HySeas III: The World's First Sea-Going Hydrogen-Powered Ferry – A Look at its Technical Aspects, Market Perspectives and Environmental Impacts

Juan Camilo Gomez Trillos, Dennis Wilken, Urte Brand, Thomas Vogt
DLR – Institut für Vernetzte Energiesysteme, Carl-von-Ossietzky-Straße 15, 26129 Oldenburg

Keywords: life cycle assessment, alternative fuels, fuel cells, emissions, electric ships

Abstract

The greenhouse gas emissions from international shipping were estimated to be 2.1% of the global emissions by 2012. In order to decrease them in the future, new measures are being taken but also new alternative power systems employing batteries, hydrogen and fuel cells and the production of alternative fuels are now under development. Currently, several projects are aiming at the implementation of hydrogen and fuel cells in Ro-on/roll-off and passenger (RoPax) ferries. In relation to this, a comparison of hydrogen and fuel cell systems against other technologies such as batteries in terms of costs, system mass and volume is presented in this paper. In addition, an overview of the market potential of RoPax ferries in Europe is given, showing that fuel cells have potential, particularly if their power is scaled up. Finally, we present the first results of the life cycle assessment carried out within the project of HySeas III, which shows that the global warming potential generated by the ship in a 30 year life would decrease by 89% compared to a ship operating with a diesel-electric system.

1. Introduction

The “Third IMO GHG Study 2014” revealed that international shipping contributed to 816 million tonnes of CO_{2eq} in 2012. This represented approximately 2.1% of the global CO_{2eq} emissions by the same year [1]. In 2018 the IMO adopted short-, mid- and long-term strategies to decrease GHG emissions of international shipping in absolute terms by 50% until 2050 compared to 2008 levels [2]. Some administrative measures, such as the obligation to report fuel consumption, and contributions to energy efficiency are already came into effect. Additionally as a measure to diminish the sulphur emissions, new regulations will come into force as for 2020, demanding either the use of low-sulphur fuels or equipping of ships with scrubbers with the aim of reducing sulphur-related emissions.

Apart from implementing strategies to monitor report and verify the emissions of ships bigger than 5,000 GT, the European Union promotes new projects which are trying to develop alternatives to the traditional power trains by using electricity and hydrogen as well as batteries and fuel cells. Although these ships are small compared to the ones employed in international shipping, such as container ships, bulkers or cruisers, their implementation may open the doors for future developments in the maritime sector. Besides being first-of-a-kind projects, these projects offer the possibility of developing the supply chain and hydrogen infrastructure, what is necessary for the development of maritime applications and their upscaling.

HySeas III is a project with the main objective of realising the world’s first sea-going hydrogen-powered fuel cell Roll-on/Roll-off/Passenger (RoPax) ferry and a business model for European islands [3]. The ship developed in the project of HySeas III intends to operate on the route between Kirkwall and Shapinsay on the Orkney Islands, Scotland. This crossing has a length of approximately 4 nm (7km) and is currently being crossed at a speed of 9.5 knots by the MF Shapinsay, a ship that will be replaced by the new prototype once it is developed. A summary of the features of the planned prototype is presented in Table 1.

Table 1. HySeas III ship specifications. Source: Project HySeas III

Specification	Value
Ship's dimensions	40m (length) × 10m (beam) × 4m (depth)
Passenger capacity	120
Rolling payload capacity	20 passenger vehicles or 2 trucks
Power train	
On-board Fuel Cell Power	600 kW
Type of fuel cells	Proton-exchange membrane fuel cells (PEMFC)
On-board Hydrogen Storage	600 kg
Type of storage	Compressed gas, 350 bar
On-board Batteries	768 kWh
Type of batteries	Li-ion, cell chemistry still to be defined

Currently, on the Orkney Islands a surplus of wind and tidal power is generated. This surplus of power cannot be exported due to limitations of the local grid and therefore will be converted into hydrogen using electrolysers within the research projects of Big Hit and Surf n' Turf [4] [5]. Afterwards, the hydrogen is compressed and stored in specific trailers containing tanks. These trailers are towed by trucks and transported by the local ferries in order to be used as stored energy for different purposes. Thus, in addition to local applications for hydrogen, such as the ship developed in the context of HySeas III, a supply chain for it is under development.

Besides the technical development of a hydrogen and fuel cell power train for a RoPax ferry, HySeas III aims at the development of innovative business models for ferry operators and coastal/island authorities and to encourage replication by dissemination of exploitable lessons. For this purpose, DLR – Institut für Vernetzte Energiesysteme is conducting market potential, environmental, social and economic analyses in order to have a holistic view on this emerging technology in comparison with conventional propulsion systems like diesel electric of diesel battery electric.

This paper aims to provide a brief description of technical aspects in order to show under what conditions hydrogen and fuel cells can provide advantages over other systems. Subsequently, an overview of the current state of the RoPax ferry market in Europe will be presented to show the type of applications that can be covered by these technologies today and what the main challenges are, particularly in terms of upscaling. Finally the results of the life cycle analysis in the particular conditions of Orkney are presented, in order to describe the advantages and disadvantages of the use of hydrogen, fuel cells and batteries from the environmental point of view.

2. Methodology

The following sections will describe the methodologies used to perform the technical, market potential and environmental assessments.

2.1. Technical Assessment of Propulsion Systems

We established a comparison between different propulsion technologies associated with different on-board energy storage systems, such as diesel, Li-ion batteries and hydrogen in compressed gas and liquid states. The converting devices used in each case such as engines and fuel cells were also included in these comparisons. The comparisons were made terms of system costs, masses and volumes. These parameters are important for giving an idea of the technical feasibility of an alternative power and energy system. Mass and volume are relevant for mobile applications because the power and energy systems must be contained in a limited space and, in opposition to stationary systems, must be carried on the ship. Therefore, additional mass represents additional energy consumption or the necessary use of lighter materials to counterbalance this effect.

