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Environmental sustainability of alternative marine propulsion technologies powered by hydrogen - a life cycle assessment approach

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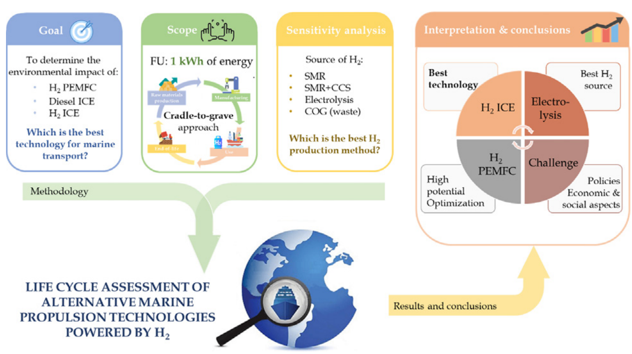
HIGHLIGHTS

- LCA of hydrogen propulsion technologies for shipping was developed.
- H_2 engine presented the lowest environmental impacts.
- The analysis was conducted in a very early degree of maturity of the devices.
- LCA proves to be a useful and key tool for moving towards sustainability.
- Policy implication is mandatory to achieve decarbonization in shipping.

GRAPHICAL ABSTRACT



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ABSTRACT

Shipping is a very important source of pollution worldwide. In recent years, numerous actions and measures have been developed trying to reduce the levels of greenhouse gases (GHG) from the marine exhaust emissions in the fight against climate change, boosting the Sustainable Development Goal 13. Following this target, the action of hydrogen as energy vector makes it a suitable alternative to be used as fuel, constituting a very promising energy carrier for energy transition and decarbonization in maritime transport. The objective of this study is to develop an ex-ante environmental evaluation of two promising technologies for vessels propulsion, a H_2 Polymeric Electrolytic Membrane Fuel Cell (PEMFC), and a H_2 Internal Combustion Engine (ICE), in order to determine their viability and eligibility compared to the traditional one, a diesel ICE. The applied methodology follows the Life Cycle Assessment (LCA) guidelines, considering a functional unit of 1 kWh of energy produced. LCA results reveal that both alternatives have great potential to promote the energy transition, particularly the H_2 ICE. However, as technologies readiness level is quite low, it was concluded that the assessment has been conducted at a very early stage, so their sustainability and environmental performance may change as they become more widely developed and deployed, which can be only achieved with political and stakeholder's involvement and collaboration.

1. Introduction

Transport is widely recognized as a significant and increasing source of pollution, especially today when the world is undergoing an environmental and energetic crisis due to the intensive use of fossil fuels (d'Amore-

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Domenech and Leo, 2019). Particularly, maritime transportation presents a great impact to the environment, being carbon dioxide (CO_2), the most important greenhouse gas (GHG) emitted by ships (IMO, 2020). According to the Fourth GHG Study (IMO, 2020), published by the International Maritime Organization (IMO) in 2020, international shipping emissions reached 1056 million tons of CO_2 equivalent in 2018, which represent approximately 2.89% of the annual GHGs. These burdens are assumed to increase by 150% - 250% in 2050 if no action to stop them is taken; this means that total emissions in 2050 are foreseen to be at 2.5 to 3.5 times today's level (Lindstad et al., 2015). In this line, decarbonization is currently considered a top priority for shipping organizations, becoming a part of their business strategies. Several actions have been developed over the years to reduce the high pollution levels in this sector to take urgent action to combat climate change and its impacts. The decarbonization of marine fuels is key to meet the GHG reduction goal set by the IMO (Ampah et al., 2021), for which it adopted mandatory measures under IMO's pollution prevention treaty (MARPOL), the Energy Efficiency Design Index (EEDI) mandatory for new ships, and the Ship Energy Efficiency Management Plan (SEEMP), which aims to promote the use of more energy efficient engines (IMO, 2020). On the other hand, the European Commission developed in 2015 the MRV regulation on "monitoring, reporting and verification of CO_2 emissions from maritime transport", whose target is to reduce the carbon footprint (CF) of shipping (European Commission, 2015). All these benchmarks are focused on the pollution from the conventional propulsion systems, which use gasoline or diesel as fuel, and their related equipment. However, a number of measures are currently being developed to implement promising alternatives to conventional fuels (Sorunmu et al., 2018), promoting the transition to green transport. In this sense, the Hydrogen Strategy for a climate-neutral Europe of the European Commission establishes a series of strategies based on regulations, investment, research, and innovation to promote descarbonization in industry, transport, and energy generation in Europe, using H_2 as energy vector (European Commission, 2020).

Hydrogen is becoming an important source of energy, and scientists around the world are involved in making this compound commercially available because of its environmentally friendly nature (Jain, 2009). Acting as energy vector, i.e., being able to store and release energy in a controlled way, makes H_2 a suitable option to be used as fuel (Akal et al., 2020), both for mobile and stationary applications (Maestre et al., 2021a), constituting a very promising energy carrier for the energy transition (Robles et al., 2019). In addition, its high mass energy density, 120 MJ/kg, and the simple way of production, just by water splitting, provides it the potential to be an inexhaustible energy source (Boudellal, 2018). However, the great importance in the energy system resides in its clean combustion, which, unlike other conventional fuels, only produces pure water and heat (Momirlan and Veziroglu, 2005). Unfortunately, the implementation of the hydrogen economy is not immediate, and although significant progress is currently being made, it is necessary to deal with technological, economic, and social barriers (Abdin et al., 2020). Main challenges reside in technical difficulties associated with H_2 storage (Cheng et al., 2007), especially in maritime applications, where this issue is more challenging than for stationary or automotive applications (Ortiz-Imedio et al., 2021). As in the case of diesel or gasoline, the chemical energy of H_2 needs a conversion into another type of useful energy, as electrical or mechanical. Hydrogen Fuel Cells (FC) are one of the most used technology, considered to be the green power source to 21st century, which provide an efficient and clean mechanism for electrochemical energy conversion (Van Hoecke et al., 2021). Among FCs, the PEMFCs (Polymeric Electrolytic Membrane Fuel Cells) are the optimum option in mobility applications (Alaswad et al., 2016) since they hold several advantages over conventional technologies, such as their high electrical efficiency, silence, low pollutant emissions, ease of installation, and rapid start-up (Díaz et al., 2014). In a PEMFC, molecular H_2 is delivered from a gas-flow stream to the anode where it is oxidized producing ions and electrons. The ions migrate through the membrane to the cathode, where oxygen from air is reduced producing water steam and heat, whereas electrons are forced through an external circuit generating an electrical current (Sharaf and Orhan, 2014). This technology is currently in development and use by several international projects. Some examples are the H_2 powered ships Nemo H_2 (eSMARTcity, 2021), Hydrogenesis (Ship Technology, 2021), FreeCO2ast (Havhydrogen, 2021), or Zemship (Proton Motor, 2021), which confirmed that it is possible to install and successfully integrate a FC system in a vessel operating with zero emissions (Tronstad et al., 2017). On the other hand, Internal Combustion Engines (ICEs) are mechanochemical devices that convert the chemical energy of a fuel into mechanical energy, usually made available on a rotating shaft (Winterbone and Turan, 2015). An ICE typically uses fossil fuels to work, but they can run on hydrogen making some adaptations of the engine (Sopena et al., 2010); substitution of the fossil fuel injectors by hydrogen injectors, addition of a nitrogen purge, and a hydrogen accumulator, among others (Ortiz-Imedio et al., in press). The operating principle of a H_2 ICE is the same as for the gasoline or diesel ones, described by the Otto cycle and diesel cycle respectively, and based on four stages: admission, compression, combustion, and exhaust (Pulkrabek, 1997). Comparing to FCs, the H_2 ICEs offer some advantages: they are able to run with less pure hydrogen (Parashuram et al., 2016), and they allow the use of the potential manufacturing infrastructure already developed for petroleum-fueled engines, which suppose an important reduction of costs and investment (White et al., 2006).

