THE ENERGY SYSTEMS ANALYSIS WITH A MULTI-CRITERIA DESIGN TOOL TO DECARBONIZE MARITIME TRANSPORT

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ABSTRACT

It is estimated that today maritime transport is responsible for approximately 3% of sulphur oxides (SOx), 15% of nitrogen oxides (NOx), and 2.5% of carbon dioxide (CO_2) globally emitted per year and, if no measures are taken, these numbers are going to increase significantly in the next years. In this context, the phase-out of conventional marine gas oil (MGO) engines represents a crucial measure to reduce the environmental impact of maritime transportation. 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 compare all the possible solutions for energy production and storage on board also considering the constraints related to the vessel type. This paper aims to present an innovative multi-criteria tool for the comparison of alternative and conventional on-board energy systems for maritime vessels, both for hotel and propulsion loads, depending on the mission taken into account. The tool, developed in MATLAB environment and named HELM (Helper for Energy Layouts in Maritime applications), includes an extended and up-to-date market database for many technologies in terms of power units (i.e. engines, fuel cells) and fuel (H_2, NH_3, CH_4, CH_3OH) storage systems, resumed in a wide range of maps that correlate costs, volumes, weights, emissions and fuel environmental hazards with the installed power and the operational hours, given by the user as input. The navigation route, the vessel typology, and its dimensions are also considered in the analysis to better identify the case study and the constraints. In this work, two different vessel typologies and applications are analysed to investigate the applicability of alternative fuels in maritime transportation: i) a passenger ferry and ii) a large container ship. For both cases, a sensitivity analysis of fuel market prices and taxes on CO_2 emissions is carried out to consider their impact on the economic sustainability of different solutions. It is worth noting that the multi-criteria analysis carried out has a general approach, allowing 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). Furthermore, the HELM database can be easily extended to other power generators and storage technologies, as well as to different types of vessels.

1 INTRODUCTION

The emissions of Green House Gases (GHG) are rising more and more worldwide, reaching a new record of 36.8 Gtons at the end of 2022 in terms of CO_2, +0.4 Gtons compared to 2021, while the total energy-related greenhouse gas emissions increased by 1.0% to an all-time record of 41.3 Gtons CO_2-eq, including also methane and nitrous oxide. Electricity and heat generation is the most impactful sector, accounting for 14.6 Gtons, followed by industry (9 Gtons) and transport (8.5 Gtons) [1]. Within the transportation sector, the impact of the maritime sector is significant, about 1056 Mtons in 2018 [2]. Nowadays, about 99% of maritime vessels in operation are powered by Internal Combustion Engines

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(ICE); 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 pollutants, i.e., NO_x, SO_x and particulate matter [3]. The International Maritime Organization (IMO) set many regulations in the last twenty years to limit emissions, with the creation of many Emission Control Areas (ECAs) for sulphur and nitrogen oxides limitation, in particular in coastal areas. In July 2023, the IMO adopted a revised version of its GHG emissions strategy [4], which targets emissions from international shipping to reach net zero by or around 2050. Member states agreed to "indicative checkpoints" that call for reducing total GHG emissions by 20% and striving for 30% by 2030 and 70% by 2040, compared to 2008 levels. In April 2023, the European Parliament adopted a reform of the EU Emission Trading System (ETS), to control CO_2 emissions from the shipping sector, for large vessels, above 5000 gross tonnage. Each company with ships trading in the European Economic Area will be required to surrender emission allowances corresponding to a certain amount of its GHG emissions over a calendar year, starting from 2024 [5]. To reach the new targets set by IMO, the introduction of low-carbon fuels and innovative technologies is a key point. The replacement of HFO with LNG [6] and methanol [7] fuelled engines is a first step but not sufficient. The introduction of zero-carbon fuels, i.e. ammonia and hydrogen, to be used in ICEs also in combination, can be another worthy solution, as investigated by many authors [8][9][10]. In parallel, the use of Fuel Cell Systems (FCS) onboard has been investigated, since they 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. Elkafas et al. [11] recently highlighted that the most promising technologies are low-temperature PEMFC fed by pure hydrogen and high-temperature SOFC as auxiliary power units for the hotel load. The utilization of PEMFC in the maritime sector has been investigated widely in the last few years, focusing on many aspects related to feasibility studies [12], experimental tests [13], dynamics, and control [14]. Investigation on SOFC has been focused on hybrid systems [15] and fuel flexibility [16]. 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. Software tools able to perform multi-criteria analysis comparing many energy solutions for different maritime vessels have been developed in recent years by Helgason [7], Pesce [17], Aspen [18], Iannaccone [19], and Zanobetti [20]. The Authors' research group also developed a software, named HELM (Helper for Energy Layouts in Maritime applications), presented in [21][22], to perform a multi-criteria sustainability analysis, based on specific indicators addressing the technological, economic, environmental, and safety performance of energy systems and fuel storage onboard. In this paper, an updated version of the HELM software is presented and applied to two different case studies. In the first case, a comparison between PEMFC and SOFC high-efficiency technologies is performed for 500 kW to satisfy the hotel load for a medium-size Ro-Pax vessel; in the second, the use of ammonia as alternative zero emission fuel for large-size internal combustion engines is evaluated as decarbonization option for large ships. The paper is organized as follows: section 2 describes the HELM multi-criteria design tool and the database for the main technologies; section 3 presents the two case studies, the main assumptions, and simulations' results; section 4 presents the main conclusions and future steps.

