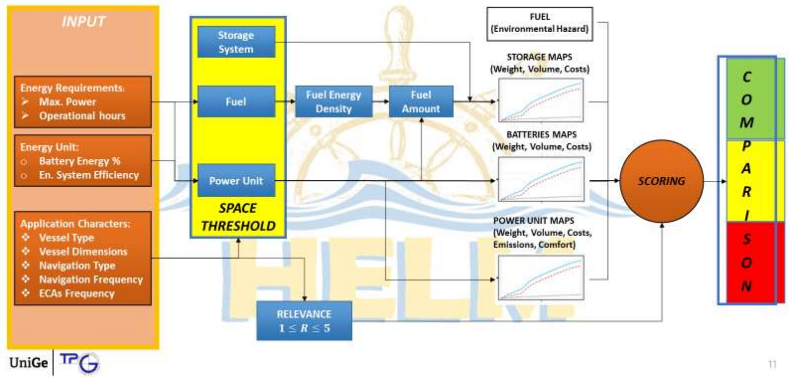

Fig. 1. Algorithm description.

In maritime applications, the evaluation of the most promising technologies must consider different aspects simultaneously (i.e. costs, emissions, volumes and weights); in order to reach reliable results, the inputs must describe the vessel and the navigation properly. As shown in Fig. 1, HELM software adopts this approach, based on the multi criteria numerical method [15].

The needed inputs are: vessel type and dimensions, energy demand (required power and operational hours), navigation frequency and type, and permanency in emission-controlled areas (ECA). These inputs generate a numerical description of the case study. Moreover, the energy solutions are accurately described with other related data: power unit efficiency, battery support in satisfying energy demand, as well as substitution ratio for dual fuel ICE and CH2 storage pressure.

Once the inputs are defined, for both power generation and storage systems, HELM employs a comparison based on the constantly updated market data. The characteristics are identified as key parameters and they are collected in a set of maps in HELM. Volumes, weights and costs are directly linked to the power unit, while the fuels drive emissions and environmental hazard values. Based on multi criteria method, HELM carries out the comparison process with a score evaluation of all technologies as a sum of key parameters. The numerical approach presented in Eq. (1) is the weighted sum, where the weights are the relevance (R_i) for each parameter, in the range 1 – 5, depending on the application and the vessel type.

$$Tot\ Score_j = \sum_i \left(\left(coeff_i \cdot \frac{v_{ij}}{v_{best_i}} \cdot Decr_j \right) \cdot R_i \right) \quad (1)$$

Where:

- i-index represents the i^{th}parameter
- j-index represents the j^{th} energy system

The numerical comparison is the ratio between a generic solution $\left(v_{ij}\right)$ and the best one (v_{best_i}) and it is performed for all the criteria. A coefficient $(coeff_i)$ is introduced to give the same and reasonable importance at each measure, even if emissions and environmental hazard are sum of sub parameters (e.g. CO_2 and NOx for emissions). Moreover, for some parameters the best value $(v_{best})_i$ are zero and to avoid the mathematical problems, two numerical correction are introduced: at the best value equal to zero is assigned the maximum score directly and, in order to guarantee the ranking given by the ratio, it is introduce the decreasing factor (a ratio between the minimum and the maximum positive values, Eq. (*2*).

$$Decr_j = 1 - \left(\frac{min_i}{max_i}\right) \tag{2}$$

Following the commonly used design process, to investigate on the energy field in maritime sector, the useful measures are: weight, volume and cost. To consider the environmental impact, two parameters are evaluated: emissions (mainly CO_2 and NOx) and the environmental hazard, in case of fuel outboard spillage.

Besides its ease of use, one of HELM greatest advantages is its large and up-to-date database, able to provide reliable information for all the solutions, including the most recent technologies in the maritime sector. Its modular structure allows including a new technology by inserting its performance maps in the program code, developed in Matlab. The technology solutions currently included are shown in Fig. 2.