However, although H_2 is a carbon-free fuel, the environmental performance of its production depends on primary sources (fossil fuels or renewable energy) and the specific process (Abejón et al., 2020). Hence, the need to analyze the environmental sustainability of these systems becomes evident. Life cycle assessment (LCA) is a methodology to evaluate environmentally a product, process, or service along the stages of its life cycle: raw materials extraction, manufacturing and distribution, use, and waste management when it is no longer useful (Fullana, 1997). Several LCA have assessed the impact of fuels and energy generation sources in the scientific literature. On the one hand, a number of authors addressed the environmental impact of FC vehicles, enabling the comparison to gasoline and diesel ones. Ahmadi and Kjeang (2015) carried out an analysis to determine the impacts of FC passenger vehicles in four Canadian provinces, whereas Shimizu et al. (2020) did it both for mobile (vehicles) and stationary (household generation system) applications. Other papers addressed an environmental comparison of H_2 FC and gasoline road vehicles (Granovskii et al., 2006), diesel or natural gas FC buses (Ally and Pryor, 2007), electric cars (Bartolozzi et al., 2013), or methanol vehicles (Bicer and Dincer, 2017). On the other hand, some authors focused their studies on H_2 for shipping applications. Gilbert et al. (2018) quantified air emissions of numerous potential fuels for shipping using secondary data, while Bicer and Dincer (2018) developed an LCA of ammonia and H_2 for sea transportation vehicles. For its part, Bilgili (2021) identified alternative fuels and their environmental damages applied in marine transportation, including biodiesel, biogas, ethanol, and methanol, among others. At this point, it is worth noting that most papers addressed H_2 FC vehicles, mostly wheeled automobiles, whereas LCA of H_2 ICEs remains unexplored.

In this context, the present paper aims to carry out the LCA of a ship propelled by a H_2 PEMFC and a H_2 ICE, in order to compare the technologies with the conventional one, a diesel ICE, from an environmental perspective. Given that the current technologies readiness level (TLR) is still quite low, this analysis consisted of an ex-ante LCA, aiming to assess emerging technologies at an early stage of development by exploring possible scenarios of their future industrial implementation. Ex-ante LCA is usually associated with various challenges, such as clear definition of the function of the future system, uncertainties and the use of specifications originated from laboratory or from pilot-plants. Therefore, this assessment at an early stage of R&D is crucial, enabling the reorientation of the technology development towards decreased environmental burdens at lower costs (Tsoy et al., 2020). Based on the previous state of art, this is the first application of LCA to determine the environmental performance of H_2 ICEs, in particular for shipping applications. Hence, this article would serve to fill a gap regarding hydrogen-based technologies for mobile applications, allowing the comparison with other propulsion alternatives already studied, such as H_2 FCs and diesel ICEs, and promoting the decarbonization of the sector towards a more sustainable mobility.

2. Materials and methods

According to the UNE-EN ISO 14040 and 14,044 standards (ISO, 2006a, 2006b) the methodology applied for the LCA should include four stages, described in the following sections: Goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

2.1. Goal, scope, and methodological framework

The goal of this study is to analyze the environmental impacts associated with a H_2 PEMFC, a H_2 ICE, and a diesel ICE destined to shipping during its whole life cycle, in order to compare the conventional technology with the H_2-based alternatives, and to determine the most suitable option. Secondary goals include the identification of the most polluting stages of the life cycle of the products, as well as the recognition of the main challenges that must be faced towards a green mobility.

The scope includes the definition of the function and the functional unit (FU). The FU is the measurement of the function of the systems analysis that enables these to be totally comparable among them (Abejón et al., 2020). Given that the function is the energy generation to propel maritime vessels, the FU defined was 1 kWh of energy obtained from the PEMFC and the ICEs systems. This reference is considered to be the proper FU to minimize possible biases in the results, in addition to being the recommended by the European Commission (Maestre et al., 2021b). Even though the most common FU for mobile applications is the distance covered by the vehicle, expressed per km, this FU was discarded since for vessels, unlike road vehicles, the impact caused differs significantly depending on the application. The two H_2-based technologies considered in this study are intended for different applications based on their output power; the PEMFC is destined to propel a small touristic boat, whereas the H_2 ICE will be used in a wind farm support vessel. Based on this, the technologies performance would be quite different. In addition, ships consume most of their fuel in maneuvering, i.e., turning, stating, berthing, etc., so that a reference unit addressing the distance covered by the ship would not make much sense, at least for the support vessel that spends most of the fuel maintaining stabilization of the ship to carry out windmill maintenance or fix operations. Finally, taking into account that most of the references that defined a FU of energy produced use 1 kWh as reference, this FU was considered to be the appropriate instead of other energy units, such as MJ.

With the aim of evaluating the systems, three scenarios were defined: 1) use of a diesel ICE, 2) use of a PEMFC system, and 3) use of a H_2 ICE. Fig. 1 shows the boundaries of the systems and the flow diagrams for the scenarios. The scope, from cradle-to-grave, included all the stages of the life cycle of the products, involving raw materials production, manufacturing, use, and end-of-life (EoL). The transport both of raw materials and products were excluded due to the low contribution showed by this phase in other LCA studies (Granovskii et al., 2006). Therefore, the first stage is the raw materials extraction and processing to obtain the materials and pieces to manufacture the devices. Subsequently, the manufacture and assembly of the products is carried out. In this stage, electricity from grid mix is required to assemble all the components. Once the devices are obtained, they are incorporated in the ships, along with the diesel or the hydrogen. In the case of the scenarios 2 and 3, H_2 produced by methane steam reforming (SMR), also known as grey H_2, was considered as base case, as it is the most implemented and economical production method and, currently, taking this source into consideration would provide the most realistic scenario for analysis (Parvatker and Eckelman, 2019). Finally, the last stage of the life cycle is the EoL of the systems, which consists of the disassembling and recycling/recovery of the materials.

2.2. Data acquisition and life cycle inventory

LCI involves the compilation and calculation procedures in order to determine the inputs and outputs of the product systems. The inputs include both material and energy flows, whereas the outputs can be products or emissions and waste to air, water, or soil (Ally and Pryor, 2007). In this study, primary data were obtained from experimental information provided by two confidential companies, as well as from own assumptions and calculations based on literature. Secondary data, i.e., background processes, were collected from the GaBi database (Sphera, 2019).