2 MULTI-CRITERIA DESIGN TOOL

2.1 HELM tool approach

The goal of the HELM software is to compare different technological solutions for power generation on maritime applications, and it can be applied to both newly built vessels or retrofitting. This comparison is based on a multi-criteria approach. Starting from a large number of inputs (application characteristics, energy requirements, energy systems), the software compares the solutions and assigns a score for each technology and evaluation criterion. The relevant criteria that are considered to evaluate

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different energy systems onboard are volume, weight, GHGs (CO_2 and CH_4, due to methane leaks) and NOx emissions, costs, environmental hazards, and noise. They are defined by means of both maps, which correlate energy requirements inputs with key-parameter (or evaluation criterion) values, and relevance, depending on the application characteristic inputs. After this evaluation process is completed, results obtained by single criteria are summed, identifying a total score for each solution and finalizing the comparison analysis. According to **Figure 1**, many inputs are required to start the comparative analysis. They are divided into two main categories. The first ones (main inputs) represent the features of each energy system, the power demand, and the autonomy: they are used to define the size of each device. This information is then used as input for the maps in order to provide the results in terms of key parameters. The second category (other inputs) characterizes the case study in terms of vessel type and dimensions, navigation type, and ECAs permanency. These inputs are used to determine the relevance of each criterion, considering vessel type, navigation route, and information obtained from different stakeholders. Weight and volume relevance are defined from the ship type: vessels for which weight is more limiting than volume (e.g. ore carriers) are characterized by an higher weight relevance, and vice versa. On the other hand, emissions and environmental hazard relevance are related to their type of navigation route: for vessel navigating inside sensible or emissions-regulated areas, previous relevance reach higher values. Lastly, due to standardization difficulty, cost relevance does not depend on the ship type, but it needs to be defined directly from the user. Relevances are used to weight the different evaluation criteria, from a minimum of 1 to a maximum of 5.

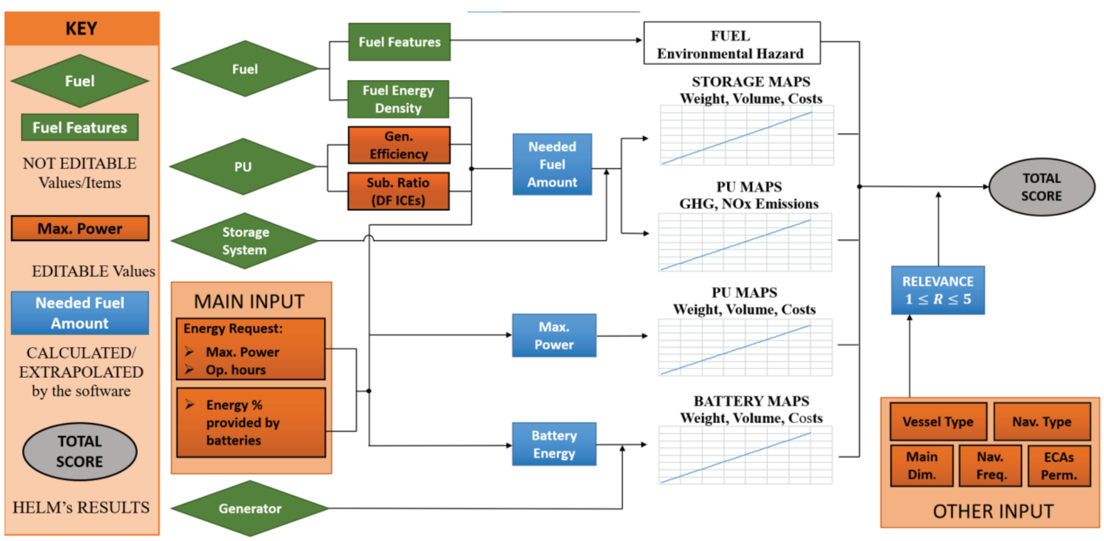

Figure 1: HELM flow chart.

For more details about HELM, the reader is referred to [21][22]. The following paragraph will present the most recent updates, in particular regarding the maps, which are the core of the tool.

2.2 Market analysis of energy systems and maps generation

To evaluate the different solutions, HELM relies on maps, i.e. empirical correlations sourced from data repositories of marine energy systems. Maps are the core of HELM, enabling the correlation of energy inputs to the volume, weight, cost for each technology component, and emissions for the power units. Therefore, market research was conducted to update the maps, gathering data from the most recent public datasheets of commercial products for marine power generation. The considered technologies include dual fuel (DF) methane, ammonia, methanol, and hydrogen internal combustion engines (ICEs), proton exchange membrane fuel cells (PEMFCs), and solid oxide fuel cells (SOFCs). Alternative

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energy storage systems include fuel tanks (compressed hydrogen (CH_2) liquid hydrogen (LH_2), liquefied natural gas (LNG), ammonia, and methanol) and batteries (BAT). Information on rated power, volume, weight, and rated efficiency (or equivalent BSEC) was extracted and their data was then compiled into a Microsoft Excel repository for subsequent analysis (Figure 2). Following the data collection phase, the values were compared to those obtained in a previous analysis. This was especially crucial for alternative power systems and energy storage, owing to their scarcity in terms of number of products on the market, particularly marine-ready systems. Indeed, while ICEs are a consolidated technology and a vast amount of data is available, PEMFCs and even more SOFCs count a few market-ready products. The same consideration applies, for example, to LH_2 and MH tanks. This translates into a less accurate prediction of size, weight, and efficiency correlations for such power systems.

