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LIFE CYCLE ASSESSMENT OF HYDROGEN AS AN ENERGY VECTOR FOR FUTURE POWER GENERATION FOR MARINE TRANSPORTATION

TRABAJO FIN DE MÁSTER (TFM)

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ABSTRACT

SCOPE

Marine transportation is one of the most polluting sectors, generating annually around 139 million of tonnes of CO_2. Additionally, large amount of nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter, and another dangerous pollutant to human health are emitted in the use of diesel, which is the most commonly fuel (Zheng et al., 2016). Moreover, its production has important impacts to the environment, not only referred to the emissions, but to the depletion of resources required for its production. Therefore, it is necessary to find more sustainable energy generation sources. In this context, and in the framework of the project "The Atlantic Network for Renewable Generation and Supply of Hydrogen to promote High Energy Efficiency – HYLANTIC", it is developed the present work aiming to determine if two cleaner technologies based on the use of hydrogen are effectively more sustainable than the current marine propulsion device; a diesel internal combustion engine (ICE). The study conducted a life cycle assessment (LCA) of three products; a diesel internal combustion engine, a hydrogen internal combustion engine and a hydrogen polymeric electrolytic membrane fuel cell system (PEMFC) to determine the environmental impacts associated to their whole life cycle. Initially it was considered the three first stages of the life cycle of the products; raw materials production, manufacturing, and use, and, afterwards, the end-of-life has been modelled, in a cradle-to-grave approach. The transport of raw materials and products was excluded from the system boundaries due to their low contribution to the total impact. Additionally, a sensitivity analysis has been carried out to evaluate the environmental viability of four types of hydrogen: grey H_2 (obtained from natural gas steam reforming), green H_2 (electrolysis with renewable energy), blue H_2 (natural gas steam reforming with CO_2 capture) and H_2 recovered from waste gaseous streams. The study followed the LCA methodology according to the UNE-EN ISO 14040 and 14044 standards, considering two functional units (FU); 1 kWh of work done by the propulsion system, which allows to compare the technologies per se, and 1 km travelled by the ships, that allow to evaluate the application. The data for the life cycle inventory (LCI) has been provided, on the hand, by partners of the project, and, on the other hand, it has been obtained from references. For the modelling of the systems and the calculation of the environmental burdens, the LCA software *openLCA 1.10.3.* and the database of the software *GaBi ts 9.0.* has been used, considering the CML 2001 impact method.

RESULTS

The comparison of technologies using 1 kWh as functional unit and considering grey H_2 as base case, showed that the hydrogen ICE had a better environmental profile than both the conventional technology and the PEMFC system, since it reported lower burdens for almost all the categories (Figure 1). This can be supported by the global warming potential (GWP), that dropped from 0.58 kg CO_2-eq (obtained for the diesel ICE) to 0.16 kg CO_2-eq. On the contrary, the PEMFC system presented, in general, a worse sustainability than the current technology, that is explained by the use of hydrogen as fuel, requiring an alternative to the conventional H_2 production method of natural gas steam reforming. In this sense, green H_2 obtained from electrolysis with

renewable energy both wind and photovoltaic, was the most suitable technology, achieving important reductions, higher than 90% in ADP fossil or GWP. On the other hand, the analysis considering the FU of 1 km allows to compare the application of the diesel and the hydrogen ICE: offshore wind farms support vessels propulsion. In this case, the suitability of the H_2 ICE compared to the diesel ICE for its use in marine transportation has also been observed.

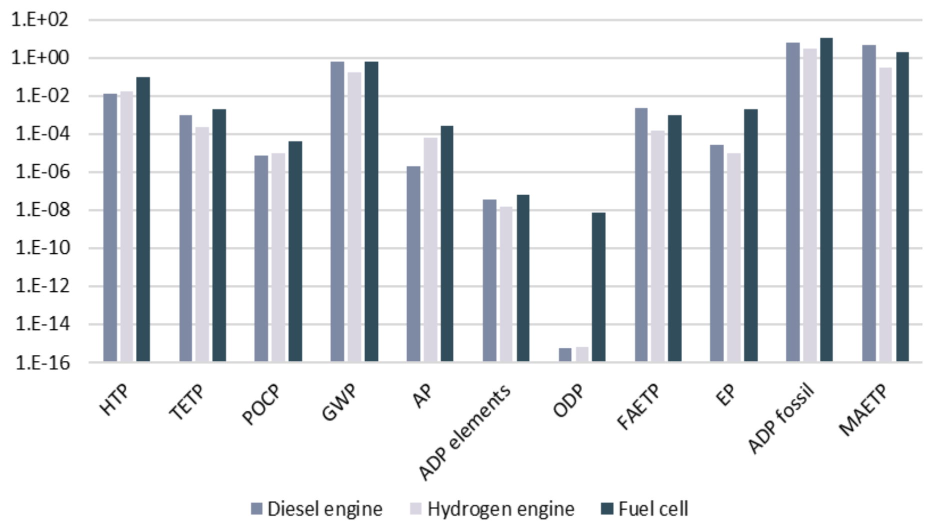


Figure 1: Comparison of the total impacts for each technology considering a FU of 1 kWh.

CONCLUSIONS

Thanks to the results of this TFM it can be concluded that the hydrogen ICE seems to be the most suitable alternative for marine transportation since it presented the lowest environmental impacts, achieving significant reductions (up to 72% in GWP) with respect to the diesel ICE. The use of the PEMFC system is in continuous development and, even though it presented higher impacts than the other alternatives using grey H_2, it appears to be a competitive technology under the appropriate conditions, such as implementing the electrolysis as H_2 production method. In general, both technologies demonstrate to offer high potential and capacity to provide propel systems for marine transportation more beneficial to the environment that those based on the current technology standard, so the future study of a social and economic analysis is proposed in order to evaluate the viability of the technologies as a whole.

RESUMEN

PLANTEAMIENTO DEL PROBLEMA

El transporte marítimo es uno de los sectores que contribuye más significativamente a la contaminación, produciendo alrededor de 139 millones de toneladas de CO_2 anuales. Sin embargo, este contaminante no es el único generado; altas cantidades de óxidos de nitrógeno (NO_x), óxidos de azufre (SO_x), material particulado y otros contaminantes peligrosos para la salud humana son emitidos en el uso del combustible más comúnmente empleado; el diésel (Zheng et al., 2016). Además, su producción tiene fuertes impactos en el medio ambiente, no solo referidos a las emisiones que genera, sino al agotamiento de los recursos necesarios para su fabricación. Es por ello necesario, encontrar fuentes más sostenibles de generación de energía. En este contexto y en el marco del proyecto "The Atlantic Network for Renewable Generation and Supply of Hydrogen to promote High Energy Efficiency – HYLANTIC", se desarrolla el presente TFM, cuyo objetivo se basa en determinar si dos potenciales tecnologías que emplean un combustible más limpio, el hidrógeno, son efectivamente más sostenibles que el método de propulsión marino actual; un motor de combustión interna de diésel (ICE). Para ello, se ha desarrollado el análisis de ciclo de vida (ACV) de tres productos; un motor de combustión interna de diésel, un motor de combustión interna de hidrógeno y un sistema de pila de combustible de membrana electrolítica polimérica (PEMFC), con el fin de determinar los impactos ambientales ligados a sus ciclos de vida completos. Para ello, se han considerado inicialmente las tres primeras etapas del ciclo de vida de los productos; producción de materias primas, ensamblaje y uso, y posteriormente, se ha modelado su fin de vida útil, en una aproximación de la cuna a la tumba. Fuera de los límites del sistema se encuentra el transporte de materias primas y productos debido a su baja contribución respecto al impacto total. Adicionalmente, se ha realizado un análisis de sensibilidad para evaluar la viabilidad ambiental de cuatro tipos de hidrógeno, obtenidos por distintos métodos de producción: H_2 gris (reformado por vapor de gas natural), H_2 verde (electrólisis con energías renovables), H_2 azul (reformado por vapor de gas natural con captura de CO_2) y H_2 recuperado de corrientes gaseosas residuales. Para llevar a cabo este estudio se ha aplicado la metodología de ACV de acuerdo a las normas UNE EN-ISO 14040 y 14044, tomando dos unidades funcionales (UF); 1 kWh de trabajo realizado por el sistema de propulsión, lo cual permite comparar las tecnologías per se, y 1 km recorrido por el barco, lo que permite evaluar la aplicación. Los datos necesarios para la recopilación del inventario de ciclo de vida (LCI) han sido proporcionados, por una parte, por socios del proyecto y, por otra parte, han sido obtenidos de bibliografía. Para el modelado del sistema y el cálculo de las cargas ambientales asociadas se ha utilizado el software de ACV *openLCA 1.10.3.* y la base de datos del software *GaBi 9.0.,* empleando el método de impacto CML 2001.

RESULTADOS

Los resultados obtenidos en el análisis de la cuna a la tumba muestran que, por una parte, comparando las tecnologías (UF de 1 kWh) y considerando H_2 gris como caso base, el motor de hidrógeno presenta un mejor perfil ambiental que la tecnología convencional y el sistema PEMFC, ya que reporta menores cargas para casi todas las

categorías ambientales (Figura 1). Esto se puede observar en la reducción del impacto en uno de los indicadores más representativos, el potencial de calentamiento global, que disminuye de 0.58 kg CO_2-eq. (obtenido para el motor diésel) a 0.16 kg CO_2-eq. Por el contrario, el sistema PEMFC presenta, en general, una peor sostenibilidad que la tecnología actual, que se explica por el uso del hidrógeno como combustible, lo que evidencia la necesidad de estudiar alternativas al método de producción de H_2 convencional de reformado por vapor de gas natural. En el análisis de sensibilidad de la fuente de H_2 se ha observado que el H_2 verde, obtenido por electrólisis con energías renovables, ya sea eólica o fotovoltaica, es la más apropiada, logrando importantes reducciones, mayores del 90% para numerosos indicadores, como ADP fósil o GWP. Por otra parte, el análisis considerando la unidad funcional de 1 km permite comparar la aplicación del motor diésel y de hidrógeno: propulsión de barcos de soporte a granjas eólicas marinas. En este caso, también se observa la idoneidad del uso del motor de H_2 frente al diésel.

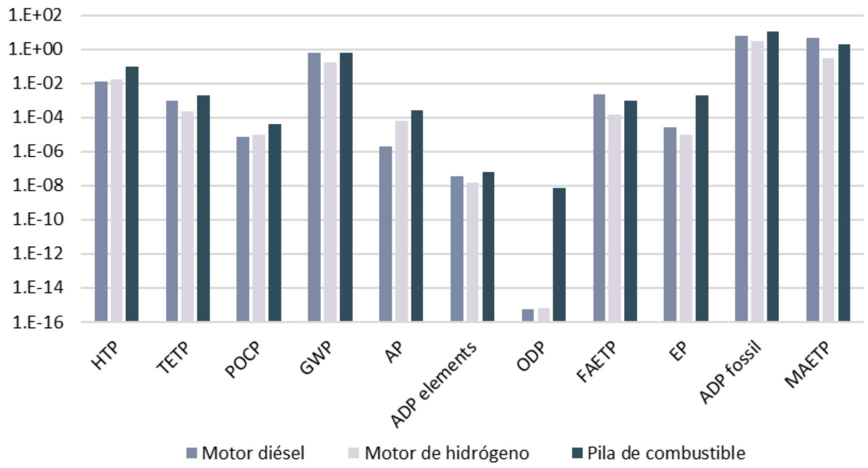


Figura 1: Comparación de los impactos totales de cada tecnología considerando la UF de 1 kWh.

CONCLUSIONES

Gracias a los resultados de este TFM se puede concluir que el motor de combustión interna de hidrógeno parece ser la alternativa más favorable para propulsión de transporte marítimo, ya que es la que presenta menores impactos ambientales, logrando reducciones muy significativas (hasta del 72% en GWP) con respecto al motor diésel. El uso de pilas de combustible se encuentra en continuo desarrollo y aunque actualmente presenta mayores impactos que las otras alternativas usando hidrógeno gris, podría llegar a ser una tecnología competitiva bajo las condiciones adecuadas, por ejemplo, implementando la electrólisis como método de producción de H_2. En general, ambas tecnologías demuestran tener gran potencial y capacidad para ser sistemas de propulsión para transporte marítimo más beneficiosos para el medio ambiente que los basados en la tecnología convencional, por lo que se propone el estudio futuro de un análisis social y económico para evaluar la viabilidad de las tecnologías en todo su conjunto.

1. INTRODUCTION

1.1. HYDROGEN AS ENERGY VECTOR

Hydrogen is the lightest and most abundant element existing in nature, essential to life and one of the most used compounds in the industry since decades. Over the years, the demand and production of hydrogen has been increasing, reaching in 2018 a global demand of around 70 million of tonnes of the pure compound, and mainly dedicated to ammonia production and refining processes (IEA, 2020). 95% of the hydrogen produced is obtained from fossil fuels, being natural gas steam reforming the most common method, with the 48% of the H_2 global production (IRENA, 2018).

The exclusive properties of this compound make it of a great importance in the industrial sector, being a useful and flexible resource that could be used in a wide number of applications. One of the most important characteristics of H_2 is its actuation as an energy vector, that is, it can store energy and release it later in a controlled way. Thus, it is remarkable the high energy density, with a value of 120 MJ/kg under standard conditions. Compared with other fuels, such as methane, gasoline, or diesel (Figure 1), hydrogen contains the largest amount of energy per kg (Boudellal, 2018). However, contrary to mass energy density, the volumetric energy density of hydrogen is notably lower than to other compounds. For example, gasoline, that is one of the most used fuels, has a value of 34.2 MJ/L, whereas that of hydrogen is several orders of magnitude lower, with a volumetric energy density of $1.05 \cdot 10^{-2}$ MJ/L under standard conditions. This means that it would be necessary a higher volume of H_2 to produce the same amount of energy (Farrell and Matthew, 1998).

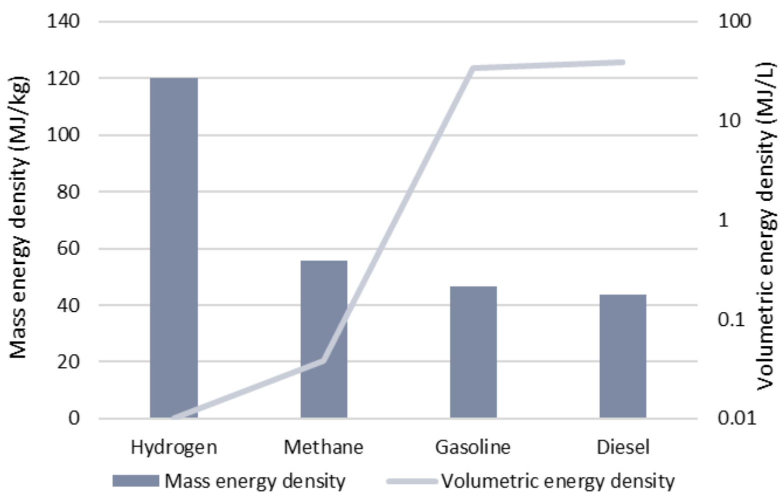


Figure 1: Comparison of fuels energy densities in MJ/kg and MJ/L (Boudellal, 2018).

Moreover, hydrogen has a clean combustion; it does not produce harmful emissions to the environment. In this regard, although so far this compound has been used mainly for products synthesis, the current pollution levels make H_2 a competitive element for conventional fuels, such as gasoline or diesel. The use of hydrogen as energy source provides the advantages of being a sustainable and an eco-friendly resource, as well as constitute an inexhaustible energy source (Dou et al., 2017). In this sense, the European Commission (European Commission, 2020) has presented a series of strategies to integrate hydrogen in the energetic system, promoting a transition to green energy. The EC establishes that H_2 can impulse in Europe the decarbonization in industry, transport, and energy generation. Thus, the UE Hydrogen Strategy approaches how to convert this potential into reality, through regulations, investment, research, innovation, and market (European Commission, 2020).

Several businesses have developed and implemented the idea of using hydrogen as fuel, both to road vehicles and maritime mobility. The first hydrogen cars have already been marketed from various automotive companies, as the cases of Hyundai Nexo (Hyundai, 2020), Honda Clarity (Honda, 2020) or Toyota Mirai (Toyota, 2020). Likewise, a number of projects are developing with the aim of implanting H_2 as fuel in shipping, achieving a zero emissions marine transport. Some examples are shown in Table 1. As can be seen, although the ships are currently in use, some projects are still in development, such as *Nemo H_2* or *Hydrogenesis*, whereas others are starting now, as *FreeCO$_2$ast*. The results obtained from the *Nemo H_2* and *Hydrogenesis* projects show that the fuel cell systems installation was successfully approved and integrated in the ship, as well as the risk assessment and onshore and onboard testing. Likewise, *Zemship* project reported that it is possible to operate a passenger ship with zero emissions, in addition to highlight other advantages as the way the ship glides silently through the water. Therefore, it was concluded that the project can be directly transferred to all areas where passenger ships of this size are operated (Tronstad et al., 2017).

Table 1: Hydrogen use projects in shipping.

Project	Companies	Year	Project location
Nemo H_2	Alewijnse Marine Systems, shipping company Lovers, Linde Gas, Marine Service North and Integral	2012-present	Amsterdam
Hydrogenesis	Bristol Packet Boat Trips, Number seven boat trips, Auriga Energy	2012-present	Bristol
ZemShip-Alsterwasser	Proton Motors, GL, Alster Touristik GmbH, Linde Group	2006-2013	Hamburg
FreeCO$_2$ast	Havila Shipping, Havyard Group ASA, Norwegian Electrical Systems	2020 onwards	Norway

However, the use of H_2 as a fuel has some challenges. It is important to consider its dangerous properties and know the precautions and considerations at the time of use and handling. Hydrogen is highly flammable, and its combustion can be produced being in contact with oxygen at high temperatures, and even its detonation under certain conditions. Despite that, the risks associated with flammability and fire risk are lower than in other fuels (Schjolberg and Ostdahl, 2008).

Another point to consider is that, although significant progress is currently being made, the implementation of the hydrogen economy is not immediate, and it is necessary to deal with various technological, economic, and social barriers. The main challenge that suppose the integration of this compound in the energetic system is its storage, transport, and distribution (Botas et al., 2005). Firstly, even though H_2 could be stored for long time periods, it requires previous treatments. The low density recommends a liquefaction process at a low temperature or a compression process at high pressure to limit storage volumes, which leads to very high energy consumptions (Nicoletti et al., 2015). Moreover, the transport and distribution of gaseous hydrogen must be done through gas pipelines, whilst the liquid compound must be moved contained in cylindric tanks. The transport, either trucks or pipes, is chosen based on the distance and product quantity. However, with the available infrastructures, the distribution cost would be excessively high to convert hydrogen in a primary energy resource. For these reasons and considering the advantages offered by this compound as fuel, this topic is still in development, but gaining great importance in the scientific field (Abdin, et al., 2020).

1.2. FUEL CELLS

A fuel cell (FC) is an electrochemical device that converts the chemical energy of a fuel into electrical energy. It provides an efficient and clean mechanism for energy conversion and it is compatible with renewable resources and modern energy carriers for sustainable development and energy security (Sharaf and Orhan, 2014), so this technology is considered to be the green power source to 21st century (Cheng et al., 2007). The static nature of FCs also means quiet operation without noise or vibration, while inherent modularity allows for simple construction and a diverse range of applications (Sharaf and Orhan, 2014). Even though this technology is showing year-on-year growth, the fuel cell industry is still facing a number of challenges to commercialization. Its cost is one major drawback and the durability of the unit and its performance is another important one, due to the degradation of materials and catalyst (Alaswad et al., 2016).

There are different types of fuel cells, such as alkaline (AFC), phosphoric acid (PAFC), molten carbonate (MCFC), solid oxide (SOFC), proton exchange membrane (PEMFC) or high temperature PEM fuel cells (HT-PEMFC). All the alternatives present diverse advantages, but it has been observed that PEMFC are the optimum option in mobility applications (Alaswad et al., 2016). This is because, among many other reasons, it has a relatively simple installation, a high tolerance for fuel impurities and a high efficiency (Tronstad et al., 2017).

Proton exchange membranes or electrolytic polymeric membrane fuel cells are devices mainly composed of three active components. The heart of a PEMFC is a polymer membrane that is impermeable to gases, but it conducts protons. This membrane that acts as the electrolyte is squeezed between two porous and electrically conductive electrodes, which are typically made of carbon. At the interface between the electrode and the polymer membrane there is a layer with catalyst particles, commonly platinum. Putting several FCs in series results in a fuel cell stack (Wang, et al., 2020).

The operating principle of PEMFC starts feeding the fuel (in this case hydrogen), in the positive side of the membrane, anode, and the transportation to the catalytic layer where it takes place the oxidation, that is, hydrogen splits into its primary constituents, a proton and an electron. The generated protons travel through the membrane up to the cathode, whereas the electrons travel through electrically conductive electrodes, through current collectors, and through the outside circuit where they perform useful work and come back to the other side of the membrane. At the same time, in the negative side of the cell, cathode, it is introduced oxygen. It travels up to the catalytic layer where it is reduced when combining with the electrons and react with the protons that travel through the membrane. Heat is given off and water is created in the electrochemical reaction and then pushed out of the cell with the excess of O_2 (Barbir 2005). The net result of these simultaneous reactions is a current of electrons through an external circuit, that is, direct electrical current. A scheme of this device is shown in Figure 2, as well as the reactions that take place.

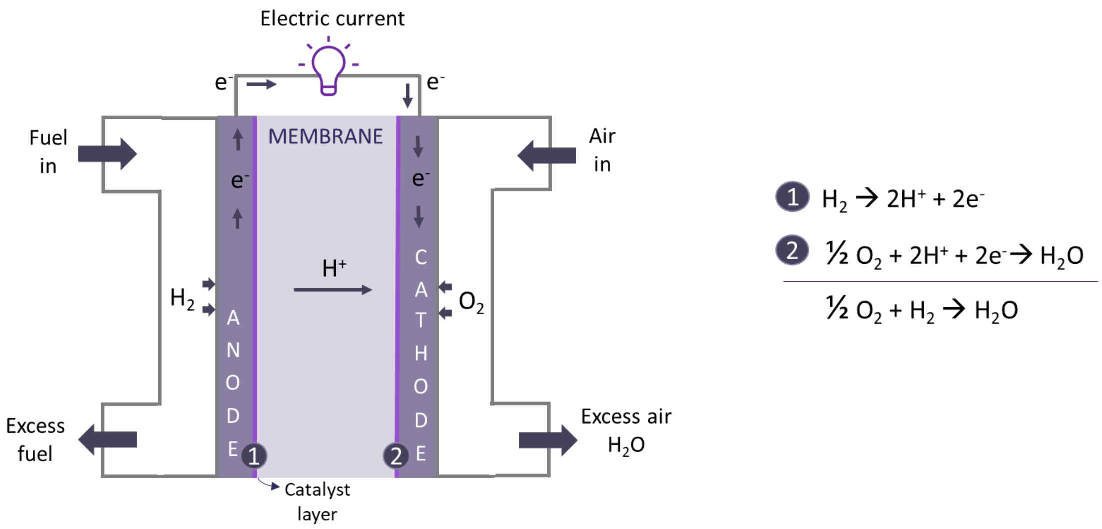


Figure 2: The basic principle of operation of a PEM fuel cell (Sharaf and Orhan, 2014).