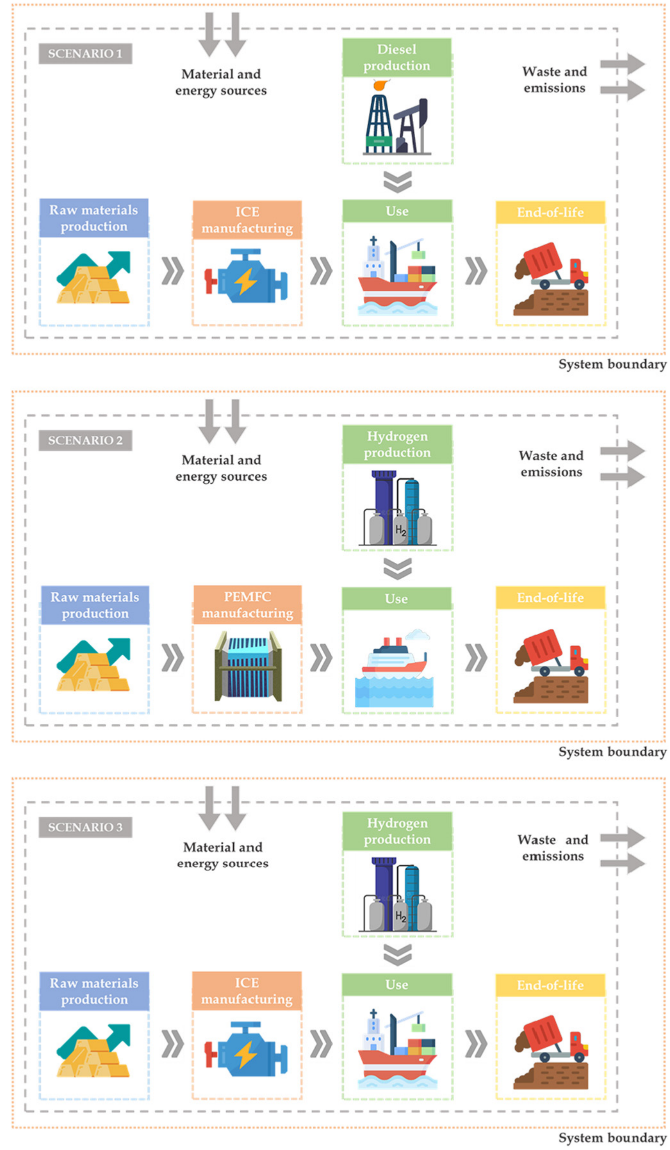

Fig. 1. System boundaries of the scenarios. Top: scenario 1 (diesel ICE), middle: scenario 2 (PEMFC), bottom: scenario 3 (H_2 ICE).

2.2.1. Raw materials production

Table 1 reports a summary of the materials for the production of the PEMFC system. The heart of the system, i.e., the PEMFC stack, was selected based on its characteristics to accomplish the expected applications. Therefore, the model FCgen® - LCS, commercialized by the company Ballard (2021), was considered. This stack was designed to reach 12 kW of power, for which 74 cells were required, adding a weight of 15.40 kg. Table S.1 of the Supplementary Materials reports a more detailed inventory, including the systems, components, subcomponents, units, etc., as well as some assumptions made to complete the LCI.

Table 2 provides a summary of the materials to manufacture the diesel and hydrogen ICEs. The model *Volvo Penta D4300I*, designed by Volvo (Volvo Penta, 2021) was chosen for the analysis since it reaches 230 kW of power, even though it was assumed to work at 205 kW, based on the recommendations of the engine manual. The total weight of the diesel ICE was about 636 kg, whereas the H_2 ICE weighed approximately 642 kg, little

Table 1
Materials for the production of one PEMFC system.

Material	Quantity (kg)
Steel	34.60
Copper cable	15.87
Aluminum	13.88
Graphite	13.20
Anodized aluminum	10.00
Plastic	6.36
Stainless steel	2.44
Polyphtalamide	2.25
Silicon	2.00
Resin	1.03
Glass fibers	0.75
Neodymium magnet	0.66
Brass	0.35
Ring core coil	0.24
Nafion®	0.19
Polyurethane foam	0.15
Paper	0.10
Rubber	0.01
Platinum	$1.80 \cdot 10^{-3}$

more than the diesel one due to the components that must be added to adapt the engine to run on H_2. Table S.2 of the Supplementary Materials reports a detailed inventory, as well as hypotheses and assumptions. The equivalence of each materials and the processes of the database is included in Table S.3 of the Supplementary Materials.

2.2.2. Manufacturing

The energy consumption for the assembling of the technologies was calculated multiplying the practical power of the equipment with the machining time. For the PEMFC system, an estimation of 1194 kWh was assumed, based on Hussain et al. (2007) and Weiss et al. (2000), whereas for the ICEs it was considered an energy input of 2750 kWh, according to Li et al. (2017).

2.2.3. Use stage

Regarding the fuels production, a H_2 flow of 0.70 kg/h was required for the PEMFC ship. For the ICEs, a diesel flow of 29.50 L/h should be introduced to reach 205 kW. Farrell and Matthew (1998) reported that a H_2 ICE has a lower power than a diesel one of the same sizes, resulting in 15% reduction in power. To maintain the output power considered (205 kW), it should be necessary a flow of 34.70 LN/h of hydrogen. The inventories of the SMR and diesel production processes were collected from the GaBi database (Sphera, 2019).

The emissions produced both in the use of PEMFC and engines were taken into account. With regard to the diesel ICE, GHG, NO_x, metals, and particulate matter emissions, among others, were estimated. The emission factors (EF) for CO_2, CH_4, and N_2O were compiled from the IPCC (Intergovernmental Panel on Climate Change) database (IPCC, 2006), whereas the remaining EF were collected from the EMEP-Corinair Emission Inventory Handbook of 2006 (EEA, 2006). The summary of the EF is reported in Table S.4 of the Supplementary Materials. The PEMFC system only generates water vapor, so these emissions were neglected. The H_2 ICE, in spite of offering a clean combustion in terms of CO_2, CO, and hydrocarbons, produces greater thermal NO_x emissions. These impacts were calculated according to the reference of Ortiz-Imedio et al. (2020), considering an engine speed of 3000 rpm and a fuel/air ratio of 1.5.

Table 2
Materials for the production of one (diesel and H_2) ICE system (Volvo Penta, 2021).