Supplier	Model	2 strokes/4 strokes	rpm	Power [kW]	SFC [g/kWh]	L [mm]	W [mm]	H [mm]	Volume [m3]	Mass [ton]	Nox [g/kWh]
Wartsila	6L20	4T	1000	960	182.39	3108	1690	2329	12.233	9.4	2.2792
Wartsila	8L20	4T	1000	1280	182.39	3783	1824	2329	16.071	11.1	2.1518
Wartsila	9L20	4T	1000	1440	182.39	4076	1824	2329	17.315	11.7	2.1017
Hyundai (HHI)	6H27	4T	1000	1860	168.76	4414	2176	2835	27.230	21.2	1.9968
Wartsila	6L25	4T	1000	2070	164.35	4980	2120	3480	36.740	23.2	1.9546
Hyundai (HHI)	7H27	4T	1000	2170	168.76	4794	2176	2835	29.574	23.5	1.9362
Wartsila	7L25	4T	1000	2415	164.35	5380	2120	3480	39.691	25.3	1.8952
Hyundai (HHI)	8H27	4T	1000	2480	168.76	5311	2176	3241	37.455	25.1	1.8852
Wartsila	8L25	4T	1000	2760	164.35	5800	2200	3700	47.212	27.8	1.8453
Hyundai (HHI)	9H27	4T	1000	2790	168.76	5691	2176	3371	41.745	27.2	1.8413
Wartsila	6L34	4T	750	3000	165.00	5352	2389	3576	45.722	35.0	1.8148
Wartsila	9L25	4T	1000	3105	164.35	6300	2200	3700	51.282	27.8	1.8023
Wartsila	8L34	4T	750	4000	165.00	6305	2555	3576	57.607	45.0	1.7133
Wartsila	8V31	4T	750	4400	150.708	6080	3111	4747	89.789	57.5	1.6809
Wartsila	9L34	4T	750	4500	165.00	6796	2609	3576	63.405	49.0	1.6734
Wartsila	8V31	4T	750	4800	159.78	6080	3111	4747	89.789	57.5	1.6519
Wartsila	10V31	4T	750	5500	150.708	6720	3111	4747	99.240	65.2	1.6076

Figure 2: Example of data table for DF NG ICEs.

To better understand the relationship between power/capacity, size, weight, and efficiency, scatter plots were created for each technology within the repository. The maps were created to correlate the rating values of components (power for engines and storage capacity for tanks and batteries) to their aforementioned criteria, such as size, weight, and efficiency (**Figure 3**). The curve fitting on scatter plots is made with a first-order polynomial for size and weight, showing an R-squared index ≥ 0.9, while efficiencies charts are fitted with logarithmic curves to better retain the underlying physical sense. Due to the smaller deviation, efficiency maps are generally less accurate.

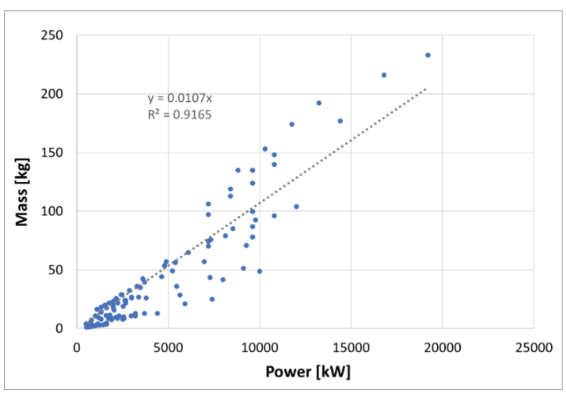

Figure 3: Example of scatter plot and fitting correlation – MDO ICEs weight.

Unlike physical data, the costs of components are often undisclosed by manufacturers. Therefore, to evaluate the price of the energy systems, specific cost values of components [$/kW] were collected from recent reports and scientific literature, and their absolute cost was computed accordingly.

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Consequently, both scatter plots and cost maps often show a perfectly linear relationship. Finally, the empirical correlations derived from the curves were implemented in the MATLAB tool for subsequent simulation processes.

3 CASE STUDIES

3.1 Case Study 1: Fuel Cells for the hotel load (500 kW)

The first study focuses on a medium-sized Ro-Ro/Pax ferry for island connection, which requires at least one day of autonomy. Although single navigation duration is usually limited (a few hours), multiple trips per day are frequent for this kind of vessel. An analysis is performed on the hotel load energy demand, which is assumed to be constant. To investigate the decarbonization of the maritime sector, a comparison between the state of the art (ICE MDO) and different fuel cell types is performed. For this first analysis, the fuel autonomy is assumed equal to 24 hours, considering navigation in a national area. The complete set of inputs is presented in **Table 1** and the relevance values (REL) are: cost 3, volume 4, weight 2, NOx 3, GHG 3, environmental hazard 5. As explained in the previous section, relevance values are determined based on the kind of vessel and the application scenario.