In order to give a more tangible idea of the magnitudes of these systems, different combinations of power and energy on board were used. We calculated the cost, weight and volume of a system using both nominal power and nominal energy stored on board according to eq. 1, eq. 2 and eq. 3. Notice that these equations assumed a linear behaviour of cost, weight and volume and therefore might introduce errors in terms of upscaling.

$$Total\ cost = \frac{cost}{kW} * P_{system} + \frac{cost}{kWh} * e_{on-board} \qquad \text{(eq.1)}$$

$$Total\ mass = \frac{mass}{kW} * P_{system} + \frac{mass}{kWh} * e_{on-board} \qquad \text{(eq.2)}$$

$$Total\ volume = \frac{volume}{kW} * P_{system} + \frac{volume}{kWh} * e_{on-board} \qquad \text{(eq.3)}$$

Whereby P_{system} is the rated power of the system, $e_{on-board}$ is the total energy stored on board in terms of the lower heating value of the fuel, $\frac{cost}{kW}$ is the cost of the converting device (i.e. diesel engine or fuel cell) per kW, $\frac{cost}{kWh}$ is the cost of the storage system per kWh of stored fuel, $\frac{mass}{kW}$ is the mass of the converting device per kW, $\frac{mass}{kWh}$ is the mass of the storage system per kWh of stored fuel including the mass of the fuel, $\frac{volume}{kW}$ is the volume of converting device per kW and $\frac{volume}{kWh}$ is the volume of both storage system and fuel per kWh of stored fuel. In the case of batteries, both power and energy are supplied by the same device. Thus only the metrics in terms of stored energy were considered as in eq. 4, eq. 5 and eq.6.

$$Total\ cost = \frac{cost}{kWh} * e_{on-board} \qquad \text{(eq.4)}$$

$$Total\ mass = \frac{mass}{kWh} * e_{on-board} \qquad \text{(eq.5)}$$

$$Total\ volume = \frac{volume}{kWh} * e_{on-board} \qquad \text{(eq.6)}$$

Batteries are rated according to the voltage and current they can supply. For instance, one battery can be specified having a nominal capacity of 165 Ah and a nominal voltage of 40.15 V. Batteries discharge and charge rates are usually described in terms of C-rates. A 1C discharge of the afore mentioned battery corresponds to a discharge at a current of 165 A for 1 h. During process, the voltage supplied by the battery is not constant, and hence the power supplied by it. This means that actually the power that a battery can supply depends on its state of charge. However, for simplicity, we will consider that 1 kWh of batteries at a discharge rate of 1C has a power of 1 kW. Some batteries are designed for discharge at higher rates, but usually the energy available at those discharge rates is lower than at 1C and higher discharge rates may compromise battery's life time.

We also assumed that the cost of diesel storage is 0 because in most of the cases the storage is integrated to ship's structure. We assumed that the weight and volume of diesel storage is mainly related with diesel fuel's gravimetric and volumetric density. We will define the effective energy stored on-board as the result of applying the energy conversion efficiency to the total amount of energy stored on board. Notice that the effective energy stored on-board is lower than the total energy, because the efficiency of devices such as fuel cells or internal combustion engines is lower than 100%. This was defined as shown in eq. 7.

$$e_{eff,on-board} = \frac{e_{on-board}}{\eta_{electric}} \qquad \text{(eq.7)}$$

Whereby $e_{eff,on-board}$ is the effective energy stored on board, $e_{on-board}$ is the total energy stored on board and $\eta_{electric}$ is the conversion device efficiency, as related Table 4. An additional assumption of this approach is the linearity in the scaling of converting and storage devices.

2.2. Market potential analysis

The market potential analysis conducted in HySeas III concerned a description of the RoPax ferry sector in Europe. The whole RoPax ferry European fleet was considered as the total available market (TAM). The size of the ships, flag and total on-board main engine size were obtained from the database SeaWeb from IHS Markit [6]. In discussions with PEM fuel cell manufacturers, they pointed out that the top limit for their systems was 2,000 kW. The ships were split between different categories according to their gross tonnage and later classified according to their engine size and filtered to get a list of ships with main on-board power under 2,000 kW. This set of ships was considered the serviceable available market (SAM). Finally, aspects related to the routes in which these ships operate were explored using the platform MarineTraffic [7]. This platform collects signals from the automatic identification system (AIS). This system transmits a signal containing the position, course, speed and a unique identification code for each ship. The ships operating in routes with longer distances or multiple nodes were selected as the most likely candidates for future applications using hydrogen and fuel cells. This selection was done taking into consideration that other technologies such as electric batteries may provide solutions for short routes as well. However, in this case the information is incomplete because AIS data is not collected for some of the ships and the current state of a few of them is unknown. A group of ships crossing distances of more than 10 km and following routes including more than 2 nodes was filtered and will be named hereafter the serviceable obtainable market (SOM). We consider that this is the possible niche where hydrogen and fuel cells can offer advantages in comparison with other technologies without further upscaling in terms of power.

2.3. Environmental Assessment

The environmental assessment carried out under HySeas III consisted of a Life Cycle Assessment (LCA) study of the proposed alternative in comparison with other particular technologies. Life Cycle Assessment is a systematic approach that allows the estimation of the potential environmental impacts of a product or service. This methodology is standardised according to ISO 14040 and ISO14044 [8] [9]. According to the aforementioned standards, an LCA must include a goal and scope definition, an inventory assessment, impact assessment and interpretation.

2.3.1. Goal

The main goal of this study was to describe the potential environmental impacts of the Fuel Cell and Battery Electric Ship (FCBES) which should be implemented on the route between Kirkwall and Shapinsay in the future. This alternative was compared with conventional propulsion systems including a diesel-electric ship (DES) and a diesel-battery electric ship (DBES). A comparison with a hypothetical battery electric ferry is also to be done on the project, but was not included in the present research due to lack of data for modelling. The aim of this analysis was to establish the benefits and drawbacks of using hydrogen, fuel cells and batteries for this transportation service.

2.3.2. Scope

We considered 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. These elements were taken into account from cradle to end-of-use. The functional unit (FU) used for this study was 1 km of crossing distance of the selected ship during a lifetime of 30 years. With an assumption of 4,034 single crossings per year and an average distance of 7 km per crossing, the ship crosses approximately 28,238 km/year and 847,140 km during the considered lifetime of 30 years.

For this analysis, we applied the impact assessment method ReCiPe 2016 with the so called hierarchist perspective (ReCiPe 2016 (H)). This method includes the impact categories global warming potential (GWP), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation, human health (OFHH), fine particulate matter formation (FPMF), ozone formation -

terrestrial ecosystems (OFTE), terrestrial acidification (TAC), freshwater eutrophication (FEU), marine eutrophication (MEU), terrestrial ecotoxicity (TEC), freshwater ecotoxicity (FEC), marine ecotoxicity (MEC), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS) and water consumption (WATC).

The primary information provided by the project was given in terms of material quantities and energy consumption from different energy carriers. The background data used in the study is based on ecoinvent 3.5 and the software utilized for the calculations is SimaPro 9.0. The cut-off system model was used as underlying philosophy for the systems taken from the database ecoinvent 3.5. [10]

2.3.3. Inventory Analysis

Different ship components were modelled using existing inventories of the database ecoinvent 3.5 or scaling inventories previously collected by other authors. These inventories were adapted in terms of size and the quantity of materials according to the specifications given in Table 1.