PEMFC stacks have been developed for both transport and stationary applications. In the case of stationary applications, these devices are connected to the electric grid to provide power. They can be used for many purposes, including stationary power units for primary power, backup power, or combined heat and power, since they can be sized depending on the required demand and destined to a wide range of installations (de Bruijn, 2005). However, the major application of PEMFCs focuses primarily on transportation because of their potential impact on the environment, such as the control of emission of the greenhouse gases (GHG). Thus, mainly road FC vehicles (FCV) have been developed and demonstrated, and some automotive companies have already commercialized their FCV (Wang, et al., 2011). Furthermore, these devices can be applied in marine mobility to face environmental issues (Rivarolo et al., 2019).

1.3. INTERNAL COMBUSTION ENGINES

An internal combustion engine (ICE) is a heat engine that converts chemical energy in a fuel into mechanical energy, usually made available on a rotating output shaft. There are several types of engines, but the most used currently are diesel or gasoline internal combustion engines (Winterbone, 2015). These devices shown in Figure 3, are composed of a huge number of components. The block is the most important, which is normally named engine because the rest of components are connected to it, and it is where the combustion takes place. The remaining compounds comprise the cylinder head, used as support and cover; pistons, which generate the combustion; camshaft, which control the valves; crankshaft that converts the lineal movement of the pistons into circular movement; intake and exhaust manifolds, which supply the fuel/air mixture to the cylinders and collect the exhaust gases, respectively; and crankcase that closes the block engine and collects the oil (Van Basshuysen and Schafer, 2002).

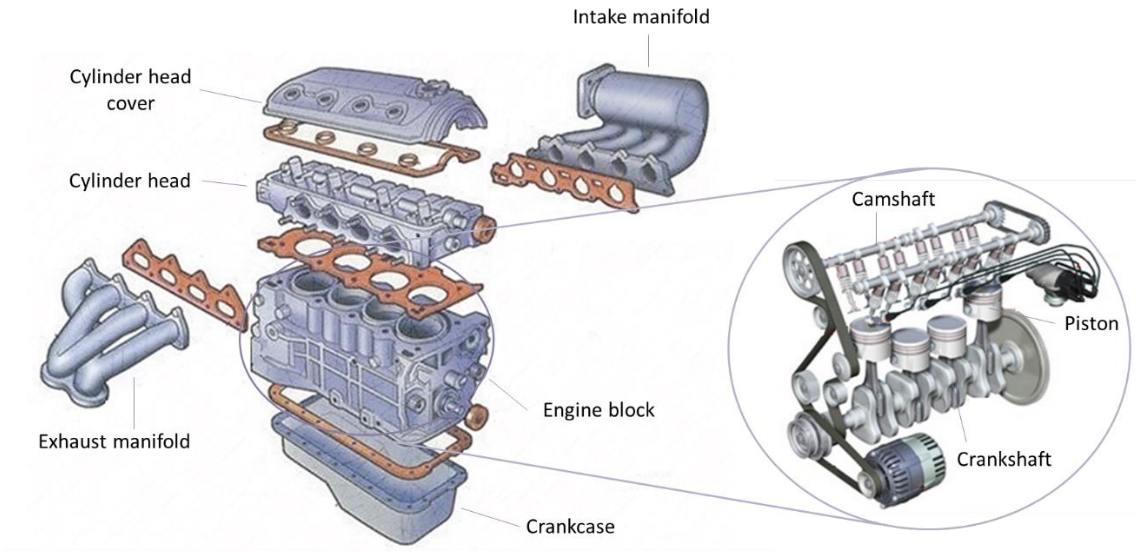


Figure 3: Internal combustion engine components (Sankar, 2017).

In ICEs the fuel is introduced, and its chemical energy is first converted to thermal energy by means of combustion or oxidation with air inside the engine. This thermal energy raises the temperature and pressure of the gases within the engine, and the high-pressure gas then expands the mechanical mechanisms of the engine. This expansion is converted by the mechanical linkages to a rotating crankshaft, which is the output of the engine. The crankshaft, in turn, is connected to a transmission and/or power train to transmit the rotating mechanical energy to the desired final used (Pulkrabek, 1997). The thermodynamic processes that take place in this process are known as Otto cycle. In a four-stroke engine there are four phases, as described below and shown in Figure 4.

1. Admission. The piston travels from the top dead centre (TDC) to the bottom dead centre (BDC). The intake valve is open whilst the exhaust valve is close. The descent movements make the fuel and air introduce in the combustion chamber.
2. Compression. Once the piston reaches BDC, the intake valve is closed and the piston starts to ascend, which reduce the chamber volume. This action compresses the air-fuel mixture.
3. Combustion. When the piston reaches TDC a spark is generated, producing an explosion in the combustion chamber. This explosion accelerates the piston back towards BDC.

4. Exhaust. Once the piston is on BDC the exhaust valve is open to release the combustion products (Berruga, 2018).

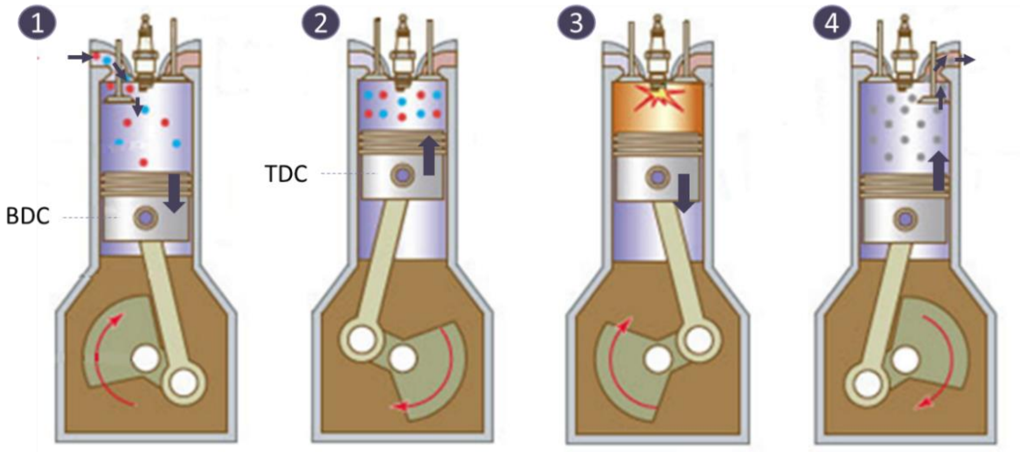


Figure 4: Combustion engine strokes: 1) admission; 2) compression; 3) combustion; and 4) exhaust (Guttikunda, 2009).

Internal combustion engines are mainly used both in road and marine transportation using fossil fuels, which constitute one of the major contributors to the world's air pollution problems. In the combustion four major pollutant emitted are hydrocarbons, carbon monoxide, nitrogen oxides and solid particulates (Pulkrabek, 1997). An alternative to generate a cleaner energy is to convert diesel or gasoline engines to hydrogen engines which is based on the same operating principle, although it is necessary to make some adaptations. Some of these changes are the substitution of the fossil fuel injectors by hydrogen injectors, the addition of a nitrogen purge or a hydrogen accumulator. It has been observed that these modified devices offer a better efficiency than gasoline-fuelled engines (Sopena et al., 2010). Moreover, comparing to fuel cells, they offer a number of advantages: they are cheaper, they run with less pure hydrogen (Chitragar et al., 2016) and they offer the potential to utilize manufacturing infrastructure already developed for petroleum-fuelled engines. As opposed, the hydrogen combustion presents some difficulties at high engine loads. The low ignition energies of hydrogen-air mixtures cause frequent unscheduled combustion events, and high combustion temperatures of mixtures closer to the stoichiometric composition lead to increased NO_x production, which would be a downside from an environmental point of view (White, et al., 2016).

1.4. LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a tool used to evaluate environmentally a product in all the stages of its life cycle: raw materials extraction, manufacturing and distribution of the product, use and waste management when it is no longer useful (Fullana, 1997). LCA is developed according to the requirements defined in the UNE-EN ISO 14040 and 14044 standards (AENOR, 2006). This tool provides information that, combining with economic, social, and working aspects, can be used to different indirect and direct applications, as product development and improvement, strategic planning, public policy making, marketing, etc. (Rebitzer et al., 2004).

A complete life cycle of a product comprises raw materials extraction, manufacturing and processing, transport, use and end-of-life. These stages are shown in Figure 5. This type of LCA is known as “cradle to grave” analysis, being the cradle the obtention of the raw materials and the grave the disposal of the product. In the case the LCA only evaluates the stages prior to the product use phase, this is a “cradle to gate” approach. With these three concepts (cradle, gate and grave) it can be described all the possible analysis in a life cycle of a product, considering the different stages depending on the study to be developed (Cays, 2017). Therefore, the most common scopes, in addition to those mentioned, are: “gate to gate”, which considers the activities of the production process, “gate to grave” that involves the use phase and the final disposal of the product, and “cradle to cradle”, which encompasses the whole life cycle of the product.

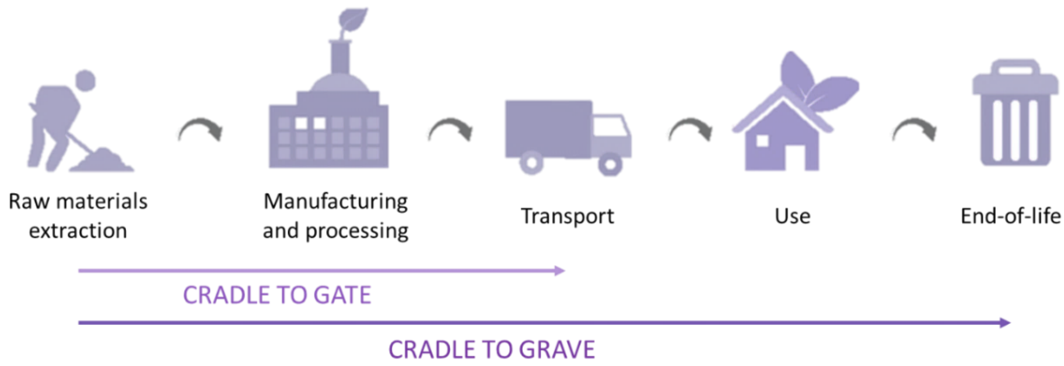


Figure 5: Life cycle stages (Cays, 2017).

Regarding the methodology, an LCA study considered four interrelated work phases, as shown in Figure 6:

1. Goal and scope. This phase provides a description of the product system in terms of the system boundaries, which define the unitary processes that should be included in the system, and the functional unit, whose objective is to relate the inputs and the outputs (Rebitzer et al., 2003). Therefore, the goal establishes the planned application, the reasons to make the study, the intended audience and if the results are to be used in comparative statements for dissemination. The scope should define the product system, functional unit (FU), boundaries, impact categories and evaluation method, assumptions, and limitations, among other points to consider (AENOR, 2006).
2. Life cycle inventory (LCI). During this stage it is conducted the compilation and calculation procedure in order to determine the inputs and outputs of the product system. The inputs include material flows, such as raw materials, and energy; whereas the outputs can be both products and emissions or wastes to air, water, or soil (AENOR, 2006).
3. Life cycle impact assessment (LCIA). Its aim is to evaluate the importance of the environmental impacts using the results of the LCI. This phase involves the association of the inventory data with the specific impact categories and the

indicators of these categories, and gives information to the interpretation phase (AENOR, 2006). This process is normally developed in four stages, although the last two are optative: classification, characterization, normalization, and valorisation (Fullana, 1997).

4. Life cycle interpretation. The results of the life cycle inventory and impact evaluation are considered together, so this phase provides results consistent with the objective and scope of the study, that lead to conclusions, explain the limitations, and give recommendations (AENOR, 2006).

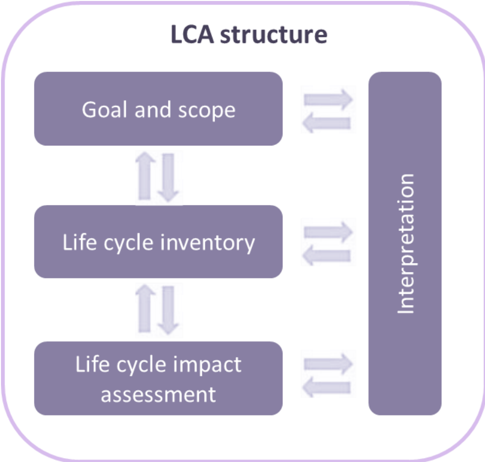


Figure 6: Life cycle assessment work phases (Rebitzer et al., 2003).

1.5. REVIEW OF LCA STUDIES OF HYDROGEN VEHICLES

The development of more sustainable fuels and mobility technologies is at its peak due to currently environmental problems. Because of this, LCA is a tool progressively more used to quantify the environmental impacts associated to the life cycle of these systems. Table 2 reports a review of scientific articles of LCA of hydrogen vehicles. This tool was firstly used to analyse the impact of H_2 in vehicles by Granovskii et al. (2006). From that date the research topic has gained importance. Granovskii et al. (2006) or Gilbert et al. (2018) broach their studies mainly to the production of the hydrogen, while others as Bartolozzi et al. (2013) or Bicer and Dincer (2017) focus their analysis on the whole life cycle of the system, that is, both the hydrogen production and manufacturing and use of the devices in the vehicle. Moreover, road vehicles, and specially cars, are the most studied applications.

In addition, most authors focus their LCA studies on hydrogen fuel cell vehicles, whereas other devices as H_2 combustion engines have hardly been developed. Moreover, almost every article compares the LCA of hydrogen FC road vehicles with other conventional cars, as gasoline, diesel or electric, so, as consequence, articles that develop other kind of transport or device are difficult to find. This justify the development of this project, in which it is realized a comparative analysis of the life cycle of a ship fuelled by hydrogen, using a FC and a combustion engine, and propelled by diesel, which is the conventional and current technology.

Table 2: Literature revision of LCA in hydrogen vehicles

Authors	Year	Location	Objective of the study
Granovskii et al.	2006	Canada	To compare the LCA of hydrogen cycle, obtained from different methods, to the gasoline cycle with the aim of determinate the efficiency of a PEMFC vehicle
Ally and Pryor	2007	Australia	To evaluate the environmental impact and energy demands of an hydrogen fuel cell bus transportation system life cycle and compare it to diesel and natural gas bus transportation systems
Bartolozzi et al.	2013	Italy	To evaluate by LCA the technological, economic, social and environmental impact of hydrogen as fuel and compare this alternative to electric vehicles
Ahmadi and Kjeang,	2015	Canada	To develop a comprehensive LCA to investigate the opportunities for hydrogen FCV implementation in Canada and provide guidance on suitable methods for hydrogen production
Bicer and Dincer	2017	n.a.*	To compare both fuel and vehicle cycles for each of the options of hydrogen, electric and methanol driven vehicles evaluated via LCA
Gilbert et al.	2018	n.a.	To develop an LCA of several potential fuels to its application in shipping
Shimizu et al.	2020	Japan	To analyse the implementation effects of hydrogen technologies of fuel cell vehicles in Japan through life cycle assessment

*n.a.: not available

1.6. OBJECTIVES

The work has been developed within the framework of the project "The Atlantic Network for Renewable Generation and Supply of Hydrogen to promote High Energy Efficiency – HYLANTIC" of the Interreg Atlantic Area programme (European Commission, 2020). The HYLANTIC project aims to establish an excellent transnational network to advance the R&D, implementation, and commercialisation of hydrogen as an energy vector for future power generation in the Atlantic Area (AA), thus providing energy efficient solutions to strategic sectors in the Atlantic Region such as transport, marine, ultra-low energy building supply, and/or portable and stationary devices (European Commission, 2020).

Based on the goal of HYLANTIC, this research aims to carry out an LCA of a ship propelled by a hydrogen PEMFC, and a diesel and hydrogen ICEs, in order to compare the technologies from an environmental perspective. Based on the previous state of art, this is the first work that apply this tool to determine the environmental performance of a PEMFC and a H_2 ICE used for marine transport applications. In addition, the LCA serves other two purposes: To determine the importance of the systems production compared to their use phase and to determine the optimum hydrogen production method through a performance of a sensitivity analysis. To reach these purposes, some specific objectives have been raised and developed.

1. Definition of the goal and scope, which includes the definition of the system, the functional unit, and the boundaries, as well as other points to consider as assumptions and limitations.
2. Compilation of the inputs and outputs of the systems, based on the information provided by the partners of the HYLANTIC project or bibliographic sources, with the aim of obtaining a thorough life cycle inventory.
3. Selection of the impact categories and indicators, and the evaluation method that are more suitable for the system under study.
4. Modelling of the system through *OpenLCA 1.10.3* software (Greendelta 2020). In this stage the *GaBi ts 9.0.* (Thinkstep, Ltd.) database has been considered.
5. Evaluation of the environmental impacts and results analysis to find the critical stages of the system and propose improvements.

2. METHODOLOGY

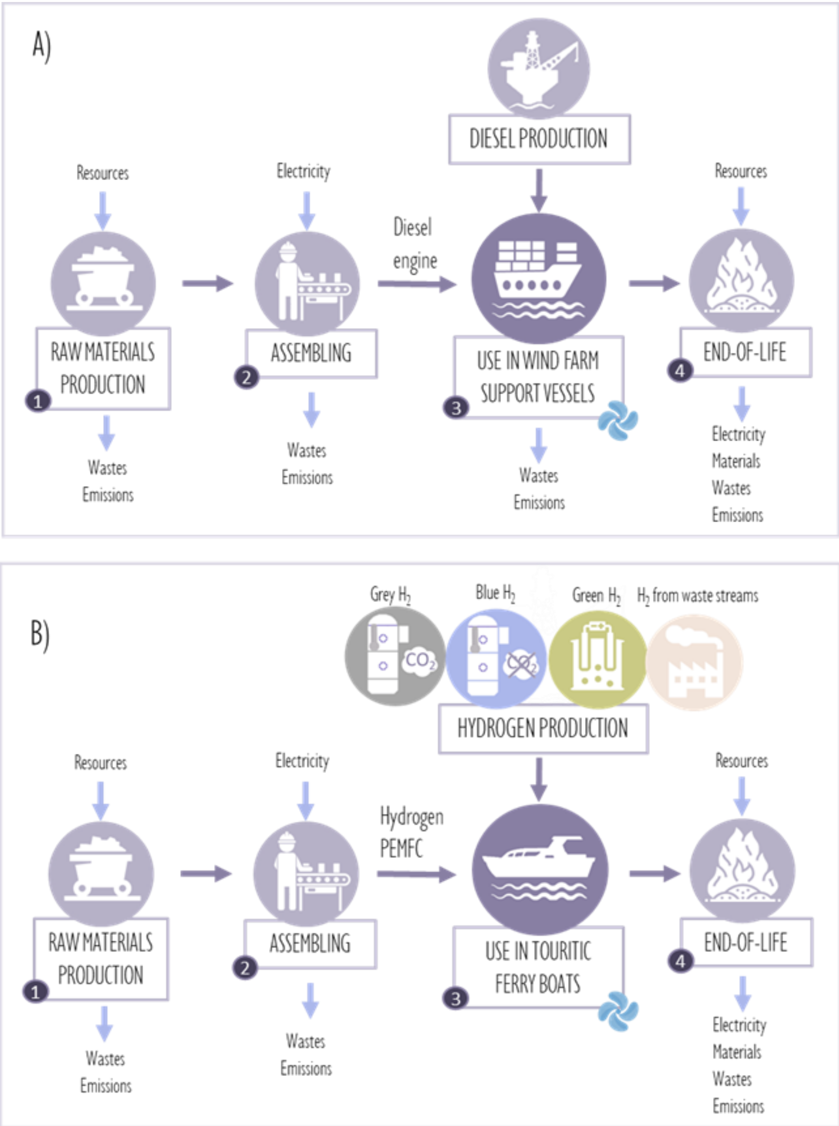
In this chapter it will be described the LCA methodology used to evaluate the life cycle of the three products; the PEMFC system and the diesel and hydrogen ICEs. For this purpose, the guidelines described in the UNE-EN ISO 14040 standard have been followed (AENOR, 2006).

2.1. GOAL AND SCOPE

The goal of this project is to compare the environmental impact of the conventional propulsion technology used for marine transportation, a diesel ICE, with two potential sustainable alternatives: a hydrogen PEMFC system and a hydrogen ICE, that is an adaptation of the current technology so it is able to operate using hydrogen instead of diesel. With the aim of knowing which option is less harmful to the environment to its application in maritime transportation, it will be carried out the LCA of each device, for which three scenarios have been defined: 1) use of a diesel ICE as wind farms support vessels propulsion technology, 2) use of a PEMFC system to its application in touristic ferry boats, and 3) use of a H_2 ICE as propulsion technology for wind farms support vessels.

The scope includes the definition of the functional unit (FU). As it has been mentioned, two new potential technologies for ship propulsion have been assessed: a H_2 PEMFC system and a H_2 internal combustion engine. However, these technologies have been proposed for different applications, and, unlike other means of transport, as cars, buses, trucks, etc., there is a great variability in the applications defined for the ships (wind farm support vessels and touristic boats). For that reason, two different functional units have been considered for comparison purposes. Firstly, the FU of 1 kWh of work is defined in order to compare the technologies. This reference is considered to be the proper FU to minimize possible biases in the results due to the specific use of the technology. On the other hand, the FU of 1 km travelled by the ship is also used with the aim of comparing the systems to reference values reported for different applications using the most used technology in this application. To do this, the lifetime (LT) of the systems has been defined. On the one hand, a partner of the HYLANTIC project supplied values of 20,000 hours and 30,000 hours of LT for the ICEs and the PEMFC system, respectively. On the other hand, the LT expressed in kilometres travelled by the ships in their whole lives is assumed. For the PEMFC system, the distance is 230,000 km, which is calculated based on the route of the touristic boat and its daily schedule. For the ICEs, the distance is 200,000 km and it has been calculated based on literature. The calculations required to obtain this LT are reported in Annex I.

Figure 7 shows the flow diagram with the system boundaries for scenarios 1, 2 and 3. The study, with cradle-to-grave approach, includes all the processes within the life cycle phases, excluding transportation due to a lack of data and low contribution observed in other LCA studies. Thus, the considered stages are: 1) raw materials extraction and production, 2) manufacturing and assembling, 3) use, and 4) end-of-life. Therefore, the first stage is the raw materials extraction and processing to obtain the necessary compounds to manufacture the devices. Subsequently, the manufacture and assembly of the products is carried out, either the PEMFC or the ICEs systems. In this stage electricity from grid mix is required to assemble all the components. Once the devices are obtained, they are incorporated in the ship, along with the hydrogen obtained from four different sources. In the case of the PEMFC system, its potential application is the propulsion of touristic ferry boats, whereas the engines propel offshore wind farms support vessels. Regarding the hydrogen source, grey hydrogen, which is obtained by natural gas steam reforming (SMR), has been considered as base case, as it is the most implemented and economical production method. On the other hand, the sensitivity analysis has been performing taking into account three alternatives: blue H_2, which is obtained by SMR with a carbon capture and storage process (CCS); green H_2, that is produced by electrolysis powered by renewable energy, such as wind or photovoltaic power; and H_2 recovered from a gaseous waste stream of a coke oven. From this phase, emissions and electricity are generated, and this energy is used to shift the propeller and move the ships. Finally, the last stage is the end-of-life of the products, which involve their disposal and recycling.



