

Chapter 2

Life Cycle Assessment of a Hydrogen and Fuel Cell RoPax Ferry Prototype



Juan Camilo Gomez Trillos, Dennis Wilken, Urte Brand, and Thomas Vogt

Abstract Estimates for the greenhouse gas emissions caused by maritime transportation account for approx. 870 million tonnes of CO₂ tonnes in 2018, increasing the awareness of the public in general and requiring the development of alternative propulsion systems and fuels to reduce them. In this context, the project HySeas III is developing a hydrogen and fuel cell powered roll-on/roll off and passenger ferry intended for the crossing between Kirkwall and Shapinsay in the Orkney Islands in Scotland, a region which currently has an excess of wind and tidal power. In order to explore the environmental aspects of this alternative, a life cycle assessment from cradle to end-of-use using the ReCiPe 2016 method was conducted, contrasting the proposed prototype developed within the project against a conventional diesel ferry and a diesel hybrid ferry. The results show that the use of hydrogen derived from wind energy and fuel cells for ship propulsion allow the reduction of greenhouse gas emissions of up to 89% compared with a conventional diesel ferry. Additional benefits are lower stratospheric ozone depletion, ionizing radiation, ozone formation, particulate matter formation, terrestrial acidification and use of fossil resources. In turn, there is an increase in other impact categories when compared with diesel electric and diesel battery electric propulsion. Additionally, the analysis of endpoint categories shows less impact in terms of damage to human health, to the ecosystems and to resource availability for the hydrogen alternative compared to conventional power trains.

Keywords Hydrogen · Fuel cells · LCA · Shipping emissions reduction

The original version of this chapter was revised: The legend of the figure 2.2 was corrected. The correction to this chapter is available at https://doi.org/10.1007/978-3-030-50519-6_17

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2.1 Introduction

According to the “Third IMO GHG Study 2014”, international shipping emitted 796 million tonnes of CO₂, or considering other emissions, 816 million tonnes of CO₂eq in 2012 and represented approximately 2.1% of the global CO₂eq emissions in the same year (Smith et al. 2015). Estimates for 2018 amount to 870 million tonnes of CO₂ (DNV GL–Maritime 2019). Moreover, an increase of between 50% and 250% of CO₂ is expected on a business-as-usual scenario by 2050 (Smith et al. 2015). This has led to efforts in reducing the sector’s greenhouse gas (GHG) emissions. Consequently, the Marine Environment Protection Committee (MEPC) of the IMO issued the Resolution MEPC.304(72) in 2018, adopting an initial strategy for reducing GHG emissions, aiming to reduce them by 50% by 2050 using share of emissions in 2008 as reference level. This resolution describes short, medium and long term measures for this purpose. Within this resolution, short term measures are related with energy efficiency and regulations; however, the implementation of zero-carbon or fossil-free fuels together with emission reduction mechanisms are the only measures envisioned in the long term to reduce GHG emissions (International Maritime Organization 2018).

So far, the strategy of the European Union in this regard consists of monitoring, reporting and verification in the first place, establishing greenhouse gas reduction targets in the second place and further measures including market-based measures as a last step (European Commission 2019). The first step already commenced with the obligation from January 1st 2018 for large ships over 5000 gross tonnage to monitor and report their CO₂ emissions when loading or unloading cargo or passengers at ports in the European Economic Area (EEA) (European Commission 2019). However, another strategy paired with the long term ambition of reducing or decarbonising the shipping sector is the development of low carbon fuels and alternative power and propulsion systems for ships.

2.1.1 Ferries and Project HySeas III

Ferries are ships conveying passengers and goods, especially over a relatively short distance and as a regular service.¹ Roll on/roll-off/Passenger (RoPax) ferries have the special feature of being designed to carry wheeled payload, particularly vehicles, and passengers. According to numbers from the database SeaWeb IHS Markit, 42% of the RoPax ferry ships listed globally are in European registers, meaning that approximately 1400 operate in Europe (IHS Markit 2019). Around 40% of the fleet is more than 30 years old (IHS Markit 2019). The average lifetime of ferries is around 35 years, meaning that many of these ships will require replacement or retrofitting in the near future to continue with the transportation services.

¹<https://www.lexico.com/en/definition/ferry>.

In this context, the current research project HySeas III (2018–2021) has the motivation to realise the first sea-going RoPax ferry powered by hydrogen and fuel cells (HySeas III Project 2019). The ship will be 40 m long, 10 m wide, and will have a capacity of 120 passengers and 20 passenger vehicles or 2 lorries. It is intended that the ship will operate at the crossing between Kirkwall and Shapinsay in the Orkney Islands, Scotland. The sister projects BIG HIT and SURF ‘N’ TURF are already developing a hydrogen supply chain at this location, including production via electrolyzers, storage, transportation in high pressure tanks and applications linked to the use of hydrogen (BIG HIT Project 2019; Surf ‘N’ Turf Project 2019). The production of hydrogen will be mainly based on wind power and tidal power available at the location, and could supply the ship developed by project HySeas III in the near future. Moreover, the use of hydrogen has been envisioned as an option for the routes Barra–Eriskay and Stornoway–Ulapool also in Scotland (Point and Sandwick Trust 2019).

In addition to the technical development of a hydrogen-powered fuel cell RoPax ferry prototype, HySeas III aims to assess the economic, environmental and social impacts of the particular application under development. The main driver is the reduction of the environmental impact of ships. Thus, the HySeas III consortium decided to conduct an environmental assessment of the prototype considering different aspects surrounding the project. Life cycle assessment (LCA) is a methodology that allows consideration of environmental aspects and potential environmental impacts throughout the life cycle of a product (DIN Deutsches Institut für Normung e.V., Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040). Therefore, this methodology was selected to perform the environmental analysis of the ship to be built by HySeas III.