Table 2. Components considered for ship's life cycle in this LCA

Diesel Electric Ship (DES)	Ref	Diesel Battery Electric Ship (DBES)	Ref	Fuel Cell Battery Electric Ship (FCBES)	Ref
Hull and Structure 190 tonnes of Steel, 20 tonnes of Aluminium	[11] [10]	**Hull and Structure** 190 tonnes of Steel, 20 tonnes of Aluminium	[11] [10]	**Hull and Structure** 190 tonnes of Steel, 20 tonnes of Aluminium	[11] [10]
Diesel Engine 2 x 375 kW	[10] [12]	**Diesel Engine** 2 x 375 kW	[10] [12]	**Fuel Cells** 600 kW, 50% efficiency, Pt load of 0.4mg/cm^2, 5 replacements during lifetime	[13] [14]
Electric Generator 2 x 300 kW	[10]	**Electric Generator** 2 x 300 kW	[10]	-	-
-	-	**On-Board Batteries** NMC 1:1:1, 90% charging efficiency, 3 replacements during lifetime	[15]	**On-Board Batteries** NMC 1:1:1, 90% charging efficiency, 3 replacements during lifetime	[15]
-	-	-	-	**Hydrogen Tanks** 350 bar, carbon fiber	[13] [14]

Fuel consumption and electricity consumption were modelled as shown in Table 3, according to current estimations of future ship performance. We considered both for the electricity supplied to the ship and for the production of hydrogen wind power, since this represents approximately the current situation in the Orkney Islands.

Table 3. Fuel and electricity consumption of the different considered alternatives. Source: Project HySeas III

Type of Ship	Diesel [kg/crossing]	Electricity [kWh/crossing]	Hydrogen [kg/crossing]
DES	54.9	-	-
DBES	48.2	40.7	-
FCBES	-	40.7	13.59

3. Results

3.1. Technical Assessment of Propulsion Systems

Table 4 describes the cost, mass and volume metrics of energy converters and energy storage systems. Power devices are equipment converting the chemical energy of a fuel into electricity, mechanical energy and heat. In the case of batteries, the same device provides power and stores energy. Energy storages are the containers in which energy (often) in the form of chemical substances or fuels are stored. It is evident from the table that PEMFC have comparable gravimetric powers in relation to diesel engines. Nickel-manganese-cobalt (NMC) Li-ion batteries have less power per unit of mass when discharged at 1C than the other power devices, but comparable volumetric power densities to the other systems. In our study, we assumed battery costs of 500 EUR/kW according to information supplied by project partners. A prospect for a 20 MW/80 MWh system describes a system price of 324 EUR/kWh (357 USD/kWh) in 2018, with falling prices in the near future [16].

Regarding the energy storage, batteries have the lowest gravimetric energy density followed by compressed hydrogen and liquid hydrogen. In terms of volumetric energy density, batteries have the lowest value, followed by compressed hydrogen and liquid hydrogen. Notice that the storage cost of hydrogen is low in terms of kWh in comparison with lithium-ion batteries.

Table 4. Comparison of different energy converters and energy storage systems. References are shown in brackets.

<table>
<tr><td colspan="6">Power device</td></tr>
<tr><td>Description</td><td>Unit</td><td colspan="2">PEMFC</td><td>NMC
Li-ion
Batteries</td><td>Diesel Engine</td></tr>
<tr><td>Gravimetric power density</td><td>kW/kg</td><td colspan="2">0.256* [17]</td><td>0.118** [18]</td><td>0.255</td></tr>
<tr><td>Volumetric power density</td><td>kW/m3</td><td colspan="2">129* [17]</td><td>180 [18]</td><td>221</td></tr>
<tr><td>Efficiency</td><td>%</td><td colspan="2">50</td><td>90</td><td>40</td></tr>
<tr><td>Cost</td><td>EUR/kW</td><td colspan="2">1,500*** [19]</td><td>550** [11]</td><td>300</td></tr>
<tr><td>Lifetime</td><td>-</td><td colspan="2">30,000 – 20,000 hours</td><td>6400 cycles (80% DoD)</td><td>Variable</td></tr>
<tr><td colspan="6">Energy Storage</td></tr>
<tr><td>Description</td><td>Unit</td><td>Compressed H_2, composite storage</td><td>Liquid Hydrogen</td><td>Batteries</td><td>Diesel fuel</td></tr>
<tr><td>Gravimetric energy density</td><td>kWh/kg</td><td>1.40 (350 bar) [11]</td><td>3.82 [20]</td><td>0.118* [18]</td><td>11.86</td></tr>
<tr><td>Volumetric energy density</td><td>kWh/m3</td><td>371 (350 bar) [11]</td><td>1,342 [20]</td><td>180 [18]</td><td>9,963</td></tr>
<tr><td>Storage cost</td><td>EUR/kWh</td><td>30.5 [11]</td><td>11.6 [21]</td><td>550 [11]</td><td>0****</td></tr>
</table>

* Includes balance of plant: air compressor and cooling system.

**Assumption: discharge at 1C. Therefore 1kWh of batteries is considered with a power of 1kW in this table. Higher discharge rates are possible

***The MariGreen report quoted a price for a conventional 100 kW fuel cell system currently of around 150,000 EUR

**** Diesel tanks are usually integrated into ship.

We will explore the following propulsion systems in the next section.

- PEM Fuel Cell + Compressed Hydrogen Storage
- PEM Fuel Cell + Liquid Hydrogen Storage

- Batteries
- Diesel Engine + Diesel fuel

This does not entirely coincide with the alternatives presented for the environmental analysis, as here it is intended to give a more general overview, while the LCA specifically describes the design planned for the prototype to be implemented in Orkney.

3.1.1. Cost comparison of hydrogen and fuel cell systems, Li-ion batteries and diesel engines

Figure 1 shows the comparison of system costs in terms of the effective on-board energy storage. In the case of fuel cells, increasing the power capabilities of the propulsion system has a higher impact than increasing the energy storage on board because the storage costs are relatively low. The results also show that fuel cells and hydrogen (both compressed and liquid) are favoured from the cost perspective when a higher amount of energy should be stored on board, as it would be the case of a ship requiring crossing long distances, routes including multiple nodes or without the possibility of refuelling/recharging for long terms. Diesel systems are at the bottom of Figure 1 showing that the costs of these systems are still lower than the other systems when big energy storage on-board is required. According to Figure 1, batteries provide a cost-effective solution when the amount of energy to be stored on-board is reduced, as is the case with the current electrified ferries. In turn, fast charging stations, able to recharge the on-board batteries should be established in order to guarantee a regular service. This are not taken into account in this analysis, but may also add to the costs of the system. We also depict the estimated cost of the system implemented in project HySeas III. The use of batteries on-board allows additional on-board storage, but also increases slightly the system cost. Additionally, the system designed in the project could supply additional power using fuel cells and batteries.