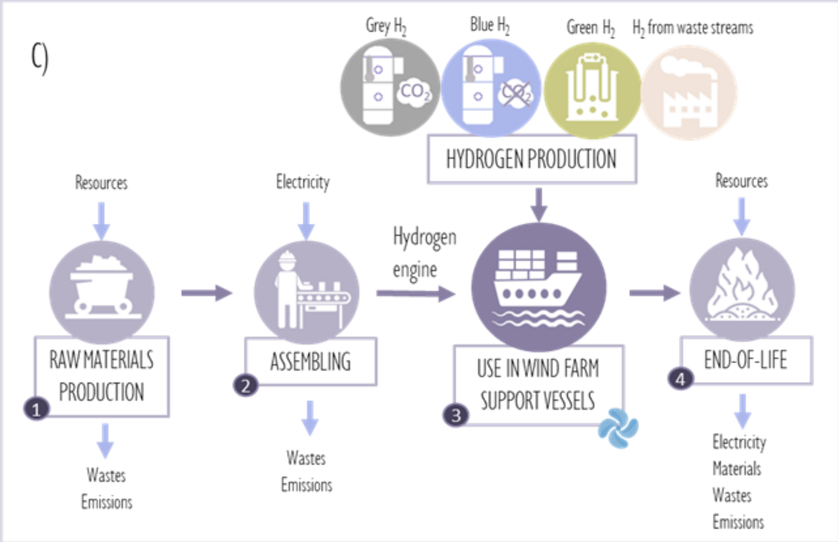


Figure 7: Flow diagrams of the systems. A) scenario 1: diesel ICE, B) scenario 2: PEMFC system, and C) scenario 3: H_2 ICE.

2.2. LIFE CYCLE INVENTORY

2.2.1. Raw materials production

The chosen PEMFC and ICEs have been selected depending on their characteristics to accomplish the expected applications. Therefore, the fuel cell stack considered in the project is the model *FCgen®- LCS*, commercialized by the company *Ballard* (Ballard, 2020), designed to reach 12 kW of power. For the manufacturing of this system, apart from the stack, it is necessary a set of components that allow its optimum performance, that are an oxygen extraction system, a cooling system, an electric control unit, a hydrogen system, an energy storage, and sensors, among others elements. These data were provided by a confidential company, which is a partner of the project. A summary of the amount of the materials for the PEMFC system manufacturing is reported in Table 3, whereas the whole LCI, that includes the components, subcomponents, elements, materials, units and quantities is included in Table A.2. of the Annex II. With the information provided by the company no detailed information of the system was possible by now, so the following assumptions were made:

- The stack consists of 74 cells and its weight is about 15.40 kg. Moreover, due to the lack of data on the weight of the stack components, these values were calculated taking into account the data reported by Evangelisti et al. (2017) and Stropnik et al. (2019). Therefore, it has been estimated a contribution to the total mass of the stack of 85.70% by the bipolar plates, 13.05% by the end plates and 1.25% by the membrane.
- No information about the amount of platinum catalyst was available. However, technical datasheets from Ballard report 10-20 g per FC vehicles. Given that an FC vehicle typically uses 60-120 kW FCs (Toyota Mirai has a 114kW FC), an amount of 15 g of platinum catalyst per 100 kW FC has been assumed. Thus,

since the FC ship operates at 12 kW of power, an amount of 1.80 g of platinum was calculated.

- Given that the membrane material was not specified, Nafion®, a sulfonated tetrafluoroethylene-based fluoropolymer–copolymer made by *DuPont*, has been considered as it is currently the standard membrane material for this type of fuel cells (Simons and Bauer, 2015). Due to this material is not available in the *GaBi ts 9.0.* database (GaBi, Ltd.) the environmental impacts have been manually added in the software according to Stropnik et al. (2019).
- Data related to some components materials was not available. For that reason, this information was based on typical materials for the specific components, for instance, copper cables as wiring elements.
- Information regarding the engine that convert the electrical energy into mechanical energy was not available. Therefore, an estimation based on Hernández et al. (2015) was used. A permanent magnet (PM) motor was considered, which uses a neodymium magnet, made from an alloy of neodymium, iron and boron. This engine reaches 12 kW of power, as the fuel cell system, and weighs approximately 40 kg. The impacts of this component, calculated from Hernández et al. (2015), have been manually added in *openLCA* software.

Table 3: Materials for 1 PEMFC system production.

Material	Quantity	Unit
Copper cable	15.87	kg
Aluminium	13.88	kg
Steel	34.60	kg
Platinum	1.80	g
Glass fibres	0.75	kg
Neodymium magnet	0.66	kg
Stainless steel	2.44	kg
Plastic	6.36	kg
Brass	0.35	kg
Graphite	13.20	kg
Polyphtalamide	2.25	kg
Ring core coil	0.24	kg
Nafion®	0.19	kg
Polyurethane foam	0.15	kg
Paper	0.10	kg
Anodized aluminium	10	kg
Resin	1.03	kg
Silicon	2	kg
Rubber	0.01	kg

Regarding the ICE, the model *Volvo Penta D4-300I*, designed by *Volvo* (Volvo Penta, 2020), was chosen for the analysis since it reaches 230 kW of power, even though it is assumed to work at 205 kW, based on the recommendations of the engine manual. The whole inventory of the diesel engine was obtained from the Volvo Penta website (Volvo Penta, 2020), which provides a cutting of the ICE, whereas the information of the adaptation of the diesel engine to run hydrogen was supplied by a partner of the HYLANTIC project. Table 4 shows a summary of materials to manufacture the diesel and H_2 engine system, while the complete inventory, distinguishing the parts of the device and its material and mass, is reported in Table A.3. of the Annex II. The weight of the diesel internal combustion engine is about 636 kg, whereas the engine with the adaptation weighs about 642 kg. In this case, some assumptions have also been made:

- Since the number of components that make up the engine is too large to be covered by this study, the elements that provide 1% or lower of the mass of each system have been considered negligible. Therefore, it has been taking into account about the 99% of the mass of the engine.
- Even though the weight of the elements was specified in the Volvo Penta website (Volvo Penta, 2020), information about the materials was not available. For this reason, the materials have been considered based on those commonly used, which has been obtained from different commercial houses that market the engine elements.

Table 4: Materials for 1 ICE system production.

Material	Diesel ICE	H_2 ICE	Unit
Cast iron	232.75		kg
Rubber	16.74		kg
Brass	11.93		kg
High density polyethylene	8.34		kg
Ethylene-propylene rubber	7.15		kg
Copper cable	4.80		kg
Polypropylene	4.06		kg
Vinyl resin	1.47		kg
Base oil	0.60		kg
Silicon oxide	0.49		kg
Polyester	0.23		kg
Paper pleats	0.20		kg
Steel	174.21	176.43	kg
Aluminium	93.13	93.81	kg
Plastic	42.16	42.26	kg
Stainless steel	20.57	21.36	kg
Cast aluminium	3.82	6.59	kg

2.2.2. Manufacturing and assembling

Information related to the resources required to assemble the devices was not available. Therefore, the energy consumption was calculated multiplying the practical power of the process assembling equipment with the machining time. For the PEMFC system, an estimation of 1,194 kWh was assumed, based on Hussain et al. (2007) and Weiss et al. (2000), whereas for the ICEs was considered an energy input of 2,750 kWh, according to Li et al. (2013).

2.2.3. Use

In this phase, the inventory mainly consists of the fuels production processes and the emissions generated in the devices' operation, that is, the combustion of the fuel, which are only produced using diesel. For the FC ship, a hydrogen flow of 0.70 kg/h is required. For the diesel ICE a fuel flow of 29.50 L/h is introduced to reach the necessary operation power of 205 kW, whereas for the hydrogen engine no real data was available. Farrell and Matthew (1998) reported that a hydrogen ICE has a lower power than a diesel one of the same sizes, so it results in 15% reduction in power. Given that it has been considered an output power of 205 kW to the ICE ship, to maintain this value it should be necessary a flow of 34.70 L/h of hydrogen. Moreover, in the case of hydrogen as fuel, as mentioned, different production methods have been considered. Grey hydrogen is obtained from SMR, so emissions regarding the technology manufacture and use have been taking into account. Blue hydrogen is produced by SMR with CCS, in which the post-combustion method of chemical adsorption with monoethanolamine (MEA) was considered. In this case, the model of the CCS system was not available in the LCA software, so its manufacturing and use was estimated from Pehnt and Henkel (2009). The size of the adsorption column and the materials for its manufacture have been calculated based on the natural gas required for the SMR process, whereas the electricity and the amount of MEA was calculated based on the amount of carbon dioxide captured. Table 5 shows the resources for the manufacturing of the CCS system, as well as the main emissions associated to the use of MEA. In addition, the emissions to air regarding the adsorbent production are reported in Table 6.

Table 5: Inventory for the CCS system manufacture and use (Pehnt and Henkel, 2009).

	Material	Quantity	Unit
Inputs	Electricity	1,368.00	$kJ/t_{CO2,cap}$
	Steel	43.51	kg/TJ_{NG}
	Concrete	207.60	kg/TJ_{NG}
	MEA	1.50	$kg/t_{CO2,cap}$
Outputs	NO_x	41.80	kg/TJ_{NG}
	NH_3	194.00	kg/TJ_{NG}
	MEA	0.01	$kg/TJ_{CO2,cap}$

Table 6: Emissions to air resulting from the production of 1 kg of MEA (Pehnt and Henkel, 2009).

Emission	Quantity	Unit
CO_2	3130	g/kg of MEA
CO	2.02	g/kg of MEA
Ethylene	0.17	g/kg of MEA
Ethylene oxide	1.64	g/kg of MEA
Ammonia	23	g/kg of MEA
Methane	6.71	g/kg of MEA
NMVOC	2.02	g/kg of MEA
NO_x	7.32	g/kg of MEA
Particulate matter PM2.5	7.27	g/kg of MEA
Particulate matter PM10	0.46	g/kg of MEA
Particulate matter>PM10	0.78	g/kg of MEA
SO_2	8.66	g/kg of MEA

Regarding green hydrogen, photovoltaic and wind power have been considered to feed the electrolysis process. In this case, both the manufacture of the electrolysis technology and the electricity production have been taking into account to determine the impacts of the system. The hydrogen production process itself does not produce emissions except water vapour. Finally, hydrogen recovered from waste gaseous streams is used. It has been considered a coke oven gas stream (COG), whose molar composition is 60.20% H_2, 4.70% N_2, 26.20% CH_4, 2.10% CO_2 and 6.80% CO (Yáñez et al., 2018). To separate hydrogen from the gaseous mixture, pressure swing adsorption (PSA) was used. This technology is based on the separation of a compound through its adsorption in a solid surface while it is subjected to high pressures (Zhu et al., 2019). Given that the COG stream is considered not to be pressurized, it is required an energy input to perform this process, in which it is obtained hydrogen with a purity of 99.97%. The rest of components are burnt in a torch generating emissions to air. The minimum and real energy required to separate H_2 was calculated using as reference the article of House et al. (2011). Therefore, it has been obtained the inventory reported in Table 7, which shows the energy and COG mass required.

Table 7: Inventory for the hydrogen recovery system.

	Resource	Engine	Fuel cell	Unit
Inputs	COG stream	27.50	6.17	kg/h
	Power	9.75	2.18	kW
Outputs	Hydrogen	3.11	0.70	kg/h

2.2.4. End-of-life (EoL)

The end-of-life of the PEMFC system (Figure 8) starts with the dismantling of the device, for which the same energy than for the assembling has been assumed, of 1,194 kWh. EoL management options have been considered for the individual components of the stack. To recover platinum from the catalyst a hydrometallurgical method has been used. This process consists of five stages: leaching, separation via liquid-liquid extraction, regeneration, precipitation, and filtration. The inventory of the reactants for the recovery of the Pt, 1.80 g, is reported in Table 8. As product, ammonium hexachloroplatinate, $[NH_4]_2PtCl_6$, is obtained. This compound could be reconverted into platinum, but this stage was not considered in this study since the process is underdeveloped. However, it has been assumed that 1 kg of this compound avoided the burden of 1 kg of platinum extracted (Duclos et al., 2017).

Table 8: Inventory of the platinum recovery process (Duclos et al., 2017).

	Material	Quantity	Unit
Inputs	Platinum	1.80	g
	HCl	0.36	kg
	HNO_3	0.03	kg
	Deionised water	2.44	kg
	Cyanex	0.15	kg
	Pentanol	0.80	kg
	NaOH	0.10	kg
	NH_4Cl	0.03	kg
	Electricity	3.86	MJ
Outputs	$[NH_4]_2PtCl_6$	1.89	g

Regarding the EoL of the end plates, an aluminium recovery process is carried out. Firstly, the compound is melted in a furnace, requiring 400 kWh per tonne of Al (Li et al., 2013). Then, the product is used to produce secondary aluminium ingots. In this process, a substitution factor of 1:1 is assumed, that is, 1 kg of secondary Al substitutes 1 kg of primary Al, so environmental burdens are avoided (Allegrini et al., 2015). The disposal of the membrane, composed of the copolymer Nafion®, is produced in a landfill, as well as that of the magnets of the electrical engine, whereas the bipolar plates, made of graphite, are sent to a Waste-to-Energy (WtE) plant, in which a recovery of energy is produced in the combustion (Handley et al., 2002).

In relation to the rest of the components of the FC system, its disposal depends on the material. It has been considered that part of the components, mainly pumps, valves, sensors, and compressor, among others, could be reused, whereas the rest is disposed of, as it is reported in Table A.4. of the Annex II. Plastic cannot be reused or recovered because it is mainly found in pieces with other materials as metals. So, plastic, is sent to an incineration plant with energy recovery. For metals, the same recovery process as for Al is carried out in order to produce new products. For steel and stainless steel 600 kWh of energy per tonne is required. For copper cables, the plastic and the metal parts are separated, and Cu is melted, considering an energy of 1,223 kWh per tonne. Finally, new copper cables are obtained (Li et al., 2013).

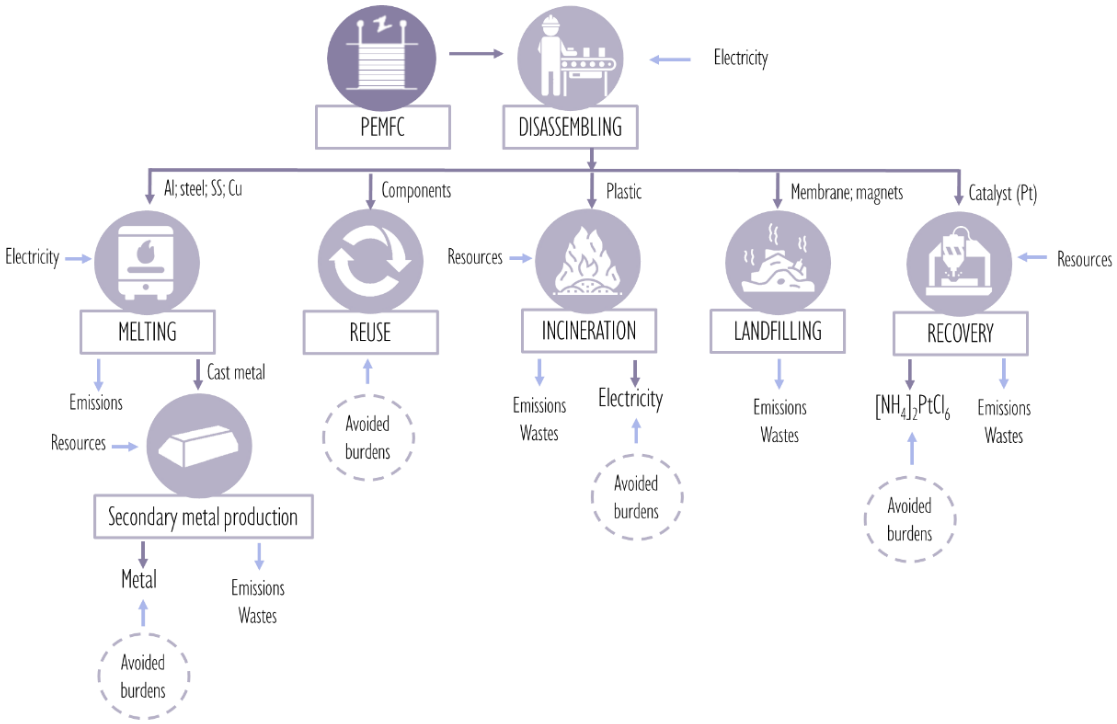


Figure 8: End-of-life of the PEMFC system.

Regarding the ICEs, the disassembling process required 2,750 kWh of energy. For ICEs, it is estimated that 85.70% of the components can be directly reused, that supposed about 90% of the materials. Therefore, according to Li et al. (2013), 69% of steel, 99% of cast iron and 83% of aluminium pieces are refurbished and reused.

The remaining mass of these metals is sent to a furnace for melting and, later, produce ingots. Likewise, brass is recovered. The disposal and recovery of the plastics and copper cables is the same as for the PEMFC system. The flow diagram that represents the EoL of the ICEs is presented in Figure 9.

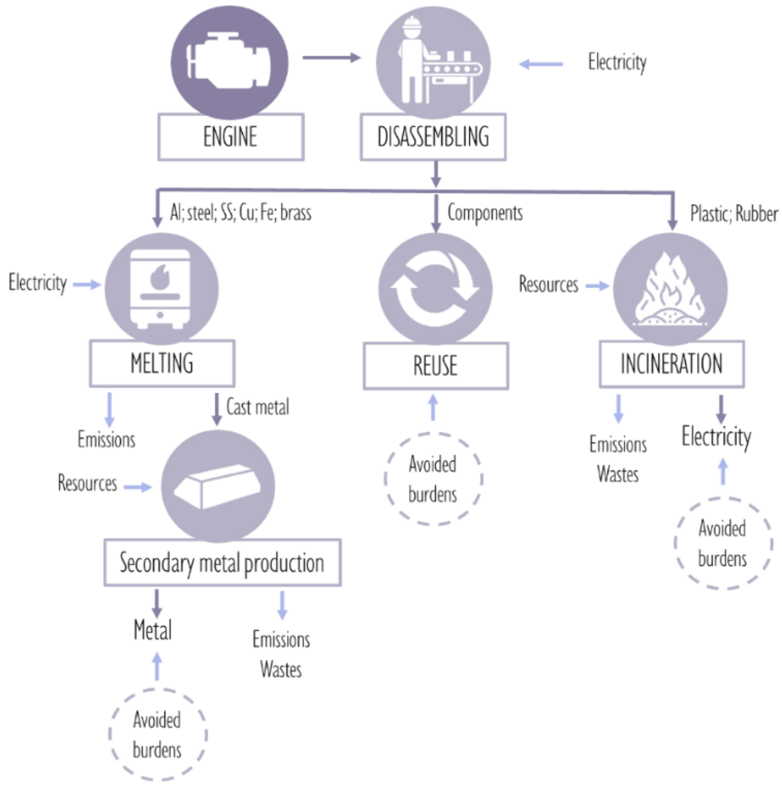


Figure 9: End-of-life of the ICEs.

2.3. LIFE CYCLE IMPACT ASSESSMENT

The life cycle impact assessment has been carried out by the modelling of the systems with the software *openLCA 1.10.3* (Greendelta, 2020). In order to quantify the environmental impacts, the database and the CML 2001 method (Guinee et al., 2002) has been used, as it is one of the most extensively applied. This method is based on the analysis of eleven impact categories, which have been selected because they determine the impact to several environmental phenomena through different perspectives (emissions, sources use, toxicity, etc.), and they provide a global vision of the sustainability of the system.

These indicators are listed in Table 9, whereas a description is reported in Table A.5. of the Annex III.

Table 9: Impact categories of the CML 2001 method.

Impact categories	Unit
Global Warming Potential (GWP 100 years)	kg CO_2 eq.
Acidification Potential (AP)	kg SO_2 eq.
Eutrophication Potential (EP)	kg PO_4^{3-} eq.
Ozone Layer Depletion Potential (ODP)	kg R11 eq.
Abiotic Depletion Potential (ADP) elements	kg Sb eq.
Abiotic Depletion Potential (ADP) fossil	MJ
Freshwater Aquatic Ecotoxicity Potential (FAETP)	kg DCB eq.
Human Toxicity Potential (HTP)	kg DCB eq.
Marine Ecotoxicity Potential (MAETP)	kg DCB eq.
Photochemical Ozone Creation Potential (POCP)	kg C_2H_4 eq.
Terrestrial Ecotoxicity Potential (TETP)	kg DCB eq.

3. RESULTS AND DISCUSSION

In this chapter, the results of the LCI and LCIA have been interpreted. Firstly, it has been analysed the impacts for each system considering the three first stages of the life cycle; raw materials production, manufacturing, and use, and, subsequently, the end-of-life of the products has been included. Finally, a comparative assessment of the impacts obtained in this study against other reference values reported for comparable and different applications has been carried out. Both in the cradle to use phase and the end-of-life analysis the results are just discussed considering the FU of 1 kWh because the FU of 1 km is not adequate to compare the technologies. The latter has been just considered in the cradle-to-gate analysis in order to quantify the impacts of the whole life cycle of the systems and be able to make a comparison with the reference values.

3.1. CRADLE-TO-USE PHASE ANALYSIS

3.1.1. Scenario 1: Diesel ICE

Firstly, the environmental impact of the diesel ICE, which is the conventional propulsion technology for marine transportation, has been analysed.

The contribution to the environmental indicators of the raw materials production, assembling and use phases is shown in Figure 10. The use phase had a larger environmental impact compared to the other two phases for almost all indicators: ADP fossil, GWP 100 years, EP, ADP elements, POCP, and the environmental categories addressing toxicity, MAETP, FAETP, TETP and HTP. Analysing the total absolute impact values, which are shown in Table 10, GWP 100 years and ADP fossil reached values of 0.58 kg CO_2-eq. and 5.73 MJ, respectively, with a use phase contribution higher than 99%. ADP fossil impact is explained by the diesel production, as it is obtained from fossil resources, whereas GWP 100 years impact is mainly associated to the fuel combustion, which supposes about 88% of the GWP impact. EP, ADP elements and POCP indicators showed contributions of the use phase larger than 91%, mainly caused by the emissions generated in the fuel production. In relation to toxicity categories, contributions of the use phase between 51% and 95% were observed, being the FAETP the highest. Likewise, these impacts were caused by the diesel production process.

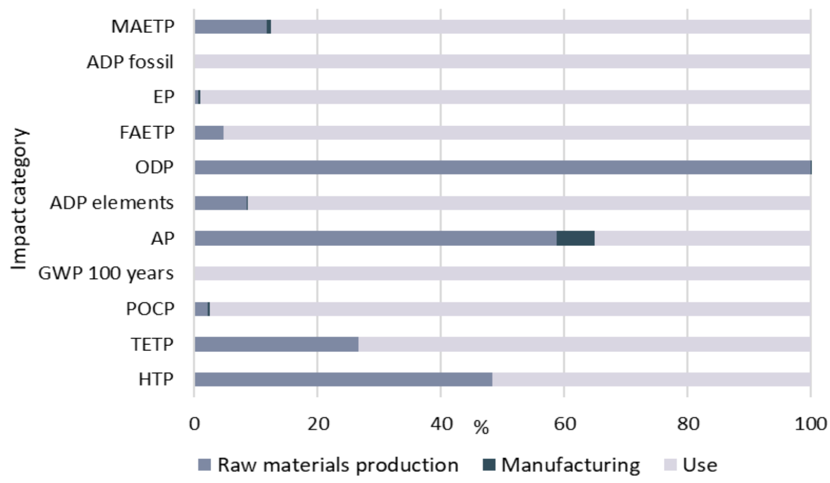


Figure 10: Percent contribution of the life phases of the diesel ICE to each impact category considering a FU of 1 kWh.