2.1.2 Previous Approaches of Life Cycle Assessment of Alternative Fuels for Ships

Several authors have previously approached the topic of life cycle assessment of alternative fuels for ships. Gilbert et al. analysed different fuels and production paths considering the impacts on three greenhouse gases (CO₂, CH₄ and N₂O) and three local pollutants (SO_x, NO_x and PM) (Gilbert et al. 2018). Liquid hydrogen was found as the best alternative in terms of reducing GHG emissions and local pollutants, but only if it is produced by the use of renewable energy and particularly of wind power. This study also served to demonstrate the applicability in practice and upscaling up to industrial level. Nevertheless, this study only considered the life cycle of energy carriers, leaving aside the life cycle of the equipment.

A bachelor thesis performed by Jokela et al. conducted a life cycle assessment of a hydrogen-electric ferry, finding a reduction of 79% of the global warming potential (GWP) emissions of the assessed alternative compared to a conventional diesel

ferry (Jokela et al. 2019). This analysis considered the ferry connection Hjelmeland–Skipavik–Nesvik in Norway. In that case, 50% of the electricity used for ship propulsion must come from hydrogen, while the remaining 50% shall be electricity from on-board batteries, which are charged at the docking sites. The functional unit in this study was the 3 km crossing between Hjelmeland and Nesvik, consisting of 13 min crossing time and 7 min at the quay. Moreover, the authors assumed a fuel cell power system of 746 kW and batteries with a capacity of 746 kW. After using the CML-IA impact assessment method, the authors calculated an impact of 5.2 kg CO₂eq/crossing for the hydrogen-electric ferry and 24.8 kg CO₂eq/crossing for the diesel ferry (Jokela et al. 2019). In comparison to the ferry analysed by Jokela et al. the ferry developed in HySeas III would have a different operation profile and specifications, and hydrogen would be produced using different electricity sources.

Other LCAs for electric vehicles and fuel cell vehicles have shown the relevance of taking the equipment or even the infrastructure into account (Nordelöf et al. 2014; Marmiroli et al. 2019). Although the impact of these components in terms of GWP might be low, their impact in other impact categories can be relevant, and therefore additional impact categories were highlighted in this study.

2.2 Methodology

The methodology of life cycle assessment (LCA) in compliance with the ISO 14040 and ISO 14044 standards was employed to estimate the environmental impact of different ship alternatives (DIN Deutsches Institut für Normung e.V., Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040; DIN Deutsches Institut für Normung e.V., Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen (ISO 14044)). The next section describes the application of the methodology according to the four basic steps required by these standards for conducting an LCA study: goal and scope definition, inventory analysis, impact assessment and interpretation of the results.

2.2.1 Goal

The main goal of this study was to conduct an environmental assessment of the proposed hydrogen powered fuel cell RoPax ferry developed within the project HySeas III, which is to be implemented on the route Kirkwall–Shapinsay. This alternative was compared with other conventional propulsion systems, including diesel engines and diesel hybrid systems in conjunction with on-board batteries operating on the same route. The aim of this analysis was to establish the benefits and drawbacks of using hydrogen and fuel cells for this transportation service.

The intended audience for this study are decision-makers related to the maritime sector, industry, politicians, scientists, companies and the public in general. The

background data used in the study is based on ecoinvent 3.5 (Wernet et al. 2016) and the software utilized for the calculations was SimaPro 9.0. Primary data in terms of modelled energy consumption and component sizing was collected from the project partners, particularly those involved with the construction and trials of the power system (Ferguson, Ballard, Kongsberg) and with the operation of current ferries and of the future prototype (Orkney Council–Marine Services). The information gaps not fulfilled by project partners or protected as part of their business secrets were covered using literature sources as described in the next sections.

2.2.2 Scope

The main service provided by the operation of RoPax ferries is the transportation of passengers and vehicles. In order to perform this task, different elements are necessary. Within this analysis, an on-board power source to propel the ship and at the same time cover the internal energy demand of the different systems, a storage system of fuel carriers on-board, a dispensing unit to load the fuel on the storage system of the vessel and the upstream supply chain of the energy carrier used during this operation were considered. These were taken into account from cradle to end-of-use, meaning that the final disposal of the ship and its components were not considered for this approach. Other elements such as the quayside facilities employed as link between the ship and the mainland and the personnel involved in the operation of the ship were not taken into account in the analysis and therefore are considered out of the scope.

Considered Ship Systems and Functions

According to Papanikolaou, a ship's design involves considerations for a variety of subsystems serving a series of functions, divided into payload functions and ship inherent functions (Papanikolaou 2019). The payload functions are related to the provision of cargo (passengers) spaces, cargo handling and cargo treatment, whereas the ship inherent functions involve the carriage or transport of cargo or in other words the hull, superstructures and a propulsion/power unit together with fuel to enable the transport from A to B (Papanikolaou 2019). The main reason for choosing these subsystems is that these are the ones that would differ between different propulsion alternatives, as would be the case of a hydrogen powered fuel cell ferry.