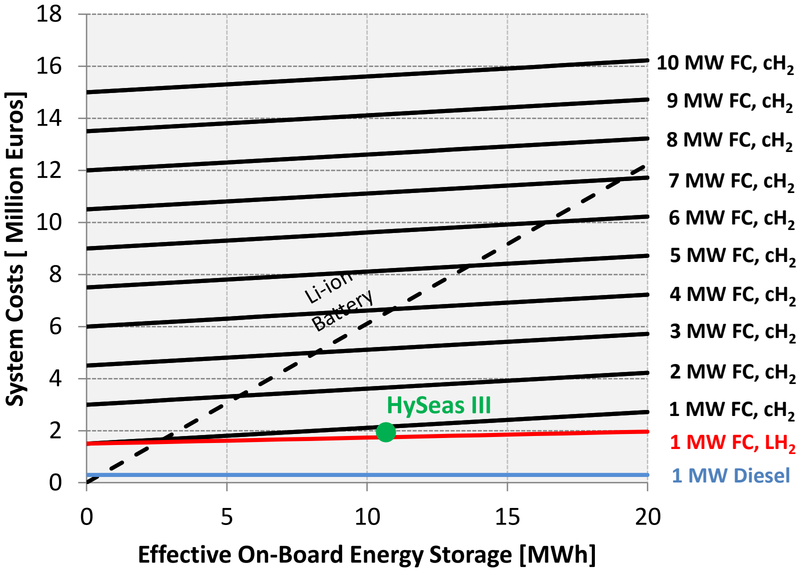

Figure 1. Comparison of Li-ion batteries systems and compressed hydrogen and fuel cells in terms of system cost.

3.1.2. Weight and volume comparison of hydrogen and fuel cell systems and Li-ion batteries

Figure 2 shows a comparison of batteries, compressed hydrogen and PEM fuel cell systems in terms of system weight (left) and system volume (right) showing that fuel cells are favoured when larger on-board energy storage is required in terms of weight. In terms of volume, batteries have a slightly lower volume compared with compressed hydrogen and fuel cells for the same amount of energy and could be a more mass and volume effective solution in applications requiring high power for a short time. This leads to a lower demand for effective on-board energy such as the case of short ferry crossings. In turn, due to the limited on-board energy storage, the ship has often to be recharged what might require important charging infrastructure at the docking locations and limit the range of the ship. The power requirement is essentially dependent on the docking time available for charging.

The shorter this time, the higher the power required for this purpose. Some current solutions use battery systems on-shore to diminish the impact of ship charging on the grid.

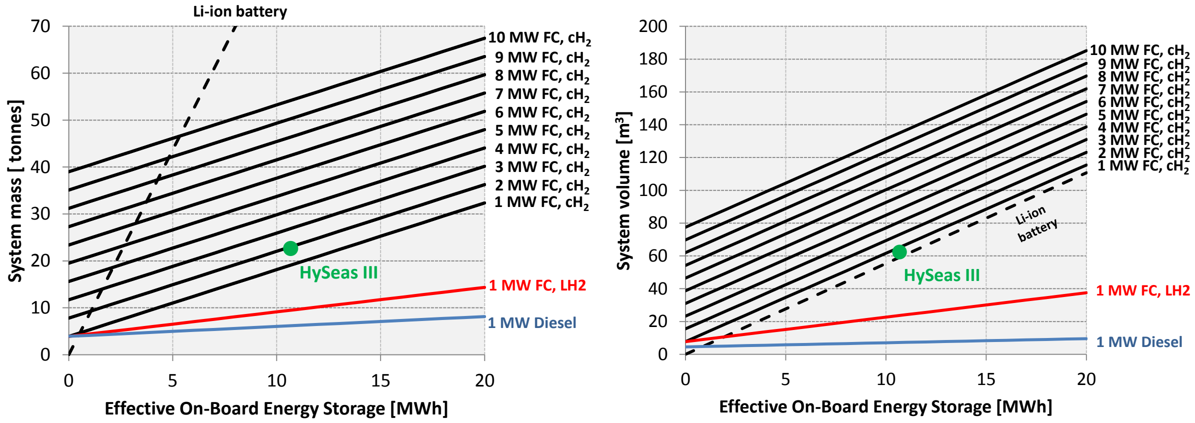

Figure 2. Comparison of Li-ion Batteries Systems and Compressed Hydrogen and Fuel cells in Terms of System Weight (left) and system Volume (right).

Nevertheless, the propulsion planned within HySeas III includes both Li-ion batteries and fuel cells. The combination of these two technologies allows capturing the advantages of both systems and reduces the size of the fuel cell system necessary for the operation. In that case, the batteries are used as peak shaving devices, by supporing the fuel cell propulsion system when demand is high and recharging when there is a surplus of power generated on-board by the fuel cell. Additionally this system takes advantage of the higher energy efficiency of batteries and minimises the amount of hydrogen necessary to operate the ship. This is achieved by the fact that batteries can also be recharged via a connection to the mainland when the ship is not in operation. As a matter of comparison, if an exclusive battery system would be used in the HySeas III case, this system would have a mass of 93 tonnes, which is more than 4 times the mass estimated for the system combining both, fuel cells and batteries.

3.2. Market Potential Analysis

3.2.1. Total Available Market

The RoPax ferry fleet in Europe is comprised by approximately 1,350 ships (SeaWeb IHS Markit) representing 42% of the global fleet. Around 40% of the fleet is more than 30 years old and must be replaced soon. According to data of scraped RoPax ferries obtained from Sea-Web of IHS Markit, more than 80% of the RoPax ferries are active for more than 30 years [6]. Figure 3 shows that the country with the highest number of RoPax ferries is Norway followed by Greece, Italy and the United Kingdom. In most of the countries, the fleet is mainly encompassed by ships of less than 2,000 GT. This means that most of the ships are of relatively small size. According to the data contained in the database SeaWeb from IHS Markit, the total capacity of the main engines of the European fleet amounts to a total power of 11.8 GW.