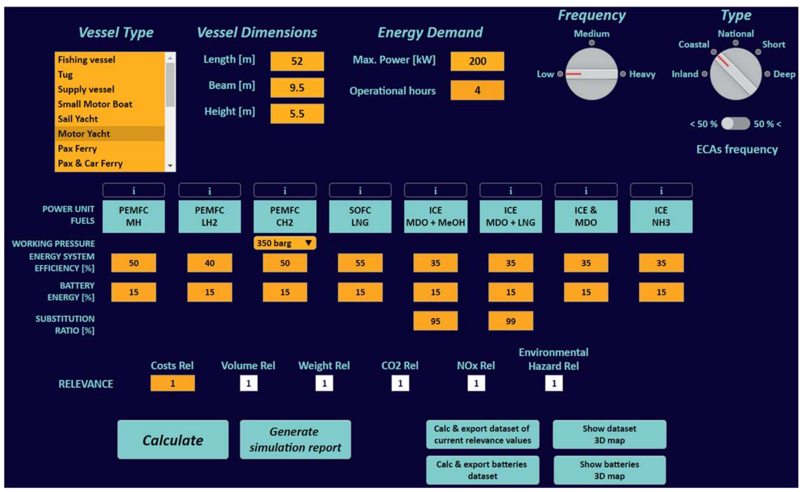

Fig. 2. Input setup.

3 Case Study

Two different case studies are investigated in this paper: the first one is related to the propulsion system for a research vessel, while the second considers the energy demand for hotel load for a yacht.

3.1 ZEUS research vessel

The research vessel is the first Italian ship with hydrogen fuel cell propulsion, named ZEUS (Zero-Emission Ultimate Ship), designed by Fincantieri S.p.A. and powered by PEMFC and batteries [8]. The propulsion system is based on 2×71 kW PEMFC fuelled by hydrogen stored into 48 Metal Hydride tanks (H_2 capacity around 45kg), hybridized with 150 kWh stored energy in Li-ion batteries. The vessel was officially launched in 2022 [16]. The investigated vessel has 25 m length and weighs 170 tons. Since the vessel operates in inland water, emission relevance is high, while cost importance is minimum as the ZEUS was developed in the research project *TecBia* [8]. Tab. 1 reports the main features.

Table 1. Simulation inputs (ZEUS characteristics and relevance)

Vessel Type	Research vessel	**Cost REL.**	1
Vessel length	25 m	**Volume REL.**	2
Max. Power	140 kW	**Weight REL.**	1
Operational hours	7 h	**CO_2 REL.**	5
Batteries Energy (FC)	15 %	**NOx REL.**	5
Navigation Type	Inland	**Env. Haz. REL.**	5

Fig. 3 shows the energy systems comparison results obtained through the HELM tool. For this application, the most promising solutions are represented by PEMFC fuelled by hydrogen and hybridized with Li-ion batteries. Compressed hydrogen (CH2), liquid hydrogen (LH2) and metal hydrides (MH) are considered as fuel storage systems. Due to the only water emission, PEMFC maximize CO_2 and NOx emission scores and obtain good values in terms of weight as well. In case of MH utilization for hydrogen storage, weights are significantly higher. Traditional solution (ICE MDO) is superior from volume, weight and cost standpoints; however, it is negatively affected by low environmental score, which is the most relevant for this application. It is worth noting that, since both power and autonomy are quite low, the amount of hydrogen to be stored on-board is limited, making the solution sustainable.

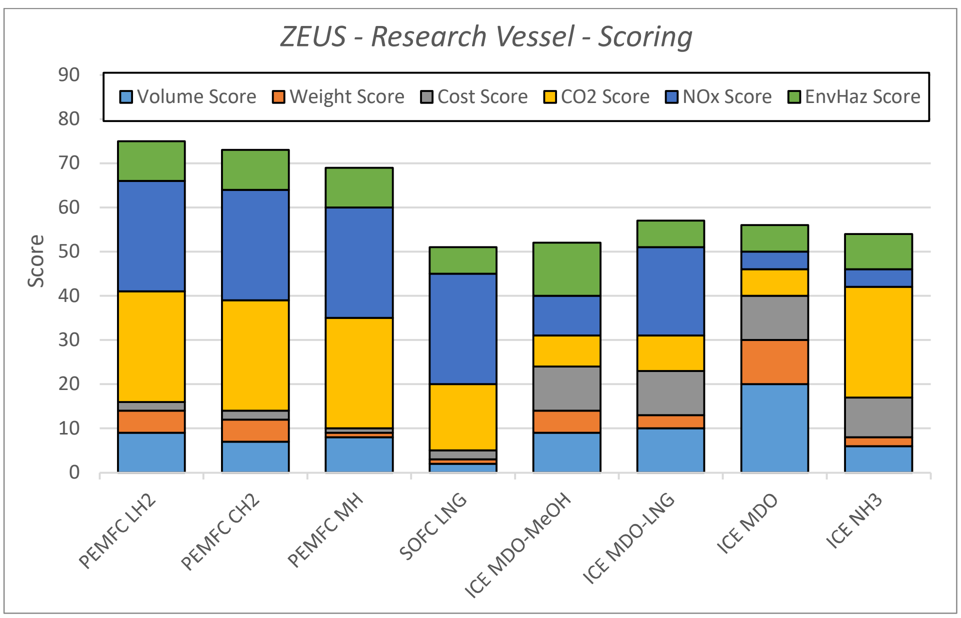

Fig. 3. HELM scores for ZEUS research vessel.