Table 2.1 shows a summary of the inherent and payload functions. This work focusses on inherent functions, including structure, machinery and tanks, which themselves are comprised of the listed subsystems. and among them underlined subsystems. Only those underlined functions were considered within the scope of this work. Those functions are performed by different components in the ship, as will be described in the inventory analysis section. The structure was included to estimate the impact of the hull material in comparison to other components. Moreover, the machinery and tanks were included because they constitute the different propulsion systems and vary between the considered alternatives. The other functions were

Table 2.1 Ship functions

Inherent function		Payload function	
Structure	<u>Hull</u> , poop deck, forecastle <u>superstructures</u>	Cargo units	Containers, trailers, cassettes, pallets, bulk/break bulk
Crew facilities	Crew spaces, Service spaces, stairs and corridors	Cargo spaces	Holds, deck cargo spaces, cell guides, tanks
Machinery	Engine and pump rooms, <u>engine casing</u> , funnel, steering and thrusters	Cargo handling	Hatches and ramps, cranes, cargo pumps, lashing
Tanks	<u>Fuel and lub oil</u> , water and sewage, ballast and voids	Cargo treatment	Ventilation, heating and cooling, pressurising
Comfort systems	Air conditioning, water and sewage		
Outdoor decks	Mooring, lifeboats, etc.		

Adapted from (Papanikolaou 2019)

not considered here, as they would not diverge considerably among the different alternatives, and due to lack of information at this design stage.

Functional Unit

The functional unit (FU) used for this study was 1 km of crossing distance of the selected ship during the lifetime considered for the purposes of this study of 30 years. The lifetime of the ships was selected according to the lifetime described for previous RoPax ferries by databases such as SeaWeb from the company IHS Markit, given that most of the ships reach at least this lifetime. Furthermore, the selection of the functional unit in terms of distance was done because the RoPax ferries have the two main functionalities of transporting passengers and transporting vehicles, which would require additional allocation of the environmental impacts to each one of the functions. The operation of the ships was considered as comprised by 4034 single crossings per year with an average distance of 7 km per crossing and an average service speed of 9.5 knots corresponding with the service currently performed between Kirkwall and Shapinsay. Therefore the ship crosses approximately 28,238 km/year and 847,140 km during the considered lifetime of 30 years.

Impact Assessment Method and Allocations Procedures

The hierarchist perspective of the impact assessment method ReCiPe 2016, hereafter ReCiPe 2016 (H), was selected based on the broad impact categories covered by this method, its global scope and the possibility of considering both mid-point and end-point impacts. The hierarchist perspective is the consensus model most commonly used in scientific models (Huijbregts et al. 2016). The cut-off system model was used as underlying philosophy for the systems taken from the database ecoinvent 3.5.

2.2.3 Inventory Analysis

Previous studies have pointed out that the complete life cycle of vehicles involves the life cycle of the fuel, usually called well-to-tank life cycle, and the life cycle of the equipment (Nordelöf et al. 2014). Beyond that, some authors include the infrastructure life cycle in the case of future electric vehicles, i.e. charging systems, to describe the complete life cycle (Marmioli et al. 2019). Although this approach has been mainly used for vehicles, it can be extended to ships, as is the case in the project HySeas III.

This approach is shown in Fig. 2.1, where the different components considered for ship manufacturing as well as for ship energy supply are displayed for the three different alternatives considered in this work. On one side, the ship is manufactured using different components to accomplish the functions previously described in Table 2.1. On the other side, the energy supply of the ship consists of diesel, electricity or hydrogen, which in this case was considered as produced from wind energy. These two life cycles merge in the use phase of the ship. As mentioned before, the use phase is followed by a final disposal phase, which was not considered here.

Life Cycle of the Ship

Today most of the ships with similar features use marine diesel as fuel or, in the case of bigger ships with low-speed engines, heavy fuel oil. However, diesel was considered in this analysis, since it is the fuel mainly used for small ships. Diesel is burned in internal combustion engines to obtain mechanical energy for propulsion and at the same time heat and electricity for different applications of the ship, usually

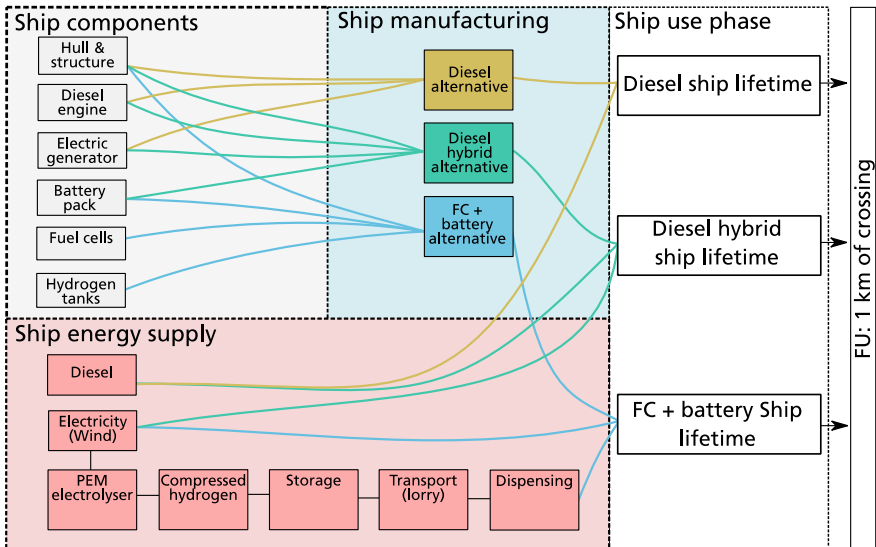


Fig. 2.1 Abstraction of ship and energy supply life cycle as modelled in this work

known as hotel load. In some cases, this is undertaken by a diesel-electric system in which all the mechanical energy is converted to electricity, which is further used for electric thrusters and on-board systems in opposition to the case in which the engine is coupled directly or via a gearbox to a propeller. In comparison to diesel powered systems, fuel cell outputs are heat and electricity. The latter can be used for feeding electric thrusters and any on-board systems in a similar way as done in the case of a diesel-electric system. Additionally, ships can be propelled by a hybrid system of a combustion engine and batteries installed on-board. This is done to operate internal combustion engines at their most efficient point, while batteries can give support during peak conditions by discharging and charging again at low load conditions or from the mains. Batteries produce mainly electricity and therefore are employed mainly in electric propulsion systems.