<table>
<tr><th>Material</th><th>Quantity diesel ICE (kg)</th><th>Quantity H₂ ICE (kg)</th></tr>
<tr><td>Steel</td><td>174.21</td><td>176.43</td></tr>
<tr><td>Aluminum</td><td>93.13</td><td>93.81</td></tr>
<tr><td>Plastic</td><td>42.16</td><td>42.26</td></tr>
<tr><td>Stainless steel</td><td>20.57</td><td>21.36</td></tr>
<tr><td>Cast aluminum</td><td>3.82</td><td>6.59</td></tr>
<tr><td>Cast iron</td><td colspan="2">232.75</td></tr>
<tr><td>Rubber</td><td colspan="2">16.74</td></tr>
<tr><td>Brass</td><td colspan="2">11.93</td></tr>
<tr><td>High density polyethylene</td><td colspan="2">8.34</td></tr>
<tr><td>Ethylene-propylene rubber</td><td colspan="2">7.15</td></tr>
<tr><td>Copper cable</td><td colspan="2">4.80</td></tr>
<tr><td>Polypropylene</td><td colspan="2">4.06</td></tr>
<tr><td>Vinyl resin</td><td colspan="2">1.47</td></tr>
<tr><td>Base oil</td><td colspan="2">0.60</td></tr>
<tr><td>Silicon oxide</td><td colspan="2">0.49</td></tr>
<tr><td>Polyester</td><td colspan="2">0.23</td></tr>
<tr><td>Paper pleats</td><td colspan="2">0.20</td></tr>
</table>

2.2.4. End-of-life

The EoL of the systems starts with the dismantling of the devices, for which the same energy as for the assembling was assumed since the same machinery was used, and the energy consumption should be similar. Hence, 1194 kWh for the PEMFC system and 2750 kWh for the ICEs systems were considered. In relation to the FC, EoL management options were selected for the individual components of the system. Regarding the stack, a valorization of Pt catalyst was assumed in order to obtain a secondary compound. A hydrometallurgical method, which consists of five stages (leaching, separation via liquid-liquid extraction, regeneration, precipitation, and filtration) was considered for this purpose. The inventory of the reactants for the recycling of the Pt (1.80 g), is reported in Table S.5 included in the Supplementary Materials. The main product of this treatment is ammonium hexachloroplatinate, $[NH_4]_2PtCl_6$, so it was assumed that 1 kg of this compound avoided the burden of 1 kg of platinum extracted (Duclos et al., 2017). Likewise, the recovery of aluminum of the end plates includes the melting of the Al in a furnace, requiring 400 kWh per ton of Al (Suzuki and Tsujimura, 2015), and then, the product is used to produce secondary Al ingots. A substitution factor of 1:1 was assumed, i.e., 1 kg of secondary Al substitutes 1 kg of primary Al (Allegrini et al., 2015). The membrane, composed of the copolymer Nafion® and the magnet of the electrical engine are disposed of in landfill, whereas the bipolar plates, made of graphite, are sent to a Waste-to-Energy (WtE) plant (Handley et al., 2002). In relation to the remaining components of the FC system, i.e., pumps, valves, sensors, and compressor, among others, could be reused, whereas the rest is disposed of in a landfill. Plastic pieces are sent to an WtE plant, while metal ones are recovered to produce new products. For steel and stainless steel 600 kWh of energy per ton is required, and for copper cables, the Cu is melted, considering an energy of 1223 kWh per tonne (Li et al., 2013).

Regarding the ICEs, it was estimated that around 85% of the components can be directly reused, which suppose about 90% of the materials. Therefore, according to Li et al. (2013), 69% of steel, 99% of cast iron, and 83% of aluminum pieces are refurbished and reused. The remaining mass of these metals is sent to a furnace for melting, and, later, to produce secondary ingots. The disposal and recovery of the plastics and copper cables is the same as for the PEMFC system.

2.3. Life cycle impact assessment

The life cycle impact assessment (LCIA) includes the selection of impact categories, the assignation of the LCI results to the impact categories selected (classification) and the calculation of indicators results (characterization) (ISO, 2006b). The modelling was performed with the software openLCA 1.10.3 (Greendelta, 2021) and the CML 2001 method (Guinée et al., 2002). This LCIA method was considered appropriate because it has the highest number of characterization factors compared to other methods, and it is the most widely used in LCA studies addressing hydrogen energy systems (Valente et al., 2017). In addition, the midpoint CML family of methods is the one recommended by the FC-HyGuide (Masoni and Zamagni, 2011), which is a specific LCA guidance for H_2 and FC technologies. Eleven CML categories were analyzed to have a global vision of the impact of the systems: Global Warming Potential (GWP), expressed in kg CO_2 eq., Acidification Potential (AP), measured in kg SO_2 eq., Eutrophication Potential (EP), expressed in kg PO_4^{3-} eq., Ozone Layer Depletion Potential (ODP), measured in kg R11 eq., Abiotic Depletion Potential elements and

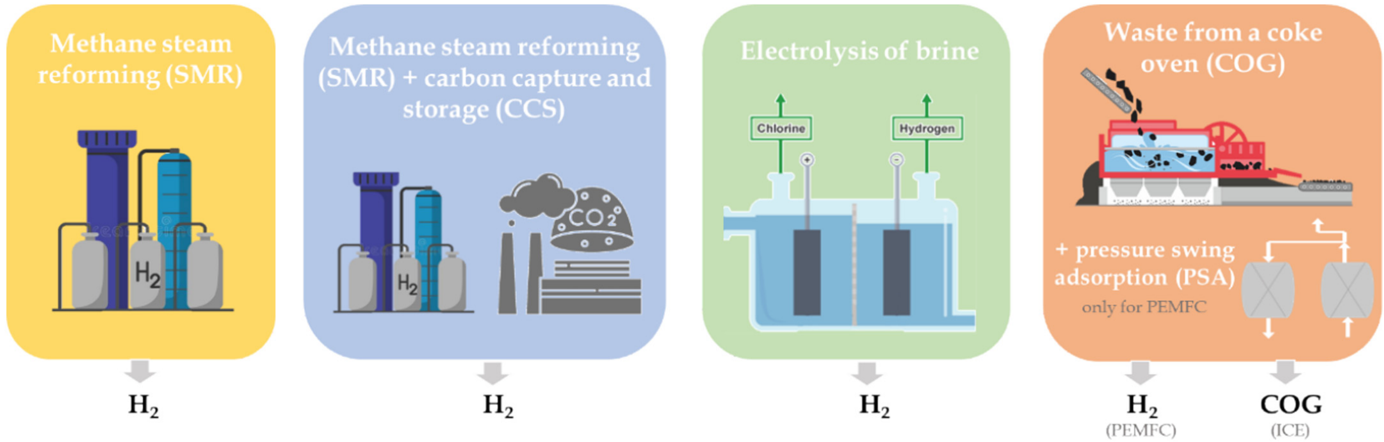

Fig. 2. Hydrogen sources considered in the analysis.

fossil (ADP elements and ADP fossil respectively), measured in kg Sb eq. and MJ respectively, Freshwater Aquatic Ecotoxicity Potential (FAETP), Human Toxicity Potential (HTP), Marine Ecotoxicity Potential (MAETP), Terrestrial Ecotoxicity Potential (TETP), expressed in kg DCB eq., and Photochemical Ozone Creation Potential (POCP), estimated in kg C_2H_4 eq.