Due to hydrogen solutions scores proximity, a deeper analysis is performed comparing absolute volume, weight, costs and emissions values, referred to complete systems (

Table **2**). Since power units are the same, differences between three technologies depend on the storage system. LH2 maximizes volumetric energy density, reducing system volume; concerning weight, values are similar to 350 bar CH2 results. This is due to weight of tanks capable to maintain cryogenic conditions (– 253 °C) for LH2 storage. MH technology is more critical in terms of weight and costs but it represents an easier and safer hydrogen storage method in comparison with previous ones. High pressures or cryogenic conditions are avoided, making MH the best solution for reduced spaces in a real on-board integration scenario, compatibly with case studies weight and cost relevance.

Table 2. Volume, weight, costs and emissions absolute values for ZEUS best technologies.

Technology	**Tot. VOL [m^3]**	**Tot. WGT [tons]**	**Tot. Cost [k$]**
PEMFC LH2	5.2	2.8	1,506
PEMFC CH2	6.4	2.6	1,471
PEMFC MH	6.3	10.8	2,909

3.2 Auxiliary Propulsion Unit (APU) of Super Yacht

In the second case study, HELM is used to analyse the hotel load of a super yacht line from Baglietto shipyard [17], built with a large battery pack used mainly as APU. To increase the electric autonomy, the shipyard develops the real scale prototype of the hydrogen system that can be installed on board. The considered power unit for this application is a 200 kW PEMFC system with 70 kg H_2 stored in metal hydrides, and 198 kWh battery pack.

In an APU analysis, every systems have a 15% of energy provided by the battery. The analysis' set up is described in **Table 3**.

Table 3. Simulation inputs (Motor Yacht characteristics and relevance).

Vessel Type	Motor Yacht	**Cost REL.**	1
Vessel length	52 m	**VOL REL.**	3
Max. Hotel Power	200 kW	**WGT. REL.**	3
Operational hours	6 h	**CO2 REL.**	5
Batteries Energy	15 %	**NOx REL.**	5
Navigation Type	Coastal, ECAs >50%	**ENV HAZ REL.**	5

Fig. 4 shows that the PEMFC is a promising technology for APU, in a scenario with high environmental interest. In case of compressed or liquid H2 storage, the scores are higher than the one for traditional solution (ICE MDO), because they are quite competitive also in terms of weight and volume, despite they cannot reach the state-of-the-art solution levels. However, considering the operative condition for this case study as a leisure vessel, refrigerated storage systems as LNG and LH2 are not considered adequate, since they foresee complex systems and they need continuous monitoring by specific personnel.

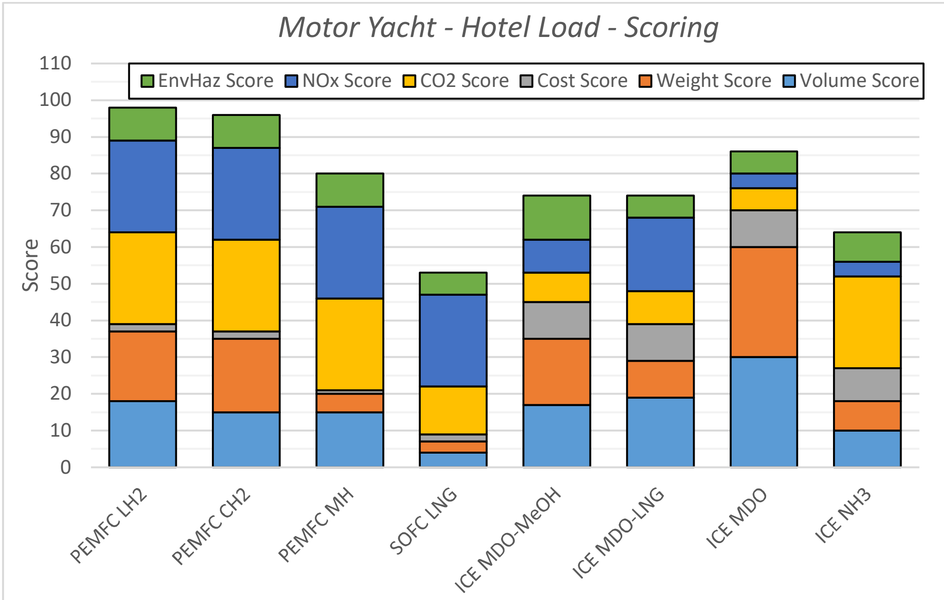

Fig. 4. HELM scores for Motor Yacht Case Study.

