EcoDesign strategies for zero-emission hydrogen fuel vessels scenarios

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***Abstract* — Maritime Shipping emissions represent the 13% of the overall EU greenhouses gas emissions (GHG) of the whole transport sector. It is estimated that they could increase between 50% and 250% by 2050 under a business-as-usual scenario, undermining the objectives of the Paris Agreement. From 2021, the European Commission adopted a series of legislative proposals to achieve climate neutrality in the EU by 2050, including the intermediate target of at least 55% net reduction in GHG emission by 2030. Despite hydrogen is worldwide considered a valid option to reach the emission reduction targets, being part of the IMO strategy also, a common approach to face the design challenges due to hydrogen introduction in waterborne transport is not yet available. Focus of this study is the adoption of hydrogen-based propulsion technologies for passenger ferries, with the aim to draft the strategies that can be adopted to reach that goal. An overview of the current state-of-the-art of hydrogen-based fuel passenger ships is presented: the EcoDesign Strategy Wheel (a tool to helps embed sustainability into any innovation and consider life-cycle impacts of the product) has been chosen to highlight the different approaches adopted by the designers of the existing vessels. The same tool has then been applied to three reference scenarios developed within the EU-funded project "e-SHyIPS" (Ecosystemic knowledge in Standards for Hydrogen Implementation on Passenger Ship). The outcome is a comparison among the two approaches highlighted during the analysis, which provides design support during the future challenges designers and shipbuilders will be called to face during the design loop phases.**

Keywords — sustainable mobility, maritime passengers' ships, yacht design, Ecodesign strategies, zero-emission ship, smart mobility, maritime life-cycle

I. Introduction

Maritime transport is an essential vector for European trade and a driver of economic growth: it contributes to thriving economic hubs in coastal areas and around our ports. In 2019, almost half of the maritime traffic in the EU was from ships engaged exclusively in domestic routes and voyages, mainly due to the frequent crossings made by Ro-ro pax ships (roll-on, roll-off passenger ships/ferries), and cruise ships [1]. In the same year, most of the port calls in the EU were made by Ro-pax ships (41%) and passenger ships (18%) such as ferries, cruise ships, and other smaller ships. Altogether, these two ship types covered more than half of the port call activity (59%). Furthermore, Ro-pax ships in 2018 reported around 20 million tons of CO2 emissions, primarily concentrated in the Baltic, the North Sea, and the Mediterranean [1]. Despite progress in recent years and the increasing number of vessels addressed to passengers' water mobility, maritime transport remains an important source of greenhouse gas (GHG) emissions and other harmful pollutant emissions to water and air. When looking at the EU's GHG inventory, produced under the United Nations Framework Convention on Climate Change (UNFCCC), maritime transport contributed 13.5% of the total EU GHG emission from transport in 2018. In 2020, the International Maritime Organization (IMO) projected the sector's GHG to increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios [2]. Even if these predictions do not take account of the effects of the COVID-19 pandemic, which could lower the growth of the maritime sector for several years to come, such growth in emissions is not compatible with the EU's 2050 climate-neutrality target. Alternative fuels and energy sources such as biofuels, synthetic fuels, hydrogen, ammonia, or batteries are emerging as alternatives to conventional fossil fuels, not only for passengers' ships but also for tanker vessels, which require a high-power demand. Research has already revelated the potential benefits of the hydrogen fuel cell market for the maritime sector, and despite the cost challenges, hydrogen is the most promising clean fuel option for the global shipping industry [3]: blue and green hydrogen can provide a pathway for the shipping industry to reduce its GHG emissions significantly. In addition, hydrogen fuel cells are relatively quiet, with limited noise pollution and only releasing water vapor and oxygen as by-products, virtually eliminating air and water pollutants during fuel consumption. Those insights highlight the importance of moving forward a more sustainable passengers' ship design process to reduce the GHG accounted to this market share. This challenge can be faced by introducing zero-emission fuels such as hydrogen and fuel cell stacks and by establishing new hierarchies among the project steps to reach a comprehensive sustainable design process. This study aims to provide an overview of the possible strategies that in the next future should be adopted to face the challenge of introducing hydrogen-based fuel in passengers' ships' fleet.