Table 10: Summary of the impact values to each indicator obtained for the diesel ICE considering a FU of 1 kWh.

Impact category	Total	Raw materials production	Manufacturing	Use
HTP (kg DCB eq.)	**1.31E-02**	6.30E-03	9.22E-06	6.75E-03
TETP (kg DCB eq.)	**9.04E-04**	2.41E-04	3.00E-08	6.64E-04
POCP (kg Ethene eq.)	**7.81E-06**	1.65E-07	2.24E-08	7.63E-06
GWP 100 years (kg CO_2 eq.)	**5.80E-01**	5.95E-04	3.21E-04	5.79E-01
AP (kg SO_2 eq.)	**4.06E-06**	2.38E-06	2.52E-07	1.42E-06
ADP elements (kg Sb eq.)	**3.60E-08**	3.05E-09	9.17E-11	3.29E-08
ODP (kg R11 eq.)	**2.42E-16**	2.42E-16	4.40E-22	9.22E-25
FAETP (kg DCB eq.)	**2.10E-03**	9.74E-05	5.97E-07	2.00E-03
EP (kg Phosphate eq.)	**2.55E-05**	1.62E-07	7.77E-08	2.53E-05
ADP fossil (MJ)	**5.73E+00**	6.41E-03	3.25E-03	5.72E+00
MAETP (kg DCB eq.)	**4.72E+00**	5.49E-01	3.28E-02	4.13E+00

On the contrary, the raw materials phase had the greatest impact in the categories of AP and ODP, and a significant contribution in some ecotoxicity indicators, mainly HTP. In AP category, raw materials production represented 58% of the total impact. Figure 11 shows the contribution of the ICE components to this indicator, whereas the impacts values are reported in Table A.6. of the Annex IV. The materials production used in the cooling system contributed about 41% of the impact on this phase, mainly due to aluminum production. The engine component, which is the most important part of the device, only had a contribution of 8%. The ODP indicator also showed a higher impact in the raw materials extraction mainly due to the copper wire and cast aluminum production. Nevertheless, the total absolute value was practically negligible, $2.42 \cdot 10^{-16}$ kg R11 eq.

Finally, the manufacturing phase had only a remarkable impact on the AP category, due to the production of the electricity to assemble the components of the ICE, with an absolute value of $2.52 \cdot 10^{-7}$ kg SO_2-eq/kWh.

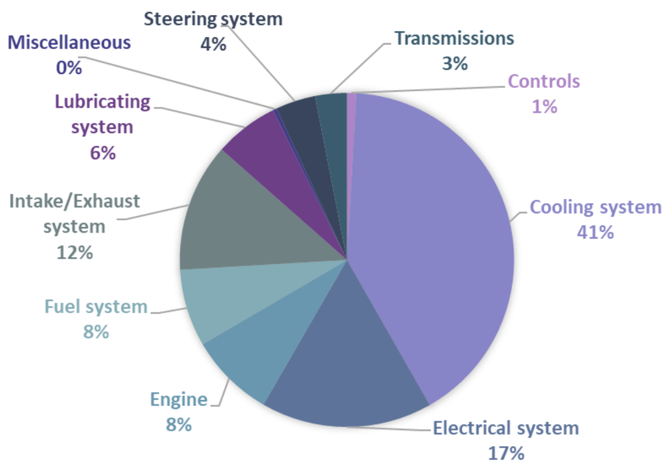


Figure 11: Impact contribution of the diesel ICE components to the AP indicator considering a FU of 1 kWh.

Based on the results, and concretely on the GWP 100 years category, which is one of the most important in studies addressing transportation, it can be said that an improvement in the design of the system will not lead to a great improvement in its sustainability, since the production of the components does not have much impact in most of the indicators. Given that the fuel use and production suppose the largest impact, it is justified the interest to study other strategies for the use of other more sustainable fuels, as hydrogen, either in technologies that allow the use of this compound, such as fuel cells, or in adaptations of existing technologies to allow them to run hydrogen, as engines.

3.1.2. Scenario 2: PEMFC system

The first alternative technology considered that allows the use of H_2 as fuel was the PEMFC system. The contribution to the environmental indicators of the raw materials production, manufacturing and use phases is shown in Figure 12.

The use phase had a larger environmental impact compared to the manufacturing phase for the ADP fossil, GWP 100 years, AP and POCP categories. GWP 100 years and ADP fossil indicators showed the higher contribution to this phase, 99.6% and 99.8%, respectively, with total absolute values of 0.62 kg CO_2-eq. and 11.02 MJ per kWh, that are presented in Table 11. These values are associated with the environmental burdens from the hydrogen production method, in this case, SMR. This process uses fossil resources to synthetize the compound, and generates large amounts of GHG, mainly carbon dioxide and methane, which produce the high values of the ADP fossil and GWP 100 years indicators. In relation to the AP and POCP, total values of $2.60 \cdot 10^{-4}$ kg SO_2-eq., and $4.04 \cdot 10^{-5}$ kg ethene-eq. were obtained per kWh, respectively. Emissions of nitrogen oxides are the main contributors to AP, with a percentage of about 90%. Other emissions, such as sulphur dioxide, supposes 74% of the impact. For the POCP indicator, methane and carbon monoxide constitute the 40% of the total impact.

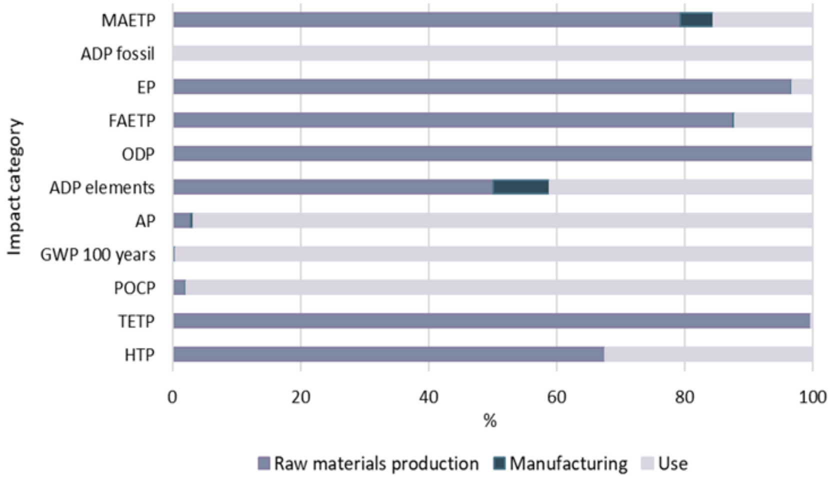


Figure 12: Percent contribution of the life phases of the PEMFC system to each impact category considering a FU of 1 kWh.

Table 11: Summary of the impact values to each indicator obtained for the PEMFC system considering a FU of 1 kWh.

Impact category	Total	Raw materials producion	Manufacturing	Use
HTP (kg DCB eq.)	**1.34E-01**	9.02E-02	3.91E-05	4.33E-02
TETP (kg DCB eq.)	**3.67E-03**	3.66E-03	1.50E-07	9.34E-06
POCP (kg Ethene eq.)	**4.04E-05**	8.15E-07	8.30E-08	3.92E-05
GWP 100 years (kg CO_2 eq.)	**6.22E-01**	1.50E-03	1.59E-03	6.17E-01
AP (kg SO_2 eq.)	**2.60E-04**	7.41E-06	1.25E-06	2.52E-04
ADP elements (kg Sb eq.)	**1.01E-07**	5.06E-08	8.79E-09	4.15E-08
ODP (kg R11 eq.)	**2.67E-11**	2.67E-11	7.56E-21	4.73E-17
FAETP (kg DCB eq.)	**1.66E-03**	1.45E-03	2.95E-06	2.02E-04
EP (kg Phosphate eq.)	**1.06E-03**	1.02E-03	3.57E-07	3.45E-05
ADP fossil (MJ)	**1.10E+01**	1.36E-02	1.48E-02	1.10E+01
MAETP (kg DCB eq.)	**3.15E+00**	2.49E+00	1.62E-01	4.90E-01

On the other hand, the impact categories of ADP elements, ODP, EP, and the environmental indicators addressing toxicity, MAETP, FAETP, TETP and HTP, presented a higher contribution due to the raw materials production, reaching total impacts of $1.01{\cdot}10^{-7}$ kg Sb-eq., $1.06{\cdot}10^{-11}$ kg R11-eq., $1.06{\cdot}10^{-3}$ kg phosphate-eq., 3.15 kg DCB-eq., $1.66{\cdot}10^{-3}$ kg DCB- eq., $3.63{\cdot}10^{-3}$ kg DCB-eq., and $1.31{\cdot}10^{-1}$ kg DCB-eq. per kWh, respectively. In the categories of ADP elements, ODP and HTP around a 60% of the impact was due to the production phase, while for the rest of the mentioned indicators the contribution was higher than 80%. The impact of this phase comes from the production of certain components, as shown in Figure 13. The absolute values of the impacts of each component are reported in Table A.7. of the Annex IV. As can be seen in Figure 13i shows that, the stack, the cooling system, the energy storage system, and other elements called as miscellaneous had a similar contribution to the ADP elements category. However, on the TETP and other toxicity indicators that showed similar contributions to that of the TETP, the energy storage/conversion system and other additional elements had a contribution of practically 100%. These impacts are caused mainly by the production processes of copper sheets and copper wires, in which emissions of heavy metals to atmosphere are emitted, as copper, mercury or arsenic, which give rise to the impact on the toxicity indicators.

Finally, the MAETP and ADP elements impacts were slightly increased by the electricity production of the manufacturing phase.

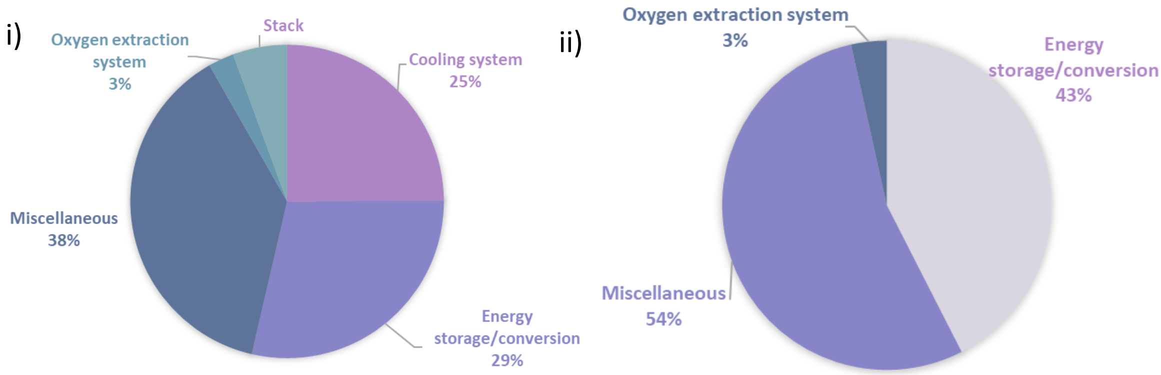


Figure 13: Impact contribution (%) of the PEMFC system components to the i) ADP elements indicator and ii) TETP indicator, considering a FU of 1 kWh.

The results denoted that, although the contribution of the raw materials production phase was significant in some categories, the absolute values of the impacts were relatively low, whereas the indicators that presented a higher contribution of the use phase the absolute values are considerably higher. Therefore, the use of hydrogen in a PEMFC system could be equal to or more polluting than diesel, which support the interest of investigating alternatives to the conventional production method and other technologies as the H_2 ICE.

3.1.3. Scenario 3: H_2 ICE

Firstly, the adaptation of the diesel ICE proposed to be run with hydrogen has been analysed in order to know if the changes lead to significant negative impacts. It has been considered that the energy requirements to assembly both devices were the same (a fair assumption given that the majority of the engine remains intact), so only the influence on the raw materials production phase will be analysed. Table 12 presents the absolute impact values obtained in the raw materials production phase for both, the diesel, and the hydrogen ICEs. As can be seen, the variation of the impact on the categories was equal or lower than 1%, so the modification of the diesel engine did not present significant changes. That is explained by the low weight of the new components, as well as by the fact that they are made from materials similar to those of the rest of the engine. Therefore, it was examined whether the replacement of fuel, i.e. diesel by hydrogen, results in large variations.

Table 12: Impacts of the raw materials production phase for the diesel and hydrogen ICE considering a FU of 1 kWh.

Impact category	Diesel engine	Hydrogen engine	Variation
HTP (kg DCB eq.)	6.30E-03	6.31E-03	0.08%
TETP (kg DCB eq.)	2.41E-04	2.41E-04	0.02%
POCP (kg Ethene eq.)	1.65E-07	1.67E-07	0.89%
GWP 100 years (kg CO2 eq.)	5.95E-04	5.99E-04	0.66%
AP (kg SO2 eq.)	2.38E-06	2.41E-06	0.91%
ADP elements (kg Sb eq.)	3.05E-09	3.06E-09	0.23%
ODP (kg R11 eq.)	2.42E-16	2.44E-16	1.04%
FAETP (kg DCB eq.)	9.74E-05	9.75E-05	0.05%
EP (kg Phosphate eq.)	1.62E-07	1.63E-07	0.80%
ADP fossil (MJ)	6.41E-03	6.45E-03	0.55%
MAETP (kg DCB eq.)	5.49E-01	5.52E-01	0.58%

Figure 14 presents the percent contribution of the raw materials production, manufacturing, and use phase. The use phase had a larger contribution than the manufacturing and the raw materials production phases in ADP fossil, EP, ADP elements, AP, GWP 100 years, HTP and POCP. In GWP and ADP fossil categories the use phase had a contribution higher than 99%, reaching total values of 0.16 kg CO_2-eq. and 2.87 MJ per kWh, respectively, as it is shown in Table 13. As in the PEMFC system, these emissions are associated with the hydrogen production process. EP, AP and POCP reached total impacts of $9.26 \cdot 10^{-6}$ kg phosphate-eq., $6.83 \cdot 10^{-5}$ kg SO_2-eq. and $1.04 \cdot 10^{-5}$ kg ethene-eq., respectively, and are mainly caused by the nitrogen oxides emissions. The ADP elements impact, $1.40 \cdot 10^{-8}$ kg Sb-eq., is associated with the consumption of non-renewable elements and resources used in the life cycle of the process, as lead, silver, zinc, etc. Finally, the impact of the HTP is due to dioxins generated in the hydrogen production process.

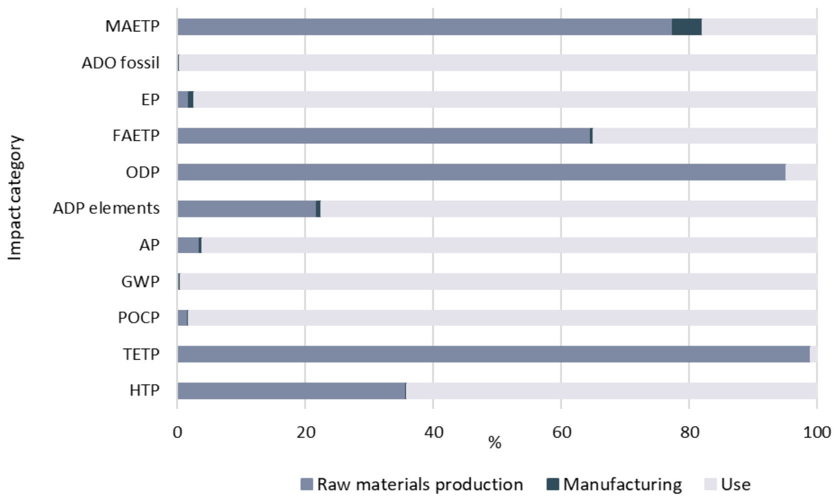


Figure 14: Percent contribution of the life phases of the H_2 ICE to each impact category considering a FU of 1 kWh.

Table 13: Summary of the impact values to each indicator obtained for the H_2 ICE considering a FU of 1 kWh.

Impact category	Total	Raw materials production	Manufacturing	Use
HTP (kg DCB eq.)	**1.76E-02**	6.31E-03	9.22E-06	1.13E-02
TETP (kg DCB eq.)	**2.43E-04**	2.41E-04	3.00E-08	2.44E-06
POCP (kg Ethene eq.)	**1.04E-05**	1.67E-07	2.24E-08	1.02E-05
GWP 100 years (kg CO_2 eq.)	**1.62E-01**	5.99E-04	3.21E-04	1.61E-01
AP (kg SO_2 eq.)	**6.83E-05**	2.41E-06	2.52E-07	6.56E-05
ADP elements (kg Sb eq.)	**1.40E-08**	3.06E-09	9.17E-11	1.08E-08
ODP (kg R11 eq.)	**2.57E-16**	2.44E-16	4.40E-22	1.23E-17
FAETP (kg DCB eq.)	**1.51E-04**	9.75E-05	5.97E-07	5.28E-05
EP (kg Phosphate eq.)	**9.24E-06**	1.63E-07	7.77E-08	9.00E-06
ADP fossil (MJ)	**2.87E+00**	6.45E-03	3.25E-03	2.86E+00
MAETP (kg DCB eq.)	**7.13E-01**	5.52E-01	3.28E-02	1.28E-01

On the other hand, ODP and indicators addressing toxicity, MAETP, FAETP and TETP, had a higher impact by the raw materials production than by the other phases. The absolute values of the impacts by the raw materials production phase are reported in Table A.8 of the Annex IV. For both the TETP and FAETP categories, the impact is mainly due to the production process of copper wires, associated to heavy metal emissions to air, such as copper, mercury or arsenic, with a total value of $2.43 \cdot 10^{-4}$ kg DCB-eq. and $1.51 \cdot 10^{-4}$ kg DCB-eq. However, for the MAETP category, which reached 0.71 kg DCB-eq./kWh, aluminum production is the most harmful process, being the cooling system the component with the highest impact.

Based on this information, it can be said that the use of hydrogen instead of diesel in an ICE presents, in general, an important improvement in the sustainability of the system. In some categories the impacts have increased due to the contribution of the raw materials production phase is the highest, and the adaptation components suppose an increasement in the weight and, therefore, in the burdens. However, this rise is very low comparing to the environmental benefits that are produced in other categories. Anyway, as already mentioned, this impact could be further reduced if other alternative sources of hydrogen were considered.

3.1.4. Influence of the hydrogen production method

In order to improve the sustainability of the system different alternatives of hydrogen sources more environmentally friendly have been proposed and analysed. Figure 15 and Figure 16 show the absolute values of the use phase to each impact category, for the PEMFC system and H_2 ICE, respectively, using the different types of hydrogen: grey, blue, green (with wind and photovoltaic energy) and recovered from waste. Naturally, the raw materials production and manufacturing phases have the same impact independently of the hydrogen source. The trend of the results in the use phase is the same for both technologies, but the impacts and the influence of the H_2 source on the whole life cycle differ considerably for the PEMFC system and the H_2 ICE, as Table A.9. and Table A.10. of the Annex IV report.

For both systems, the use of grey hydrogen and blue hydrogen had similar impacts in TETP, ADPE, ODP, FAETP, ADPF and MAETP, whereas higher values were found in the blue H_2 for HTP, POCP, AP and EP. Only a lower impact in the GWP indicator was produced in the blue hydrogen. This is because the process of natural gas steam reforming is the same, but in the case of blue hydrogen the CO_2 capture system is included. Therefore, on the one hand, when considering the manufacturing process of the CCS plant, the impacts are increased due to the production of raw materials. However, on the other hand, the use of the CCS system reduces 90% of CO_2 emissions by capturing the compound. The total impacts of the systems considering the raw materials production, manufacturing and use phases (Table A.9 and Table A.10) of the GWP indicator dropped from 0.62 kg CO_2-eq. to 0.11 kg CO_2-eq. for the PEMFC system and from 0.26 kg CO_2-eq. to 0.02 kg CO_2-eq. for the ICE; this represents a reduction of almost 80% in CO_2-equivalent emissions.

For green hydrogen, the use of wind or photovoltaic energy did not provide significant changes. An increase of the impacts in the use phase was produced on TETP, MAETP, ODP and AP indicators, being the variation on the MAETP the most significant. Analysing the influence of the H_2 source on the total impact of the systems, considering the three first life cycle stages, a variation of about 50% or higher downwards was observed for the ICE (Table A.10), whereas for the PEMFC system, the EP and HTP indicators showed also small variations (Table A.9). In relation to the toxicity indicators, while the impacts on the TETP and MAEPT increased those on the HTP and FAETP decreased. This is because for the TETP and MAEPT the environmental impact of the hydrogen production method is greater, due to air emissions affecting these categories have a very high impact factor, whereas for the human and freshwater ecotoxicity it has a lower value. The GWP 100 years indicator reached a total value of $6.02 \cdot 10^{-2}$ kg CO_2-eq. for the PEMFC system and of $4.35 \cdot 10^{-3}$ kg CO_2-eq. for the H_2 ICE considering wind electricity, whereas using photovoltaic energy the impacts were $6.08 \cdot 10^{-2}$ kg CO_2-eq. for the PEMFC system and $4.50 \cdot 10^{-3}$ kg CO_2-eq. for the ICE. These values were much lower than those obtained for grey hydrogen and even for blue hydrogen, with a reduction about a 90% and an 97%, respectively. This makes sense since the electrolysis is a clean process that only generates water, so it does not emit greenhouse gases and the system only has the emissions associated with the manufacturing and the raw materials production. Finally, the ADP fossil impact was significantly reduced too, about 95%, dropping from 11.01 MJ to 0.58 MJ in the fuel cell and from 2.87 MJ to 0.15 MJ in the engine. As conclusion, the improvement associated to the use of green hydrogen comes from the electrolysis process itself, not observing a significant influence of the renewable energy source considered, at least for the alternatives studied (wind and photovoltaic).

Finally, regarding the hydrogen recovered from a waste gaseous stream, 9 of the 11 categories presented lower impacts, both just in the use phase and in the whole life cycle of the systems. The reduction in the category of ADP fossil was noteworthy, dropping from 11.01 MJ to 0.84 MJ for the PEMFC system, and from 2.87 MJ to 0.22 MJ for the H_2 ICE. This is explained by the fact that the steam reforming process is not carried out, so the consumption of fossil fuels is significantly reduced, being the only impacts caused by the electricity production. For the GWP indicator, an increasement of 35% and 23% for the PEMFC and the ICE systems, respectively, was observed. The reason is that, even though there is not hydrogen production process as the SMR, the H_2 recovery requires a high energy consumption and a large amount of emissions associated to the coke oven gas stream is emitted. Despite the fact that this waste stream is conducted to a torch in order to reduce the impact of the methane and monoxide carbon, the total CO_2 emissions are high enough to represent a significant increase on the impact of GWP. On the other hand, the impact on MAETP indicator was higher too, which is based on the use of electricity.