For purposes of this work, three alternatives differing in terms of their propulsion system and fuels were considered. A first alternative, representing the conventional diesel-electric system, is referred hereafter as diesel electric ship (DES). A second design, considering a diesel electric system assisted by on-board batteries that can be charged by on-board electricity generation or connection to the mains, is named diesel battery electric ship (DBES). Finally, an alternative design using hydrogen stored in high pressure tanks, fuel cells and batteries, as designed in project HySeas III, is referred as fuel cell battery electric ship (FCBES). Since fuel cells and batteries produce electricity, an electric generator was not considered necessary in this case.

The different assumptions considered in this work are summarised in Table 2.2. The diesel engine was modelled by upscaling the inventory in ecoinvent 3.5 for a marine engine construction, which is given in terms of 1000 kg. A 375 kW engine has a mass of approximately 1800 kg (Volvo Penta 2019). Two of those engines would add around 3600 kg, giving a mass scaling factor of 3.6 compared to the system in ecoinvent 3.5. On the other hand, ecoinvent 3.5 includes systems for 200 kW electric generators with a weight of 850 kg. A 500 HP (375 kW) motor has a weight of approximately 1177 kg, giving a weight scaling factor of 1.38. When two generators are considered in order to meet the power requirements, a total scaling factor of 2.77 is obtained.

In the case of fuel cells, the inventories published by Miotti et al. and Bekel and Pauliuk were adapted using ship on-board power (Miotti et al. 2017; Bekel and Pauliuk 2019). Miotti et al. published inventories for an 85 kW fuel cell system, which were scaled up to 600 kW by using a factor of 7.06. Moreover, the hydrogen storage system was modelled as bundles of carbon fibre tanks each containing 5.6 kg of hydrogen, as previously modelled by Miotti et al. and Bekel and Pauliuk (2017, 2019). Given that the total hydrogen on-board storage would have a capacity of 600 kg, 108 tanks were considered.

On-board Lithium-Nickel-Manganese-Cobalt-Oxide (NMC) 1:1:1 lithium ion batteries were also considered as assisting the propulsion system in a similar way as previously stated for the DBES. The inventories for this component were taken as described by Ellingsen et al., and scaled-up according to the size of the batteries considered for the future ship (Ellingsen et al. 2013). Ellingsen et al. described power packs of 22 kWh, which were scaled up to 768 kWh by using a factor of 28.8. The

Table 2.2 Assumptions for ship components according to project specifications

Ship Component	Specification	Lifetime	Reference
Hull and Structure	190 tonnes of steel 20 tonnes of aluminium	30 years	HySeas III
Diesel Engine	2 × 375 kW 40% efficiency	30 years	Scaled from ecoinvent 3.5
Electric generator	2 × 300 kW 99% efficiency	30 years	Scaled from ecoinvent 3.5
Battery set	768 kWh NMC 1:1:1 Li-ion batteries 90% charging efficiency Produced in Germany	10 years (3 battery sets in total during life time)	Ellingsen et al. (2013)
Fuel cells	Proton exchange membrane 600 kW 50% efficiency Pt load: 0.4 mg/cm ² Lifetime of 20,000 h	7 years (5 fuel cell system changes in total during life time)	Miotti et al. (2017) Bekel and Pauliuk (2019)
Hydrogen tanks	Carbon fibre 600 kg of hydrogen storage 350 bar	30 years	Miotti et al. (2017) Bekel and Pauliuk (2019)

amount of energy assumed for the manufacturing of battery cells was 280 kWh/kg of cells, according to the average value shown by Ellingsen et al. (2013). The German grid contained in ecoinvent 3.5 was assumed for the production of battery cells.

Additionally, the materials for the hull and structure, namely steel and aluminium, were considered similar in all the cases and included as a part of the inventories. The estimations for the amount of materials were provided by Ferguson Marine Ltd and were specified as 190 tonnes of low alloyed hot rolled steel and 20 tonnes of aluminium alloy, metal matrix composite. However, no manufacturing processes were considered for the construction of the ship, because at this stage it is still unknown how much energy and consumables will be required for the construction. Other materials such as glass, furniture or the ship's electronic system were not considered in the analysis because they do not differ considerably between the different alternatives and belong to other functions of the ship.

Ship's Energy Supply

With a view to the ship's energy supply, a lower heating value (LHV) of 42.7 MJ/kg for diesel and its production by the global supply of fossil fuels as modelled in the database ecoinvent 3.5 were assumed. The emissions of its combustion were modelled using a fishing vessel included in the database ecoinvent 3.5. Furthermore, it was assumed that the electricity supply for the hydrogen production originated from

Table 2.3 Energy carriers and electricity consumption of each of the considered ship alternatives

Type of ship	Diesel (kg/crossing)	Electricity (kWh/crossing)	Hydrogen (kg/crossing)
Diesel	54.9	–	–
Diesel hybrid	48.2	40.7	–
FC + battery ship	–	40.7	13.59

Source estimations of HySeas III consortium

wind power, as it is the current situation in the Orkney Islands, where the future prototype will operate. Consequently, hydrogen was considered as produced using wind electricity and a proton exchange membrane (PEM) electrolyser to obtain compressed hydrogen. The electricity consumption for hydrogen production was assumed to be 50 kWh/kg H₂ and the inventories for PEM electrolysers were modelled according to the inventories published by Wulf and Kaltschmidt (2018). After being produced and compressed, hydrogen is stored in trailers with a capacity of 200 kg at 350 bar, which are then conveyed for a distance of 6 km. For calculation purposes a distance of 12 km was considered, as the trailers must be driven back to the production site. Finally, the energy carrier is delivered to the ship by a dispensing unit, which in this case was assumed to be similar to a natural gas dispensing unit, in the same line as the assumption done by Wulf and Kaltschmidt (2013).