The comparison in terms of weight, volume, costs and emissions' absolute values for the most promising solutions is reported in Table 4. For metal hydrides, the main disadvantages are high weights and costs; therefore, CH2 storage seems to be the better alternative to the diesel engine. However, the shipyard chooses metal hydrides technology, for safety reasons, as low working pressures (maximum 40 bar) are required for this system. Moreover, metal hydrides powders can be directly refilled from electrolyser, without energy consumption for fuel compression or liquefaction.

Table 4. Volume, weight, costs and emissions absolute values for Motor Yacht's best technologies.

Technology	Tot. VOL [m^3]	Tot. WGT [tons]	Tot. Cost [k$]	Tot CO2 [kg]	Tot NOx [kg]
PEMFC CH2	6.0	2.4	1,766	0	0
PEMFC MH	5.9	9.2	3,014	0	0
ICE MDO	3.1	1.6	338	560.6	6.6

4. Conclusions

In this paper, zero emissions technologies for both propulsion and hotel loads systems are compared with traditional state-of-the-art solutions (i.e. ICE fuelled by MDO), considering weights, volumes, costs and emissions. The analysis is performed for two different case studies, aiming at propulsion (case 1) and hotel load (case 2) for two different vessels. In view of both case studies results, multi-criteria analysis carried out by HELM for zero emissions solutions, confirms technologies that have been chosen to be fitted on board, demonstrating the software reliability in a preliminary design feasibility stage context. As demonstrated through the analysed case studies, HELM allows extending the comparison to different vessels and scenarios, highlighting its flexibility of use. In next future, the HELM software will be investigated for applications in different contexts, to further validate it.

References

1. IMO Fourth IMO Greenhouse Gas Study. International Maritime Organization, 197–212 (2021).
2. S. Horvath, M. Fasihi, C. Breyer, En. Conv. And Man. **164,** 230-241 (2018).
3. P. Balcombe, J. Brierley, C. Lewis, et al, En. Conv. And Man, **182,** 72-88 (2019).
4. M. Prussi, N. Scarlat, M. Acciaro, V. Kosmas, J. of Cleaner Prod, **291**, 125849 (2021).
5. A. Benet, A. Villalba-Herreros, R. d'Amore-Domenech, T.J. Leo, J. of Power Sources **548**, 232066 (2022).
6. D. Bellotti, M. Rivarolo, L. Magistri, En. Conv. And Man. **260**, 115565 (2022).
7. L. Van Biert, M. Godjevac, K. Visser, P.V. Aravind, J P. Sources **327**,345–64 (2016).
8. M. Cavo, E. Gadducci, D. Rattazzi, M. Rivarolo, L. Magistri, Int. J. of Hydrogen En. **46**, 32630-32644 (2021).
9. E. Gadducci, T. Lamberti, M. Rivarolo, L. Magistri, Int. J. of Hydrogen En. **47**, 22545-22558 (2022).
10. O.B. Inal, J.-F. Charpentier, C. Deniz, Ren. And Sust. En. Rev., **156**, 111965 (2022).
11. H. Sapra, J. Stam, et al., App. En., **281**, 115854 (2021).
12. U.M. Damo, M.L. Ferrari, A. Turan, A.F. Massardo, Energy, **168**, 235-246 (2019).
13. R. Chauvy, R. Lepore, P. Fortemps, G. De Weireld, Sust. Prod. and Cons., **24**, 194-210 (2020).
14. A. Priftis, E. Boulougouris, O. Turan, A. Papanikolau, Oc. Eng. **156**, 347-357 (2018).
15. M. Rivarolo, D. Rattazzi, L. Magistri, A.F. Massardo, En. Conv. And Man., **244**, 114506 (2021).
16. A.G. Elkafas, M. Rivarolo, et al, Processes, **11**, 97 (2023).
17. https://www.baglietto.com/bzero/ [last access 20/3/2023].