II. Research Question

ently, there are many conceptions regarding maritime el sustainability. However, the current approach to

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hydrogen vessel design lacks a clear vessel design methodology and a dedicated normative framework: the technology readiness level permits to adopt hydrogen and fuel cell stacks on board, however the stakeholders and designers are still missing a systematic approach from concept design phase to engineering design stage [4]. In this regard, when designing for comprehensive sustainability (not only the one addressed to the propulsion system emissions), the level of ambition must be even higher than usual: the challenge addressed to the designers is to reach less degradation in our environment and less depletion of materials, by not only introducing hydrogen as a propulsion engine. According to this consideration, the central goal of this research is to highlight a series of approaches that can be adopted in designing hydrogen-based fuel passengers' ships thanks to case studies and scenarios analysis. This goal is addressed through the following research question*: together and beyond the adoption of hydrogen-based fuels, what strategies can designers and shipbuilders adopt to develop more sustainable passenger ships?* The derived outcome allows for new sustainability considerations for hydrogen power vessels to be developed. Those considerations can complement existing research in the field and create a more comprehensive overview of the approaches that should impact the various aspects of vessel design to understand common strategies, market trends, and shipbuilding challenges in front of a new kind of vessel.

III. RESEARCH METHODOLOGY

According to the scope of the research question, a two-step methodology was adopted, consisting of (i) initial analysis of a series of case studies of already existing passengers' ships powered by hydrogen and fuel cell stacks, and (ii) a subsequent one of the scenarios vessels described below. For both steps, the way adopted to elaborate the gathered data has been the EcoDesign Strategy Wheel [5], also called Life Cycle Design Strategy [6], which is an essential tool in design for sustainability. The purpose of the tool is to transform the qualitative information into more effective working and designing tools: it helps visualize the strategies that can be followed for EcoDesign processes [5]. Furthermore, the EcoDesign strategy can also be used to describe the product requirements, as quantitatively as possible. It is a form of environmental product benchmarking, showing what aspects of a product design should be improved, compared to its alternatives, which are the real case studies in this study. This tool only works when two or more products (designs) are compared since scores are not absolute but relative and often subjective. For this reason, the chosen tools fit well with the research materials, which are the existing case studies, divided and analyzed accordingly with the reference scenarios drafted during the next step of the methodology. More into detail, as can be seen in Fig.1, the EcoDesign Strategy Wheel presents 8 EcoDesign strategies. Furthermore, the reference methodology also explains, for each of the 8 strategies, how sustainability advancement should be achieved, addressing some specific action to be put in place [6]. Due to their similarities, it is

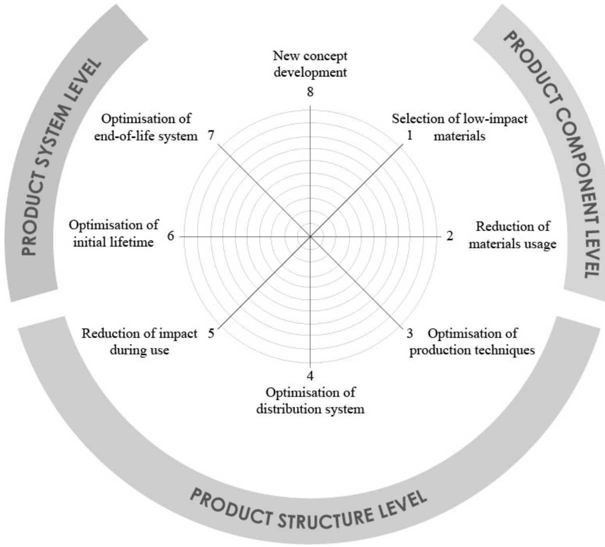

Fig. 1. EcoDesign Strategy Wheel

possible to relate those actions with the product life phases addressed in the of product lifecycle management (PLM) process [7]. More into details, the Beginning of Life (BOL) phase includes in practice the design and manufacturing of a system or product: it can synthesize to represent the recursive implementation of activities that enable the eventual utilization of the system/product. During this phase of maritime vessel development, use cases, trade studies, requirement analysis, and other activities are undertaken to satisfy stakeholder needs. Can be considered parts of the BOL processes the following EcoDesign Strategies:

- *New concept development*: dematerialization, shared used of the product, integrations of functions, functional optimization of product (components).
- *Selection of low-impact materials*: cleaner materials, renewable materials, lower energy content materials, recycled materials, recyclable materials.
- *Reduction of materials usage*: reduction in weight, reduction in (transport) volume.
- *Optimization of production technique*: alternative production techniques, fewer production steps, lower/cleaner energy consumption, less production waste, fewer/cleaner production consumables.
- *Optimization of distribution system*: less/cleaner/reusable packaging, energy-efficient transport mode, energy-efficient logistics.
- *Optimization of initial lifetime*: reliability and durability, easier maintenance and repair, modular product structure, classic design, strong product-user relation.

Middle of Life (MOL) phase includes the deployment, utilization, and maintenance of the system [7], and can be considered part of this process the following strategy:

- *Reduction of impact during use*: lower energy consumption, cleaner energy source, fewer consumables needed, cleaner consumables, no waste of energy/consumables

Then, during the End of Life (EOL) phase, the product's most valuable parts and materials can be recovered for the vessel to be effectively recycled (disassembled, remanufactured, reused, etc.). The strategy part of this phase is the following one:

- *Optimization of end-of-life system*: reuse of product, remanufacturing/refurbishing, recycling of materials, safer incineration.

The feasible improvement actions mapped during the analysis phase can then be grouped according to the classification of the eight EcoDesign strategies. As mentioned above, the first activity performed was the market analysis and the state-of-the-art understanding concerning the target of interest, which is maritime passengers' ships. A series of relevant case studies have been collected and analyzed according to their main features such as dimension, building techniques, hull materials, performed routes, and general arrangement to be able to compare them. The aim of these activities is twofold: to collect the existing knowledge in terms of the state of the art of hydrogen-based fuel passengers ship and to start understanding common approaches, market trends, and shipbuilding challenges in front of a new kind of vessel. The second part of the methodology was enhanced through the scenarios built within the tasks of the EU funded project e-SHyIPS (Ecosystemic knowledge in Standards for Hydrogen Implementation on Passenger Ship), which involves European countries working together to define the new guidelines for an effective introduction of hydrogen in the maritime passenger transport sector and to boost its adoption within the global and EU strategy for a clean and sustainable environment, towards the accomplishment of zero-emission navigation scenarios. The three scenarios presented in this study have been derived from data gathered during contextual inquiry activities and then validated thanks to a structured and semi-structured interview with focus groups. Furthermore, to have a well-founded basis for the research, a focus group was performed with industry experts involved in the design, development, maintenance, and operation of vessels and the design and development of hydrogen fuel solutions.

The final results of the applied methodology are three different EcoDesign Strategy wheels, one for each reference scenario, showing a comparison with the existing case studies approach and the scenarios' one.