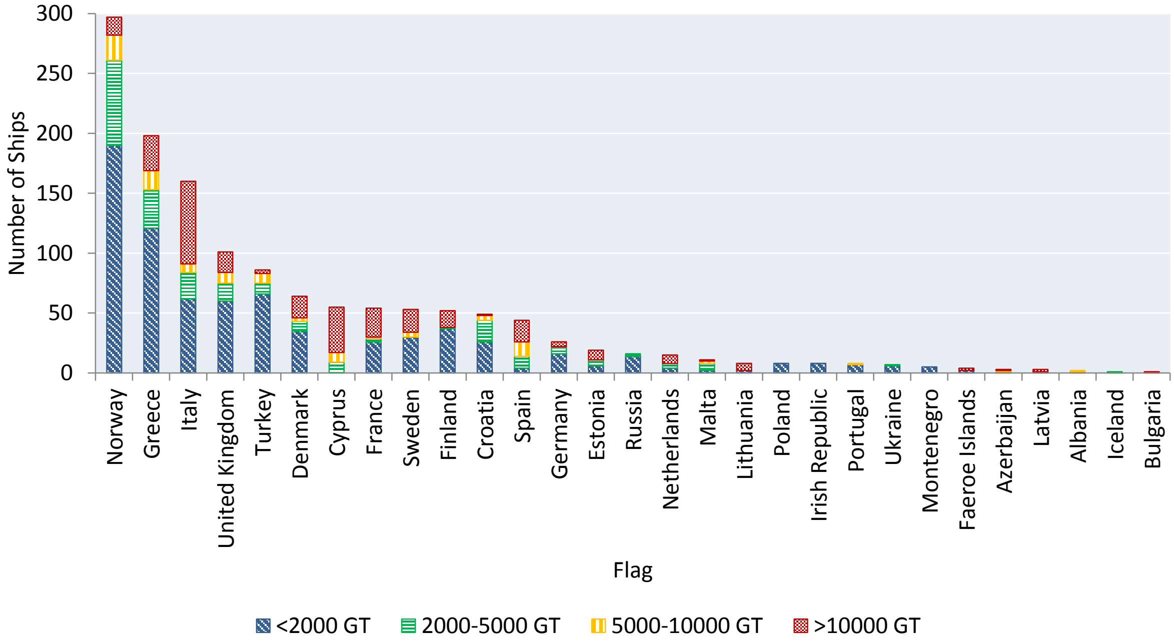

Figure 3. Number of RoPax ferries per country classified by gross tonnage. Source: SeaWeb – IHS Markit [6]

3.2.2. Serviceable Available Market

The upscaling of fuel systems is still a challenge for facilitating the uptake for bigger ships. According to personal communication with Ballard, the current limit for PEM fuel cell systems is approximately 2MW. Bigger systems are currently under development. This might be relevant to meet the power requirements of the current fleet as is shown in Figure 4 and Figure 5. The figures represent the total power of the current European RoPax ferry fleet. If this limitation is taken into account, 82% of the steel-hulled ships in the category <2,000 GT could be propelled using fuel cells. On the other hand, 20% of the ship segment between 2,000 and 5,000 GT can be covered and 0% of the segments between 5,000 – 10,000 GT and >10,000 GT.

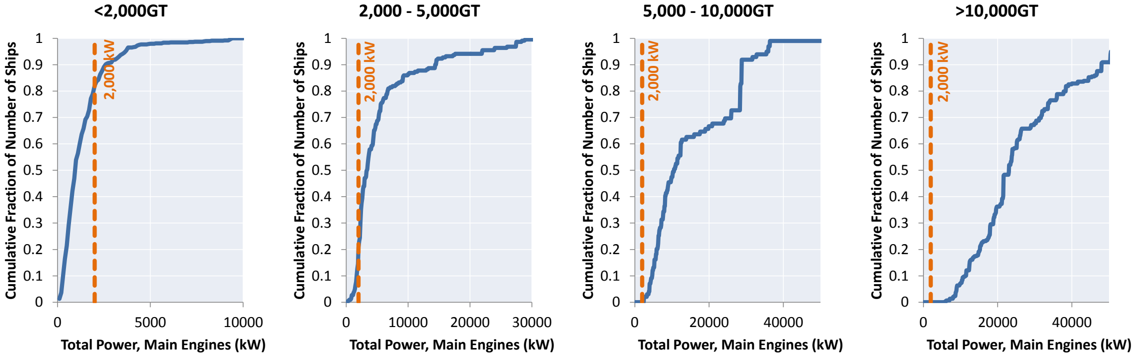

Figure 4. Steel-hulled ships main engine total power distribution among the different size segments in Europe. The orange line shows the current capabilities of PEM fuel cells (2,000 kW). Own illustration with data from IHS Markit SeaWeb®

In the case of aluminium-hulled ships, which are usually built using this light material to reduce the weight and are equipped with high power engines in order to reach high speeds, 35% and 3% of the ships belonging to the category <2,000 GT and 2,000 – 5,000 GT have total on-board power of main engines under 2MW. In all cases, the other two categories have engines over 19 MW (5,000 – 10,000 GT) or 36 MW (>10,000 GT). As shown in Figure 5, up-scaling the power may allow covering a higher market share, but a particular challenge in the case of aluminium-hulled ships is the mass and internal volume, because they are commonly built as catamarans or trimarans.

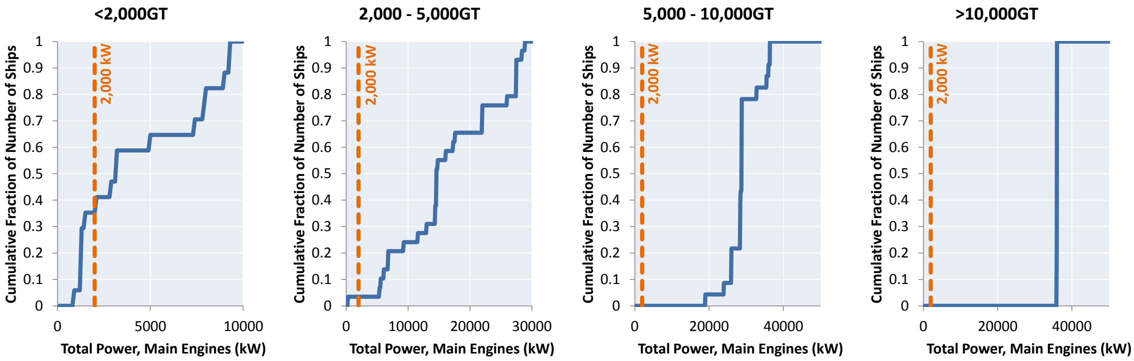

Figure 5. Aluminium-hulled ships main engine total power distribution among the different size segments in Europe. The orange line shows the current capabilities of PEM fuel cells (2,000 kW). Own illustration with data from IHS Markit SeaWeb®

Considering this criterion to define the serviceable available market, we found a total of 683 ships that have on-board main engines under 2 MW. Their main engines have in total a power of 637 MW.