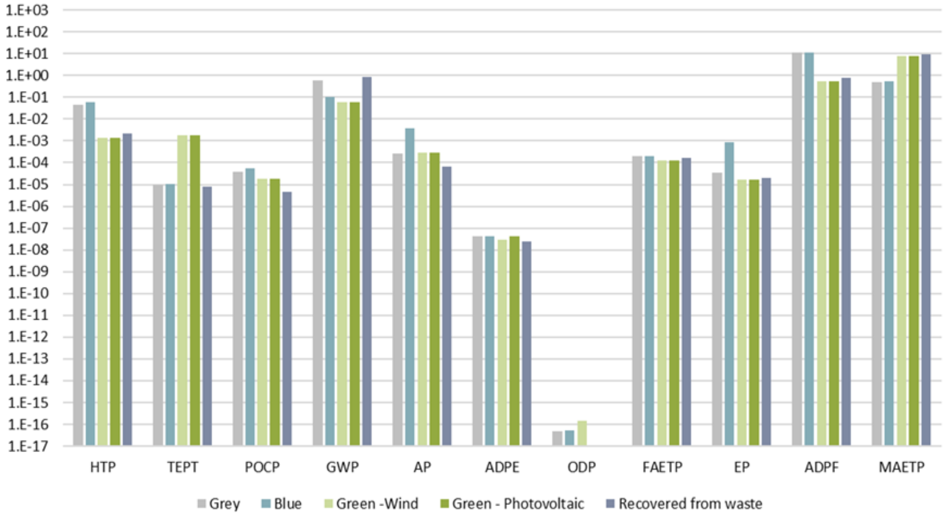


Figure 15: Impact of the hydrogen source on the use phase for the PEMFC system considering a FU of 1 kWh.

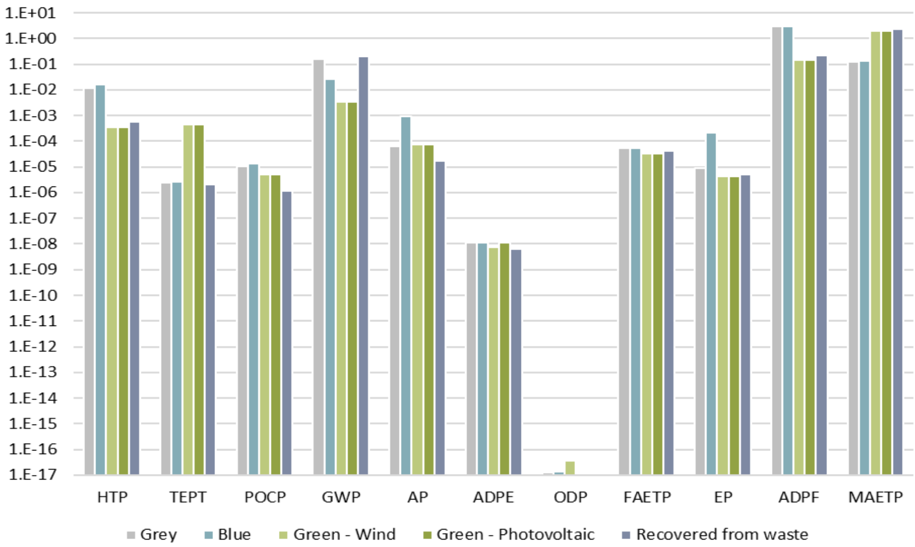


Figure 16: Impact of the hydrogen source on the use phase for the hydrogen ICE considering a FU of 1 kWh.

3.2. END-OF-LIFE

In this chapter, the impacts obtained from the EoL of the systems are presented. The results are just discussed considering the FU of 1 kWh of work done, because, as it has been mentioned, the functional unit of 1 km is not adequate to compare the technologies.

3.2.1. Scenario 1: Diesel ICE

Figure 17 shows the contribution of the EoL of the materials to each impact category for the diesel ICE. The absolute values of the impacts are reported in Table A.11. of Annex IV. The impacts of the EoL phase were negative in all categories except in ODP, which means that avoided burdens are associated with waste disposal processes. The environmental burden of the ODP indicator is due to the secondary aluminium production. Aluminium disposal had the major contribution to the EoL, avoiding as minimum the 40% of the environmental impact. This is explained by, on the one hand, the direct reuse of the Al components in other engine, and, on the other hand, the recovery of Al, which produces secondary ingots that substitutes primary aluminium. The disassembling process of the engine components had a negative impact in the EoL phase, since it is required electricity that produce emissions and wastes. Regarding the plastic and rubber disposal a positive environmental impact was produced for almost all the impact categories. This is due to the incineration process, which produce energy that is introduced in the electricity grid mix avoiding burdens. However, a negative contribution in GWP indicator could be observed, since the incineration process generates emissions that contribute to the greenhouse effect. In relation to the cast iron and steel a positive impact was observed too, which is associated with the reuse of the material. In the recovery process of these metals no burdens were avoided since the considered production process for primary metals was the same as for those secondary. Finally, the copper cables and brass disposal had hardly any impact.

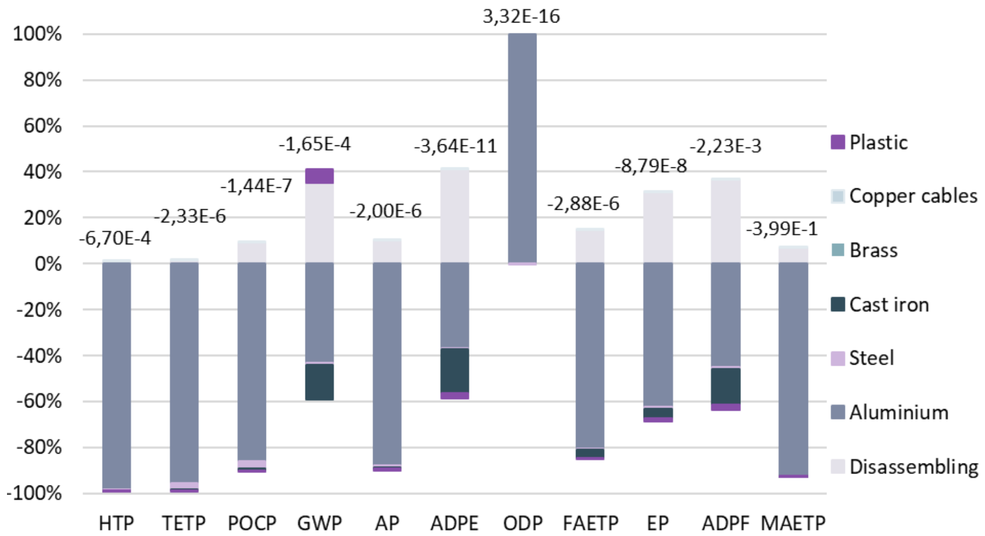


Figure 17: Contribution of the EoL phase of the materials to each impact category for the diesel ICE.

3.2.2. Scenario 2: PEMFC system

The contribution of the materials disposal to each impact category is shown in Figure 18, whereas the absolute values are reported in Table A.12 of the Annex IV. As can be observed, the impacts were negative for 8 of 11 categories, whereas for the GWP 100 years, ODP, EP and ADP fossil indicators, positive burdens were obtained. In the case of GWP and ADP fossil categories, this impact is explained mainly by the use of the electricity required for the disassembling process of the FC system, while for the EP and ODP indicators the burdens come from the electric engine recycling process. The direct reuse of more than half of the components supposed a great positive impact in the environmental analysis of the system since this process avoids burdens for almost all categories. On the contrary, the grid mix electricity had an important contribution on the POCP, GWP, AP, and ADP fossil indicators, causing the impacts to increase, as did the electric engine recycling. Regarding the recycling of the metals, steel and copper cables disposal had a negative impact in the sustainability of the system since its recovery does not avoid burdens. The EoL management of the end plates and plastic pieces entailed a benefit for the system, so electricity is produced in the incineration plant, whereas the membrane, which is sent to a landfill, had a negative impact, although it is negligible since the weight of this component is very low. In relation to the end plates, made of aluminium, a recovery process was carried out, so burdens were avoided in the secondary Al ingot production. Finally, the recovery process of the platinum catalyst presented a negative impact. This is explained by the use of reactants required to the hydrometallurgical method carried out to produce ammonium hexachloroplatinate. However, on the ADP elements category the impact was positive since a substitution ratio of Pt and $[NH_4]_2Cl_6Pt$ of 1 has been considered.

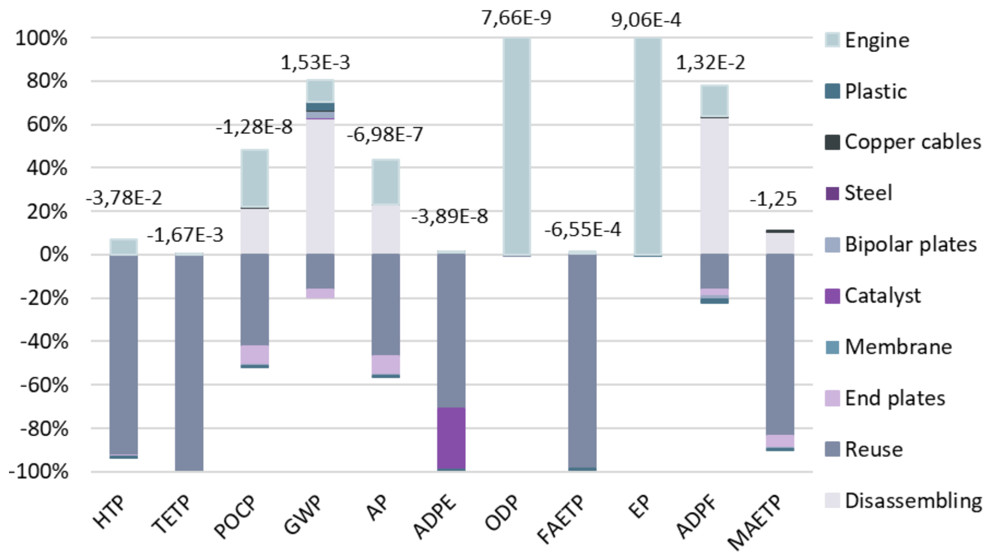


Figure 18: Contribution of the EoL phase of the materials to each impact category for the PEMFC system.

3.2.3. Scenario 3: H_2 ICE

Figure 19 represents the impact contribution of the EoL of the materials for the H_2 ICE. As can be seen, the trend is the same as for the diesel ICE. Avoided burdens and, therefore, environmental benefits, were produced by the aluminium, plastic, cast iron and steel disposal, whereas impacts were observed for copper cables and brass EoL, and for the electricity of the disassembling process. However, the absolute values of the impacts to each impact category, reported in Table A.13. of the Annex IV, were slightly higher than those for the diesel ICE, so the avoided burdens of the system were larger. This is explained by the additional components for the engine adaptation to run hydrogen, that have been added without taking off the original elements, which suppose a higher weight of each material.

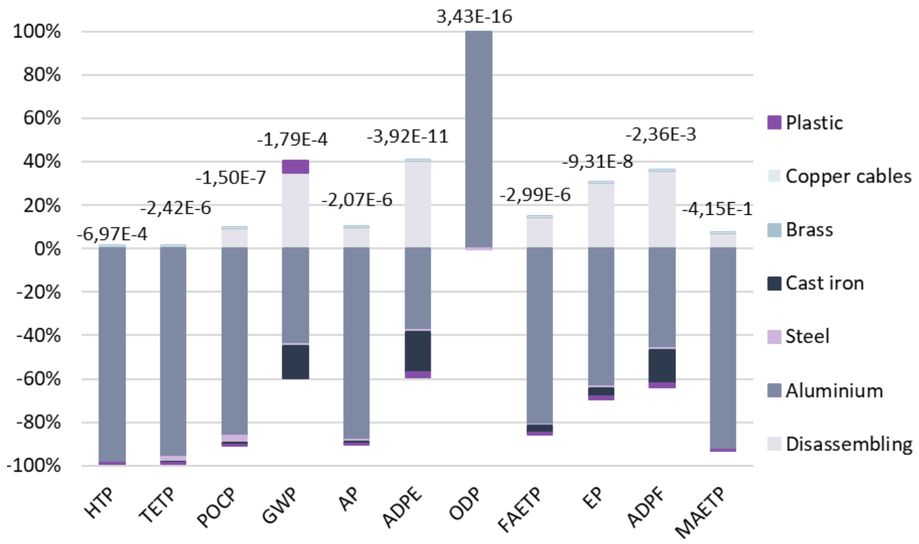


Figure 19: Contribution of the EoL phase of the materials to each impact category for the H_2 ICE.

3.3. CRADLE-TO-GRAVE ANALYSIS

In order to know the environmental impact of the whole system and to carry out a more rigorous comparison between the results obtained in this study and those obtained from LCA references, the cradle-to-grave assessment is carried out. Therefore, both FU of 1 kWh and 1 km have been considered in this chapter. In this analysis all the life cycle stages have been assumed: raw materials production, manufacturing, use and end-of-life. The contribution of the phases to each impact category considering both FU is shown in Figure 20 (for diesel ICE), Figure 21 (for PEMFC), and Figure 22 (for H_2 ICE), whereas the absolute values of the impacts are reported in Table A.14. and A.15. considering the FU of 1 kWh and in Table A.16. and Table A.17. using the FU of 1 km.

Comparing the values with those obtained in the analysis without considering the EoL, no great influence by the disposal processes was observed for the diesel ICE; except for AP and ODP categories: the former decreased by about 50%, while the latter was significantly increased, both due to secondary aluminium production. However, it was still observed that the use phase has most contribution to the impact for each category.

Figure 20: Contribution of each life cycle phase on the impact categories for the diesel ICE considering a FU of 1 kWh.

In relation to the PEMFC system, the indicators addressing toxicity, and ADP elements category, were significantly reduced, between a 27% and 46% depending on the H_2 source (Table A.15), due to the avoided burdens of the components reuse and recovery. However, the impact on the ODP category was increased and mainly caused by the disposal process of the electrical engine, which produces large burdens in the landfilling of the neodymium magnets. The raw materials production and use phases continued to be those that produced the greatest impact.

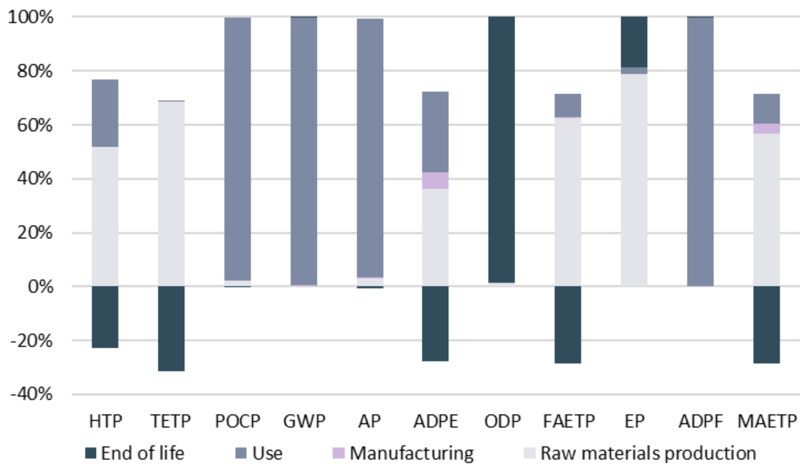


Figure 21: Contribution of each life cycle phase on the impact categories for PEMFC system considering grey H_2 and a FU of 1 kWh.

Finally, regarding the H_2 ICE, the largest influence was observed in the ODP and MAETP categories. In the case of ODP category, its impact is due to the secondary Al production, just like the diesel ICE. However, the value of the MAETP indicator was reduced between a 14% and 60%, depending on the type of hydrogen. As for the diesel ICE, the use phase is the one that produces the most significant burdens.

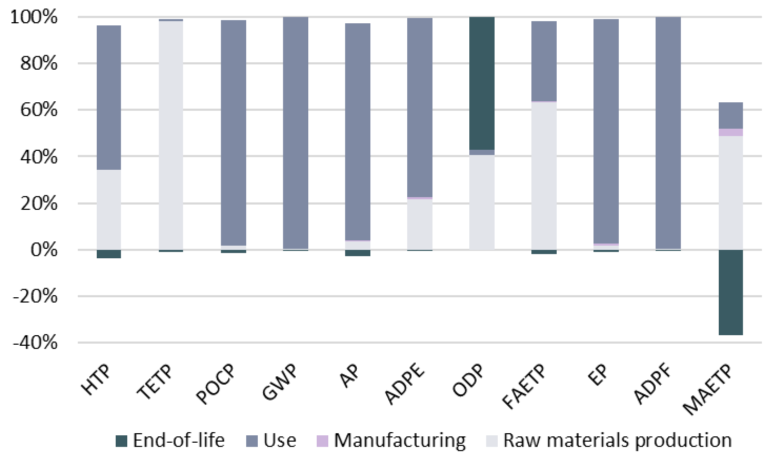


Figure 22: Contribution of each life cycle phase on the impact categories of the H_2 ICE considering grey H_2 and a FU of 1 kWh.

3.3.1. Comparison of the PEMFC and ICEs systems

Once the impacts on the categories of the CML 2001 evaluation method have been analysed for the PEMFC system and the ICEs separately, a comparison has been made to determine the most environmentally friendly device for ship propulsion.

Firstly, the functional unit of 1 kWh has been analysed in order to compare the technologies. Figure 23 shows a comparison between the impacts of the whole life cycle of PEMFC and the ICEs, whereas Table A.18. of the Annex IV reports the absolute values of each phase.

At this point, it is worth noting that the ICE has a weight of about 640 kg while the PEMFC system weighs approximately 105 kg; however, normalizing by unit power (1 kW) the power-to-weight ratio (or specific power) obtained for both systems (0,11 and 0,32 kW/kg, for the PEMFC system and the ICE, respectively) is quite similar, suggesting that it is not likely that the results are significantly affected by scaling effects. In this sense, although, in general, the materials used for the manufacture of the devices are relatively similar (copper cables, aluminium, steel, etc.), the amount of materials differs significantly. In addition, it should be noted that the PEMFC stack includes materials with a high impact on certain categories, such as platinum (with a high contribution to the ADP elements impact category).

In relation to the raw materials production phase, the PEMFC system had a slightly higher environmental impact than the engines for all the impact categories. However, in most cases, the differences were not significant as all the impacts were relatively small compared to the overall impact (see absolute values of each phase reported in Table A.18. of the Annex IV). Regarding the manufacturing phase, the same trend as in the raw materials production phase can be observed. The energy to assemble the engine was higher than that required for the assembly of the FC, since it is composed by more components, which implies more time and power. However, the output power of the engine is considerably higher than that of the PEMFC system and, therefore, the impact of the latter is higher. With respect to the use phase, the impact of the PEMFC system was higher than that of the hydrogen engine for all the categories. These results evidence that the PEMFC system had a relatively poorer performance than the H_2 ICE and resulted to be as polluting as the current technology (diesel ICE). This may be explained by the fact that the flow required by the stack to do 1 kWh of work is about four times greater than that required by the ICE, so the environmental impact must be higher. Finally, the EoL supposed a greater improvement in the sustainability of the PEMFC system than for the ICEs, since the avoided burdens associated with the disposal processes were, in general, higher and the emissions and wastes lower. However, the absolute values of the impacts of the EoL were quiet low compared to those of the other life cycle phases. Globally, as Figure 23 shows, the hydrogen ICE was the most sustainable technology for energy production since for all the categories the impacts obtained are lower than those presented by the PEMFC system and the diesel ICE.

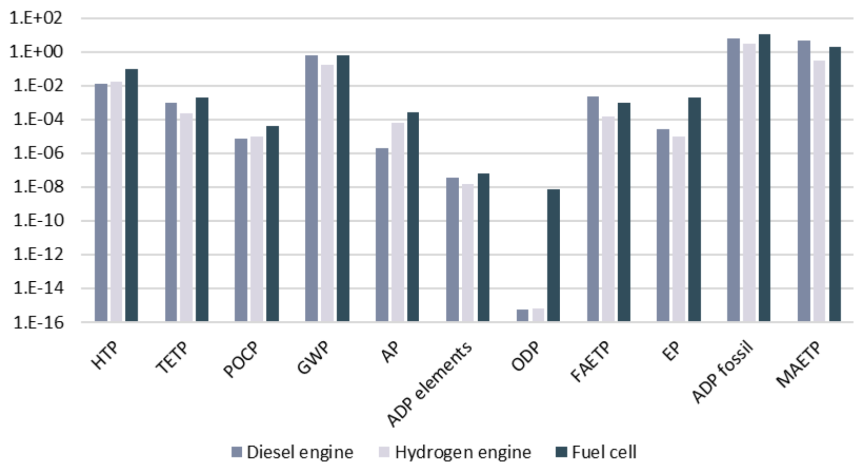


Figure 23: Impact of the whole life cycle for each device considering a FU of 1 kWh.

On the other hand, the functional unit of 1 km travelled by the ship has been analysed with the aim of comparing of the application of the devices in marine transportation. Figure 24 shows a comparison between the three technologies for each impact category, considering the whole life cycle of the products, whereas Table A.19. of the Annex IV reports the absolute values for each phase.

The trend of the results was contrary to that obtained for the FU of 1 kWh, reporting lower environmental impacts by the PEMFC system. This is explained by the fact that the lifetime of the PEMFC system, 230,000 km, is considerably higher than that assumed for the ICEs, 200,000 km, whereas for the work done is the opposite. Taking that into account, these results did not provide a good reference for comparison purposes, as the applications defined for each technology differ considerably. For that reason, just a comparison between the diesel and the hydrogen ICEs has been done.

Regarding the raw materials production, both the diesel and the H_2 ICE presented similar environmental impacts since the materials and quantities of materials to produce the technologies were almost the same. Likewise, for the manufacturing phase, the burdens associated with both systems were equal because the electricity required to assemble the devices is the same. In relation to the use phase, the diesel internal combustion engine presented larger impacts than the hydrogen ICE in 7 of 11 categories. Therefore, the hydrogen ICE was the most suitable technology for marine application, concretely for support of offshore wind farms.

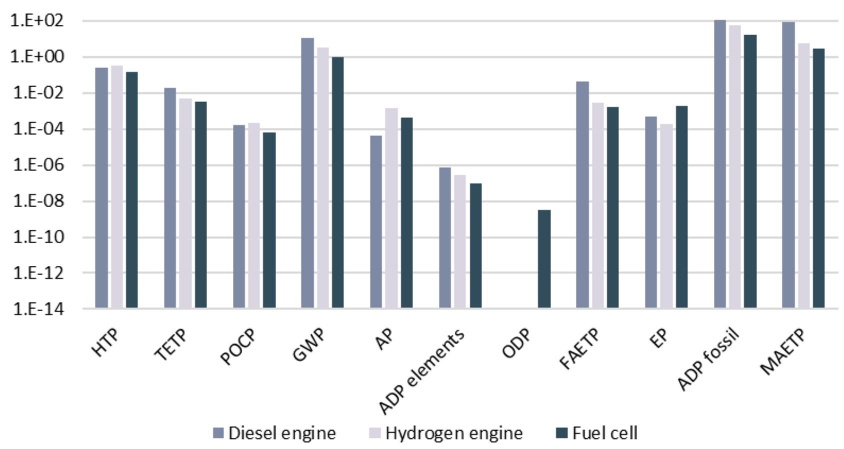


Figure 24: Impact of the whole life cycle for each device considering a FU of 1 km.

3.3.2. Comparison with other LCA studies

This chapter reviews scientific works that have applied the LCA methodology to assess the environmental behaviour of FC, as well as combustion engines. Therefore, the objective of this section is to compare the environmental performance of the alternatives studied in this work against other reference values reported for comparable and different applications. This allows to check: (i) whether the LCA conducted in this study is a representative analysis, if the results obtained are consistent with the current state of the technologies, evidencing that the strategies have been properly established for the required purpose (marine transport), and (ii) the level of influence that the application given to the technology may present. For the latter, the unit of distance travelled expressed in km has been considered as FU because that is the most common unit used in the literature as comparison basis.