2.4. Influence of the hydrogen source

Finally, an analysis of different scenarios was conducted to investigate the effect of different H_2 sources to the overall impact of the technologies. The four options considered in this assessment are illustrated in Fig. 2. SMR was considered as base case, as previously mentioned, due to it presents the most realistic scenario. Blue H_2 avoids great amount of direct CO_2 emissions, adopting carbon capture and storage (CCS) afterwards the SMR (Boretti, in press). The CCS technology considered was chemical absorption with monoethanolamine (MEA), which is a post-combustion capture strategy to reduce CO_2 of gaseous streams (Luis, 2016). Tables S.6. and S.7 of the Supplementary Materials collect the inventory data for the manufacturing and use of this unit. Secondly, electrolysis of brine is other suitable and cleaner alternative, in which, along with H_2, other compounds with high-market value such as NaOH or HCl are produced. The inputs and outputs of this technology were collected from the GaBi database (Sphera, 2019). Finally, a gaseous waste stream of a coke oven, later referred to as COG, was considered as an alternative to promote the circular economy taking advantage of a waste stream. For the use of COG in the FC, the purification of H_2 is carried out in a pressure swing adsorption unit (PSA) (Yáñez et al., 2020), which separates H_2 through its adsorption in a solid surface while it is subjected to high pressures (Sircar and Golden, 2006). The modelling of the PSA unit was developed using as basis the energy demand and the corresponding mass flows according to Abejón et al. (2020). To determine these energy requirements, detailed in Table S.8 in the Supplementary Materials, the minimum and real work to achieve a 99.97% H_2 flow was calculated, based on the reference of House et al. (2011). On the contrary, the COG stream can directly feed the ICE to produce energy without the need of the PSA (Uma et al., 2004).

3. Results and discussion

3.1. Cradle-to-grave analysis

This section provides the environmental impacts produced by the systems considering the base case, i.e., implementing SMR as H_2 production method. The reductions in the impact categories achieved by the H_2-based technologies compared with the diesel ICE are illustrated in Fig. 3, as well as the total burdens, reported in Table 3.

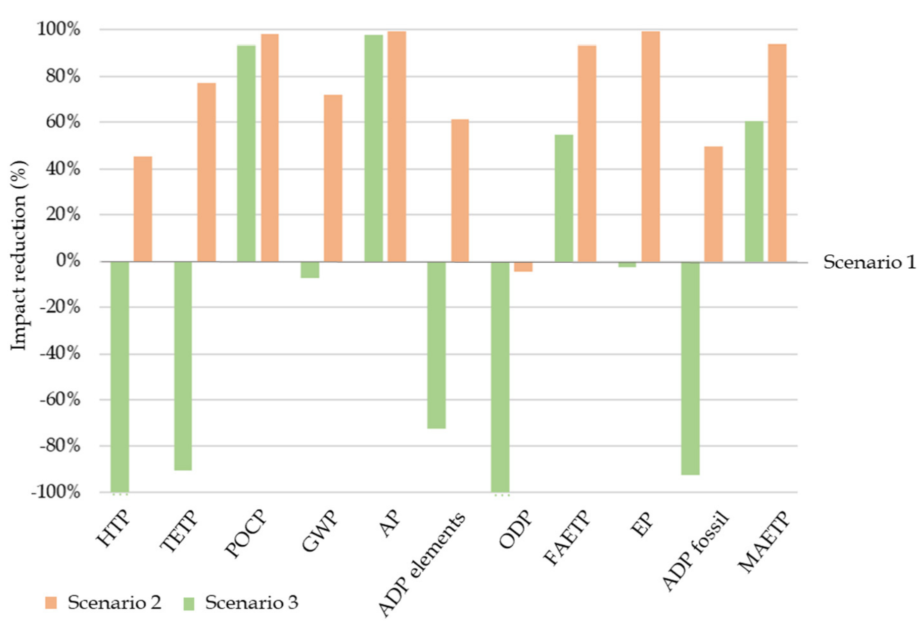

Fig. 3. Reductions in the impact categories achieved in the scenario 2 (PEMFC) and scenario 3 (H_2 ICE).

Table 3
Total environmental impacts per FU (1 kWh). Green cells represent lower impacts than diesel ICE, while red ones indicate higher impacts.

Impact category	Scenario 1	Scenario 2	Scenario 3
HTP (kg DCB eq.)	$3.09\cdot10^{-2}$	$9.36\cdot10^{-2}$	$1.69\cdot10^{-2}$
TETP (kg DCB eq.)	$1.05\cdot10^{-3}$	$2.00\cdot10^{-3}$	$2.41\cdot10^{-4}$
POCP (kg Ethene eq.)	$6.20\cdot10^{-4}$	$4.03\cdot10^{-5}$	$1.03\cdot10^{-5}$
GWP 100 years (kg CO_2 eq.)	$5.80\cdot10^{-1}$	$6.23\cdot10^{-1}$	$1.62\cdot10^{-1}$
AP (kg SO_2 eq.)	$1.21\cdot10^{-2}$	$2.59\cdot10^{-4}$	$6.62\cdot10^{-5}$
ADP elements (kg Sb eq.)	$3.60\cdot10^{-8}$	$6.20\cdot10^{-8}$	$1.39\cdot10^{-8}$
ODP (kg R11 eq.)	$5.74\cdot10^{-16}$	$2.07\cdot10^{-9}$	$6.00\cdot10^{-16}$
FAETP (kg DCB eq.)	$2.20\cdot10^{-3}$	$9.96\cdot10^{-4}$	$1.48\cdot10^{-4}$
EP (kg Phosphate eq.)	$1.27\cdot10^{-3}$	$1.30\cdot10^{-3}$	$9.15\cdot10^{-6}$
ADP fossil (MJ)	5.73	11.02	2.87
MAETP (kg DCB eq.)	4.83	1.90	0.30

Based on Fig. 3, scenario 3, i.e., the H_2 ICE system, turned out to be an appropriate cleaner technology for shipping because, based on current public domain information, it reported lower impacts than the diesel ICE in ten of the eleven indicators. Reductions between 45.35% (HTP) and 99.28% (EP) were achieved, representing an important environmental benefit, whereas an increase of 4.53% was reported in ODP. For its part, scenario 2, i.e., the PEMFC system, reported significant decreases in POCP (93.50%), AP (97.86%), FAETP (54.73%), and MAETP (60.66%), while other five indicators experimented considerable growths, ranging from 72.33% (AP) to higher than 100% (HTP and ODP). In EP and GWP slight rises were accomplished, of 2.71% and 7.46%, respectively. In order to identify the origin of these emissions and focus on critical materials, the contribution of each life cycle stage to the overall impact was assessed, as Fig. 4 depicts.

GWP 100 years, ADP fossil and ADP elements are the most characteristic indicators addressing decarbonization. GHG emissions ranged from 0.16 (H_2 ICE) to 0.62 kg CO_2 eq. (PEMFC), with a contribution of the use stage to the total impact of practically 100% in the three scenarios. For the H_2-based technologies, these burdens came from the hydrogen production process (SMR), as the PEMFC and ICE themselves do not generate carbon emissions. In turn, half of GWP impact of scenario 1 was produced in the combustion of diesel in the engine, whereas the other half was generated in the diesel production. Likewise, ADP fossil impact, that laid between 2.87 (H_2 ICE)