Table 1: Ro-Ro Pax hotel load, input parameters, and relevance values.

Vessel Type	Length [m]	Beam Hull [m]	Beam Upper [m]	High Hull [m]	High Upper [m]	Max Power [kW]	Op. hours [h]	Nav. Freq. [-]	Nav. Type [-]	Annual mission [-]
Pax & Car Ferry	73.6	15	15	4	10	500	24	Heavy	3	210

Figure 4 shows the scores obtained for the considered solutions. The key points of the state-of-the-art solution are the compactness, low cost, and weight, due to the high power density, the simplicity of the storage tank and the high market availability. In terms of costs and volume, generally, ICE-based solutions obtain higher scores, while FC systems, in particular PEMFC fed by hydrogen, can achieve up to 100% emissions reduction, resulting in a maximum score for GHG and NOx criteria.

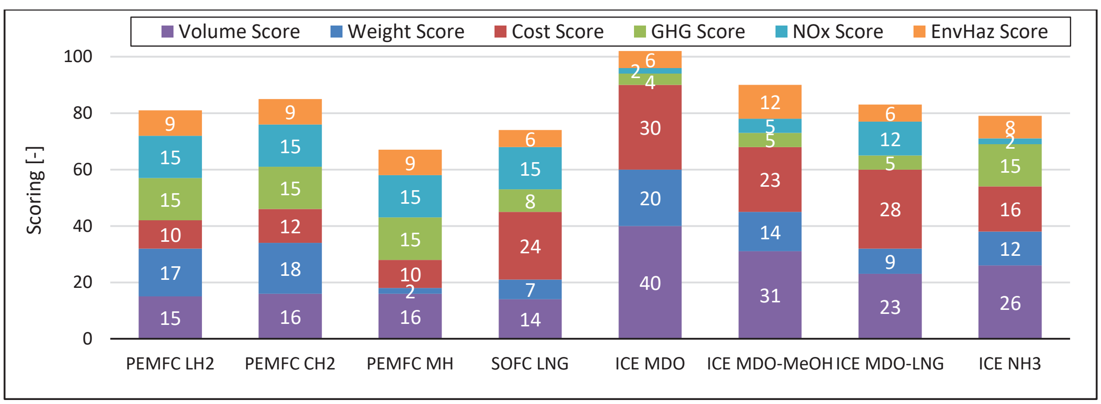

Figure 4: Ro-Ro Pax hotel load, 24h National navigation - FCs vs SoA.

Medium sized Ro-Ro Pax ferries generally sail on short routes (<24 hours), often as connection with islands. However, these routes are in national waters or coastal areas, where the necessity for emissions reduction is stronger. Moreover, the amount of fuel stored on board can be different, guaranteeing autonomy for less than one day or multiple days of activity. It is necessary to consider this variability when analysing different power systems. Thus, a sensitivity analysis is performed to understand in

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which scenarios FC-based systems can be a promising alternative. It is assumed that the hotel load works continuously also during the loading and unloading activities, as well as during the night to ensure energy supply to the crew. An increment of the autonomy up to 48 and 72 hours is considered. The results are shown in **Table 2** and **Table 3**.

Table 2: Ro-Ro Pax hotel load, 48h National navigation - FCs vs SoA

Technology	Vol Score	Wgt Score	Cost Score	GHG Score	NO_x Score	Env Haz Score	Total Vol [m^3]	Total Wgt [tons]	Total Cost [k$]	GHG [tons]	NO_x [kg]	Efficiency [%]
PEMFC LH_2	10	13	10	15	15	9	91.5	21.7	43,607	0	0	40
PEMFC CH_2	11	13	12	15	15	9	87.5	21.2	35,593	0	0	50
PEMFC MH	11	2	9	15	15	9	87.3	176.6	45,927	0	0	50
SOFC LNG	15	8	24	8	15	6	60.7	35.1	17,950	10,302	0	53
ICE MDO	40	20	30	4	2	6	23.4	14.2	14,087	21,368	251.8	35

Table 3: Ro-Ro Pax hotel load, 72h National navigation - FCs vs SoA

Technology	Vol Score	Wgt Score	Cost Score	GHG Score	NO_x Score	Env Haz Score	Total Vol [m^3]	Total Wgt [tons]	Total Cost [k$]	GHG [tons]	NO_x [kg]	Efficiency [%]
PEMFC LH_2	9	12	10	15	15	9	133.8	31.7	44,119	0	0	40
PEMFC CH_2	9	12	12	15	15	9	127.8	30.9	35,831	0	0	50
PEMFC MH	9	1	8	15	15	9	127.6	264.1	51,332	0	0	50
SOFC LNG	17	9	23	8	15	6	67.7	40.2	18,098	15,452	0	53
ICE MDO	40	20	30	4	2	6	28.4	18.2	14,088	32,053	377.7	35

In terms of absolute values of the volume, weight and cost, the best solution is still the ICE MDO, but the SOFC costs are anyhow competitive and the weight of the PEMFC and CH_2 is the lowest among the FCs system, and only half more than the ICE MDO. Considering navigation in a coastal area makes it possible to investigate the effect of higher emission relevance values for each solution, due to the presence of protected areas close to coasts. In fact, their value is increased from 3 to 4 in this scenario. Since the maximum score for different areas in not the same, they are compared in **Figure 5** as percentages.