IV. CASE STUDIES COLLECTION AND ANALYSIS

Thirteen case studies have been gained thanks to desk research performed to map the existing fleets in terms of passengers' ships. Case studies were identified as highly relevant and were thus collected to frame the current state of the art of fuel cell applications in waterborne transport and to clearly understand the characteristics and market volumes of Hydrogen-based fuels. The case studies have been selected among a broader range of results according to the TRLs (Technology readiness levels) to get only helpful information to the study development. In particular, their range of TRL is estimated to be at least around Level 7, which refers to system adequacy validated in a simulated environment. The vessels already existing and operating have been analyzed accordingly to common features such as main dimension, displacement, construction techniques, passengers' capacity, performed routes, and installed engines. Accordingly, to their similarities, the analyzed vessels have been grouped into three main clusters, which are the three most relevant shares in which the market of passengers' fleet could be divided: fast water-busses vessels, roll-on roll-off ferries, and luxury cruise ships. These groups are named Small, Medium, and Large, as for the scenarios presented in the next chapter and with which have been compared. It is important to remember that, among the 14 case studies presented, the majority are launched vessels already in use, while 5 of them are concept or ongoing feasibility studies, and some information could be not yet available. Despite this, these data are a tangible signal of the market's direction, which is slowly moving forward a more sustainable path. TABLE I includes all the relevant information of the presented case studies. Some initial considerations on the case studies can be made.

TABLE I. Case studies

	status	vessel type	vessel/ project name	shipyard/ company	main dimensions	propulsion system	H2 storage option
#1	launched (2009)	waterbus (100 pax)	*FCS Alsterwasser*	Alster-Touristik GmbH	LOA 25,5 m Beam 5,36 m	PEM FC (100 Kw) + battery	12 tanks (50 kg) at 350bar
#2	launched (2009)	waterbus (88 pax)	*H2 Nemo*	Rederij Lovers	LOA 21,95 m Beam 4,95 m	PEM FC (60 Kw)+ battery	6 tanks (24 kg) at 350 bar
#3	launched (2021)	waterbus (75 pax)	*Sea Change*	All American Marine	LOA 21,95 m Beam 7,31 m	PEM FC + battery	10 tanks (246 k) at 250 bar
#4	launched (2017)	waterbus (16 pax)	*Hydroville*	Compagnie Maritime Belge	LOA 14 m Beam 4,2 m	Hybrid (Diesel /H2 ICE)	compressed 205 l at 200 bar
#5	launched (2013)	waterbus (12 pax, 2 crew)	*Hydrogenesis*	Weston-super-Mare shipyard	LOA 11 m Beam 3,6 m	FCH + battery	compressed
#6	launched (2021)	ferry (290 pax, 80 cars)	*Hydra*	Weston x Norled	LOA 82,4 m Beam 17 m	PEM FC + battery	liquid H2 stored on rooftop
#7	concept (2019)	fast ferry (300 pax)	*AERO*	Brødrene Aa	/	FCH + battery	compressed 600 kg at 350 bar
#8	launched (2011)	ferry (600 pax)	*New York Hornblower Hybrid*	All American Marine, Dereckter	LOA 47 m Beam 12 m	Diesel / PEM FC + battery	liquid
#9	concept (2021)	fast ferry (150 pax)	*SF-BREEZE*	Sandia National Laboratories	LOA 33 m Beam 10 m	PEM FC (120 kW)+ battery	1 Type C liquid 1200 kg
#10	feasibility study	luxury cruise ship (300 pax,100 crew)	*MM130*	Northern Xplorer	/	FCH + battery	/
#11	feasibility study	cruise ship	/	/	/	/	/
#12	feasibility study	cruise ship (900 pax, 500 crew)	/	/	LOA 230 m	FCH + battery	liquid H2
#13	ongoing	cruise ship (640 pax)	*Havila fleet vessel*	Tersan Shipyard	LOA 120 m Beam 20 m	FCH + battery	liquid H2