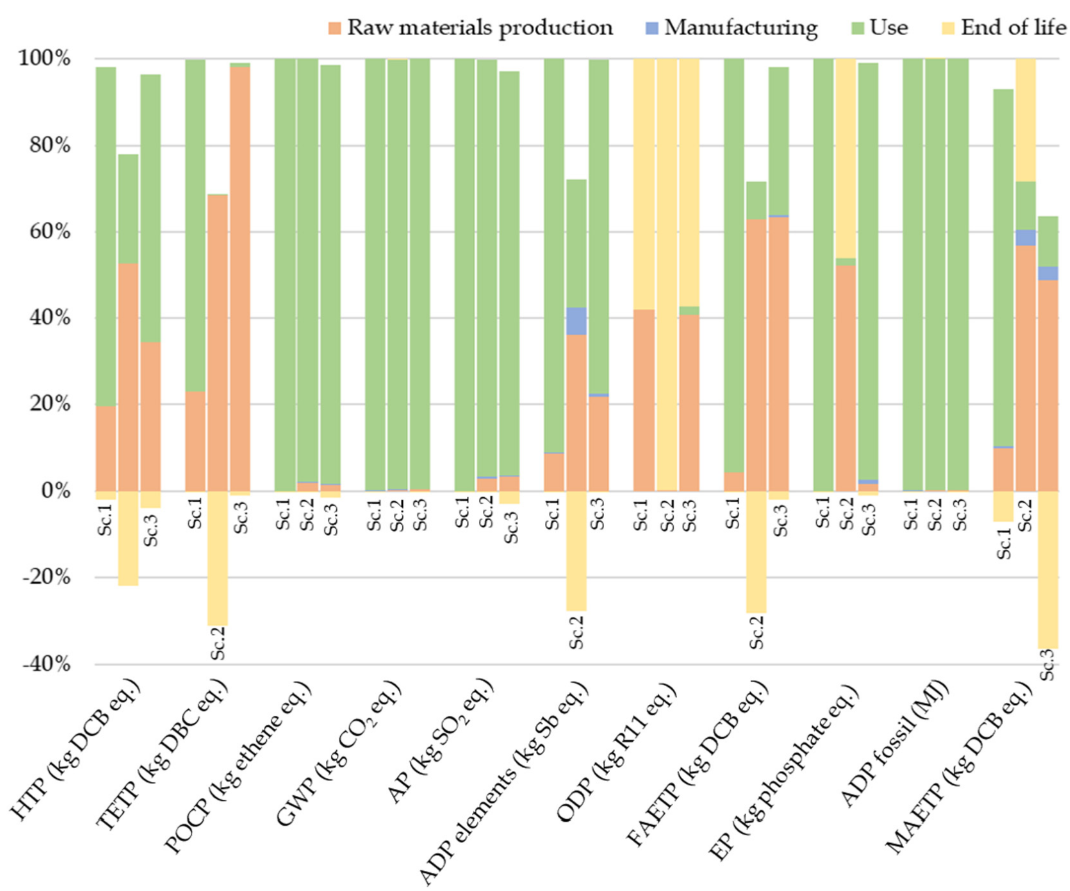

Fig. 4. Contribution of each life cycle stage on the impact categories. First bar: scenario 1, middle bar: scenario 2; last bar: scenario 3.

Table 4
GWP 100 years impact related to the technologies.

Technology	GWP (kg CO_2 eq./kWh)	Reference
Diesel ICE	0.58	Present study
	0.64	Alkaner and Zhou (2006)
	0.60	Gilbert et al. (2018)
	0.52	Ellingsen et al. (2016)
PEMFC system	0.62	Present study
	1.06	Alkaner and Zhou (2006)
	0.64	Bicer and Khalid (2020)
	1.00	Gilbert et al. (2018)
	0.51	Strazza et al. (2010)
H_2 ICE	0.16	Present study
	0.34	Desantes et al. (2020)

and 11 MJ (PEMFC), was totally caused by the fuels production; diesel comes from oil, whereas the SMR required fossil resources to synthetize H_2. However, for the case of ADP elements, there was a clear difference between the ICEs and the FC. In scenarios 1 and 3, resource depletion was highly caused by the use phase, with a contribution around 80% of the total. On the contrary, raw materials production proved to be the critical stage in scenario 2 due to the use of stack-specific materials, such as platinum, which was identified as a critical material.

Toxicity-related indicators were primarily influenced by the raw materials production and use stages. For FAETP and MAETP, both H_2-based technologies presented environmental benefits, while for HTP and TETP scenario 2 reported higher burdens than scenario 1. In MAETP, FAETP, and TETP, the type of fuel made the difference in the impacts. In these indicators, the use stage presented the major contribution in scenario 1, whereas raw materials production did it in scenarios 2 and 3, where hydrogen is required. For HTP, the components that assemble the PEMFC had a greater impact than those of the ICEs, since the raw materials production was identified as the main carrier of human toxicity effects in scenario 2. Regarding EP, in scenarios with a combustion engine (1 and 3), raw materials production had practically no impact, while in the PEMFC (scenario 2) 60% of the emissions came from this stage. This is explained by the fact that, whereas ICEs are made of common materials, such as aluminum, iron, or steel, the PEMFC require unique components with important impacts associated, like the Nafion® membrane. Finally, both in AP and POCP the use stage represented the major hotspot of the systems due to the fuels' production.

In relation to the manufacturing or assembling stage, it had a small contribution in all impact categories since electricity from grid mix is the only resource required in this stage. In turn, EoL had the greatest influence in scenario 2, with significant avoided burdens in HTP, TETP, ADP elements and FAETP due to the reuse of materials of the PEMFC and the recovery processes of metal components. It is worth noting the positive impact of the EoL in ODP for all scenarios, which is caused in the case of the ICEs by the aluminum recovery process, and in the case of the FC by the recycling of the permanent magnet electric motor.

To compare the environmental performance of the technologies studied in this work against reference values reported by other authors, a bibliographic search was carried out. This allows checking if the conducted LCA is a representative analysis and if the results obtained are consistent with the current state of the technologies, evidencing that the strategies were properly established for the required purpose (shipping). Table 4 shows GWP impacts reported by LCA-related references, considering the FU of 1 kWh. As observed, GHG emissions calculated in this study are in the range of the values found in literature. Both in the case of the diesel ICE and H_2 PEMFC, the emissions calculated, 0.58 kg CO_2 eq./kWh and 0.62 kg CO_2 eq./kWh respectively, are quite similar to those reported by other authors. GHG emissions of diesel ICE ranged between 0.52 (Ellingsen et al., 2016) and 0.64 kg CO_2 eq./kWh (Alkaner and Zhou, 2006). On the other hand, burdens for the PEMFC reached 0.51 kg CO_2 eq./kWh (Strazza et al., 2010), 0.64 kg CO_2 eq./kWh (Bicer and Khalid, 2020), or nearly 1.00 kg CO_2 eq./kWh (Gilbert et al., 2018; Alkaner and Zhou, 2006). Finally, only one paper that reported the environmental impact values for the H_2 ICE system was found, which can be explained by the fact that this technology has hardly been studied from an environmental perspective. Desantes et al. (2020) reported 0.34 kg CO_2 eq./kWh, which is double that the one calculated in this study (0.16 kg CO_2 eq./kWh). This may be due to the fact that this author evaluated an H_2 ICE for its application in road vehicles (cars), so that both design and operation of the engine are influenced. In view of the results, the H_2 ICE is a competitive alternative for ships propulsion, so it reported the lowest environmental impacts. Nevertheless, the PEMFC system presents great potential and obtains similar impacts than the diesel ICE, so it must be studied in detail and optimized in order to assure its competitiveness.

3.2. Influence of the H_2 source

In this section, given that the use of the technologies was the most critical life cycle stage, an analysis based on the H_2 production method was carried out. Fig. 5 illustrates the environmental impact of the scenario 2 (PEMFC) and scenario 3 (H_2 ICE) considering a cradle-to-grave approach and the different H_2 sources previously mentioned in Section 2.4: SMR, SMR + CCS, brine electrolysis, and COG.