The energy consumption was modelled according to the current calculations performed within project HySeas III and considering the different efficiencies mentioned in Table 2.2. The consumption of the different energy carriers and electricity per crossing is shown in Table 2.3. According to these assumptions, the diesel prototype would have a yearly fuel consumption of 221,579 kg or 263,784 l when a density of 0.840 kg/l is considered for this fuel. Current consumption of MF Shapinsay, the ferry serving this route at present time was 170,400 l in 2018 (Orkney Island Council. Passengers, vehicles and fuel consumption of Orkney Marine Services Ships (Personal communication), 20/03/2019). Although the MF Shapinsay is smaller than the prototype developed in project HySeas III, making comparisons difficult, these figures give an idea of the magnitude of fuel consumption.

2.3 Results: Impact Assessment and Interpretation

The following section describes the results obtained for the midpoint and endpoint assessment and the single scores obtained from the ReCiPe 2016 (H) method.

2.3.1 Midpoint Characterisation

The main motivation for using hydrogen as fuel and fuel cells as energy converter lies in the reduction of GWP emissions. As summarized in Table 2.4, when wind power and PEM electrolysis are used to produce hydrogen which supplies FCBEs propulsion, the reduction of GWP from cradle to end-of-use is approximately 89% in comparison to the DES alternative. The DBES alternative together with electricity produced using wind power may allow reductions of approximately 8% compared to the reference DES case. FCBEs has additional lower impacts regarding SOD, IR, OFHH, FPMF, OFTE, TAC and FRS. On the other hand, the FCBEs shows higher impacts compared to the DES and DBES in terms of FEU, MEU, TEC, FEC, MEC, HCT, HNCT, LU, MRS and WATC. The results for the DBES in comparison with the DES alternative are 6% higher in SOD and 25% higher in IR.

A comparison between the different alternatives is shown in Figs. 2.2 and 2.3 by normalising to the highest value obtained in each impact category. Additionally, the contributions of each ship component and energy supply involved in the life cycle are displayed. Most of the impact in the categories GWP, SOD, IR, OFHH, FPMF, OFTE and FRS in the cases of the DES and DBES alternatives as displayed in are due to the use of diesel for propulsion, mainly due to the tailpipe emissions, which are avoided in the operation with hydrogen and electricity.

Most of the effects in which the FCBEs alternative has higher impact, as displayed in Fig. 2.3, are derived from the mining and refining processes of the materials employed for the ship's batteries and fuel cells as well as for wind turbines and electrolyzers for hydrogen production. Therefore, these impacts are not located where the

Table 2.4 Characterisation results of the different three alternatives using ReCiPe 2016 (H). The lowest impact is highlighted in green, middle impact in yellow and highest impact in red

Impact category	Unit	DES	DBES	FCBEs
Global warming potential (GWP)	kg CO ₂ eq/km	2.96×10 ¹	2.70×10 ¹	3.31×10 ⁰
Stratospheric ozone depletion (SOD)	kg CFC11 eq/km	7.24×10 ⁻⁶	7.27×10 ⁻⁶	2.15×10 ⁻⁶
Ionizing radiation (IR)	kBq Co ⁻⁶⁰ eq/km	3.51×10 ⁻¹	4.42×10 ⁻¹	2.63×10 ⁻¹
Ozone formation, Human health (OFHH)	kg NO _x eq/km	6.37×10 ⁻¹	5.63×10 ⁻¹	9.48×10 ⁻³
Fine particulate matter formation (FPMF)	kg PM _{2.5} eq/km	2.06×10 ⁻¹	1.85×10 ⁻¹	1.04×10 ⁻²
Ozone formation, Terrestrial ecosystems (OFTE)	kg NO _x eq/km	6.40×10 ⁻¹	5.66×10 ⁻¹	9.82×10 ⁻³
Terrestrial acidification (TAC)	kg SO ₂ eq/km	6.52×10 ⁻¹	5.85×10 ⁻¹	2.61×10 ⁻²
Freshwater eutrophication (FEU)	kg P eq/km	9.88×10 ⁻⁴	2.54×10 ⁻³	3.48×10 ⁻³
Marine eutrophication (MEU)	kg N eq/km	8.45×10 ⁻⁵	1.80×10 ⁻⁴	3.14×10 ⁻⁴
Terrestrial ecotoxicity (TEC)	kg 1,4-DCB/km	2.21×10 ¹	4.09×10 ¹	4.58×10 ¹
Freshwater ecotoxicity (FEC)	kg 1,4-DCB/km	1.07×10 ⁻¹	3.05×10 ⁻¹	9.09×10 ⁻¹
Marine ecotoxicity (MEC)	kg 1,4-DCB/km	1.75×10 ⁻¹	4.50×10 ⁻¹	1.19×10 ⁰
Human carcinogenic toxicity (HCT)	kg 1,4-DCB/km	4.76×10 ⁻¹	5.72×10 ⁻¹	1.07×10 ⁰
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DCB/km	3.40×10 ⁰	9.50×10 ⁰	1.45×10 ¹
Land use (LU)	m ² a crop eq/km	6.05×10 ⁻²	9.42×10 ⁻²	1.77×10 ⁻¹
Mineral resource scarcity (MRS)	kg Cu eq/km	3.14×10 ⁻²	2.28×10 ⁻¹	2.97×10 ⁻¹
Fossil resource scarcity (FRS)	kg oil eq/km	9.83×10 ⁰	8.89×10 ⁰	8.80×10 ⁻¹
Water consumption (WATC)	m ³ /km	5.20×10 ⁻²	6.68×10 ⁻²	8.55×10 ⁻²