First, comparing water-busses case studies, in cases 2,3, and 5, the new propulsion system's equipment has been arranged in spaces generally addressed to passengers and now converted in technical areas. On the contrary, cases 1 and 4 present quite the same general arrangement compared to the traditional equipped vessels, meaning that hydrogen storage and propulsion system have been placed in areas already addressed to technical items. Regarding medium-size passengers ferries, have been collected case studies addressed both to only-passengers and passengers plus cars/truck vessels, since this kind of ferries are extremely widespread in EU. As can be seen, cases 8 and 9 are addressed only to passengers' transport, while case 6 can carry onboard 80 cars. While the most are already existing vessels, case 7 refers to an ongoing project. For luxury-cruise ship case studies it is important to declare that few information are at this stage available, and mostly of the vessels included in this study are preliminary concepts (case 10), ongoing feasibility studies, or declarations of intent made by the shipyards or navigation company involved in the design of hydrogen-based fuel passengers' ships (cases 11, 12 and 12). Case 14 is the only one ongoing project since it is based on the retrofitting of an already existing cruise ship. According to the methodology proposed, the information collected for each case study has been analyzed with the EcoDesign Strategy Wheel tool: the results are shown in Fig. 2 and allow some assumptions on the different strategies adopted for each share of the market. To move forward a more sustainable design process, at this stage of the art one of the widespread strategies that can be applied to *small* case studies vessels [Fig. 2/a] is to optimize their end-of-life systems: EcoDesign strategies has been achieve by introducing hydrogen-based fuel propulsion in already existing vessels, allowing to reuse of existing products and reduce end-of-life waste. These kinds of vessels can easily be retrofitted, due to the lower complexity of onboards systems compared with bigger ships: hydrogen propulsion system components can be arranged in the same area where was arranged the previous machinery room. Furthermore, the reduction of impact during use is only due to the introduction of zero emission fuel such as hydrogen, and no other design strategies compete to achieve this goal in the case studies. Also, optimizing the initial lifetime is not a strategy considered at this stage, since all vessels analyzed have the same features as traditional fueled ones. For what concern Medium case studies [Fig. 2/b] approach to reach a more sustainable design, what the EcoDesign wheels highlight is that shipbuilders and designers already started working on the optimization of initial lifetime and production techniques and reduction of material usage: for example, hull shapes have been considered to reduce the vessels water resistance when sailing. Thank to this, fuel consumption and the amount of fuel that needs to be store onboard can be both reduce. However, optimization of initial lifetime and new concept development are low is that the general arrangement of the vessels considered in this study are deeply affected by the adoption of hydrogen-based fuel propulsion: more into details, the fuel storage are often placed in a very high position (compared to the center of gravity of the vessel) and this has negative consequences on the hydrostatics and hydrodynamics. Furthermore, also the passengers' compartments spaces have been reduced in new propulsion vessels. About the vessels analyzed in *large* case studies