Thanks to higher emissions relevance, the score difference between FCs and ICE MDO is reduced. In fact, the score for ICE MDO decreases by 4%, the SOFC increases by 1%, and the PEMFC solutions increase by 3-4%. Increasing operational hours is not very influential for the ICE MDO, but it has a strong impact on the scores of PEMFCs, with a score reduction of up to 7% for LH_2 and CH_2 due to the higher volumes required for hydrogen storage onboard. On the other hand, the SOFC score improves for longer autonomy values, with an increase of about 3% in the case of national navigation. This analysis highlighted the effectiveness of PEMFCs as a solution to reduce emissions in case of small autonomy, and the potential of SOFCs for vessels that require more autonomy, mainly thanks to their high efficiency and consequential reduction in fuel consumption.

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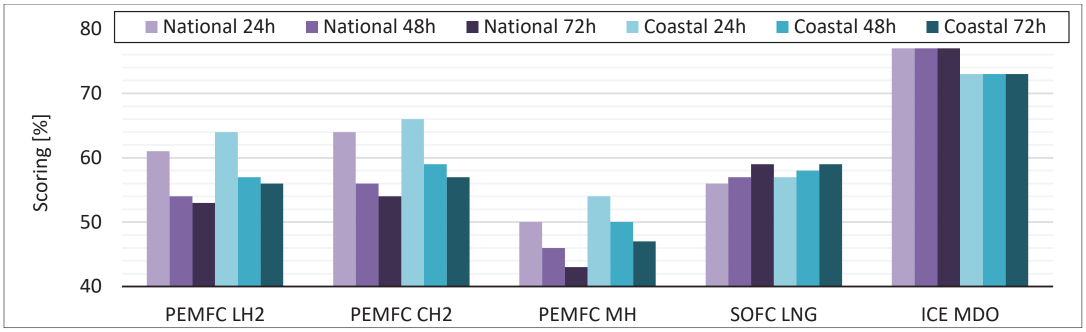

Figure 5: Results for different operational hours and navigation areas.

The results presented above refer to the current energy market scenario, where H_2 is still limited and expensive. Since hydrogen-based technologies have been growing in popularity during the past years, the price of H_2 is expected to significantly decrease in the future. To understand how this will help the employment of FCs in the naval sector, a sensitivity analysis on the hydrogen price was carried out. A reduction from 6.09 [23] to 4.00 $/kg [24] was assumed, considering a case of national navigation and different autonomies from 12 to 72 hrs. The results are reported in **Figure 6**. The price reduction improves the score of PEMFCs fuelled with MH and LH_2 by 4 points and by 5 points in the case of CH_2. These results show the potentiality of PEMFC for ships with autonomy $\leq$ 24 hrs, a field of application where also the MH solution is competitive with the SOFCs. For low autonomy, hydrogen-based energy systems can become competitive even with ICE–MDO. In fact, for 12 hrs of autonomy, Figure 6 shows that the highest score is achieved adopting PEMFCs fuelled with CH_2.

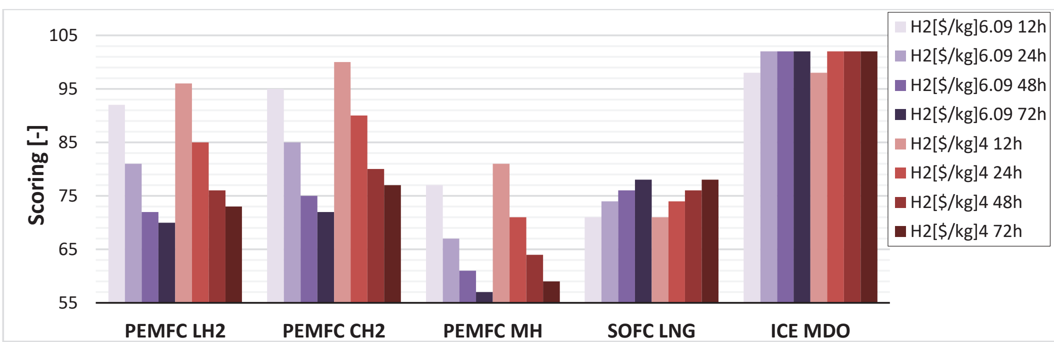

Figure 6: Results for different operational hours and H_2 prices (national navigation).