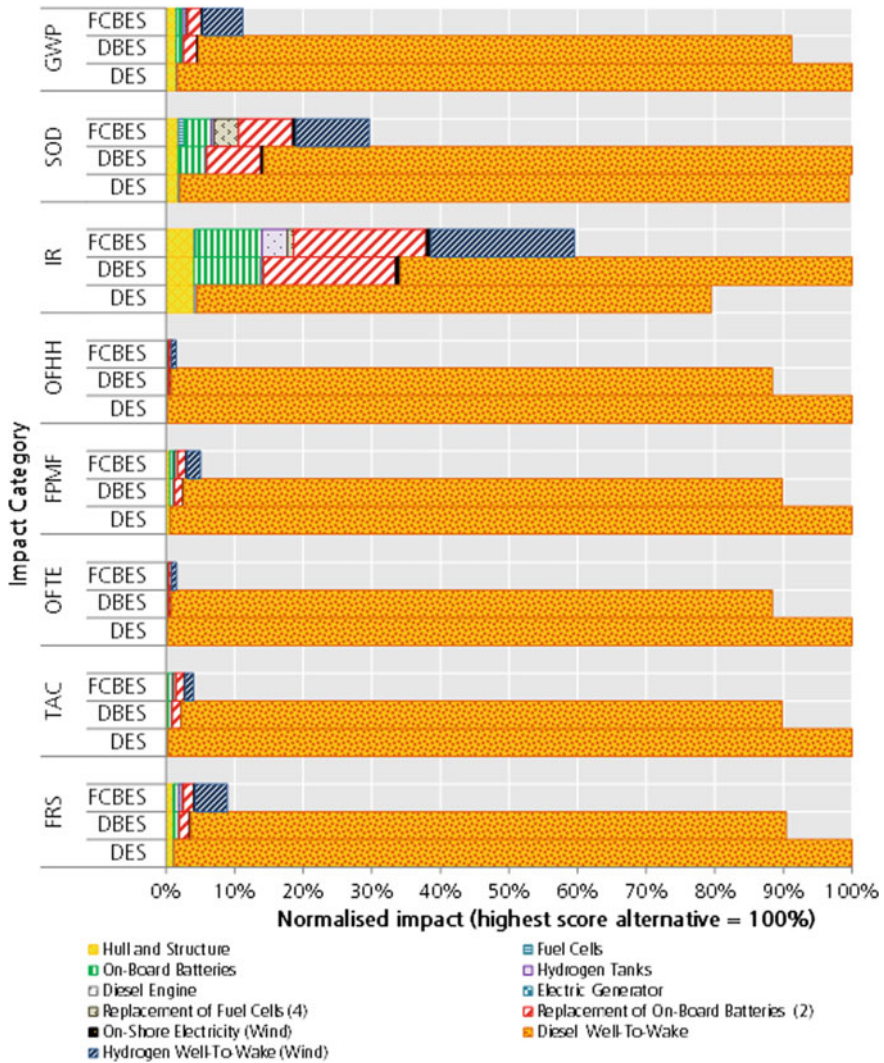


Fig. 2.2 Comparison of the midpoint impact assessment results for diesel electric ship (DES), diesel battery electric ship (DBES) and fuel cell battery electric ship (FCBES) RoPax ferry alternatives in the categories in which the FCBES has lower impact. Results normalised to the highest total impact alternative in each of the categories

ship operates, but where the materials used in the manufacture of different components are sourced. For FCBES, both fuel cells and battery replacements gather an important share of the impact, particularly in the impact categories SOD and IR.