3.2.3. Serviceable Obtainable Market

The routes followed by the ships described in the last section were identified with the help of the platform Marinetraffic [7]. Particular emphasis was done to the crossing length and the number of nodes. As previously described in the technical aspects section, the use of hydrogen and fuel cells has technical advantages in case an important amount of energy should be stored on-board. Data in this regard from 355 ships was retrieved and is summarised in Figure 6. Most of the ships follow routes that only include two nodes. In terms of distance, 127 ships crossed distances beyond 10 km. If the additional criterion of more than 2 nodes is added, 43 ships followed routes with more than 2 nodes and crossed distances beyond 10 km. We estimated the total on-board main engines to have a combined power of 54 MW.

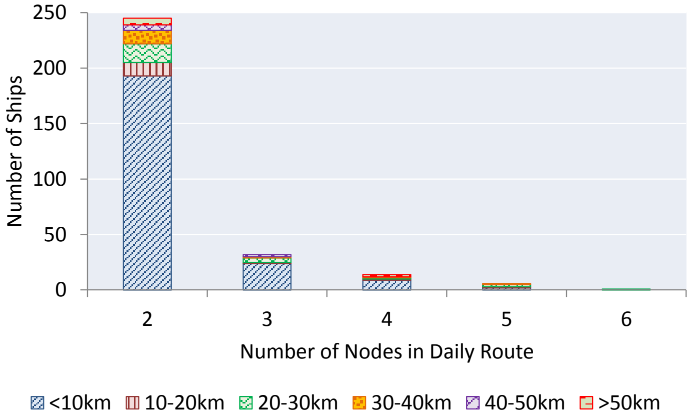

Figure 6. Number of nodes and maximum crossing distance for ships with on-board power under 2 MW. Built using data from the platform MarineTraffic.

3.3. Environmental Impacts

3.3.1. Impact Assessment and Interpretation

Figure 7 compares the different alternatives and shows that the proposed ferry using hydrogen produced employing wind power, fuel cells and electricity from the mainland (mainly wind power) allows a reduction of approximately 89% of the global warming potential emissions along the assumed lifetime of 30 years. The FCBES alternative also allows reductions compared with the diesel alternatives for the impact categories SOD, IR, OFHH, FPMF, OFTE, TAC, FRS and WATC. However, an increase in the categories FEU, MEU, TEC, FEC, MEC, HCT, HCNT and LU was observed due to the intensive use of materials for fuel cells, hydrogen tanks and especially for batteries. These components include materials such as platinum, cobalt, nickel and manganese, which are obtained from intensive mining processes. Additionally, battery production is an intensive energy process. Therefore, most of the impact in these categories is mainly related to the sourcing of the materials employed for the construction of ships and are mainly located in the phase of raw material extraction, at the place where the materials are mined and not where the ship operates.

The DBES shows a reduction of 8% on the global warming potential emissions when compared with the DES alternative. The use of materials for production of batteries also increases the impacts in the categories FEU, MEU, TEC, FEC, MEC, HCT, HCNT and LU in comparison with the DES alternative.

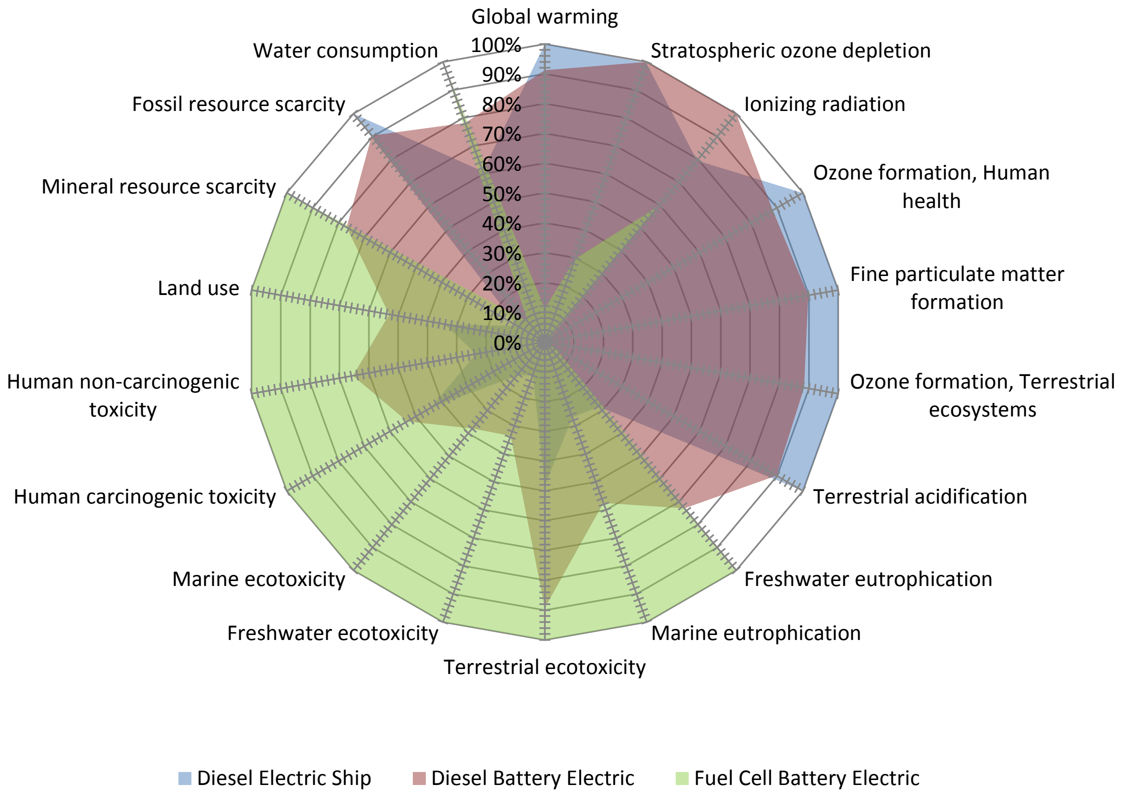

Figure 7. Comparison of the impact assessment results for diesel electric ship (DES), diesel battery electric ship (DBES) and fuel cell battery electric ship (FCBES) RoPax ferry alternatives using ReCiPe 2016 impact assessment method. Results normalised to the highest total impact alternative in each of the categories.