Table 14 and Table 15 show the GWP impact reported by LCA-related references for the systems, considering the FU of 1 kWh. The comparison will be carried out based on this indicator as it is most commonly applied in the literature when comparing the environmental performance of power generation systems.

Firstly, Alkaner and Zhou (2006) reported CO_2 equivalent emissions of 0.71 kg per kWh for an ICE that uses diesel as fuel. This value, as well as those provided by Gilbert et al. (2018) of 0.62 kg CO_2-eq., Ellingsen et al. (2016) of 0.52 kg CO_2-eq., or Ou et al. (2013) of 0.54 kg CO_2-eq., are quite similar to the results of the current study. These values have been obtained for the same engine as that considered in this study, also intended for ship propulsion. For that reason, the LCA performed is considered to be representative and a good reference for comparison.

On the other hand, for the PEMFC system, Gilbert et al. (2018) reported an impact of 0.10 kg CO_2-eq. per kWh for green hydrogen, 1.00 kg CO_2-eq. for grey hydrogen and 0.59 kg CO_2-eq. for blue hydrogen, while Strazza et al. (2010) obtained values of $7.85 \cdot 10^{-2}$ kg CO_2-eq. and 0.51 kg CO_2-eq, for the green and grey H_2, respectively. As it can be seen, the values obtained for green hydrogen are slightly higher than those obtained in this study. This may be partly because these references considered the whole life cycle of the systems, which include the raw materials and products transport stages that may have an impact on this category. On the other hand, for grey hydrogen the impact obtained in this study is within the range of values reported by the references. Moreover, the impact in these cases has been calculated based on the application of shipping, so they are considered suitable values to use as reference.

Table 14: GWP impact values (kg CO_2-eq.) obtained from LCA- references in relation to ICEs considering the FU of 1 kWh.

System	Fuel	Present study	Alkaner and Zhou, 2006	Gilbert et al., 2018	Ellingsen et al., 2016	Mayyas et al., 2017	Ou et al., 2013
Engine	Diesel	**0.58**	0.71	0.62	0.52	0.85	0.54
	Green H_2	**4.50E-03**	n.a.	n.a.	n.a.	n.a.	n.a.
	Grey H_2	**0.16**	n.a.	n.a.	n.a.	n.a.	n.a.
	Blue H_2	**2.80E-02**	n.a.	n.a.	n.a.	n.a.	n.a.
	H_2 recovered from waste	**0.20**	n.a.	n.a.	n.a.	n.a.	n.a.
Application		Ship					

* n.a.: not available

Table 15: GWP impact values (kg CO_2-eq,) obtained from LCA- references in relation to FC systems considering the FU of 1 kWh.

System	Fuel	Present study	Gilbert et al., 2018	Strazza et al., 2010	Granovski et al., 2016
Fuel cell	Green H_2	**6.02E-02**	0.10	7.85E-02	7.90E-02
	Grey H_2	**0.62**	1.00	0.51	0.31
	Blue H_2	**0.11**	0.59	n.a.	n.a.
	H_2 recovered from waste	**0.84**	n.a.	n.a.	n.a.
Application		Ship			Road vehicle

* n.a.: not available

On the other hand, impacts from references which consider the FU of 1 km are reported in Table 16 and Table 17.

Considering this functional unit, only references for road transport application have been found for the PEMFC system. In this study, values of $9.55 \cdot 10^{-2}$ kg CO_2-eq, 0.97 kg CO_2-eq and 0.17 kg CO_2-eq to green, grey, and blue hydrogen, respectively, have been obtained. Pehnt (2010), Simons and Bauer (2015), or Gao and Winfield (2012), reported values for grey H_2 of 0.15 kg CO_2-eq, 0.30 kg CO_2-eq and 0.19 kg CO_2-eq, respectively, which are much lower than those obtained in the present study. This can be explained by the fact that the defined application is different. If the distance travelled is considered as functional unit, the impact caused by the ships will be significantly greater than that caused by road vehicles, because most of the fuel is consumed in docking operations, stabilization maneuvers against tides, etc. Likewise, considering green hydrogen as fuel, the obtained results are slightly higher than those reported by Pehnt (2010) and Miotti et al. (2017).

Regarding the ICEs, an impact of 11.90 kg CO_2-eq. for the diesel ICE is obtained in this study. This value is slightly higher than that obtained from Iribarren et al. (2011), 10.14 kg CO_2-eq., which can be explained by the fact that in the reference a fishing ship is evaluated, instead of a wind farm support vessel. Comparing with the impacts reported by Pehnt (2010), Simons and Bauer (2015), or other authors, the carbon footprint calculated in the present study is much higher, because these references reported values for road transportation. Related to the hydrogen ICE, GWP values of $8.91 \cdot 10^{-2}$ kg CO_2-eq., 3.32 kg CO_2-eq. and 0.57 kg CO_2-eq. considering green, grey and blue hydrogen, respectively, have been obtained. The only reference to compare these values is that of Penht (2010), although it is not a very rigorous comparison since the results are obtained for a road vehicle.

Table 16: GWP impact values (kg CO_2-eq.) obtained from LCA- references in relation to FC systems considering the FU of 1 km.

System	Fuel	Present study	Pehnt, 2010	Evangelisti et al., 2017	Simons and Bauer, 2015	Gao and Winfield, 2012	Bartolozzi et al., 2012	Chang et al., 2019	Miotti et al., 2017
Fuel cell	Green H_2	**9.42E-02**	5.00E-02	n.a.	n.a.	n.a.	0.17	n.a.	7.00E-02
	Grey H_2	**0.97**	0.15	0.13	0.30	0.19	n.a.	2.92E-02	0.22
	Blue H_2	**0.17**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	H_2 recovered from waste	**1.32**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Application		Ship	Road vehicle						

* n.a.: not available

Table 17: GWP impact values (kg CO_2-eq.) obtained from LCA-references in relation to ICEs considering the FU of 1 km.

System	Fuel	Present study	Iribarren et al., 2011	Pehnt, 2010	Evangelisti et al., 2017	Simons and Bauer, 2015	Gao and Winfield, 2012	Miotti et al., 2017	Eriksson et al., 2016
Engine	Diesel	**11.90**	10.14	0.15	0.17	0.273	0.27	0.19	0.289
	Green H_2	**8.91E-02**	n.a.	4.00E-02	n.a.	n.a.	n.a.	n.a.	n.a.
	Grey H_2	**3.32**	n.a.	0.16	n.a.	n.a.	n.a.	n.a.	n.a.
	Blue H_2	**0.57**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	H_2 recovered	**4.08**	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Application		Ship		Road vehicle					

* n.a.: not available

4. CONCLUSIONS

Based on the results obtained in the life cycle assessment of the propel systems for marine transportation considering a cradle-to-grave approach, the following conclusions have been drawn. Analysing the current technology for marine transportation (diesel ICEs), it can be confirmed that the use phase had the largest contribution to the categories that hold significant impacts throughout the life cycle of the system; ADP fossil, GWP 100 years and MAETP. Therefore, it was inferred that any improvement in the design of the system will not lead to a major enhancement of its sustainability, which supported the interest to investigate alternative technologies and more environmentally friendly fuels.

Regarding the novel technologies and considering the base case (in which grey hydrogen is used), the H_2 ICE presented lower environmental impacts than the current technology. On the one hand, the adaptation of the diesel engine to be run with H_2 did not lead to a significant increase on the impact by the raw materials production phase, so it was viable to modify it. On the other hand, the use of H_2 in the engine presented lower burdens than the diesel, so it is the most preferable technology for energy production and its application in marine transportation, concretely for propulsion of wind farms support vessels. On the contrary, the PEMFC system reported the largest environmental impacts for almost all the categories, which makes it a more polluting technology than the diesel ICE. This fact can be supported by the values of GWP 100 years, for which a reduction of about 72% can be observed for the H_2 ICE, whereas an increasement of 7% was obtained for the PEMFC system comparing to the diesel ICE. This justified the motivation of the study of hydrogen production processes alternatives to the most common SMR.

Based on the above, in addition to grey hydrogen (produced by SMR), three additional types of H_2 have been analysed; i) green H_2 (produced by electrolysis with renewable energy), ii) blue H_2 (obtained from SMR+CCS) and iii) recovered H_2 from gaseous waste streams. Overall, the green hydrogen one was found as the best alternative leading to a significant reduction of the environmental burdens of most concerning categories. In particular, a reduction greater than 90% were observed for the ADP fossil and the GWP 100 years indicators. The environmental benefits of the green hydrogen come from the application of the electrolysis process per se as long as it is powered by renewable energy sources. Taking all the above into account, the use of the green hydrogen is recommended to put hydrogen driven technologies into practice.

To sum up, the H_2 ICE seems to be the most suitable alternative because the impacts resulting from the application of this technology are in general lower than those of the PEMFC system. However, under appropriate conditions (e.g. using green hydrogen instead of grey) the scale seems to balance, as the PEMFC system appears to be as good as the H_2 ICE. Anyway, both technologies demonstrate to have a good environmental performance and the capacity to provide propel systems for marine transportation more environmentally friendly than those based on the current technology standard (diesel ICEs). Nevertheless, the environmental analysis performed should be complemented with an economic and social analysis to determine which one is the most sustainably advantageous technology as a whole.

5. NOMENCLATURE

AA	Atlantic Area.
ADP elements	Abiotic depletion potential of elements, kg Sb equivalent.
ADP fossil	Abiotic depletion potential of fossils, MJ.
AFC	Alkaline fuel cell.
AP	Acidification potential, kg SO_2 equivalent.
BDC	Bottom dead centre.
CCS	Carbon dioxide capture and storage.
COG	Coke oven gas.
CTV	Crew transport vessels.
EoL	End of life.
EP	Eutrophication potential, kg phosphate equivalent.
FAETP	Freshwater aquatic ecotoxicity potential, kg 1,4- DCB equivalent.
FCV	Fuel cell vehicles.
FU	Functional unit.
GHG	Greenhouse gases.
GWP	Global warming potential, kg CO_2 equivalent.
HTP	Human toxicity potential, kg 1,4- DCB equivalent.
HT-PEMFC	High temperature proton exchange membrane fuel cell.
ICE	Internal combustion engine.
LCA	Life cycle assessment.
LCI	Life cycle inventory.
LCIA	Life cycle impact assessment.
LT	Lifetime.
MAETP	Marine ecotoxicity potential, kg 1,4- DCB equivalent.

MCFC	Molten carbonate fuel cell.
MEA	Monoethanolamine.
ODP	Ozone layer depletion potential, kg R11 equivalent.
PAFC	Phosphoric acid fuel cell.
PEMFC	Proton exchange membrane fuel cell.
PM	Permanent magnet.
POCP	Photochemical ozone creation potential, kg ethene equivalent.
SMR	Steam methane reforming.
SOFC	Solid oxide fuel cell.
TDC	Top dead centre.
TETP	Terrestrial ecotoxicity potential, kg 1.4- DCB equivalent.
WtE	Waste-to-Energy.

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7. ANNEX

7.1. ANNEX I: ESTIMATION OF THE ICEs LIFETIME

As mentioned, the potential application of the hydrogen and diesel ICEs is wind farms support vessels propulsion. Given that there is no detailed information of the route of the ship, an assumption has been carried out based on literature. The support vessel is considered to be a crew transport vessel (CTV), since the size of the engines is not so large to power a large support boat. The function of this vessel is to transport the crew through the offshore turbines to perform maintenance and repair works. A hypothetical offshore wind farm of 200 MW of power, located 59 km from shore, and with 45 turbines has been considered based on average data of wind farming in 2019 (EEA, 2009). The frequency and duration of the common maintenance tasks of the turbines per year have been reported by Raknes et al. (2015). Therefore, the annually time required by the CTV to make these activities is summarized in Table A.1., and it is about 5,267 hours. The CTVs are required to return to the depot by the end of the shift, which lasts 12 hours. Thus, the vessel can operate for 448 complete shifts per year. Considering the lifetime of the engines (20,000 hours), it operates for 3.76 years. Assuming the 118 km of round trip, 196,550 km has been calculated. A final approximation of 200,000 km has been made considering the distance that the ship travels through the turbines.

Table A. 1: Annual turbine maintenance time.

Maintenance task	Time (h)
Preventive maintenance	2,700
Triggered alarms	270
Manual reset	1,012.5
Minor repair	1,012.5
Medium repair	272.25
Whole maintenance	**5,267.5**

7.2. ANNEX II: INVENTORY DATA FOR THE TECHNOLOGIES

Table A. 2: Complete inventory of the PEMFC system.

Component	Subcomponent	Units	Element	Material	Quantity (kg)
Fuel cell stack	-	1	Bipolar plates	Graphite	13.20
			End plates	Aluminium	2.01
			Membrane	Nafion	0.19
			Catalyst	Platinum	1.80E-03
Electric control unit	-	1	Enclosure	Plastic	0.10
			Printed circuit boards	PCB	0.20
Instrumentation	Throttle	1	Enclosure	Plastic	0.10
			Mechanism	Steel	0.30
Oxygen extraction system	Filter	2	Filter media	Paper+PU foam	0.20
			Frame	Aluminium	0.05
			Gasket	Urethane foam	0.05
	Compressor	1	Casing	Aluminium	0.50
			Electric motor	Steel	1.60
			Printed circuit boards	PCB	0.20
			Wires	Copper cable	0.20
	Humidity exchanger	1	-	PPA	2.25
			-	GF	0.75
			Screws	Steel	0.10
	Bulkhead connector	1	-	Plastic	0.10
	Mass air flow meter	1	Body	Plastic	0.10
			Wires	Copper cable	3.00E-03
			Screws	Steel	2.00E-03
Hydrogen system	Valves	4	Body	Stainless Steel	0.95
			Solenoid coil	Ring core coil 80 g	0.24
			Solenoid coil (housing)	Plastic	0.06
	Secondary pressure regulator	1	-	Plastic	0.08
			-	Stainless Steel	0.02
	Recirculation pump	1	Electric motor	Steel	0.40
				Plastic	0.10
	Water separator	1	Body	Plastic	0.10
			Fittings	Brass	1.00E-03
	Bulkhead connector	2	Body	Plastic	0.05
			Wahser	Rubber	0.01
Cooling system	Heat exchanger	1	Body	Aluminium	1.50
			Tube stack	Cupro Nickel	1.50
	Mixer valve	1	Body	Brass	0.10
			-	Plastic	0.05
			-	Stainless Steel	0.05

Component	Subcomponent	Units	Element	Material	Quantity (kg)
Cooling system	Filters	2	Body	Plastic	0.25
			Filter media	Resin	0.50
	Pump	1	Body	Plastic	0.02
			Electric motor	Steel	0.55
	Bulkhead connector	2	Body	Plastic	0.05
			Wahser	Rubber	0.01
Energy storage/conversion	Power management unit	1	Housing	Aluminium	5.00
			Printed circuit boards	PCB	0.25
			Wiring	Copper cable	1.75
	DC/DC converters	2	Body	Aluminium	0.50
			Printed circuit boards	PCB	0.25
			Wiring	Copper cable	1.25
	Relays	2	Coils	Steel	0.25
			Connectors	Brass	0.25
			Casing	Plastic	0.10
	Diodes	1	Heat sink	Aluminium	0.01
			Casing	Plastic	0.01
Sensors	Pressure	3	-	Stainless Steel	0.15
	Temperature	3	-	Stainless Steel	0.02
	Current sensor	1	Housing	Aluminium	0.05
			Coils	Steel	0.10
	Voltage sensor	1	Lungs	Copper	0.01
Miscellaneous	Gas/fluid fittings, tubes,	1	-	Stainless Steel	1.00
	Electrical harness	1	Main material	Copper	10.00
			Insulation	Plastic	5.00
	Enclosure fan	1	Body	Plastic	0.10
			Electrical motor	Steel	0.10
	Enclosure	1	-	Anodized aluminium	10.00
	Hoses	1	-	Silicon	2.00
Electrical engine	-	1	Electrical engine	Steel	31.20
				Aluminium	4.26
				Copper	2.66
				Magnets	0.66
				Resin	0.53
				Other materials	0.69

Table A. 3: Complete inventory of the ICEs system.

Component	Subcomponent	Element	Units	Material	Quantity (kg)
Engine	Cylinder head, exchange	Cylinder head	1	Cast iron	55.00
		Valve cover	1	Aluminum	7.11
	Cylinder block and flywheel housing	Cylinder block	1	Cast iron	83.50
		Flywheel housing	1	Steel	12.46
	Camshaft and camshaft chain	Set of camshaft (2)	1	Steel	27.00
		Idler gear	1	Steel	4.07
		Cover	1	High density PE	5.59
	Crank mechanism	Connecting rod	2	Cast aluminum	2.04
		Crankshaft	1	Steel billet	44.00
		Gear	1	Steel	3.99
		Vibration damper	1	Rubber	11.48
		Flywheel	1	Steel	21.80
	Balancer shaft	Housing	1	Sheet steel	8.11
	Engine suspension	Rubber cushion	2	Rubber	2.78
Lubricating system	Lubricating system	Sump	1	Sheet steel	4.25
		Pipe reatiner	1	Aluminum	0.32
		Oil pump	1	Aluminum	5.33
		Oil strainer	1	Aluminum	0.23
		Baffle plate	1	Aluminum	0.59
		Sealing compound	1	Silicone oxide	0.49
Fuel system	Fuel system	Set of hoses (4)	1	High density PE	0.53
		Rail	1	Steel	2.20
		Set of delivery pipes (3)	1	Steel	0.62
		Injector	1	Steel	0.57
				Plastic	0.14
		Gear	1	Steel	1.04
		Lubricant	1	Base oil + additives	0.60
	Fuel pump	High-pressure pump	1	Aluminum	7.55
		Solenoid valve	1	Stainless steel	0.20
		Intermediate plate	1	Steel	0.75
	Fuel filter and water separator	Fuel filter	1	Steel	1.76
				Paper pleats	0.20
		Lever guard	1	Copper cable	0.70
Intake and exhaust system	Turbo, induction and exhaust manifold	Exhaust manifold	1	Cast iron	7.37
		Inlet manifold	1	Cast iron	2.86
		Set of screws (17)	1	Stainless steel	0.52
		Turbocharger	1	Aluminum	12.42
		Set of pipes (2)	1	Steel	0.69
		Exhaust pipe elbow	1	Steel	3.37
		Set of connectors (3)	1	Steel	1.68
		Bracket	1	Aluminum	0.46
		Support	1	Steel	0.66
	Exhaust riser kit, inboard	Exhaust riser	1	Cast iron	3.01
		Isolation	1	Steel	0.44
	Air filter	Air cleaner	1	Plastic	3.24
				Cellulose	0.81
		Hose	1	High density PE	0.66

Component	Subcomponent	Element	Units	Material	Quantity (kg)
Cooling system	Heat exchanger and expansion tank	Heat exchanger	1	Aluminum	30.50
		Set of hoses (6)	1	Rubber	1.06
		Fuel cooler	2	Brass	1.09
		Expansion tank	1	Polypropylene	1.08
	Rear bracket for external keel cooling	Bracket	1	Aluminum	1.17
	Keel cooling	Hose attachment	2	Rubber	0.87
	Oil cooler for engine with keel cooling	Oil cooler	1	Brass	8.38
	Dry exhaust pipe for external keel cooling	Exhaust pipe elbow	1	Steel	2.50
	Water pump	Coolant pump	1	Aluminum	4.78
	Charge air cooler	Charge air cooler	1	Stainless steel	11.50
	Seawater pump and hoses	Seawater pump	1	Stainless steel	5.45
	Extra expansion tank kit	Expansion tank kit	1	Polypropylene	2.98
	Cooling water intake	Water inlet	1	Rubber	1.48
				Steel	4.45
	Hot water outlet	Hot water outlet	1	Steel	0.96
Controls	Electronic control for side installation, EVC-E	Sail control	1	Plastic	1.77
				Steel	0.20
	Control for side mounting, EVC-E2	Control lever	1	Plastic	4.23
				Steel	0.47
	Electronic speed control, inboard, single	Control lever	1	Plastic	2.24
				Steel	0.25
	Control for top installation single with	Control lever	1	Plastic	1.66
				Steel	0.18
	Sailboat electronic control lever EVC-E2	Sail control	1	Plastic	1.80
				Steel	0.20
	Control cables	Control cable	1	Copper cable	2.25
Electrical system	Alternator with installation parts	Alternator	1	Aluminum	6.77
		Belt tensioner	1	Rubber	1.00
		Set of screws (6)	1	Stainless steel	0.45
	Extra pulley	Pulley	1	Aluminum	2.60
	Starter motor	Starter motor	1	Steel	9.20
	Control unit, ECU	Control unit	1	Cast aluminum	1.78
	Shut down system, control panel, EVC-E2	Control panel	1	Aluminum	0.87
		Set of diodes (5)	1	Aluminum	0.27
				Plastic	0.27
		Set of cables (4)	1	Copper cable	0.54
	Alternator cables, EVC-E2	Alternator kit, Y-split	1	Aluminum	1.45
	Autopilot, EVC-E2	Display	1	Plastic	0.46
		Set of cables (5)	1	Copper cable	0.77
	4" color display, EVC-E2	Display, kit	1	Plastic	1.47
	Tank meter kit for fuel	Fuel gauge	1	Plastic	1.00
				Copper	0.25
	Antenna for dynamic positioning system EVC-E2	Antenna	1	Aluminum	4.90
Transmissions	Connecting kit reverse gear HS63AE	Flexible coupling	1	Rubber	3.99
		Set of hoses (4)	1	High density PE	1.56
		Oil cooler	1	Brass	2.45
		Adapter	1	Plastic	7.70
	Interceptor IS600	Kit	1	Plastic	9.18
		Kit	1	Aluminum	2.50
	Reverse gear HS63AE. Ratio 2.04:1	Reversing gear kit	1	Cast iron	81.00

Component	Subcomponent	Element	Units	Material	Quantity (kg)
Steering system	Main station for inboard, EVC-E2	Steering wheel hub	1	Plastic	2.59
		Starter switch	1	Aluminum	0.42
	Steering system, EVC-E2	Rudder position sensor	1	Stainless steel	0.33
		Conversion kit	1	Stainless steel	1.47
		Steering wheel adjusment	1	Plastic	1.75
		Steering wheel	1	Vinyl resines	1.47
	Joystick EVC-E2	Control knob	1	Plastic	1.19
		Display	1	Plastic	0.20
		Set of cables (2)	1	Copper cable	0.29
	Power steering pump kit, SN2004033424	Power steering pump	1	Aluminum	2.90
		V-ribbed belt	1	Polyester	0.23
		Radiator	1	Steel	0.69
		Reservoir	1	Plastic	0.18
		Set of hoses (3)	1	Rubber	1.24
Miscellaneous	Belt guard for engines without compressor	Belt protector	1	Plastic	1.10
		Set of brackets (4)	1	Steel	0.30
		Set of screws (9)	1	Stainless steel	0.65
	Universal bracket	Universal bracket	1	Steel	15.37
Adaptation	Custom panel	-	1	Aluminium	0.68
	Purge valve	-	1	Stainless steel	0.57
	Pressure and temperature sensor	-	1	Stainless steel	0.23
	Hydrogen fuel rail	-	1	Steel	2.20
	Hydrogen gas injector	-	2	Steel	0.02
		-		Plastic	0.01
	Auxiliary ECU	-	1	Die-cast aluminium	2.77
	Thermal fuse	-	1	Copper wire	5.00E-04
		-		Plastic	5.00E-04
	MAP sensor	-	1	Plastic	0.10

Table A. 4: Components to reuse and recycle of the FC system.