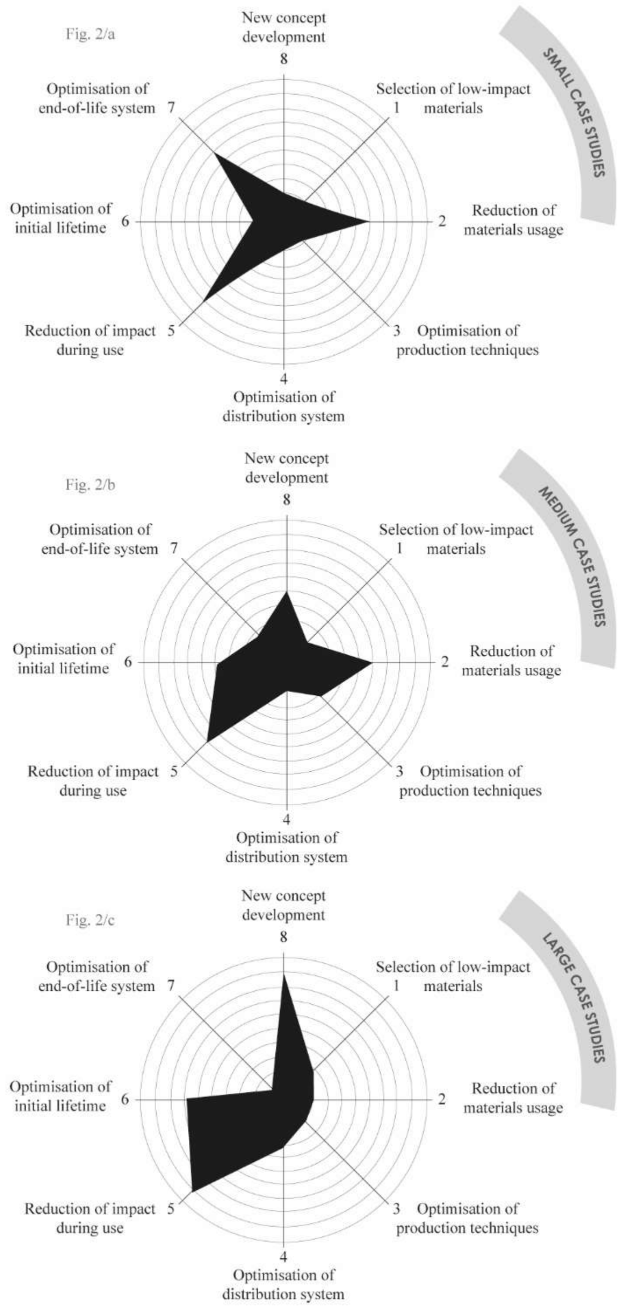

Fig. 2. Case studies EcoDesign Strategy wheels

[Fig. 2/c], the EcoDesign strategy wheels represent an initial draft of the possible approaches: no launched vessels exist, and the data only refers to ongoing feasibility studies. The reason lies in the fact that in such complex vessels the introduction of a new propulsion system requires a more comprehensive approach to the design, in which all the variables need to be considered. New concept is now under development: for those reason, optimization of end-of-life system is a strategy that now is not variable, despite for one ongoing project of retrofitting. Since we are dealing with new concept development, the focus, at this stage, is on the optimization of initial lifetime.

V. SCENARIOS EVALUATION AND ANALYSIS

As anticipated in the methodology, the second part of the study analyzes three functional scenarios previously built and validated within the context of the ongoing EU-funded project e-SHyIPS. Especially in the advanced design process, like in this case, scenarios are the elaboration of megaprojects aimed at defining the trajectories of innovation to conceptualize at the stage of product development. The three scenarios have been derived from data gathered during contextual inquiry activities and then validated thanks to a structured and semi-structured interview with a focus group, performed with industry experts involved in the design, development, maintenance, and operation of vessels as well as the design and development of hydrogen fuel solutions: the primary purpose this stage was to clarify the different possibilities offered by the market contest and trends. Furthermore, scenarios definition has been set according to the growing market demands for each vessel size, even if it is essential to clarify that the three scenarios diversify from each other according to their operation profile much more than for their hull's geometry: vessels with the same length could have different operation profiles and consequently different energy demand and fuel space storage requirements. More specifically, as concerning Scenario Small, fast waterways vessels are a widespread means of transport, especially in geographic areas such as Northern Europe, where people and goods are daily moved along canals due to the morphology of the territory. Scenario Medium represents the roll-on-roll-off vessels that are still very recommended due to the global freight and passenger market growth. On the other hand, Scenario Large addresses a rising target: the luxury cruise ship one. This market share is indeed estimated to grow significantly in 2021-2029, especially in Europe [8].