4. Discussion

Currently, it is not clear in which kind of application niche hydrogen storage and fuel cells will fit in the future, as these technologies are still in development. However, according to the technical assessments, hydrogen and fuel cells seem to be more suitable for applications in which large energy storage on-board is required. The main advantages in favour of hydrogen and fuel cell are system costs and mass. The use of liquid hydrogen might bring additional benefits regarding the latter point. Nevertheless, hydrogen's critical point is -239.96°C. This means that no liquid hydrogen exists above this temperature, and therefore the use of liquid hydrogen entails the use equipment suited for these conditions, which is commonly known as cryogenic technologies. This increases the complexity and costs of hydrogen handling.

Additionally, liquid hydrogen infrastructure is not widely spread in Europe what may represent an additional barrier to make hydrogen available in liquid state. Moreover, it has been estimated that liquefaction requires an additional energy input of about 13.4 kWh/kg H_2 at small scales, which considerably increases the liquid hydrogen costs and represents approximately 26.8% of its energy content. Moreover, when liquid hydrogen is stored, even in highly insulated containers, eventually boils off due to environment heat input. This increases the pressure in the container, requiring cooling with an additional energy cost, or in some cases venting. However, the operational costs were not taken into account in this analysis yet, but will be analysed in future assessments to be conducted as a part of the life cycle costing within the project.

One important limitation of the technical assessment is the assumption of linearity when the systems are up-scaled. However, it is known that up-scaling follows different scaling factors. Additionally, these technologies are constantly evolving, particularly in terms of costs, and therefore the assumptions made here could change considerably in the following years.

As a hint of the market potential, Europe represents one of the biggest markets for RoPax ferries and hydrogen and fuel cells could be a solution to diminish the greenhouse gas emissions generated by this sector. With the help of the current PEM fuel cell systems size, whose current system limits are considered by the project partners at around 2 MW, an important amount of ships from category under 2,000 GT can be already powered using PEM fuel cells. The upscaling of fuel cell systems is necessary to be able to cover the power requirements of bigger ships. The method employed to obtain the serviceable obtainable market has the limitation of using data from a limited number of days. Many ships change their routes and frequency during the year and this could lead to errors when a ship is assumed as always operating in the same route. Using comprehensive AIS datasets could lead to a more complete description of the operational profiles of different ships and to the energy requirements in each case. However, powering bigger ships with bigger propulsion systems will require more energy storage on-board, in order to have a reasonable range.

The estimated PEMFC market in 2018 had a volume of 590 MW [22]. The power estimated for the TAM, SAM and SOM was 11.8 GW, 637 MW and 54 MW respectively. Thus, RoPax ferries might represent an important demand for the fuel cell industry if implemented. If these systems can be up-scaled, the market potential might grow towards the biggest value of the last ones described. In connection with the technical assessment, hydrogen could provide an alternative to store on-board considerable amounts of energy with lower system costs and mass than batteries.

Finally the environmental analysis shows a considerable reduction of 89% the global warming potential in comparison with a diesel electric alternative, when the ship is considered from cradle to end-of-life and the hydrogen and electricity are produced using wind power. The reduction found for this impact category of 89% is higher than the one of 79% described in previous studies, such as the previous assessment done by Jokela et al [23]. However, both studies have different assumptions, functional units, employed different assessment methods and assume ships of different size. Thus both studies are not totally comparable. However, both studies found higher impacts in comparison to diesel alternatives in terms of abiotic depletion, human toxicity, freshwater toxicity, marine toxicity and terrestrial toxicity derived from the production of the materials used for the different ship components. Recycling of these materials might decrease the impact of the use of these materials returning them for reuse or diminishing the amounts of materials that need to be mined. However, the disposal scenarios were still not considered and will make part of future analysis.

5. Conclusion and Future Work

Related to the technical assessment, we compared propulsion system costs, masses and volumes of on-board energy storage systems in conjunction with energy converters. This included compressed hydrogen and liquid hydrogen with fuel cells, diesel tanks with diesel engines and batteries. The results of this study show that hydrogen and fuel cells have advantages in comparison to other technologies such as batteries especially when a large on-board energy storage is required. Particularly, these advantages consist in lower system cost and lower system mass. The use of alternative propulsion systems using hydrogen and fuel cells or batteries entails higher system costs, mass and volume compared to traditional alternatives such as diesel engines. Compressed hydrogen and fuel cells seem to be favoured when operation requires a high amount of energy on-board in terms of system cost and weight compared with battery systems. The use of liquid hydrogen may further reduce the weight and volume requirements of an on-board hydrogen and fuel cell system, but entails the challenge of using cryogenic technology, which might increase hydrogen costs considerably due to the additional energy required to liquefy this substance.

On the other side, we explored the European RoPax ferry market, in order to give a brief description of it and show were hydrogen and fuel cells most likely can be implemented. An upscaling of PEM fuel cell systems beyond 2MW is necessary to cover the demand of bigger RoPax ferries, although the power requirements of around 80% of the steel-hulled and 35% of the aluminium-hulled RoPax ferries of less than 2,000 GT can be already covered with the existing systems of less than 2 MW. The power estimated for the total available market, serviceable available market and the serviceable obtainable market was 11.8 GW, 637 MW and 54 MW respectively, which is considerable when compared with the current supply of 590 MW in 2018.

Moreover, we also explored the environmental effects of the compressed hydrogen and fuel cell ferry developed in the project HySeas III by means of life cycle assessment (LCA). Most of the electricity produced in the Orkney Islands in Scotland comes from renewable resources, such as wind and tides. This electricity will be used for charging the on-board batteries and converted to hydrogen employing electrolysers. The use of hydrogen and electricity produced using wind power and on-board batteries and fuel cells, allows a reduction of 89% of the global warming potential in comparison with a traditional diesel electric ferry. Additionally, the impact in other categories, such as stratospheric ozone depletion, ozone formation, particulate matter formation and terrestrial acidification are also reduced in comparison with the diesel electric and diesel battery electric alternatives. Nevertheless, there is a relative increase in other impact categories such as freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, Freshwater ecotoxicity, marine ecotoxicity, Human carcinogenic and non-carcinogenic toxicity, land use, mineral resource scarcity and water use compared to the diesel electric and diesel battery electric alternatives. These impacts are mainly in the extraction phase of the materials and not in the place where the ship would operate and derive mainly from mining processes. It is important to say that these impacts are higher but not necessarily big in absolute terms.

Future activities in HySeas III include an on-shore string power test including real size fuel cells, batteries and a hydrogen supply tested under real operational conditions. Following this, a complete prototype of the ship will be built and placed on service in the route Kirkwall - Shapinsay. Further analyses, including the development of a life cycle cost model to analyse the economic aspects of implementing this technologies and a job creation potential analysis to delve into the social impact of such, will be conducted within the next phases of the project.