For both schemes, the SMR + CCS produced lower impacts in GWP indicator, whereas the remaining ten categories experimented increases to a lesser or greater extent. This is explained by the fact that the H_2 production process was the same, i.e., SMR, but in the case of blue H_2 it was considered the manufacturing of the CCS plant, causing some categories to increase due to the production of the raw materials. In counterpart, the use of the CCS reduced 90% of direct CO_2 emissions through the capture of the compound in the adsorbent. This made the carbon footprint of the system decreased from 0.62 kg to 0.11 kg CO_2 eq./kWh in scenario 2, and from 0.16 to 0.028 kg CO_2 eq./kWh in scenario 3, representing a reduction of almost 80% of the total GHG emissions. This analysis stated that the implementation of CCS is not as favorable as expected initially, even though GWP was importantly reduced, highlighting the need for applying environmental tools such as LCA, which enable the evaluation of different impact categories to obtain a global vision of the systems.

Regarding the electrolysis, slightly higher burdens were obtained in four of the eleven categories compared to SMR, which was associated to the manufacturing of the technology. Significant reductions in GWP indicator were observed, dropping from 0.62 to 0.062 kg CO_2 eq. (90%) in scenario 2 and from 0.16 to 0.004 kg CO_2 eq. (97%) in scenario 3. This makes sense since the electrolysis of brine does not emit pollutants, generating only sodium hydroxide and chlorine that can be used to other purposes. A decrease of around 95% was achieved in ADP fossil indicator, which is caused by the lack of use of fossil resources, while, on the contrary, increases were observed in ADP elements, specially in scenario 2. In light of these results, electrolysis demonstrated to have great potential, managing to reduce the impact of technologies significantly, making the H_2-based technologies competitive against diesel ICEs.

Finally, in relation to the use of a COG stream, nine of the eleven categories presented lower impacts for the PEMFC compared to the SMR, whereas for the ICE ten indicators reached smaller values. In both systems the trend of the burdens was quite similar. The reduction in the category of ADP fossil was noteworthy, dropping from 11.01 MJ to 0.85 MJ in the scenario 2, and from 2.87 MJ to $7.34 \cdot 10^{-3}$ MJ in the scenario 3. On the contrary, GWP impacts grew for this H_2 source, being the increase very significant for the ICE due to the direct emissions of CO_2 generated in the combustion of the gaseous mixture. For ADP elements, results varied from the ICE to the PEMFC. In scenario 2, this indicator experimented an increase of more than 100%, whereas in the ICE it decreased around 32%. At this point, it would be advisable to optimize the process to make it a competitive alternative, considering, for instance, a renewable energy source, such as solar or wind electricity, as the energy required for the H_2 purification was identified as the hotspot of the technology.

3.3. Challenges and implications for policy and industry

This paper aims to fill an existing research gap lying in the understanding and comparison of ships with two different decarbonization strategies:

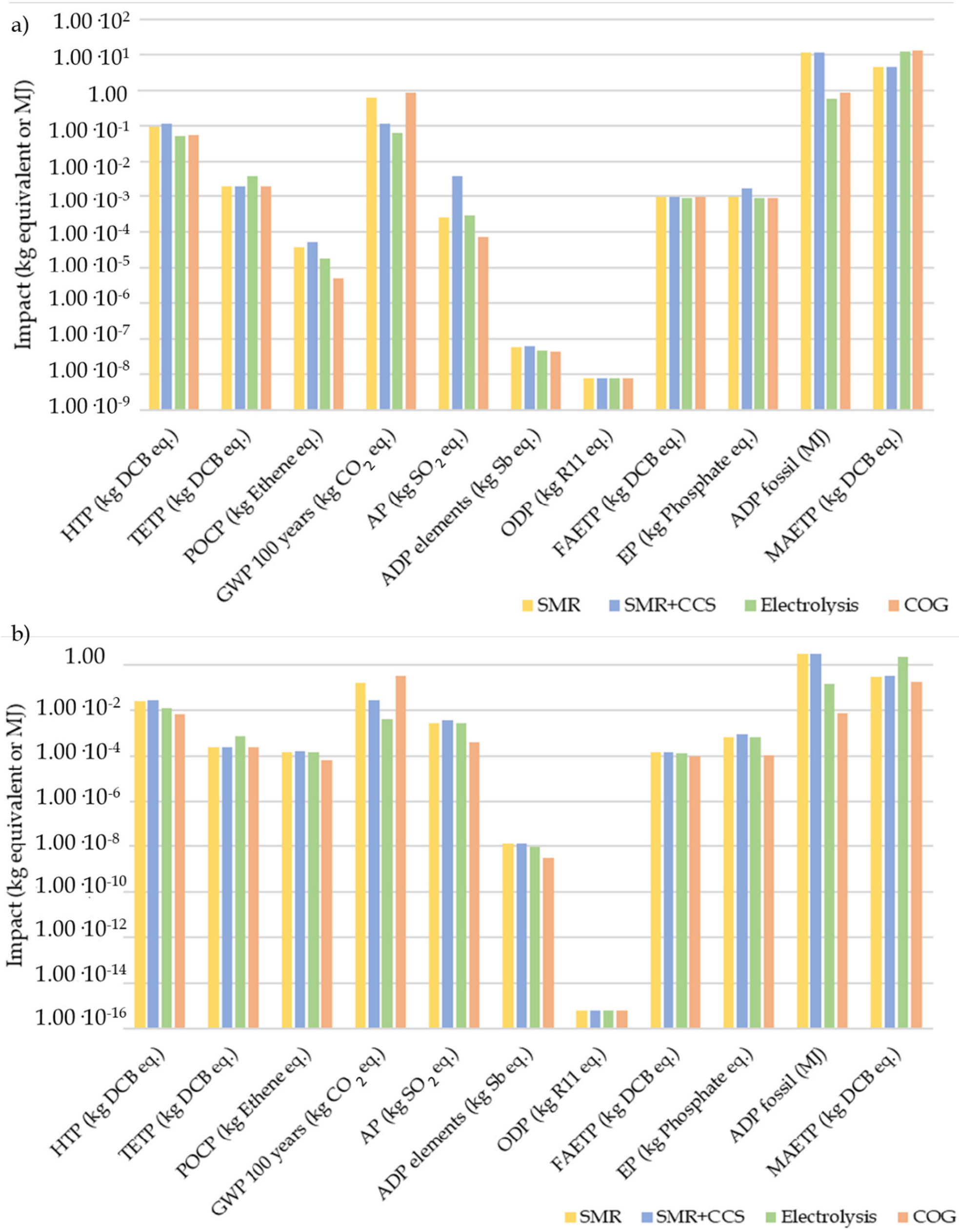

Fig. 5. Environmental impacts per FU (1 kWh) for each H_2 source in a) scenario 2, and b) scenario 3.

the use of PEMFC (scenario 2) and the consumption of H_2 in an internal combustion engine (scenario 3). Fig. 6 summarizes the results of scenarios 2 and 3 compared to scenario 1 (diesel ICE), with the indicators more related to decarbonization.