Recycling	Reuse
Fuel cell stack	Compressor- Oxygen system
Electric control unit	Isolation valve- Hydrogen system
Throttle- Instrumentation	Safety valve- Hydrogen system
Filter- Oxygen system	Purge valve- Hydrogen system
Humidity exchanger- Oxygen system	Recirculation pump- Hydrogen system
Bulkhead connector- Oxygen system	Liquid purge valve- Hydrogen system
Mass air flowmeter- Oxygen system	Heat exchanger- Cooling system
Pressure regulator- Hydrogen system	Mixer valve- Cooling system
Water separator- Hydrogen system	Pump- Cooling system
Y-filter- Hydrogen system	Power management unit- Energy storage
De-ionizing filter- Hydrogen system	DC/AC converter- Energy storage
Diodes- Energy storage	Enclosure
Gas/fluid fittings, tubes, hoses…	Pressure sensor
Electrical harness	Temperature sensor
Enclosure fan	Current sensor
Hoses	Voltage sensor
Electrical engine	Bulkhead connector- Hydrogen system
	Relays- Energy storage

7.3. ANNEX III: DESCRIPTION OF THE IMPACT CATEGORIES OF THE CML 2001 METHOD

Table A. 5: Impact categories of the CML 2001 method (Ministry for the environment, 2020).

Impact categories	Unit	Description
Global Warming Potential (GWP 100 years)	kg CO_2 eq.	It is related to GHG emissions, which raises the average temperature of the earth.
Acidification Potential (AP)	kg SO_2 eq.	It refers to substances with low pH that are emitted to water and soils in a degree that they do not have chance to become naturally neutralized.
Eutrophication Potential (EP)	kg PO_4^{3-} eq.	It is defined as the potential to cause over-fertilisation of water and soil which result in increased growth of biomass.
Ozone Layer Depletion Potential (ODP)	kg R11 eq.	It is the relative amount of degradation to the ozone layer that a substance can cause.
Abiotic Depletion Potential (ADP) elements	kg Sb eq.	It refers to the depletion of non-living resources, as fossil fuels, natural elements as minerals, etc.
Abiotic Depletion Potential (ADP) fossil	MJ	
Freshwater Aquatic Ecotoxicity Potential (FAETP)	kg DCB eq.	It is related to the impact on freshwater ecosystems, as a result of emissions of toxic substances to air, water and soil.
Human Toxicity Potential (HTP)	kg DCB eq.	It refers to the impact on human life, as a result of emissions of toxic substances to air, water and soil.
Marine Ecotoxicity Potential (MAETP)	kg DCB eq.	It refers to the impact on marine ecosystems, as a result of emissions of toxic substances to air, water and soil.
Photochemical Ozone Creation Potential (POCP)	kg C_2H_4 eq.	It quantifies the relative abilities of volatile organic compounds (VOCs) to produce ground level ozone.
Terrestrial Ecotoxicity Potential (TETP)	kg DCB eq.	It refers to impacts of toxic substances on terrestrial ecosystems.

7.4. ANNEX IV: RESULTS OF THE LCA

Table A. 6: Environmental impact values to each indicator obtained for the diesel ICE considering a FU of 1 kWh.

		RAW MATERIALS PRODUCTION											MANUFACTURING	USE		
Impact category	Total	Controls	Cooling system	Electrical system	Engine	Fuel system	Intake/exhaust system	Lubricating system	Miscellaneous	Steering system	Transmissions	Total	Electricity	Diesel production	Diesel combustion	Total
HTP (kg DCB eq.)	**1.31E-02**	2.79E-03	2.54E-04	1.74E-03	5.12E-05	9.27E-04	8.92E-05	4.50E-05	5.94E-08	3.88E-04	1.88E-05	**6.30E-03**	**9.22E-06**	6.75E-03	0	**6.75E-03**
TETP (kg DCB eq.)	**9.04E-04**	1.17E-04	2.26E-06	6.82E-05	2.36E-07	3.68E-05	3.14E-07	2.64E-07	1.95E-08	1.54E-05	3.23E-07	**2.41E-04**	**3.00E-08**	6.64E-04	0	**6.64E-04**
POCP (kg Ethene eq.)	**7.81E-06**	1.74E-09	6.51E-08	2.77E-08	1.89E-08	1.26E-08	2.11E-08	1.04E-08	1.10E-09	6.39E-10	6.14E-09	**1.65E-07**	**2.24E-08**	7.63E-06	0	**7.63E-06**
GWP 100 years (kg CO2 eq.)	**0.58**	8.39E-06	1.67E-04	7.29E-05	1.31E-04	3.27E-05	6.31E-05	2.99E-05	2.83E-06	1.89E-05	6.79E-05	**5.95E-04**	**3.21E-04**	4.57E-02	0.53	**5.79E-01**
AP (kg SO2 eq.)	**4.06E-06**	2.16E-08	9.74E-07	3.95E-07	1.97E-07	1.78E-07	2.97E-07	1.48E-07	8.91E-09	9.21E-08	7.31E-08	**2.38E-06**	**2.52E-07**	1.42E-06	0	**1.42E-06**
ADP elements (kg Sb eq.)	**3.60E-08**	1.09E-09	1.00E-10	7.32E-10	3.88E-10	3.46E-10	1.49E-11	2.07E-10	2.77E-12	1.51E-10	1.99E-11	**3.05E-09**	**9.17E-11**	3.29E-08	0	**3.29E-08**
ODP (kg R11 eq.)	**2.42E-16**	1.16E-16	1.52E-19	6.91E-17	3.99E-18	3.71E-17	3.59E-20	1.26E-20	4.86E-20	1.52E-17	1.41E-20	**2.42E-16**	**4.40E-22**	9.22E-25	0	**9.22E-25**
FAETP (kg DCB eq.)	**2.10E-03**	4.62E-05	1.61E-06	2.74E-05	3.80E-07	1.47E-05	4.71E-07	2.25E-07	1.97E-08	6.21E-06	2.37E-07	**9.74E-05**	**5.97E-07**	2.00E-03	0	**2.00E-03**
EP (kg Phosphate eq.)	**2.55E-05**	2.25E-09	6.07E-08	2.65E-08	1.98E-08	1.19E-08	2.04E-08	9.92E-09	7.10E-10	6.17E-10	8.89E-09	**1.62E-07**	**7.77E-08**	2.53E-05	0	**2.53E-05**
ADP fossil (MJ)	**5.73**	2.20E-04	1.58E-03	7.46E-04	1.64E-03	3.21E-04	6.41E-04	2.83E-05	3.46E-05	2.63E-04	9.40E-04	**6.41E-03**	**3.25E-03**	5.72	0	**5.72**
MAETP (kg DCB eq.)	**4.72**	6.32E-02	1.66E-01	1.12E-01	3.28E-02	5.34E-02	5.74E-02	2.89E-02	2.89E-04	2.35E-02	1.19E-02	**5.49E-01**	**3.28E-02**	4.13	0	**4.13**

Table A. 7: Environmental impact values to each indicator obtained for the PEMFC system considering a FU of 1 kWh.

		RAW MATERIALS PRODUCTION											MANUFACTURING	USE
Impact category	Total	Cooling system	Electric control unit	Energy storage	Hydrogen system	Instrume n-tation	Miscellaneous	O_2 extraction	Sensors	Stack	Electric engine	Total	Electricity	Hydrogen from SMR
HTP (kg DCB eq.)	**0.13**	2.25E-04	1.95E-08	3.76E-02	-5.20E-07	3.83E-08	4.72E-02	2.94E-03	3.90E-06	1.58E-04	2.15E-03	**9.02E-02**	**3.91E-05**	**4.33E-02**
TETP (kg DCB eq.)	**3.67E-03**	7.53E-07	3.43E-11	1.56E-03	1.86E-07	1.94E-09	1.98E-03	1.28E-04	2.46E-08	5.36E-07	1.04E-06	**3.66E-03**	**1.50E-07**	**9.34E-06**
POCP (kg Ethene eq.)	**4.04E-05**	4.37E-08	6.97E-11	1.07E-07	4.81E-09	2.45E-10	4.19E-08	2.12E-08	1.17E-09	4.07E-08	5.55E-07	**8.15E-07**	**8.30E-08**	**3.95E-05**
GWP 100 years (kg CO2 eq.)	**0.62**	1.01E-04	5.93E-07	2.73E-04	1.25E-05	9.79E-07	1.60E-04	1.18E-04	2.92E-06	5.32E-04	3.04E-04	**1.50E-03**	**1.59E-03**	**0.62**
AP (kg SO2 eq.)	**2.60E-04**	7.39E-07	3.61E-10	1.59E-06	8.65E-08	1.19E-09	5.85E-07	1.86E-07	1.78E-08	7.31E-07	3.48E-06	**7.41E-06**	**1.25E-06**	**2.52E-04**
ADP elements (kg Sb eq.)	**1.01E-07**	1.26E-08	7.76E-14	1.45E-08	3.96E-11	2.07E-13	1.93E-08	1.33E-09	2.76E-12	2.83E-09	3.07E-11	**5.06E-08**	**8.79E-09**	**4.15E-08**
ODP (kg R11 eq.)	**2.67E-11**	6.85E-18	2.11E-29	1.55E-15	4.15E-20	1.03E-20	3.06E-15	5.80E-15	5.55E-21	9.91E-19	2.67E-11	**2.67E-11**	**7.56E-21**	**4.73E-17**
FAETP (kg DCB eq.)	**1.66E-03**	1.13E-06	5.42E-09	6.16E-04	2.24E-07	6.00E-09	7.80E-04	4.79E-05	3.11E-08	7.74E-07	4.81E-06	**1.45E-03**	**2.95E-06**	**2.02E-04**
EP (kg Phosphate eq.)	**1.06E-03**	6.34E-08	1.08E-10	1.04E-07	3.69E-09	2.03E-10	4.42E-08	2.78E-08	1.06E-09	8.24E-08	1.02E-03	**1.02E-03**	**3.57E-07**	**3.45E-05**
ADP fossil (MJ)	**11.01**	1.05E-03	1.95E-05	2.56E-03	9.84E-05	2.28E-05	2.24E-03	1.50E-03	2.35E-05	2.00E-03	4.03E-03	**1.36E-02**	**1.48E-02**	**10.98**
MAETP (kg DCB eq.)	**3.15**	1.16E-01	2.98E-05	1.10E+00	2.26E-03	1.81E+00	1.07E+00	9.56E-02	2.66E-03	1.02E-01	-	**2.49E+00**	**0.16**	**0.49**

Table A. 8: Environmental impact values to each indicator obtained for the hydrogen ICE considering a FU of 1 kWh.

		RAW MATERIALS PRODUCTION												MANUFACTURING	USE
Impact category	**Total**	**Controls**	**Cooling system**	**Electrical system**	**Engine**	**Fuel system**	**Intake/Exhaust system**	**Lubricating system**	**Miscellaneous**	**Steering system**	**Transmissions**	**Adaptation**	**Total**	**Electricity**	**Hydrogen from SMR**
HTP (kg DCB eq.)	**1.76E-02**	2.79E-03	2.54E-04	1.74E-03	5.12E-05	9.27E-04	8.92E-05	4.50E-05	5.94E-08	3.88E-04	1.88E-05	5.28E-06	**6.31E-03**	**9.22E-06**	**1.13E-02**
TETP (kg DCB eq.)	**2.43E-04**	1.17E-04	2.26E-06	6.82E-05	2.36E-07	3.68E-05	3.14E-07	2.64E-07	1.95E-08	1.54E-05	3.23E-07	5.62E-08	**2.41E-04**	**3.00E-08**	**2.44E-06**
POCP (kg Ethene eq.)	**1.04E-05**	1.74E-09	6.51E-08	2.77E-08	1.89E-08	1.26E-08	2.11E-08	1.04E-08	1.10E-09	6.39E-10	6.14E-09	1.47E-09	**1.67E-07**	**2.24E-08**	**1.02E-05**
GWP 100 years (kg CO2 eq.)	**0.16**	8.39E-06	1.67E-04	7.29E-05	1.31E-04	3.27E-05	6.31E-05	2.99E-05	2.83E-06	1.89E-05	6.79E-05	3.95E-06	**5.99E-04**	**3.21E-04**	**0.16**
AP (kg SO2 eq.)	**6.83E-05**	2.16E-08	9.74E-07	3.95E-07	1.97E-07	1.78E-07	2.97E-07	1.48E-07	8.91E-09	9.21E-08	7.31E-08	2.17E-08	**2.41E-06**	**2.52E-07**	**6.56E-05**
ADP elements (kg Sb eq.)	**1.40E-08**	1.09E-09	1.00E-10	7.32E-10	3.88E-10	3.46E-10	1.49E-11	2.07E-10	2.77E-12	1.51E-10	1.99E-11	6.98E-12	**3.06E-09**	**9.17E-11**	**1.08E-08**
ODP (kg R11 eq.)	**2.57E-16**	1.16E-16	1.52E-19	6.91E-17	3.99E-18	3.71E-17	3.59E-20	1.26E-20	4.86E-20	1.52E-17	1.41E-20	2.51E-18	**2.44E-16**	**4.40E-22**	**1.23E-17**
FAETP (kg DCB eq.)	**1.51E-04**	4.62E-05	1.61E-06	2.74E-05	3.80E-07	1.47E-05	4.71E-07	2.25E-07	1.97E-08	6.21E-06	2.37E-07	4.89E-08	**9.75E-05**	**5.97E-07**	**5.28E-05**
EP (kg Phosphate eq.)	**9.24E-06**	2.25E-09	6.07E-08	2.65E-08	1.98E-08	1.19E-08	2.04E-08	9.92E-09	7.10E-10	6.17E-10	8.89E-09	1.30E-09	**1.63E-07**	**7.77E-08**	**9.00E-06**
ADP fossil (MJ)	**2.87**	2.20E-04	1.58E-03	7.46E-04	1.64E-03	3.21E-04	6.41E-04	2.83E-05	3.46E-05	2.63E-04	9.40E-04	3.52E-05	**6.45E-03**	**3.25E-03**	**2.86**
MAETP (kg DCB eq.)	**0.71**	6.32E-02	0.17	0.11	3.28E-02	5.34E-02	5.74E-02	2.89E-02	2.89E-04	2.35E-02	1.19E-02	3.20E-03	**0.55**	**3.28E-02**	**0.13**

Table A. 9: Total impacts considering the raw materials production, manufacturing and use phases, and variation comparing with grey hydrogen for the PEMFC system.

	Grey H_2	Blue H_2		Green H_2 - Wind		Green H_2 - Photovoltaic		Recovered from waste H_2	
Impact category	Value	Value	Variation	Value	Variation	Value	Variation	Value	Variation
HTP (kg DCB eq.)	1.34E-01	1.52E-01	14.01%	9.16E-02	-31.44%	9.15E-02	-31.46%	9.24E-02	-30.83%
TETP (kg DCB eq.)	3.67E-03	3.67E-03	0.03%	5.46E-03	48.66%	5.43E-03	47.92%	3.67E-03	-0.03%
POCP (kg Ethene eq.)	4.04E-05	5.35E-05	32.39%	1.96E-05	-51.42%	1.97E-05	-51.18%	5.46E-06	-86.48%
GWP 100 years (kg CO2 eq.)	0.62	0.11	-82.78%	6.02E-02	-90.32%	6.08E-02	-90.22%	0.84	35.45%
AP (kg SO2 eq.)	2.60E-04	3.89E-03	1392.89%	2.98E-04	14.36%	2.98E-04	14.53%	7.73E-05	-70.32%
ADP elements (kg Sb eq.)	1.01E-07	1.01E-07	0.47%	8.77E-08	-13.08%	1.03E-07	2.18%	8.37E-08	-17.07%
ODP (kg R11 eq.)	2.67E-11	2.67E-11	0.00%	2.67E-11	0.00%	2.67E-11	0.00%	0.00	0.00%
FAETP (kg DCB eq.)	1.66E-03	1.66E-03	0.05%	1.58E-03	-4.77%	1.58E-03	-4.74%	1.62E-03	-2.42%
EP (kg Phosphate eq.)	1.06E-03	1.86E-03	75.91%	1.04E-03	-1.68%	1.04E-03	-1.66%	1.04E-03	-1.41%
ADP fossil (MJ)	11.01	11.01	0.03%	5.81E-01	-94.72%	5.87E-01	-94.66%	0.84	-92.34%
MAETP (kg DCB eq.)	3.15	3.18	0.98%	10.32	228.02%	10.47	232.63%	11.58	267.87%

Table A. 10: Total impacts considering the raw materials production, manufacturing and use phases, for each impact category and variation comparing with grey hydrogen for the H_2 ICE.

	Grey H_2	Blue H_2		Green H_2 - Wind		Green H_2 - Photovoltaic		Recovered from waste H_2	
Impact category	Value	Value	Variation	Value	Variation	Value	Variation	Value	Variation
HTP (kg DCB eq.)	1.76E-02	2.25E-02	27.62%	6.66E-03	-62.17%	6.66E-03	-62.21%	6.87E-03	-60.97%
TETP (kg DCB eq.)	2.43E-04	2.43E-04	0.12%	7.02E-04	188.96%	7.02E-04	188.89%	2.43E-04	-0.12%
POCP (kg Ethene eq.)	1.04E-05	1.37E-05	31.79%	5.07E-06	-51.32%	5.10E-06	-51.08%	1.38E-06	-86.76%
GWP 100 years (kg CO2 eq.)	0.16	2.80E-02	-82.69%	4.35E-03	-97.31%	4.50E-03	-97.22%	0.20	23.00%
AP (kg SO2 eq.)	6.83E-05	9.68E-04	1316.71%	7.80E-05	14.27%	7.82E-05	14.44%	2.06E-05	-69.90%
ADP elements (kg Sb eq.)	1.40E-08	1.41E-08	0.87%	1.05E-08	-24.63%	1.45E-08	4.06%	9.49E-09	-32.12%
ODP (kg R11 eq.)	2.57E-16	2.58E-16	0.59%	2.82E-16	10%	2.44E-16	-4.80%	2.44E-16	-4.80%
FAETP (kg DCB eq.)	1.51E-04	1.51E-04	0.14%	1.30E-04	-13.66%	1.30E-04	-13.57%	1.40E-04	-6.92%
EP (kg Phosphate eq.)	9.24E-06	2.08E-04	2149.60%	4.61E-06	-50.05%	4.67E-06	-49.50%	5.35E-06	-42.05%
ADP fossil (MJ)	2.87	2.87	0.03%	0.15	-94.64%	0.16	-94.59%	0.22	-92.26%
MAETP (kg DCB eq.)	0.71	0.72	1.13%	2.58	262.44%	2.62	267.75%	2.91	308.41%

Table A. 11: Absolute values of the EoL impacts to each impact category for the diesel ICE considering the FU of 1 kWh.

Impact category	Total	Dissambling	Aluminum					Steel		Cast iron		Brass	Copper cables	Plastic and rubber		
		Electricity grid mix	Reuse	Recovery				Reuse	Recovery	Reuse	Recovery	Recovery	Recovery	Incineration		
				Melting	Secondary Al production	Avoided charges Al	Total		Melting		Melting	Melting	Melting	Incineration	Avoided charges elect.	Total
HTP (kg DCB eq.)	**-6.70E-04**	7.91E-06	-5.66E-04	1.93E-08	2.03E-06	-1.11E-04	-1.09E-04	-6.38E-07	1.25E-07	-1.55E-06	2.63E-09	1.50E-08	8.00E-09	3.79E-08	-4.91E-07	-4.53E-07
TETP (kg DCB eq.)	**-2.33E-06**	3.03E-08	-1.92E-06	7.32E-11	6.85E-10	-3.75E-07	-3.74E-07	-6.54E-08	4.78E-10	-8.83E-09	1.01E-11	5.85E-11	3.17E-11	4.39E-11	-1.88E-09	-1.84E-09
POCP (kg Ethene eq.)	**-1.44E-07**	1.68E-08	-1.28E-07	4.15E-11	2.73E-10	-2.50E-08	-2.47E-08	-5.95E-09	2.66E-10	-1.85E-09	5.57E-12	3.17E-11	1.70E-11	1.83E-10	-1.04E-09	-8.59E-10
GWP 100 years (kg CO_2 eq.)	**-1.65E-04**	3.21E-04	-3.32E-04	7.82E-07	2.66E-06	-6.51E-05	-6.17E-05	-1.31E-05	5.07E-06	-1.35E-04	1.07E-07	6.08E-07	3.25E-07	7.03E-05	-1.99E-05	5.04E-05
AP (kg SO_2 eq.)	**-2.00E-06**	2.52E-07	-1.84E-06	6.15E-10	2.30E-09	-3.60E-07	-3.57E-07	-2.83E-08	3.98E-09	-1.35E-08	8.29E-11	4.78E-10	2.56E-10	1.78E-09	-1.57E-08	-1.39E-08
ADP elements (kg Sb eq.)	**-3.64E-11**	8.54E-11	-6.59E-11	2.15E-13	2.02E-12	-1.28E-11	-1.05E-11	-2.54E-12	1.34E-12	-3.90E-11	2.97E-14	1.61E-13	8.62E-14	-9.77E-14	-5.29E-12	-5.39E-12
ODP (kg R11 eq.)	**3.32E-16**	3.14E-27	-9.00E-20	7.65E-30	3.32E-16	-1.76E-20	3.32E-16	-3.49E-19	4.95E-29	-1.79E-27	1.04E-30	5.94E-30	3.18E-30	9.79E-30	-1.95E-28	-1.85E-28
FAETP (kg DCB eq.)	**-2.88E-06**	5.97E-07	-2.76E-06	1.46E-09	9.90E-09	-5.40E-07	-5.28E-07	-1.98E-08	9.42E-09	-1.44E-07	1.98E-10	1.13E-09	6.05E-10	1.32E-09	-3.71E-08	-3.58E-08
EP (kg Phosphate eq.)	**-8.79E-08**	7.21E-08	-1.22E-07	1.76E-10	5.73E-10	-2.39E-08	-2.32E-08	-3.25E-09	1.14E-09	-8.78E-09	2.39E-11	1.37E-10	7.32E-11	4.80E-10	-4.48E-09	-4.00E-09
ADP fossil (MJ)	**-2.23E-03**	3.00E-03	-3.15E-03	7.30E-06	3.77E-05	-6.16E-04	-5.71E-04	-1.13E-04	4.73E-05	-1.28E-03	9.95E-07	5.68E-06	3.03E-06	7.39E-06	-1.86E-04	-1.79E-04
MAETP (kg DCB eq.)	**-3.99E-01**	3.28E-02	-3.64E-01	7.99E-05	5.47E-03	-7.12E-02	-6.57E-02	-1.04E-03	5.18E-04	-1.93E-04	1.09E-05	6.21E-05	3.32E-05	2.87E-05	-2.04E-03	-2.01E-03

Table A. 12: Absolute values of the EoL impacts to each impact category for the PEMFC system considering the FU of 1 kWh.