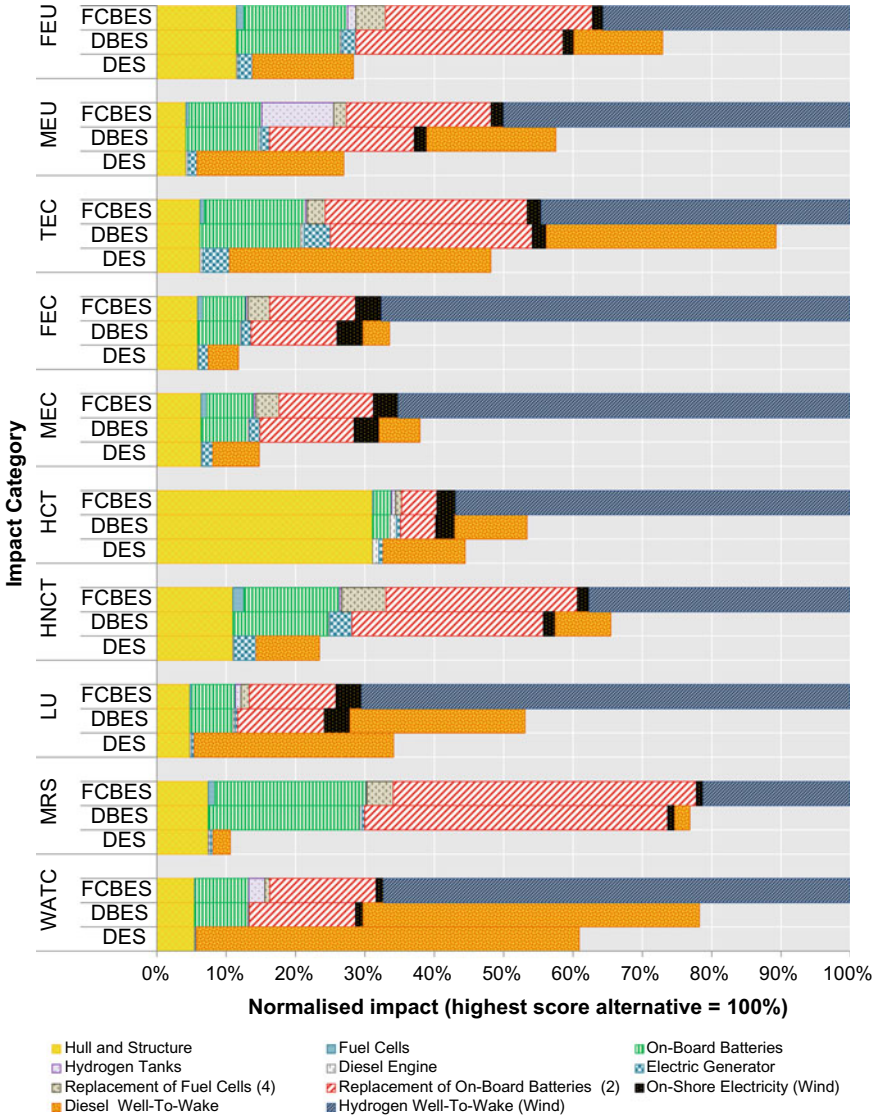


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2.3.2 Electricity Source and the Impact in Global Warming

In the last section, wind power was assumed as source of electricity, which is considered to be a reasonable assumption for Orkney given that the current hydrogen projects source their electricity mainly on local wind turbines and tidal conversion devices. However, the use of other electricity sources for the production of hydrogen may change radically the GHG emissions resulting from the use of hydrogen, as is described in Fig. 2.4.

The use of wind power allows the maximum reduction of GHG emissions compared to the diesel alternatives. Using a ground mounted photovoltaic system allows a reduction of approximately 66% of the GHG emissions compared to the diesel alternative, which is relatively lower compared to wind power, but still favourable compared to conventional alternatives. If electricity from sources such as natural gas conventional plants, the low voltage grid from the UK or oil power plants is used, the emissions in comparison to the diesel electric base case increase by 86%, 103% and 366% respectively. Therefore, the use of hydrogen produced via electrolysis is only meaningful from the global warming perspective if the electricity utilised during the process comes from low carbon sources such as wind power or photovoltaic systems.

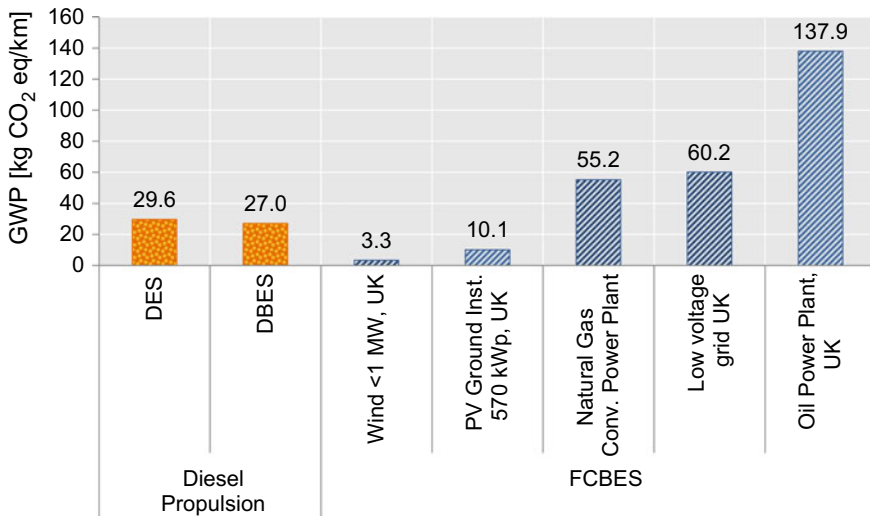


Fig. 2.4 Comparison of Global Warming Potential (GWP) for diesel electric ship (DES), diesel battery electric ship (DBES) and fuel cell battery electric ship (FCBES) employing different electricity sources for hydrogen electrolysis

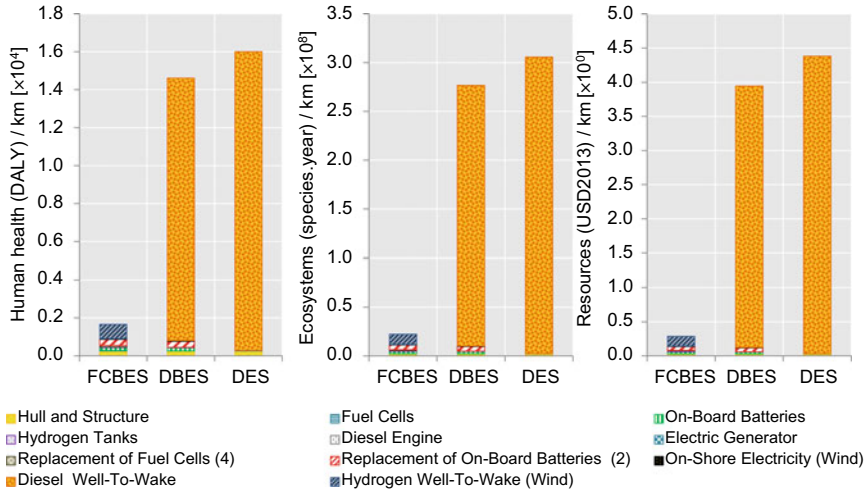


Fig. 2.5 Comparison of the endpoint assessment results for diesel electric ship (DES), diesel battery electric ship (DBES) and fuel cell battery electric ship (FCBES) RoPax ferry alternatives. From left to right: damage to human health ($\times 10^4$), to ecosystems ($\times 10^8$) and to resource availability ($\times 10^0$)

2.3.3 Endpoint Characterisation

The ReCiPe 2016 method allows endpoint characterisation by assigning the impacts to three endpoint categories related to protection areas. These endpoint categories are known as damage to human health, damage to ecosystems and damage to resource availability. The indicators for the impacts are reported in terms of Disability-Adjusted Life Year (DALY), species/year and increased cost respectively.