Environmental burdens intensity

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	Scenario 3	Scenario 1	Scenario 2
GWP 100 years (kg CO_2 eq.)	1.62 10^{-1}	5.80 10^{-1}	6.23 10^{-1}
ADP fossil (MJ)	2.87	5.73	11.02
ADP elements (kg Sb eq.)	1.39 10^{-8}	3.60 10^{-8}	6.20 10^{-8}

Fig. 6. Summary of the impacts associated with decarbonization.

As explained in the previous section, scenario 3, associated with the H_2 ICE, appeared to be the most favorable in terms of decarbonization. The main indicator that allows us to evaluate the progress of the energy transition in the sector, GWP, reflected the significant reduction in GHG emissions, achieving a 72% drop with respect to scenario 1. The implementation of this technological proposal would make it possible to achieve the goal of a 30% reduction in GHG emissions by 2030, and would contribute significantly to reaching a climate neutrality scenario by 2050. Thus, this technology is in line with the objectives of the European Green Deal, helping Europe to the transition to a green and sustainable economy. On the contrary, always taking into account the low degree of maturity of H_2 FCs at present, the incorporation of this technology would not only be detrimental from an emissions point of view, but also from the perspective of consumption of non-renewable resources. However, in view of the speed of technical development and technological advance of the technologies, it is possible that in the short-medium term future this alternative will be as viable as the hydrogen engines analyzed in this study.

Although this work presents an advance in the field, there is still a long way to go. There are so far several challenges mainly related to the modelling, 'proof of concept', and the implementation of the technologies onboard (Romano and Yang, 2021), causing the environmental performance of the systems to be distorted in reality. In addition, other promising technologies and measures could be implemented to facilitate the pathway to achieve the international target of 90% GHG emissions reduction by 2050. The use of alternative fuels stands out between all the measures. The application of liquefied natural gas (LNG), ammonia, or methanol, among other biofuels, are applied in shipping on an experimental basis due to their high potential (Mallouppas and Yfantis, 2021). However, there exists no ready solutions to avoid the GHG emissions in the short-term, since as in the case of H_2, most of their environmental performance depend on the degree of sustainability of their production processes, and other technical and economical variables. On the other hand, several operational and technological changes could reduce shipping emissions via increased efficiency, such as the use of wind propulsion assistance, slow steaming, low resistance hull coatings, and waste heat recovery systems (Balcome et al., 2019).

Policy action and industry agreement is also crucial to encourage the advancement of emerging innovative technologies and fuels. In order to boost the diffusion and maturity level of H_2 energy systems, several measures are needed, such as the deployment of standards across the hydrogen technology manufacturing and installation industry, as well as policies to encourage the spread of low carbon vehicles (Parra et al., 2019). From a stakeholder perspective, vehicle and energy companies must stand out for their involvement in hydrogen energy R&D and reformation technology by taking part in projects and energy research programs that promote this initiative and facilitate the accessibility and availability of this resource to consumers (Solomon and Banerjee, 2006). In turn, current regulations across the mobility and power industry need to be adapted for an effective penetration of H_2 energy systems (Parra et al., 2019). Even though there is a broad scientific and political consensus that the sector's emissions need to be reduced, there is no agreement on how the transition would be achieved politically: there is no market case nor significant pressure for a transformative shift in the adoption of new technologies or the introduction of low-carbon fuels (Gössling et al., 2021). Therefore, it is mandatory that policy-makers create frameworks that incentivize the emerging role of cross-sectoral technologies by strengthening and amending the existing renewable energy policies, developing public and industrial promotional programs and incentives, establishing standards, targets, and evaluation systems, or facilitating the access for national and international stakeholders (Adiyita and Aziz, 2021).

4. Conclusions

Currently, environmental challenges related to transport, particularly to shipping, are focused on reducing the emissions derived from the use of fossil fuels. To guarantee cleaner and more sustainable mobility, it is necessary to evaluate alternative technologies and low carbon fuels assessing and acting on all stages of their life cycle. In this study, LCA was used to compare and determine the viability of two hydrogen-fueled propulsion technologies, PEMFC and ICE, to traditional diesel ICEs in terms of GHG emissions, resource use and toxicity potentials, among other environmental issues.

Based on LCA results, both H_2-based technologies presented great potential to become a future diesel substitute. The H_2 ICE seemed to present the best environmental performance, reporting significant reductions in ten of the eleven indicators compared with the conventional technology. In turn, the H_2 PEMFC showed important decreases in four impact categories, whereas the remaining seven increased to a lesser or greater extent. Focusing on decarbonization-related indicators, it is worth noting that H_2 ICE would facilitate the energy transition in shipping in a medium to long-term, as it achieved reductions between 45% and 72% in GWP, ADP fossil and ADP elements, while for the PEMFC these burdens grew from about 7% to 90%. However, it cannot be unquestionably concluded that ICE is the most sustainable alternative, or that FC has a poor environmental performance, as LCA was conducted at a very early stage, where the technologies readiness level is still quite low. In fact, H_2 ICEs or hybrid vehicles have not been demonstrated yet, and the sustainability of the technologies may change as they become more widely deployed and developed, which is only possible with policy involvement. Their potential becomes more evident when analysing different H_2 sources. Both technologies demonstrated their crucial role in sustainable mobility due to the low (ICE) or non-existent (PEMFC) polluting emissions in their use, presenting a great environmental behavior if cleaner production processes are implemented. Hence, the development, optimization and implementation of cleaner technologies such as brine electrolysis or the recovery of H_2 from a waste stream, is strongly recommended to put into practice and introduce these promising alternatives into the market.

However, there is still a long way to reach a hydrogen-based economy. Numerous challenges must be overcome to achieve this transition, mainly related to technical aspects, such as incomplete regulations or specifications, economic, like high costs and investments, or social ones, such as unclear public acceptance. At a time when concern for environmental problems, specially climate change, is at its highest point, it is worrying and surprising the lack of involvement and scarcity of supporting policies to achieve the transition. The development of the H_2 industry needs explicit and active support from governments, establishing technological strategies, providing financial support for R&D of H_2 production or storage technologies, as well as infrastructure, integrating social stakeholders and achieving social acceptance. Only the establishment of a strong government intervention framework will help to reduce the risk in the early transitional business cases, so it is essential the full cooperation between governments, enterprises, scientific research institutions and public.

CRediT authorship contribution statement

Ana Fernández-Ríos: Software, Investigation, Validation, Writing – original draft. **Germán Santos**: Conceptualization, Investigation, Validation, Writing- review and edition. **Javier Pinedo**: Conceptualization, Investigation, Validation, Writing- review and edition. **Esther Santos**: Validation, Writing- review and edition. **Israel Ruíz-Salmón**: Validation, Writing- review and edition. **Jara Laso**: Validation, Writing- review and edition. **Amanda Lyne**: Resources, Writing- review and edition. **Alfredo Ortiz**: Writing- review and edition, Project administration, Funding acquisition. **Inmaculada Ortiz**: Validation, Writing- review and edition. **Ángel Irabien**: Validation, Writing- review and edition. **María Margallo**: Conceptualization, Methodology, Investigation, Validation, Writing- review and edition, Supervision **Rubén Aldaco**: Conceptualization, Methodology, Investigation, Validation, Writing- review and edition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153189.

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