3.2 Case Study 2: ammonia ICE for large ships propulsion

In the second case study, a large-size ferry/ro-ro vessel (approx. 33.600 GT), owned by ANEK LINES and operating between Greece and Italy, has been analysed, focusing on the propulsion power. For this ship, a sample voyage between Patra (GR) and Ancona (IT) has been considered as operational scenario. A travel time of about 9 hours has been identified for this pathway, calculating it from both cruising speed and distance between the two harbours. Subsequently, a 25% increase on the previous crossing time, has been applied in order to consider both departure and arrival speed transients. This assumption is consistent with the voyage duration obtained considering the average Speed Over Ground (16.5 kn), identified by IMO 4th GHG study for this type of ship and size bin [25]. The operational power has been evaluated by means of an approximated cubic law between required power and speed. Following this approach, and considering cruising speed as an operational feature, the power load resulted to be around 80% of the installed one. The expected annual number of missions has been identified following

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indications reported in the same IMO 4th GHG report. To do this, the average number of days at sea was assumed, based on the ship type and size bin [25]. Concerning the cost relevance value, it can be set directly by the user based on each specific scenario, as **Table 4** shows. For this case, a value of 4 was chosen. The assumption of a quite high value is justified by an economical reason since the goal of this ship is to maximize its earnings. Furthermore, the main power system of the vessel has a very large size and represents an important investment for the shipbuilder. Therefore, particular attention to the costs must be considered to model the most realistic scenario. Other parameters' relevances are automatically defined by the software, identifying the same small case study's values.

Table 4: Large-size case study's main features.

Vessel Type	Length bp [m]	Hull Beam [m]	Hull Height [m]	Inst. Power [kW]	Op. Power [kW]	Op. hours [h]	Nav Freq	Nav Type	Annual Missions
Pax & Car Ferry	175	27	10	26,185	21,185	12	Heavy	National	480

This ship represents a demo vessel in the ENGIMMONIA project [26], focused both on clean technologies and ammonia-fuelled ICE on board integration. For this reason, a particular focus on ammonia and alternative fuels comparison has been carried out, taking into account different worldwide ammonia prices (Northwest Europe, Far-east Asia, and Middle East) [27], and future possible carbon tax scenarios (0 \$/tons, considered as baseline, 50 \$/tons, 150 \$/tons and 300 \$/tons). Concerning the price of other fuels, a globally averaged value has been taken into account. Fuel prices and carbon tax values considered in this study are represented in **Table 5**. At first, a baseline scenario was analysed to determine the scores of various technological solutions, considering Northwest Europe NH_3 price (600 \$/MT) and no carbon tax. Then, a further cost evaluation was carried out to identify the carbon tax value for which an ICE fed by ammonia becomes the most promising solution for this type of ship, considering the three different NH_3 prices.

Table 5**:**Worldwide fuel prices considered in this study.

NH3 Price			MeOH Price	LNG Price	MDO Price
Middle East	Far-East Asia	Northwest Europe			
480 \$/tons	530 \$/tons	600 \$/tons	440 \$/tons	800 \$/tons	650 \$/tons

Figure 7 represents the total score obtained by each solution. Since the power requirement of this ship widely exceeds the nominal power of both PEMFCs and SOFCs commercially available today, they are considered not applicable to this case study. Therefore, the only suitable solutions are represented by ICEs fed by various fuels. According to the results in **Figure 7**, a conventional ICE fuelled by MDO represents the most promising solution, even if comparable with the MeOH alternative. This is due both to physical and technical fuel features. Indeed, MDO is liquid at ambient conditions, allowing it to avoid particularly voluminous, heavy, and expensive storage systems. Both volumetric and gravimetric energy densities are high, allowing the storage of a relatively small amount of MDO to meet the ship's energy requirements. Furthermore, due to the absence of carbon taxes, costs are not affected by emissions, giving MDO and LNG the highest cost scores (40). As it is possible to note, the total score for MeOH is quite close to MDO. This is due to the same fuel storage easiness. However, because of the lower MeOH energy density, which is halved in comparison with the MDO, a larger amount of fuel needs to be stored in order to provide the same amount of energy, affecting both weight and volume scores. Instead, higher emission scores (both on GHG and NOx) can be reached by MeOH, due to the reduced NOx and CO_2 emissions, as it happens for LNG. Concerning ammonia, it does not emerge as a particularly promising solution in this scenario. Reduced energy density, together with the necessity to store it in more complex tanks, and the considered fuel price scenario, ensure that it reaches the

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lowest score. On the other hand, being ammonia a totally carbon-neutral fuel, the maximum score on GHG emission is achieved. It is worth noticing that the score on NOx emissions is subjected to some uncertainties, due both to a limited knowledge on actual emissions of NH_3 power units and the effectiveness of dedicated abatement systems. Therefore, a more conservative approach was adopted to estimate the NOx score, producing a score comparable with the MDO solution.