- **Scenario Small: fast water-busses –** Small fast ferries mainly working in inland waters, such as cross rivers and fluvial operations, offering regular daily water-based public transport service to customers. This kind of vessel is widespread in the lagoon or fjords areas, where, due to the morphology of the territory, daily transport takes place mainly on internal waters. The reference vessel is an existing fast waterbuss operating in Rotterdam, of the length of 24,4 meters, primarily delivered to water-based public transport companies to provide passengers urban mobility along the inland water paths. Thanks to the flexible design, the vessels can be arranged with different internal and external layouts, according to the market demands.
- **Scenario Medium: roll-on roll-off ferries –** Medium dimensions ferries mainly operating as roll-on roll-off passengers' ships. This acronym illustrates ships with roll-on and roll-off features for the carriage of commercial vehicles and private cars with the provision to accommodate large numbers of passengers separately for shorter voyages. More specifically, as these ships contain a mix of both passenger and cargo features, they must respond to a series of strict safety and technical parameters. The reference vessel for this scenario is an existing vessel of the length of 118,80 meters which operates daily routes to the islands of Zakynthos, Kefalonia, and Ithaca. In addition to cars and truck decks and passenger accommodations, plenty of amenities are offered on-board: bars, restaurants, children's facilities, and a shopping arcade.
- **Scenario Large: small luxury cruise ship –** Small/mid-size luxury cruise ship primarily characterized by a high level and a high number of services offered to a circumscribed circle of users. The reference project for this scenario definition is Celebrity Cruise's latest vessel called Flora, launched in 2019: it is the first ship to be built, especially for the Galápagos Islands. The design allows ensuring the destination remains the center of attention during sailing. Moreover, the ship contains features that mix both pleasure yacht and passenger ship ones. It operates among Galapagos Islands, providing a weekly cruise-in mainly coastal waters.