6. Acknowledgements

HySeas III consortium is comprised by Ferguson Marine (Scotland), the University of St Andrews (Scotland), Orkney Islands Council (Scotland), Kongsberg Maritime (Norway), Ballard Power Systems Europe (Denmark), McPhy (France), Interferry (Belgium/US) and DLR – German Aerospace Center acting as main contributor of this document. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 769417. Additionally, we would also like to thank all project partners of HySeas III who kindly contributed with data and feedback.

References

[1] T. Smith, E. O'Keeffe, L. Aldous, S. Parker, C. Raucci and M. Traut, “Third IMO GHG Study 2014,” 2015. [Online]. Available: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf. [Accessed 02 10 2019].

[2] International Maritime Organization, “Annex 11 - Resolution MEPC.304(72) - Initial IMO strategy on reduction of GHG emissions from ships,” 13 04 2018. [Online]. Available: http://www.imo.org/en/OurWork/Documents/Resolution%20MEPC.304(72)%20on%20Initial%20IMO%20Strategy%20on%20reduction%20of%20GHG%20emissions%20from%20ships.pdf. [Accessed 02 10 209].

[3] Project HySeas III, “The Project,” 2019. [Online]. Available: https://www.hyseas3.eu/. [Accessed 16 10 2019].

[4] BIG HIT, “About the Project,” 2019. [Online]. Available: https://www.bighit.eu/about. [Accessed 16 10 2019].

[5] SURF 'N' TURF Project, “SURF 'N' TURF,” 2019. [Online]. Available: http://www.surfnturf.org.uk/. [Accessed 16 10 2019].

[6] IHS Markit, “SeaWeb,” 2019. [Online]. Available: https://maritime.ihs.com/Account2/Index. [Accessed 16 10 2019].

[7] MarineTraffic – Global Ship Tracking Intelligence, “MarineTraffic,” 2019. [Online]. Available: https://www.marinetraffic.com. [Accessed 10 16 2019].

[8] DIN Deutsches Institut für Normung e.V., Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen (ISO 14044:2006); Deutsche und Englische Fassung EN ISO 14044:2006, Berlin, 2006.

[9] DIN Deutsches Institut für Normung e.V., Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040:2006); Deutsche und Englische Fassung EN ISO 14040:2006, Berlin, 2006.

[10] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema, “The ecoinvent database version 3 (part I): overview and methodology.,” *The International Journal of Life Cycle Assessment,* p. 1218–1230, 21(9).

[11] Project HySeas III, *Personal communication,* 2019.

[12] Volvo Penta, “IPS650/800,” 219. [Online]. Available: https://pubs.volvopenta.com/ProdDocs/Home/Disclaimer?publication=47709257&lang=en-US. [Accessed 08 10 2019].

[13] K. Bekel and S. Pauliuk, “Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany,” *The International Journal of Life Cycle Assessment,* pp. 1-18, 2019.

[14] M. Miotti, J. Hofer and C. Bauer, “Integrated environmental and economic assessment of current and future fuel cell vehicles,” *International Journal of Life Cycle Assessment ,* pp. 22:94-110, 2017.

[15] L. A.-W. Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen and A. H.

Strømman, “Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack,” *Journal of Industrial Ecology,* pp. Volume 18, Number 1, 2013.

[16] J. Frith, “Lithium-Ion Batteries: The Incumbent Technology,” 08 04 2019. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/6.1_frith_energy_storage.pdf. [Accessed 16 10 2019].

[17] Ballard, “FCveloCity-HD (Product Specifications),” 2019. [Online]. Available: https://www.ballard.com/docs/default-source/motive-modules-documents/fcvelocity_hd_family_of_products_low_res.pdf. [Accessed 16 10 2019].

[18] Leclanché, “Energy M2 Modules (G-NMC),” 2019. [Online]. Available: https://www.leclanche.com/wp-content/uploads/2019/04/LECLANCHE-plaquette-G-NMC-KMWEB.pdf. [Accessed 16 10 2019].

[19] MARIKO, FMA, VKA RWTH Aachen University (Project MariGreen), “Perspectives for the Use of Hydrogen as Fuel in Inland Shipping - A Feasibility Study,” 10 2018. [Online]. Available: http://marigreen.eu/wordpress_marigreen/wp-content/uploads/2018/11/Hydrogen-Feasibility-Study-MariGreen.pdf. [Accessed 10 28 2019].

[20] J. J. Minnehan and J. W. Pratt, “SAND2017-12665: PRactical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels,” Sandia National Laboratories, 2017. [Online]. Available: https://energy.sandia.gov/wp-content/uploads/2017/12/SAND2017-12665.pdf. [Accessed 16 10 2019].

[21] J. W. Pratt and L. E. Klebanoff, “SAND2016-9718: Feasibility of the SF-BREEZE: A Zero-Emission, Hydrogen Fuel Cell High-Speed Passenger Ferry,” 09 2016. [Online]. Available: https://energy.sandia.gov/transportation-energy/hydrogen/market-transformation/maritime-fuel-cells/sf-breeze/. [Accessed 16 10 2019].

[22] E4Tech, “The Fuel Cell Industry Review 2018,” 2018. [Online]. Available: http://www.fuelcellindustryreview.com/. [Accessed 16 10 2019].

[23] A. M. Jokela, I. G. Polden, O. S. Tanum and V. Seim, “Livsløpsanalyse av hydrogen-elektrisk ferje,” 28 05 2018. [Online]. Available: https://hvlopen.brage.unit.no/hvlopen-xmlui/handle/11250/2573591. [Accessed 02 10 2019].

[24] J. C. Gomez Trillos, D. Wilken, U. Brand and T. Vogt, “Life Cycle Assessment of a Hydrogen and Fuel Cell RoPax Ferry Prototype,” *Progress in Life Cycle Assessment 2019 ,* p. (In publication), 2019.

[25] Norled, “Norled to build the world's first hydrogen ferry,” 10 01 2019. [Online]. Available: https://www.norled.no/en/news/norled-to-build-the-worlds-first-hydrogen-ferry/. [Accessed 16 10 2019].

[26] European Commission, “Reducing emissions from the shipping sector,” 2019. [Online]. Available: https://ec.europa.eu/clima/policies/transport/shipping_en#tab-0-0. [Accessed 02 10 2019].

[27] Fuel Cells And Hydrogen Joint Undertaking, “FLAGSHIPS project to deploy two hydrogen vessels,” 2019. [Online]. Available: https://www.fch.europa.eu/news/flagships-project-deploy-two-hydrogen-vessels. [Accessed 16 10 2019].