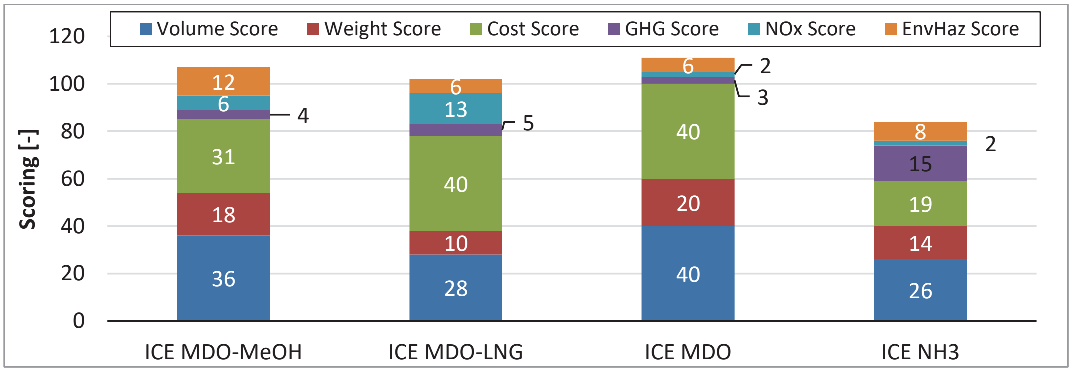

Figure 7: Baseline scenario results.

In view of both EU ETS policy [5] and IMO GHG reduction strategies [4], proposing a levy on GHG emissions, a sensitivity analysis on HELM's results has been carried out. For this purpose, three ammonia worldwide prices have been considered, as indicated in **Table** 5, together with four sample carbon tax values. **Figure 8** represents both cost and total score trends for all the ICE technologies. From the economic point of view, the best solution is represented by LNG, assuming the highest possible score for most carbon levies. This is mainly due to its high gravimetric energy density that allows to reduce fuel consumption, in comparison with MDO. In particular, this difference is such that it bridges the gap between fuel prices and technologies cost. Furthermore, increasing carbon tax values, the reduced LNG emissions augment the economic discrepancy between the two fuels. Methanol and ammonia are disadvantaged due to the larger amount of fuel needed to provide the required energy. However, by raising the CO_2 price, a quick increase of ammonia-case cost score is achieved thanks to its carbon-free emissions. This characteristic enables ammonia to become the most promising solution if carbon tax reaches 225, 270, and 350 \$/tonsCO_2 considering 480, 530, and 600 \$/MT as ammonia prices, respectively. In the case of MeOH, the impact of the CO_2 cost is not as relevant as for the ammonia case, since it is not a completely carbon-free fuel. If the same evaluation is shifted from a global point of view, considering other technical key parameters as well, carbon levies should be higher to have ammonia as the best solution: 283, 333, and 400 \$/tonsCO_2 would be required for the same previous NH_3 cost scenarios. These results are driven by worse scores for ammonia in terms of volume, weight, and NOx emissions. It is worth noticing that considering a global scenario, MeOH becomes the most promising solution for carbon tax values between 50 and 100 \$/tonsCO_2. This confirms a better position obtained by this technology from other technical parameters' points of view.

To better detail the cost study of previous technologies, focus was placed on the single cost items, taking into account a European future scenario (implying an NH_3 price equal to 600\$/MT), where an averaged carbon levy could be set (150 \$/MT). Regarding MeOH, MDO, and LNG, the same averaged prices are represented in **Table 5**.

Considering CAPEX, OPEX, fuel cost, and carbon tax as items, on a yearly basis, **Table 6** shows that the ammonia technology is the most expensive because of the fuel price, such that, neither considering the highest carbon tax sample value, it becomes competitive, as already highlighted by previous maps. Indeed, from the same **Table 6**, it is possible to notice the general strong effect of the fuel contribution on the Grand Total yearly costs, reaching almost 97% for ammonia. On the other hand, costs related to the plant components (OPEX and CAPEX, defined by spreading the total amount year-by-year), result

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to be negligible. Therefore, it is clear that a strong zero-carbon fuel price reduction, together with the adoption of a proper carbon levy value, shall be achieved to make ammonia competitive.