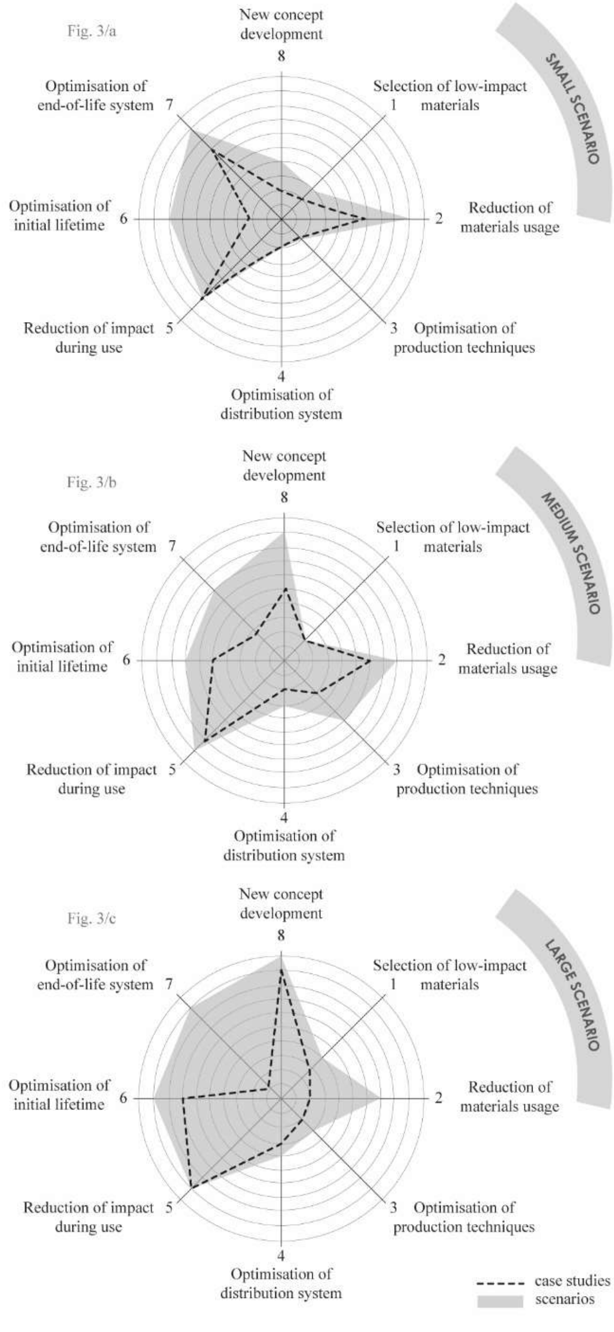

Fig. 3. Scenarios EcoDesign Strategy wheels

The subsequent step has been the graphic translation of the three different EcoDesign Strategy wheels, one for each reference scenario. The graphics displayed in Fig. 3 include, in the same wheels, both the strategies gathered from the case studies analysis (black dotted line) and drafted for e-SHyIPS scenarios (light gray area), in order to be able to easily compare the results. The strategy drafted within e-SHyIPS project for the Small scenario vessels [Fig. 3/a] is to keep the design of new units as close as possible of the traditional propulsion system' vessels' one: an optimization of the end-of-life system can be reached, allowing retrofitting activities to convert existing ships into hydrogen-based-fuel ones. Materials usage can be drastically reduced, since no new construction are needed to start the water-busses fleet conversion. However, withing this strategy, the reduction of impact during use is only addressed to the introduction of hydrogen as a fuel, and not to a reduction of fuel consumption since no improvements have been done in the vessels' efficiency. Medium scenario vessels [Fig. 3/b] strategy permits to reach a higher reduction of impact during use: this goal is achieved not only with the introduction of a zero-emission fuel, but also optimizing hull's waterline. To develop more efficient hulls can also lead, if done within a new project development, to a reduction of materials usage and optimization of production techniques. Furthermore, *Large* scenario vessels strategy [Fig. 3/c] is mainly focused on new concept. development, as currently happens in the case studies analyzed: this strategy requires a huge effort if compared to Small and Medium scenarios. Developing new concept and adopting new technologies and materials will also allow to reduce the materials usage onboard in comparison with today's strategies. Furthermore, as a long-term impact [9] of new hydrogen-based cruise ships constructions, the expectations are that also the end-of-life of cruise ships will be improved by retrofitting the existing units.

VI. DIFFERENCES AMONG CASE STUDIES AND SCENARIOS APPROACHED

The strategies adopted for the cases and scenario Small, water-busses and inland navigation units, are quite similar. In contrast, for larger units such as cruise ships, the strategy drafted for the Medium scenario is very different compared to the one currently in use. To have a clear understanding of those similarities and differences between the approaches for case studies and scenarios it is crucial to consider the different levels of complexity of vessels. Graphics in Fig. 3 show that the more complex the vessel is, the further the strategy adopted for case studies and scenarios. More into details, for Small scenario units [Fig. 3/a] the strategies adopted are quite the same, with the difference that in the future, when several hydrogen-based vessels will be on the market, also the initial lifetime can be optimized to reach further sustainable goals. Both retrofitted vessels and new ones can also select and use low-impact materials, increasing the product's sustainability. Regarding Medium scenario units [Fig. 3/b], the reduction of impact during user is higher if compared to the analyzed case studies: thanks to new concept development, which also have a higher value in scenario wheels, some critical parameters such as hydrodynamic resistance will be improved to reduce for example fuel consumption and vessels weights. The most different approaches are one of Large scenario units [Fig. 3/c]: if at this state-of-the-art is almost impossible to optimize the end-of-life system, the expectation is that after new hydrogen-based cruise ships will be properly designed and launched, it will be possible to retrofit them, also reaching an optimization of the end-of-life increase.

VII. CONCLUSION AND FUTURE RESEARCH

The outcome of this study is the different strategies that designers and shipbuilders can adopt to develop more sustainable passengers' ships, among the adoption of zero-emission fuels as a propulsion engine: improved ship design process and operation is an essential strategy to move toward more sustainable project. The derived outcome allows for new sustainability considerations for hydrogen power vessels to be developed that complement existing research in the field. The observation of the strategies adopted in the actual case studies and the comparison with the e-SHyIPS scenarios could result in further evaluations and future studies and research useful to establish the most promising strategies. For this reason, future research will have the aim to validate the strategy drafted for the presented scenarios in this study: to do so, experimental data will be gathered thanks to the know-how of the e-SHyIPS partners' involvement. Despite the challenges to be addressed are different, future research can also include a study on how the drafted strategy could be applied not only to passengers' ships but also to marine shipping ships like cargo and tanker vessels.

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