Impact category	Total	Dissambling	Engine	Pieces	Stack									Steel	Copper cables	Plastic		
					End plates (Aluminum)				Membrane	Catalyst	Bipolar plates							
		Electricity grid mix	Recycling	Reuse	Recovery				Landfill	Recovery	Incineration			Recovery	Recovery	Incineration		
					Melting	Secondary Al production	Avoides charges Al	Total			Incineration	Avoided charges elect.	Total	Melting	Melting	Incineration	Avoided charges elect.	Total
HTP (kg DCB eq.)	**-4.00E-02**	3.91E-05	7.98E-04	-4.07E-02	2.63E-08	2.78E-06	-1.51E-04	-1.49E-04	7.22E-10	4.82E-08	6.11E-08	-7.92E-07	-7.30E-07	2.36E-08	2.00E-07	6.82E-08	-8.83E-07	-8.14E-07
TETP (kg DCB eq.)	**-1.68E-03**	1.50E-07	3.24E-07	-1.68E-03	1.01E-10	9.44E-10	-5.12E-07	-5.11E-07	3.61E-10	2.21E-10	7.19E-11	-3.03E-09	-2.96E-09	9.05E-11	7.78E-10	8.02E-11	-3.39E-09	-3.31E-09
POCP (kg Ethene eq.)	**-8.70E-08**	8.30E-08	2.70E-08	-1.61E-07	5.59E-11	3.61E-10	-3.42E-08	-3.38E-08	5.58E-12	1.30E-10	3.06E-10	-1.67E-09	-1.36E-09	5.01E-11	4.17E-10	3.33E-10	-1.86E-09	-1.53E-09
GWP 100 years (kg CO2 eq.)	**1.34E-03**	1.59E-03	6.70E-05	-4.12E-04	1.07E-06	3.64E-06	-8.89E-05	-8.42E-05	3.84E-08	2.24E-06	1.13E-04	-3.21E-05	8.12E-05	9.59E-07	8.14E-06	1.26E-04	-3.58E-05	9.05E-05
AP (kg SO2 eq.)	**-1.50E-06**	1.25E-06	2.92E-07	-2.51E-06	8.33E-10	3.14E-09	-4.92E-07	-4.88E-07	3.60E-11	1.69E-09	2.86E-09	-2.53E-08	-2.24E-08	7.50E-10	6.39E-09	3.19E-09	-2.82E-08	-2.50E-08
ADP elements (kg Sb eq.)	**-3.89E-08**	4.17E-10	3.53E-13	-2.82E-08	2.94E-13	2.76E-12	-1.75E-11	-1.44E-11	-1.10E-15	-1.11E-08	-1.57E-13	-8.52E-12	-8.68E-12	2.54E-13	2.16E-12	-1.76E-13	-9.50E-12	-9.68E-12
ODP (kg R11 eq.)	**2.04E-09**	1.55E-26	2.04E-09	-2.19E-15	1.05E-29	4.54E-16	-2.41E-20	4.54E-16	6.37E-30	2.79E-29	1.58E-29	-3.14E-28	-2.98E-28	9.37E-30	7.95E-29	1.76E-29	3.50E-28	3.68E-28
FAETP (kg DCB eq.)	**-6.60E-04**	2.95E-06	1.87E-06	-6.64E-04	2.00E-09	1.35E-08	-7.38E-07	-7.22E-07	1.63E-10	4.22E-09	2.14E-09	-5.98E-08	-5.76E-08	1.78E-09	1.51E-08	2.36E-09	-6.66E-08	-6.43E-08
EP (kg Phosphate eq.)	**2.42E-04**	3.57E-07	2.41E-04	-1.76E-07	2.40E-10	7.78E-10	-3.27E-08	-3.17E-08	1.01E-10	6.11E-10	7.78E-10	-7.22E-09	-6.44E-09	2.15E-10	1.83E-09	8.61E-10	-8.06E-09	-7.19E-09
ADP fossil (MJ)	**1.07E-02**	1.48E-02	9.02E-04	-3.77E-03	9.98E-06	5.16E-05	-8.41E-04	-7.80E-04	5.52E-07	2.29E-05	1.19E-05	-3.00E-04	-2.88E-04	8.95E-06	7.59E-05	1.33E-05	-3.34E-04	-3.21E-04
MAETP (kg DCB eq.)	**-1.25**	1.62E-01		-1.32E+00	1.09E-04	7.48E-03	-9.73E-02	-8.97E-02	3.35E-06	1.87E-04	4.63E-05	-3.28E-03	-3.24E-03	9.80E-05	8.31E-04	5.16E-05	-3.66E-03	-3.61E-03

Table A. 13: Absolute values of the EoL impacts to each impact category for the H_2 ICE considering the FU of 1 kWh.

		Dissambling	Aluminum					Steel		Cast iron		Brass	Copper cables	Plastic and rubber		
				Recovery					Recovery		Recovery	Recovery	Recovery	Incineration		
Impact category	**Total**	Electricity grid mix	Reuse	Melting	Secondary Al production	Avoides charges Al	Total	Reuse	Melting	Reuse	Melting	Melting	Melting	Incineration	Avoided charges elect.	Total
HTP (kg DCB eq.)	**-6.94E-04**	7.91E-06	-5.87E-04	2.00E-08	2.10E-06	-1.15E-04	-1.13E-04	-6.47E-07	1.25E-07	-1.55E-06	2.63E-09	1.50E-08	8.00E-09	3.79E-08	-4.91E-07	-4.53E-07
TETP (kg DCB eq.)	**-2.42E-06**	3.03E-08	-1.98E-06	7.56E-11	7.10E-10	-3.88E-07	-3.87E-07	-6.63E-08	4.78E-10	-8.83E-09	1.01E-11	5.85E-11	3.17E-11	4.39E-11	-1.88E-09	-1.84E-09
POCP (kg Ethene eq.)	**-1.50E-07**	1.68E-08	-1.32E-07	4.15E-11	2.83E-10	-2.59E-08	-2.56E-08	-6.02E-09	2.66E-10	-1.85E-09	5.57E-12	3.17E-11	1.70E-11	1.83E-10	-1.04E-09	-8.59E-10
GWP 100 years (kg CO2 eq.)	**-1.79E-04**	3.21E-04	-3.44E-04	8.10E-07	2.76E-06	-6.74E-05	-6.38E-05	-1.33E-05	5.07E-06	-1.35E-04	1.07E-07	6.08E-07	3.25E-07	7.03E-05	-1.99E-05	5.04E-05
AP (kg SO2 eq.)	**-2.07E-06**	2.52E-07	-1.91E-06	6.37E-10	2.37E-09	-3.73E-07	-3.70E-07	-2.87E-08	3.98E-09	-1.35E-08	8.29E-11	4.78E-10	2.56E-10	1.78E-09	-1.57E-08	-1.39E-08
ADP elements (kg Sb eq.)	**-3.92E-11**	8.54E-11	-6.83E-11	2.23E-13	2.09E-12	-1.32E-11	-1.09E-11	-2.57E-12	1.34E-12	-3.90E-11	2.97E-14	1.61E-13	8.62E-14	-9.77E-14	-5.29E-12	-5.39E-12
ODP (kg R11 eq.)	**3.43E-16**	3.14E-27	-9.32E-20	7.92E-30	3.44E-16	-1.82E-20	3.44E-16	-3.54E-19	4.95E-29	-1.79E-27	1.04E-30	5.94E-30	3.18E-30	9.79E-30	-1.95E-28	-1.85E-28
FAETP (kg DCB eq.)	**-2.99E-06**	5.97E-07	-2.86E-06	1.51E-09	1.02E-08	-5.59E-07	-5.47E-07	-2.00E-08	9.42E-09	-1.44E-07	1.98E-10	1.13E-09	6.05E-10	1.32E-09	-3.71E-08	-3.58E-08
EP (kg Phosphate eq.)	**-9.31E-08**	7.21E-08	-1.27E-07	1.83E-10	5.95E-10	-2.47E-08	-2.40E-08	-3.30E-09	1.14E-09	-8.78E-09	2.39E-11	1.37E-10	7.32E-11	4.80E-10	-4.48E-09	-4.00E-09
ADP fossil (MJ)	**-2.36E-03**	3.00E-03	-3.26E-03	7.56E-06	3.90E-05	-6.37E-04	-5.91E-04	-1.14E-04	4.73E-05	-1.28E-03	9.95E-07	5.68E-06	3.03E-06	7.39E-06	-1.86E-04	-1.79E-04
MAETP (kg DCB eq.)	**-4.15E-01**	3.28E-02	-3.77E-01	8.27E-05	5.66E-03	-7.37E-02	-6.79E-02	-1.05E-03	5.18E-04	-1.93E-04	1.09E-05	6.21E-05	3.32E-05	2.87E-05	-2.04E-03	-2.01E-03

Table A. 14: Impact values obtained from the cradle-to-grave analysis considering the FU of 1 kWh for the diesel and H_2 ICE.

	DIESEL ENGINE		HYDROGEN ENGINE							
			Grey H_2		**Blue H_2**		**Green H_2**		**Recovered from waste H_2**	
Impact category	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave
HTP (kg DCB eq.)	1.31E-02	1.24E-02	1.76E-02	1.69E-02	2.25E-02	2.18E-02	6.66E-03	5.97E-03	6.87E-03	6.18E-03
TETP (kg DCB eq.)	9.04E-04	9.02E-04	2.43E-04	2.41E-04	2.43E-04	2.41E-04	7.02E-04	7.00E-04	2.43E-04	2.40E-04
POCP (kg Ethene eq.)	7.81E-06	7.67E-06	1.04E-05	1.03E-05	1.37E-05	1.36E-05	5.10E-06	4.92E-06	1.38E-06	1.23E-06
GWP 100 years (kg CO_2 eq.)	5.80E-01	5.80E-01	1.62E-01	1.62E-01	2.80E-02	2.79E-02	4.50E-03	4.17E-03	1.99E-01	1.99E-01
AP (kg SO_2 eq.)	4.06E-06	2.06E-06	6.83E-05	6.62E-05	9.68E-04	9.66E-04	7.82E-05	7.60E-05	2.06E-05	1.85E-05
ADP elements (kg Sb eq.)	3.60E-08	3.60E-08	1.40E-08	1.39E-08	1.41E-08	1.41E-08	1.45E-08	1.05E-08	9.49E-09	9.45E-09
ODP (kg R11 eq.)	2.42E-16	5.74E-16	2.57E-16	6.00E-16	2.58E-16	6.01E-16	2.44E-16	6.25E-16	2.44E-16	5.88E-16
FAETP (kg DCB eq.)	2.10E-03	2.10E-03	1.51E-04	1.48E-04	1.51E-04	1.48E-04	1.30E-04	1.27E-04	1.40E-04	1.37E-04
EP (kg Phosphate eq.)	2.55E-05	2.54E-05	9.24E-06	9.15E-06	2.08E-04	2.08E-04	4.67E-06	4.52E-06	5.35E-06	5.26E-06
ADP fossil (MJ)	5.73	5.73	2.87	2.87	2.87	2.87	0.16	0.15	0.22	0.22
MAETP (kg DCB eq.)	4.72	4.32	0.71	0.30	0.72	0.31	2.62	2.17	2.91	2.50

Table A. 15: Impact values obtained from the cradle-to-grave analysis considering the FU of 1 kWh for the PEMFC system.

Impact category	FUEL CELL SYSTEM							
	Grey H_2		Blue H_2		Green H_2		Recovered from waste H_2	
	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave
HTP (kg DCB eq.)	1.39E-01	9.36E-02	1.58E-01	1.12E-01	9.75E-02	5.16E-02	9.83E-02	5.24E-02
TETP (kg DCB eq.)	3.68E-03	2.00E-03	3.68E-03	2.00E-03	5.46E-03	3.79E-03	3.68E-03	2.00E-03
POCP (kg Ethene eq.)	4.19E-05	4.03E-05	5.50E-05	5.34E-05	2.11E-05	1.95E-05	6.99E-06	5.37E-06
GWP 100 years (kg CO_2 eq.)	6.23E-01	6.23E-01	1.08E-01	1.08E-01	6.10E-02	6.15E-02	8.43E-01	8.43E-01
AP (kg SO_2 eq.)	2.70E-04	2.59E-04	3.90E-03	3.89E-03	3.07E-04	2.96E-04	8.68E-05	7.58E-05
ADP elements (kg Sb eq.)	1.01E-07	6.20E-08	1.01E-07	6.25E-08	8.78E-08	4.88E-08	8.38E-08	4.48E-08
ODP (kg R11 eq.)	1.00E-10	2.07E-09	1.00E-10	2.07E-09	1.00E-10	2.07E-09	1.00E-10	2.07E-09
FAETP (kg DCB eq.)	1.67E-03	9.96E-04	1.67E-03	9.97E-04	1.59E-03	9.17E-04	1.63E-03	9.56E-04
EP (kg Phosphate eq.)	3.86E-03	1.30E-03	4.66E-03	2.10E-03	3.84E-03	1.28E-03	3.85E-03	1.28E-03
ADP fossil (MJ)	11.02	11.02	11.02	11.02	0.59	0.59	0.85	0.85
MAETP (kg DCB eq.)	3.15	1.90	3.18	1.93	10.32	9.07	11.58	10.33

Table A. 16: Impact values obtained from the cradle-to-grave analysis considering the FU of 1 km for the diesel and H_2 ICE.

Impact category	DIESEL ENGINE		HYDROGEN ENGINE							
	Cradle to use phase	Cradle-to-grave	Grey H_2		Blue H_2		Green H_2		Recovered from waste H_2	
			Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave
HTP (kg DCB eq.)	2.68E-01	2.54E-01	3.61E-01	3.47E-01	4.61E-01	4.47E-01	1.37E-01	1.22E-01	1.41E-01	1.27E-01
TETP (kg DCB eq.)	1.85E-02	1.85E-02	4.98E-03	4.93E-03	4.99E-03	4.94E-03	1.44E-02	1.43E-02	4.98E-03	4.93E-03
POCP (kg Ethene eq.)	1.60E-04	1.57E-04	2.14E-04	2.11E-04	2.81E-04	2.78E-04	1.04E-04	1.01E-04	2.83E-05	2.52E-05
GWP 100 years (kg CO_2 eq.)	11.90	11.89	3.32	3.32	0.57	0.57	0.09	0.09	4.08	4.08
AP (kg SO_2 eq.)	8.32E-05	4.23E-05	1.40E-03	1.36E-03	1.98E-02	1.98E-02	1.60E-03	1.56E-03	4.21E-04	3.79E-04
ADP elements (kg Sb eq.)	7.38E-07	7.38E-07	2.87E-07	2.86E-07	2.89E-07	2.88E-07	2.16E-07	2.15E-07	1.95E-07	1.94E-07
ODP (kg R11 eq.)	4.96E-15	1.18E-14	5.26E-15	1.23E-14	5.29E-15	1.23E-14	5.77E-15	1.28E-14	5.01E-15	1.20E-14
FAETP (kg DCB eq.)	4.31E-02	4.30E-02	3.09E-03	3.03E-03	3.10E-03	3.04E-03	2.67E-03	2.61E-03	2.88E-03	2.82E-03
EP (kg Phosphate eq.)	5.23E-04	5.21E-04	1.89E-04	1.87E-04	4.26E-03	4.26E-03	9.46E-05	9.27E-05	1.10E-04	1.08E-04
ADP fossil (MJ)	117.49	117.45	58.88	58.84	58.90	58.86	3.15	3.11	4.56	4.51
MAETP (kg DCB eq.)	96.69	88.51	14.62	6.12	14.78	6.28	52.97	44.48	59.69	51.19

Table A. 17: Impact values obtained from the cradle-to-grave analysis considering the FU of 1 km for the PEMFC system.

Impact category	FUEL CELL SYSTEM							
	Grey H_2		Blue H_2		Green H_2		Recovered from waste H_2	
	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave	Cradle to use phase	Cradle-to-grave
HTP (kg DCB eq.)	2.18E-01	1.46E-01	2.48E-01	1.76E-01	1.53E-01	8.07E-02	1.54E-01	8.20E-02
TETP (kg DCB eq.)	5.75E-03	3.13E-03	5.76E-03	3.13E-03	8.55E-03	5.93E-03	5.75E-03	3.13E-03
POCP (kg Ethene eq.)	6.56E-05	6.31E-05	8.61E-05	8.35E-05	3.31E-05	3.06E-05	1.09E-05	8.41E-06
GWP 100 years (kg CO_2 eq.)	0.97	0.98	0.17	0.17	9.55E-02	0.10	1.32	1.32
AP (kg SO_2 eq.)	4.23E-04	4.05E-04	6.10E-03	6.08E-03	4.81E-04	4.64E-04	1.36E-04	1.19E-04
ADP elements (kg Sb eq.)	1.58E-07	9.70E-08	1.59E-07	9.78E-08	1.37E-07	7.64E-08	1.31E-07	7.01E-08
ODP (kg R11 eq.)	1.57E-10	3.24E-09	1.57E-10	3.24E-09	1.57E-10	3.24E-09	1.57E-10	3.24E-09
FAETP (kg DCB eq.)	2.61E-03	1.56E-03	2.61E-03	1.56E-03	2.49E-03	1.44E-03	2.55E-03	1.50E-03
EP (kg Phosphate eq.)	6.04E-03	2.03E-03	7.30E-03	3.28E-03	6.01E-03	2.00E-03	6.02E-03	2.01E-03
ADP fossil (MJ)	17.24	17.24	17.25	17.25	0.93	0.93	1.34	1.34
MAETP (kg DCB eq.)	4.92	2.97	4.97	3.02	16.15	14.20	18.12	16.16

Table A. 18: Impact values from the cradle-to-grave analysis for each life cycle phase considering a FU of 1 kWh.

	Diesel ICE				H_2 ICE				PEMFC system			
Impact category	R.M. production	Manufacturing	Use	EoL	R.M. production	Manufacturing	Use	EoL	R.M. production	Manufacturing	Use	EoL
HTP (kg DCB eq.)	6.30E-03	9.22E-06	6.75E-03	-6.70E-04	6.31E-03	9.22E-06	1.13E-02	-6.94E-04	9.02E-02	3.91E-05	4.33E-02	-3.78E-02
TETP (kg DCB eq.)	2.41E-04	3.00E-08	6.64E-04	-2.33E-06	2.41E-04	3.00E-08	2.44E-06	-2.42E-06	3.66E-03	1.50E-07	9.34E-06	-1.67E-03
POCP (kg Ethene eq.)	1.65E-07	2.24E-08	7.63E-06	-1.44E-07	1.67E-07	2.24E-08	1.02E-05	-1.50E-07	8.15E-07	8.30E-08	3.92E-05	-1.28E-08
GWP 100 years (kg CO_2 eq.)	5.95E-04	3.21E-04	5.79E-01	-1.65E-04	5.99E-04	3.21E-04	1.61E-01	-1.79E-04	1.50E-03	1.59E-03	6.17E-01	1.53E-03
AP (kg SO_2 eq.)	2.38E-06	2.52E-07	1.42E-06	-2.00E-06	2.41E-06	2.52E-07	6.56E-05	-2.07E-06	7.41E-06	1.25E-06	2.52E-04	-6.98E-07
ADP elements (kg Sb eq.)	3.05E-09	9.17E-11	3.29E-08	-3.64E-11	3.06E-09	9.17E-11	1.08E-08	-3.92E-11	5.06E-08	8.79E-09	4.15E-08	-3.89E-08
ODP (kg R11 eq.)	2.42E-16	4.40E-22	9.22E-25	3.32E-16	2.44E-16	4.40E-22	1.23E-17	3.43E-16	2.67E-11	7.56E-21	4.73E-17	7.66E-09
FAETP (kg DCB eq.)	9.74E-05	5.97E-07	2.00E-03	-2.88E-06	9.75E-05	5.97E-07	5.28E-05	-2.99E-06	1.45E-03	2.95E-06	2.02E-04	-6.55E-04
EP (kg Phosphate eq.)	1.62E-07	7.77E-08	2.53E-05	-8.79E-08	1.63E-07	7.77E-08	9.00E-06	-9.31E-08	1.02E-03	3.57E-07	3.45E-05	9.06E-04
ADP fossil (MJ)	6.41E-03	3.25E-03	5.72	-2.23E-03	6.45E-03	3.25E-03	2.86	-2.36E-03	1.36E-02	1.48E-02	10.98	1.32E-02
MAETP (kg DCB eq.)	0.55	3.28E-02	4.13	-0.40	0.55	3.28E-02	0.13	-0.41	2.49	0.16	0.49	-1.25

Table A. 19: Impact values from the cradle-to-grave analysis for each life cycle phase considering a FU of 1 km.

	Diesel ICE				H_2 ICE				PEMFC system			
Impact category	R.M. production	Manufacturing	Use	EoL	R.M. production	Manufacturing	Use	EoL	R.M. production	Manufacturing	Use	EoL
HTP (kg DCB eq.)	1.29E-01	1.89E-04	1.38E-01	-1.37E-02	1.29E-01	1.89E-04	2.32E-01	-1.42E-02	1.41E-01	6.13E-05	6.78E-02	-6.26E-02
TETP (kg DCB eq.)	4.93E-03	6.14E-07	1.36E-02	-4.79E-05	4.93E-03	6.14E-07	4.99E-05	-4.96E-05	5.73E-03	2.35E-07	1.46E-05	-2.62E-03
POCP (kg Ethene eq.)	3.40E-06	4.59E-07	1.56E-04	-2.96E-06	3.42E-06	4.59E-07	2.10E-04	-3.07E-06	1.28E-06	1.30E-07	6.14E-05	-1.36E-07
GWP 100 years (kg CO_2 eq.)	1.22E-02	6.58E-03	1.19E+01	-3.38E-03	1.23E-02	6.58E-03	3.30E+00	-3.67E-03	2.35E-03	2.49E-03	9.66E-01	2.10E-03
AP (kg SO_2 eq.)	4.90E-05	5.17E-06	2.92E-05	-4.09E-05	4.93E-05	5.17E-06	1.35E-03	-4.25E-05	1.16E-05	1.95E-06	3.94E-04	-2.35E-06
ADP elements (kg Sb eq.)	6.27E-08	1.88E-09	6.74E-07	-7.45E-10	6.27E-08	1.88E-09	2.22E-07	-8.04E-10	7.92E-08	1.38E-08	6.50E-08	-6.09E-08
ODP (kg R11 eq.)	4.96E-15	9.01E-21	1.89E-23	6.80E-15	5.01E-15	9.01E-21	2.53E-16	7.04E-15	4.18E-11	1.18E-20	7.40E-17	3.20E-09
FAETP (kg DCB eq.)	2.00E-03	1.22E-05	4.11E-02	-5.90E-05	2.00E-03	1.22E-05	1.08E-03	-6.14E-05	2.27E-03	4.62E-06	3.17E-04	-1.03E-03
EP (kg Phosphate eq.)	3.32E-06	1.59E-06	5.18E-04	-1.80E-06	3.34E-06	1.59E-06	1.84E-04	-1.91E-06	1.60E-03	5.58E-07	5.40E-05	3.78E-04
ADP fossil (MJ)	1.32E-01	6.67E-02	117.30	-4.57E-02	1.32E-01	6.67E-02	58.69	-0.05	2.12E-02	2.32E-02	17.18	0.02
MAETP (kg DCB eq.)	11.27	6.73E-01	84.76	-8.18E+00	11.32	6.73E-01	2.62	-8.50	3.90	0.254	0.77	-1.96