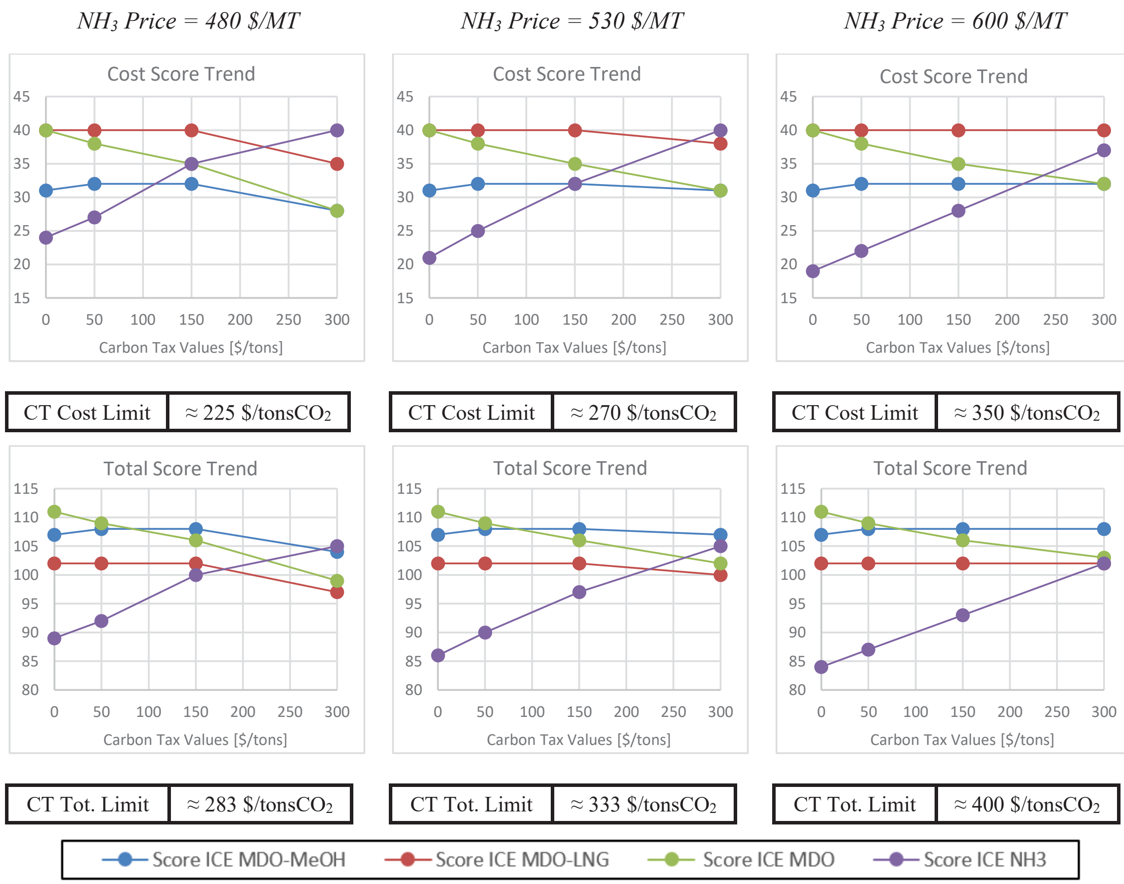

Figure 8: Cost & Total score trends mapping to identify the carbon tax limit value for both scenarios.

Table 6: Grand Total on cost for all technologies and ammonia comparison.

	Grand Total [k$/yr]	CAPEX Share	OPEX Share	Fuel Share	CT Share
LNG	25,015	3.3%	0.7%	64.4%	31.6%
MDO	28,786	2.5%	0.5%	55.8%	41.3%
MeOH	31,413	2.3 %	0.4%	66.9%	30.3%
NH_3	35,688	2.4%	0.7%	96.9%	0%

4 CONCLUSIONS

The HELM tool was used to assess the advantages of various power systems for marine applications, comparing traditional technologies and innovative solutions. The analysis focused on energy systems capable of reducing the environmental hazard, and the pollutant emissions, considering also their cost, weight, and volume. At the present state, traditional MDO ICE resulted in being the most convenient

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solution for both medium-sized Ro-Ro/Pax ferries and large-sized Ro-Ro vessels. However, the use of fossil fuels makes them unfeasible to meet the emission reduction targets of the marine sector. For pursuing this aim, further innovative technologies as CCS systems or NH_3-fed fuels cells, will be implemented in the tool, making the assessment as comprehensive and realistic as possible.

For medium sized Ro-Ro/Pax ferry, both alternative fuel ICEs and fuel cells could be adopted to reduce emissions. MeOH ICEs obtained the second highest score after MDO ICE, with a fairly low emission score but the lowest environmental hazard. Among different types of fuel cells, LH_2 and CH_2 PEMFC resulted to be the most promising thanks to their zero emissions, but LNG SOFCs can become more competitive for longer routes. A sensitivity analysis on the H_2 market price showed that a reduction from 6.09 to 4.00 $/kg would make CH_2 PEMFC the best solution, even when compared with MDO ICE. This effect would be greater for navigation in coastal areas, where lower pollution is critical.
For large-sized Ro-Ro vessels, commercially available fuel cells are too small to cover the entire power demand. Therefore, the analysis focused on alternative fuel ICEs. Also in this case, the score of MeOH ICEs is close to the MDO ICEs, with lower emissions and environmental hazard, but higher cost, volume, and weight. NH_3 ICEs are the best solution to reduce emissions, but they obtained the lowest total score. In conclusion, a sensitivity analysis showed that both a reduction of NH_3 market price and the adoption of substantial carbon taxes are necessary to make this technology competitive.

NOMENCLATURE

Abbreviations	*Descriptions*
BAT	Batteries
BoP	Balance of Plant
BSEC	Brake Specific Energy Consumption
CH_2	Compressed Hydrogen
CAPEX	Capital Expenditures
DF	Dual Fuel
ECAs	Emission Control Areas
FC	Fuel Cell
GHG	Green House Gases
HELM	Helper for Energy Layouts in Maritime applications
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LH2	Liquid Hydrogen
LNG	Liquid Natural Gas
MDO	Marine Diesel Oil
MeOH	Methanol
MH	Metal Hydrides
NOx	Nitrogen Oxides
PEMFC	Proton Exchange Membrane Fuel Cell
PU	Power Unit
REL	Relevance
Ro-Ro pax	Roll-on/Roll-of passengers
SCR	Selective Catalytic Reactor
SoA	State of the Art
SOFC	Solid Oxide Fuel Cell
TEU	Twenty-Foot Equivalent Units

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