Figure 2.5 shows that the FCBES alternative has the lowest impact in all the three impact categories, followed by DBES and DES. This suggests that although the FCBES has higher midpoint impacts in some categories, the overall impact among the protection areas is smaller. Most of the endpoint impacts of DES and DBES alternatives are generated by the combustion of diesel in terms of impacts to the human health and ecosystems and the consumption of this fossil fuel in terms of resources.

2.4 Discussion

Jokela et al. described a GWP reduction of 79% of a hydrogen electric ferry compared with a diesel ferry (Jokela et al. 2019). This is 10% lower than the one found in this study. Moreover, the work done by Jokela et al. described a GWP of 5.2 kg CO₂eq for the 3 km crossing. If this amount is adjusted to 1 km of crossing, an amount of 1.7 kg CO₂eq/km would be obtained, which is 48% lower than the one obtained in this

study. However, Jockela et al. employed different assumptions, electricity sources, functional units and impact assessment methods, leading to differences between both studies and difficulties to establish comparisons. Establishing comparisons in terms of other impact categories is more challenging due to the use of different methods, but Jokela et al. reported higher impacts of a hydrogen electric ferry in comparison with a diesel ferry in terms of abiotic depletion, human toxicity, freshwater toxicity, marine toxicity and terrestrial toxicity. Although not the main focus of this work, Jokela et al. explained that the production of raw materials used for several components may increase the impact in those categories, which is in line with the results obtained in this work.

The impact observed by substitution of fuel cells and batteries during the lifetime was considerable. Therefore, maximising the lifetime of these components may contribute to diminishing the impact in most of the impact categories. Future improvements in the manufacturing of batteries or fuel cells were not considered. These improvements may be for instance a reduction in the amount of platinum used in fuel cells, different cell chemistries for Li-ion batteries or a reduction of the energy used for producing these elements. Moreover, proper recycling may allow the reduction of the impact for obtaining new materials and therefore diminish the impact on some of the categories, but this was not considered in the present work.

The analysis using different electricity sources showed that wind power allows the maximum reduction of GWP among the considered alternatives. Other low carbon sources such as hydropower or nuclear power may also be used to produce hydrogen, but may not be available at some locations, and may face additional problems for their implementation.

The endpoint analysis showed that the FCBES has the lowest impact to human health, environment and resources, even when the impact in the midpoint categories is higher compared to the DBES and DES alternatives. Despite the fact that endpoint categories have more policy relevance because their indicators are less abstract, it is also known that they introduce more uncertainty in the results.

2.5 Conclusions

The results obtained in this study show that a hydrogen fuel cell and battery electric ferry may allow the reduction of global warming impacts from cradle to end-of-use of up to 89% when compared with a conventional diesel electric ferry on the route Kirkwall–Shapinsay. However, if hydrogen is obtained using electrolysis, low carbon electricity sources such as wind power or photovoltaic modules should be used in order to maintain the benefits related to the reduction of greenhouse gas emissions.

The use of hydrogen and fuel cells in conjunction with batteries also decreases the potential life cycle impact in terms of stratospheric ozone depletion, ionizing radiation, ozone formation–human health, fine particulate matter formation, ozone formation–terrestrial ecosystems, terrestrial acidification and fossil resource scarcity. The impacts in other categories such as fresh water eutrophication, marine eutrophication,

terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity and water consumption were higher in comparison with the diesel and diesel battery alternatives. The main reason for this lies in the sourcing of the materials employed in the manufacturing of the components used to build the hydrogen powered fuel cell or in the hydrogen supply chain. The components considered for the hydrogen powered fuel cell and battery ferry include batteries, fuel cells and high pressure tanks. Hydrogen production includes the use of wind turbines for producing electricity and electrolyzers to convert electricity to chemical energy stored in hydrogen, among others. Thus, these impacts are not generated locally in the place where the ship is operating, but in the places from which the materials used for the construction of the ship or wind turbines are obtained. The reuse of some of these components or recycling of their materials may close the loop and diminish the environmental impact of obtaining these materials. However, this was not explored in this work.

On the other hand, a diesel battery electric ship allows a reduction of global warming potential of 8% compared to a conventional diesel electric ferry when recharged using wind power. However, an increase of 6% in stratospheric ozone depletion and 25% in ionizing radiation was observed due to the production processes of batteries and their replacement along the lifetime of the ship.

Particularly, the replacement of ship components to accomplish the considered 30 years lifetime has a relevant impact in most of these categories. Surprisingly, batteries had a higher impact in relation to fuel cells in the case of the hydrogen powered fuel cell battery ship. In general, the extension of the lifetime of both fuel cells and batteries must be an important goal to minimise the environmental impact along the lifetime.

The endpoint analysis showed that the hydrogen powered fuel cell battery ship has a lower impact in terms of damage to the human health, damage to the ecosystem and damage to resource availability compared to the diesel electric and diesel battery electric alternatives, even when the impact for some of the midpoint categories are higher.

2.6 Future Work

The results presented in this study are related to the analysis of the concept developed in the first stages of the project HySeas III. The future power string trials and ship construction will allow access to specific data that can increase the level of detail and the quality of the analysis. Further comparisons with other ship propulsion architectures will be done in the near future. Additionally, other economic and social analysis will be conducted during the project to have a holistic perspective of this new application.

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